



All-dielectric Terahertz Waveguides, Devices, and Techniques

by

Harrison Lees

In fulfilment of the requirements for the degree of

Doctor of Philosophy

February 2025

Faculty of Science, Engineering, and Technology

Terahertz Engineering Laboratory

The University of Adelaide

Contents

Abstract	vii
Declaration	ix
Acknowledgements	xi
Conventions	xiii
Publications	xv
 I Context	 1
1 Introduction to Terahertz Technology	3
1.1 Terahertz Waves	3
1.2 Towards Applications	3
1.2.1 Short-range Wireless Communications	4
1.2.2 Imaging & Sensing	5
1.3 State of Terahertz Technologies	7
1.3.1 Sources	7
1.3.2 Detectors	8
1.3.3 Platforms for Systems	10
1.4 Outline of Thesis	15
 2 Substrateless Silicon Waveguides	 17
2.1 Introduction	17
2.1.1 Silicon	17
2.1.2 Evolution from Silicon on Insulator Waveguides	18
2.2 Waveguide Variants	18
2.2.1 Slab	18
2.2.2 Band-Gap Photonic Crystal	18
2.2.3 Effective-medium Clad	20

2.2.4	Unclad	20
2.2.5	Slot	21
2.2.6	Rib Waveguides	21
2.3	Passive Components	21
2.3.1	Coupling to Hollow Metallic Waveguides	21
2.3.2	Routing	22
2.3.3	Evanescent Couplers	23
2.3.4	Resonators	23
2.3.5	Filters	24
2.3.6	Polarisation Control	26
2.3.7	Antennas	26
2.4	Tunability	27
2.4.1	Mechanical	28
2.4.2	Electro-optic Effect	28
2.4.3	Thermo-optic Effect	28
2.4.4	Photo-electric Effect	29
2.5	Hybrid Integration of Sources and Detectors	30
2.5.1	Hybrid Integrated Sources	30
2.5.2	Hybrid Integrated Detectors	31
2.6	Integrated systems & Applications	31
2.6.1	Integrated Sensing Systems	32
2.6.2	Integrated Imaging Systems	32
2.6.3	Integrated Communication Systems	32
2.7	Conclusion	33

II Terahertz Integrated Circuits 35

3 Extreme Skin-Depth Waveguides 37

3.1	Introduction	37
3.2	Theory and Design	38
3.2.1	Coupling Suppression with Anisotropic Cladding	38
3.2.2	Supporting Effective Medium	40
3.3	Results	40
3.3.1	Propagation Properties	42
3.3.2	Coupling suppression	44
3.4	Conclusion	44

4 Rib Waveguides 47

4.1	Introduction	47
4.2	Analysis	48
4.2.1	Modal Analysis	48
4.2.2	Coupling to WR3.4 Waveguide	50
4.2.3	Bending	52
4.3	Experimental Characterisation	53
4.4	Conclusion	55
5	Guided Wave Components	57
5.1	Arbitrary Ratio Power Divider	57
5.1.1	Design	58
5.1.2	Fabrication & Experimental Verification	59
5.2	Thermo-optic Phase Shifter	59
5.2.1	Augmented Double Archimedean Spiral Waveguide	61
5.2.2	Resistive Heater Phase Shifter	62
5.3	Ring Resonator for Liquid Sensing	64
5.4	Conclusion	65
6	Antennas	67
6.1	Leaky-wave Antenna	67
6.1.1	Antenna Design	68
6.1.2	Leaky-wave Antenna Characterization	73
6.2	Galilean Telescope Antenna	77
6.2.1	Antenna Design	77
6.2.2	Prototype Measurements	82
6.3	Conclusion	84
III	Techniques Towards Applications	85
7	Leaky-wave Radar	87
7.1	Introduction	87
7.2	Theoretical Analysis of Performance	89
7.3	Multi-Target Tracking	91
7.4	Liquid Sensing	92
7.5	Vibrometry on Multiple Targets	94
7.6	Conclusion	95
8	Terahertz Swept Source Coherence Tomography	97
8.1	Introduction	97

8.2	Sample Characterisation with Frequency-Domain Terahertz Coherence Tomography	99
8.2.1	General concept of Swept-Source Terahertz Coherence Tomography	99
8.2.2	Characterisation of In-container Liquid with Known Phase Information	100
8.2.3	Characterisation from Absolute Reflections Spectrum (Swept-Source Terahertz Coherence Tomography)	101
8.3	Application to In-Container Liquids	103
8.4	Conclusion	107
IV	Conclusion	109
9	Conclusion	111
9.1	Thesis Summary	111
9.2	Outlook	112
9.2.1	Terahertz Integrated Circuits	112
9.2.2	Techniques Towards Applications	112
9.3	Concluding remarks	112
	Bibliography	113

Abstract

In the past decades there have been significant advances in millimetre-wave technologies such that commercial systems are now entering the market and being incorporated into the 5G telecommunications network. Simultaneously, optical photonic systems have also seen widespread adoption, with fiber optic networks forming the backbone of the global telecommunication network. Between these two are terahertz waves, a vast, but underutilised band of electromagnetic spectrum commonly defined from 0.1 to 10 THz. In part it is neglected due to technical challenges, namely, limited available power from practical sources and the lack of efficient devices. Nevertheless, though these challenges exist, overcoming them will unlock increasingly valuable spectrum, well suited for high-speed, short range wireless communications, and non-destructive evaluation. Recently, advances in diode, frequency multiplier, and photonic based terahertz sources have made terahertz generation more accessible, bringing practical terahertz devices substantially closer to reality. To compliment these modern sources, efficient components and complimentary techniques for analysis are required to enable widespread adoption.

In recent years, all-dielectric waveguides, and specifically substrateless silicon waveguides, have emerged as a candidate foundation for compact and efficient terahertz integrated systems. Through the etching of high-resistivity silicon wafers, waveguides and a wide array of passive components can be realised monolithically. This is achieved by employing effective medium techniques to locally vary the permittivity through a process of micro-patterning with sub-wavelength lattices. Conventionally, rotationally symmetric lattices are employed, resulting in in-plane isotropic effective mediums. Here, substrateless anisotropic effective mediums are employed to realise a so called extreme-skin depth waveguide, enabling compact circuitry by suppressing crosstalk between adjacent waveguides. More broadly, a scheme for including substrateless anisotropic effective medium is demonstrated which brings an additional degree of freedom to all-silicon devices. More generally, there are many components which are desirable but yet to be realised on this substrateless platform. Of these, an arbitrary ratio power divider, a thermo-optic phase shifter, a wideband endfire antenna, and a leaky-wave antenna are presented here. These contributions span foundational techniques, passive, and tunable devices, bringing a wide range of necessary functionality to a fundamentally efficient platform.

While passive components are foundational, they are not solely sufficient for practical terahertz systems, they must be integrated with active components and supported by signal processing techniques. For this reason, leaky-wave radar and terahertz swept-source optical coherence tomography, two signal processing techniques for terahertz sensing are described here to address current deficiencies. First, to circumvent the need for beam-forming, which has proved to be an ongoing challenge in the terahertz regime, leaky-wave radars have emerged but are still in their infancy. Theoretical analysis of these systems based upon the leaky-wave antenna employed is presented, showing the intrinsic link between field of view, operating bandwidth, depth, and angular resolution. This analysis is complemented by experimental demonstrations of the technique for real-time scene acquisition. Additionally, such that incoherent detectors can be deployed in place of more costly coherent detectors in sensing applications, an analysis of multi-layer systems with terahertz swept-source optical coherence tomography is detailed, specifically focusing on sensing in-container liquids. Together, these signal processing techniques facilitate the simplification of functional systems without severely compromising performance.

The efficient integrated components and complimentary signal processing techniques proposed seek to address some of the practical limitations which currently prohibit the widespread adoption of terahertz technologies. Specifically, by enhancing the functionality with new components and implementation of signal processing techniques which enable hardware simplification, we expect that practical terahertz systems for sensing and communications systems will emerge.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Harrison Lees

7/2/2025

Acknowledgements

This thesis and the research there in would not have been possible without the support of Withawat Withayachumnankul. I started working with Withawat in the Summer of 2018 as a research intern trying to measure the refractive index of thin films, and have worked continuously in his Terahertz Engineering Laboratory ever since—as an intern, an Honours student, and since 2021, a doctoral candidate. Withawat’s unrivaled commitment to terahertz research is beyond all else, inspiring, an evergreen spring of motivation for aspiring researches, myself included. I would like to thank Withawat for his time over the years and look-forward to continuing our work together.

In 2021, Daniel Headland joined my supervisory panel as my long-distance co-supervisor. Daniel has a unique approach to research, and has earned a reputation for his creativity and unconventional sense of humour, traits that I readily tried to integrate into my own outlook. When working with Daniel there is an unexplainable aura, a sense that with enough careful, first-principles thought, finite-element analysis, and raw electromagnetic intuition, all problems can be solved—and in many cases a solution emerges. I would like to thank Daniel for his dedicated supervision and look forward to what will come.

The Terahertz Engineering Laboratory has been my second home for the past 6 years and in this time I have been joined by many excellent colleagues. To Wendy S. L. Lee and Weijie Gao who mentored me as an undergraduate student, your foundational lessons have stayed with me. To, Xiaolong You, Mohamed Shehata and Stephen Li, my predecessors who contributed so much fruitful discussion throughout my candidature. A special thanks, to Panisa Dechwechprasit whose friendship and camaraderie was always appreciated. To Linxi Chen, Sakib Quader, Mariam Abdullah, Miantong Sun, James Tam, Chenchu Ma, and Komal Iqbal, it has been a privilege to watch and learn from you all. Finally, a special thanks to Bryce Chung, I estimate that we have spent more time in the lab together than any other pairing, it would have been impossible without your dedicated support.

Beyond my direct supervisors and colleagues I have also been joined by a host of other supervisors, hosts, and mentors throughout my research, and I am thankful to them all. Christophe Fumeaux, Shengjian Jammy Chen, Nghia Nguyen Trong, and their students have all influenced me throughout this time. Matthew Ibrahim, for his regular insights throughout my candidature. From University of New South Wales, Shaghik Atakaramians who hosted my visit to Sydney. From the University of Duisburg-Essen, Jan C. Balzer, Niels Benson, Andreas Klein, and their respective groups, who hosted my stay in Duisburg. From Osaka University, Masayuki Fujita, whose assistance has been greatly appreciated. From Universidad Carlos III de Madrid, Guillermo Carpintero del Barrio, for his kindness in hosting my short visit to Madrid.

I would like to acknowledge the fabrication experts and technical staff who very literally made my research a reality. At the University of Adelaide, Danny Di Giacomo and Brandon Pullen. From Australian National Fabrication Facility at The University of Sydney, Jacky He and Gloria Qiu. From The Royal Melbourne Institute of Technology, Rajour Tanyi Ako. From Osaka Research Institute of

Industrial Science and Technology, Shuichi Murakami. From the University of Duisburg-Essen, Masoud Sakaki. Without you all, my work is entirely theoretical.

More broadly, I would like to thank the terahertz community. Contrary to some people's perception academia is very social, so to everyone I have collaborated with, or simply had dinner, a beer, or a conference coffee with, I cherish your time, and hope that we can see each other in the future.

To my family, who have supported my academic endeavours for 22 years now. My mother, Marie-Louise, and father, Graham, have always been a source of inspiration academically, but their ongoing emotional support and nurture has been their greatest gift. My brothers, Tim and Ethan, are my closest confidants and frequently inspire me beyond my research.

To my partner, Imogen Larcombe, your support throughout my candidature, as in life, has been unwavering. It is impossible to quantify your impact on this Thesis, but without you I am certain it would be lesser.

Conventions

Typesetting

This thesis is typeset using L^AT_EX.

Referencing

IEEE style is employed for referencing and citation in this thesis.

System of Units

The International System of Units is used.

Spelling

Australian English spelling is adopted.

Terminology

Terminology is derived from recent, relevant academic literature. Due to the subject matter being between two mature fields, microwave electronics and integrated optics, where each field describes the same fundamental concept with different terminology an explanation is made.

Publications

First Author Journal Publications

- **Harrison Lees**, Cameron Hayes, and Withawat Withayachumnankul, Terahertz coherence tomography for in-Container liquid characterization, *Journal of Selected Topics in Quantum Electronics*, vol. 29, no. 5, art. no. 8600408, (2021).

Contribution: HL contributed theoretical analysis, experimentation, data processing, and manuscript writing.

- **Harrison Lees**, Daniel Headland, Shuichi Murakami, Masayuki Fujita, and Withawat Withayachumnankul, Terahertz radar with all-dielectric leaky-wave antenna, *APL Photonics*, vol. 9, art. no. 036107, (2024).

Contribution: HL contributed theoretical analysis, device design, experimentation, data processing, and manuscript writing.

- **Harrison Lees**, Daniel Headland, and Withawat Withayachumnankul, Terahertz extreme skin-depth waveguides, *IEEE Transactions on Terahertz Science and Technology*, vol. 14, no. 5, pp 758–767, (2024).

Contribution: HL contributed theoretical analysis, device design, experimentation, data processing, and manuscript writing.

- **Harrison Lees**, Masoud Sakaki, Daniel Headland, Niels Benson, Jan C. Balzer, and Withawat Withayachumnankul, Terahertz stepped-height waveguide with 3D-printing, *IEEE Transactions on Microwave Theory and Techniques*, Early Access, (2024).

Contribution: HL contributed theoretical analysis, device design, experimentation, data processing, and manuscript writing.

Contributing Author Journal Publications

- Jie Liang, Weijie Gao, **Harrison Lees**, and Withawat Withayachumnankul, All-silicon terahertz planar horn antenna, *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 11, pp 2181–2185 (2024).

Contribution: HL contributed experimentation and data processing.

- Panisa Dechwechprasit, **Harrison Lees**, Daniel Headland, Christophe Fumeaux, and Withawat Withayachumnankul, 1-to- N terahertz integrated switches enabling multi-beam antennas, *Optica*, vol. 10, no. 11, pp. 1551-1558 (2023).

Contribution: HL contributed device design, experimentation, and data processing.

- Jade Carter, **Harrison Lees**, Qigejian Wang, Shengjian Jammy Chen, Shaghik Atakaramians, and Withawat Withayachumnankul, Terahertz Properties of Common Microwave Dielectric Materials, *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 44, no. 11, pp. 873–884 (2023).

Contribution: HL contributed experimentation, and data processing.

- Daniel Headland, Ashish Kumar, **Harrison Lees**, Withawat Withayachumnankul, and Guillermo Carpintero, Matched dielectric slot waveguide as an all-dielectric terahertz magnetic dipole, *Optics Letters*, vol. 49, no. 5, pp. 1361–1364 (2024).

Contribution: HL contributed experimentation, and data processing.

First Author Conference Publications

- **Harrison Lees**, Daniel Headland, and Withawat Withayachumnankul, Integrated, broadband, arbitrary-ratio power division based on air-silicon effective mediums, *46th International Conference on Infrared, Millimeter, and Terahertz Waves*, (2022).

Contribution: HL contributed theoretical analysis, device design, and manuscript writing. Submission was presented as an oral presentation.

- **Harrison Lees**, Cameron Hayes, Vladimir Jiranek, and Withawat Withayachumnankul, In-container evaluation of ethanol content with terahertz technology, *Australian Wine Industry Technical Conference*, (2022).

Contribution: HL contributed theoretical analysis, device design, experimentation, and manuscript writing. Submission was presented as a poster presentation and was awarded the ‘In the Wine Light’ People’s Choice and Judge’s Choice awards.

- **Harrison Lees**, Daniel Headland, and Withawat Withayachumnankul, Substrateless terahertz integrated platform: low-cross-talk waveguide crossing, *International Symposium on Future Trends of Terahertz Semiconductor Technologies (TST2022)*, (2022). (invited)

Contribution: HL contributed theoretical analysis, device design, and manuscript writing. Submission was presented as an invited oral presentation by Withawat Withayachumnankul.

- **Harrison Lees**, Masoud Sakaki, Daniel Headland, Niels Benson, Jan C. Balzer, and Withawat Withayachumnankul, Single-mode rib waveguide for the terahertz range using 3D printed alumina, *47th International Conference on Infrared, Millimeter, and Terahertz Waves*, (2023).

Contribution: HL contributed theoretical analysis, device design, experimentation, and manuscript writing. Submission was presented as a keynote oral presentation and was recognized as an outstanding student paper, and runner-up in the student paper competition.

- **Harrison Lees** and Withawat Withayachumnankul, Terahertz antenna measurement techniques, *Australasian Symposium on Antennas*, (2024) (invited).

Contribution: HL contributed, experimentation, data processing, and manuscript writing. This invited talk was presented at the 2024 Australasian Symposium on Antennas in the

Antenna Measurement Technique Australia workshop session.

- **Harrison Lees**, Daniel Headland and Withawat Withayachumnankul, Simultaneous multi-target monitoring with terahertz leaky-wave radar, *48th International Conference on Infrared, Millimeter, and Terahertz Waves*, (2024).

Contribution: HL contributed, experimentation, data processing, and manuscript writing. This submission was accepted for an oral presentation, though the conference is upcoming.

Contributing Author Conference Publications

- Bryce Chung, **Harrison Lees**, Daniel Headland, and Withawat Withayachumnankul, Broadband and efficient terahertz beam scanning using a 3D-printed Risely prism, *48th International Conference on Infrared, Millimeter, and Terahertz Waves*, (2022).

Contribution: HL contributed experimentation, and data processing.

- Bryce Chung, **Harrison Lees**, and Withawat Withayachumnankul, Probing live PN junctions with terahertz waves, *48th International Conference on Infrared, Millimeter, and Terahertz Waves*, (2023).

Contribution: HL contributed conception, experimentation, and data processing.

- Chenchu Ma, **Harrison Lees**, Markus Wagner, and Withawat Withayachumnankul, Design of terahertz all-dielectric antenna via optimisation, *22nd International Symposium on Communications and Information Technologies*, (2023).

Contribution: HL contributed conception and device design.

List of Figures

1.1	State-of-the-art terahertz communications demonstrations.	4
1.2	State-of-the-art terahertz imaging demonstrations.	5
1.3	State-of-the-art terahertz sources.	8
1.4	State-of-the-art terahertz detectors.	9
1.5	State-of-the-art terahertz waveguides.	11
1.6	Comparison of terahertz waveguide platforms.	14
2.1	Variants of all-silicon terahertz waveguides.	19
2.2	Coupling all-silicon waveguides to hollow-metallic waveguides.	22
2.3	All-silicon routing components.	22
2.4	All-silicon evanescent couplers.	23
2.5	All-silicon resonators.	24
2.6	All-silicon filters.	25
2.7	All-silicon polarisation manipulating devices.	26
2.8	All-silicon antennas.	27
2.9	All-silicon mechanically tuned devices.	28
2.10	All-silicon devices tuned by photo-excitation.	29
2.11	Hybrid integration of sources and detectors with all-silicon waveguides.	30
2.12	Integrated systems based upon all-silicon waveguides.	31
3.1	Substrateless terahertz waveguides.	39
3.2	Analysis of the effect of cladding anisotropy on evanescent field decay.	40
3.3	Modal distributions of extreme skin-depth waveguide.	41
3.4	Mechanical support for extreme skin-depth waveguides.	41
3.5	Fabrication and measurement of straight extreme skin-depth waveguides of various lengths.	43
3.6	Fabrication and measurement of extreme skin-depth waveguides with different structural supporting waveguides.	44
3.7	Fabrication and measurement of evanescent couplers.	45
4.1	Schematic of the rib waveguide.	48

4.2	Modal analysis of alumina rib waveguides.	49
4.3	Schematic of WR3.4–alumina rib coupler.	51
4.4	Bending loss of alumina rib waveguides.	52
4.5	Design of transition between two rib waveguides with varying slab thickness.	53
4.6	Measurement of fabricated alumina rib waveguides.	54
5.1	Schematic diagram of arbitrary ratio power divider.	58
5.2	Experimental characterisation of integrated power dividers.	60
5.3	Thermo-optic effect on unclad silicon waveguides.	61
5.4	Augmented Archimedean spiral.	62
5.5	Thermo-optic phase shifter.	63
5.6	Design of alumina ring resonator.	65
5.7	Measurements of alumina ring resonator.	66
6.1	Proposed leaky-wave radar module.	68
6.2	Characteristics of waveguide-slab leakage.	69
6.3	Design of the continuously leaking waveguide.	70
6.4	GRIN anti-reflection structure design overview.	71
6.5	Auxiliary 3D-printed COC lens.	73
6.6	Experimental setup for leaky-wave antenna characterization.	74
6.7	Experimental characterization of the proposed leaky-wave antenna.	76
6.8	Schematic of Galilean telescope.	77
6.9	Proposed Galilean telescope antenna.	78
6.10	Design of tapered rod feed.	78
6.11	Design of integrated diverging lens.	79
6.12	Design of impedance matched Mikaelian lens.	81
6.13	Fabricated Galilean Telescope Antenna.	83
7.1	Visual description of the spatial mapping process used for single shot radar image retrieval.	88
7.2	Radar resolution parameters calculated from the all-silicon leaky-wave antenna.	89
7.3	Overview of leaky-wave radar system. (a) Photograph of all-silicon leaky-wave antenna, packaged with 3D-printed COC lens and coupled to WR3.4 waveguide. (b) Annotated photograph of laboratory system.	92
7.4	Demonstration of multi-object tracking with leaky-wave radar.	93
7.5	Demonstration of liquid differentiation with leaky-wave radar.	94
7.6	Simultaneous monitoring of time-varying targets with leaky-wave radar.	95
8.1	Visualisation of the band-unlimited profile in the time domain arising from a series of 3 interfaces, demonstrating the mathematical foundations of optical coherence tomography.	98
8.2	Description of the container system under analysis.	100

8.3	Annotated photograph of experimental setup.	103
8.4	Comparison of Fresnel model to measured data for drinking water.	104
8.5	Experimentally measured peak amplitudes as a function of angle of incidence.	105
8.6	Measured reflection profiles as the proportion of water to ethanol is adjusted.	105
8.7	Reflection coefficient extracted from measurement of aqueous ethanol solutions.	106
8.8	Reflection coefficient arising from an in-container sample of wine measured in real time at a sampling rate of 10 Hz.	106

List of Tables

1.1	Comparison of terahertz waveguide platforms.	14
6.1	Comparison of experimentally demonstrated leaky-wave antennas and this work. . . .	75

Part I

Context

Chapter 1

Introduction to Terahertz Technology

1.1 Terahertz Waves

Electromagnetic waves with frequency in the range 100 GHz to 10 THz are typically referred to as terahertz radiation. This spectral range is situated between the microwave and the optical far-infrared ranges. As such the technologies that inhabit this space tend to inherit properties from both of the more mature adjacent fields: microwave electronics and optical photonics. In free space, the wavelength of terahertz waves is typically sub-millimetre, on the same physical scale as a pencil tip, distinguishing them from the larger millimetre waves. The terahertz range is frequently characterised by increasing path loss experienced as the frequency scales and strong resonances with water, which hinder free-space transmission, and lead to scarce measurement of ambient terahertz waves under atmospheric conditions [1, 2]. Compounding this, there are few avenues for the natural generation of terahertz waves, examples of which being red-shifted stellar sources and limited thermal and vibrational emissions from cosmic bodies, the detection of which motivates terahertz astronomy [3–5]. At the same time, many of the artificial, electronic and photonic, generation techniques commonly employed in other frequency ranges, also begin to break down in this band, leading to what is colloquially known as the terahertz gap. In recent decades there has been a concerted effort to close this gap [6–8] from both ends of the spectrum with the development of viable sources, and functional components to harness their output. Materially, this effort is driven by the finite nature of the electromagnetic spectrum. As the microwave and millimetre wave bands become ever more congested, new bands are required to satiate the ceaseless demand for additional bandwidth, primarily for wireless communications, but also including imaging and sensing applications. Though it has been common to consider this range holistically, owing to the wideband nature of terahertz spectroscopy [9], in practice it is nigh impossible to develop functional devices that operate over this colossal band. As such most of the research is focused on smaller sub-bands, typically individual or combinations of WR bands inherited from hollow metallic waveguides. This thesis focuses on technologies in the low-terahertz or sub-terahertz range between 140 GHz and 1.1 THz, a range which spans the WR5 to WR1 rectangular waveguide bands. In this introductory chapter, the motivation for developing terahertz devices, and a broad overview of available terahertz technologies is reviewed.

1.2 Towards Applications

Whilst originally the development of terahertz technologies was primarily motivated by the scientific community, today the focus has shifted towards developing functional systems for societal adoption. Specifically, sensing and communications are the two largest areas of research being conducted today. In this section an overview of the challenges and opportunities for both streams is reviewed.

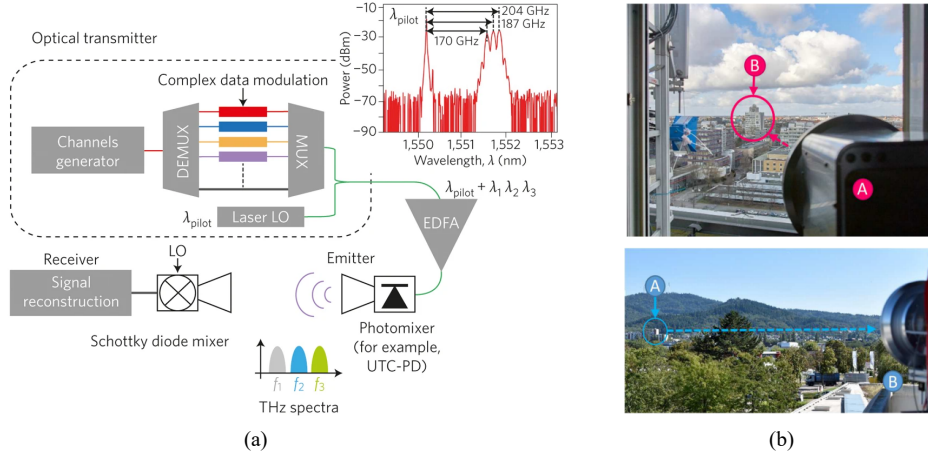


Figure 1.1: State-of-the-art terahertz communications demonstrations. (a) Terahertz photonics based communications system, adapted from [10] reproduced with permission from Springer Nature. (b) Terahertz communications over 1 km, adapted from [11], © 2020 IEEE .

1.2.1 Short-range Wireless Communications

Today, digital data traffic is still rapidly growing. This aggregate data transfer is facilitated by a vast network of intertwined, wired and wireless, technologies. Today's optical fibre links can achieve truly monumental data rates, with massive bandwidths and record-breaking aggregate data rates of 22.9 PBit/s [12]. In the realm of wired communication, there is little room for terahertz communication, optical technologies are simply superior due to the massive absolute bandwidths, aided by efficient generators and low-loss, low-cost, transmission lines in the form of optical fiber. For example, the optical C-band [13] alone spans 4.3 THz, broader than the entire spectrum considered in this thesis. However, for wireless links the transition to optical technologies is difficult due to excessive free-space loss which requires highly directional, high-power laser sources to overcome. In turn, this presents serious challenges with alignment [14]. Compounding this, free-space optical links must be un-obstructed, and are sensitive to atmospheric conditions [15]. Due to these issues, coupled with the inherent dangers of the free-space propagation of high-power optical radiation, there has not been widespread adoption of high-speed wireless optical communications [16]. As such, for wireless communications, microwave devices have long been the default technology. The absence of high path-loss allows for low gain antennas to be used to provide broad coverage. Here, the free-space path loss is lower, and generation is more efficient, providing high signal-to-noise ratios that enable complex modulation schemes, though the bandwidth is limited. As such, the natural niche for terahertz communications is broadband, high-speed communications over short distances where a wired connection is impractical—typical wireless LAN environments that are handled today by Wi-Fi. Simultaneously, by migrating some of this load from microwave to terahertz, the existing spectrum can be freed for long-range applications. This vision for terahertz communications is captured in the IEEE standard 802.15.3-2023 [17], colloquially known as 6G.

Today, demonstrations of terahertz communications in controlled settings are commonplace, with continuing improvements in aggregate data rates, system efficiency, and range. Broadly speaking there are two competing approaches to terahertz communications, namely electronic and photonic [10], though it is increasingly common to see hybrid systems [18]. Electronic systems are commonly built around frequency multipliers used to generate terahertz power, and millimetre monolithic integrated circuits (MMIC), and can produce power on the order of milliwatts, but contribute significant phase noise due to the simultaneous multiplication of the intrinsic phase noise. Conversely, optical systems that utilise photo-diodes can leverage high Q -factor optical resonators to produce terahertz power with low phase noise [19], but with less power than most electronic sources, owing to low optical to terahertz conversion efficiencies. Typically, this trade-off between power and phase-noise results in higher aggregate data rates in photonic systems as they are more amenable to high-order Quadrature Amplitude Modulation (QAM) [20], but over shorter distances. Nevertheless, with state-of-the-art

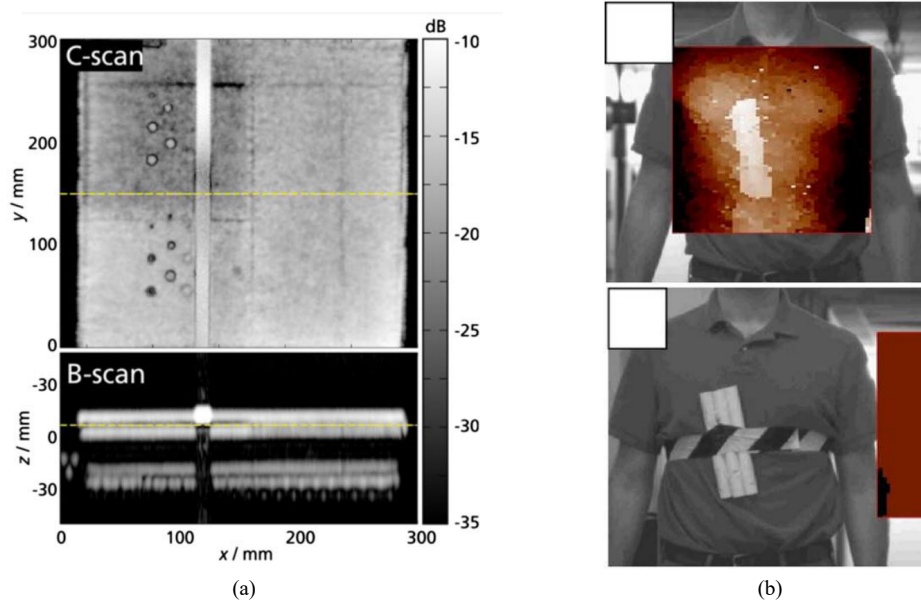


Figure 1.2: State-of-the-art terahertz imaging demonstrations. (a) Terahertz non-destructive evaluation of fibreglass composites, adapted from [22]. (b) Terahertz stand-off imaging with focused beam scanner, adapted from [23] Springer, ©2019 K.B. Cooper, et al.

components and high gain antennas, communications over a kilometre is achievable in atmospheric conditions [11, 21]. These experiments are highly encouraging, demonstrating significant progress over the last decade. The next step towards wide-spread use of these systems is standardisation and miniaturisation. To facilitate this and promote widespread adoption, significant innovation in sources, detectors, integrated devices, beam-forming, and signal processing are required.

1.2.2 Imaging & Sensing

At the same time as terahertz communication has gained traction, there has also been accelerating interest in imaging and sensing applications [24, 25], particularly for non-destructive evaluation in industrial settings [26]. As in communications, terahertz imaging seeks to fulfil the capability gap between traditional optical and microwave imaging techniques. Notably, microwaves are excellent for long range sensing, as in radar, but as resolution is intrinsically tied to wavelength cannot achieve the level of resolution required for many applications, such as security screening which require millimetre or sub-millimetre resolution in most cases. In contrast, optical imaging systems have excellent resolution, but struggle to penetrate packaging or multilayer samples, or in the case of X-rays, may cause damage to the item under test. With millimetre resolution and sufficient penetration, terahertz imaging can provide complimentary images [23], as in Fig. 1.2(a). Additionally, evolving out of terahertz spectroscopy, there are additional contrast mechanisms that may be unique to the terahertz range, particularly in crystalline structures [27]. Generally, the contrast mechanism is simply the difference in refractive index or surface profile between materials, resulting in varying reflection intensity. Here it is important to note that many reported contrast mechanisms, particularly in the field of biomedical imaging, are based upon extremely subtle changes in the properties that are extremely difficult to detect outside a laboratory setting [28]. Nevertheless, examination of burns [29], monitoring of drug-delivery [30], corneal reflectometry [31], and the detection of skin-cancers [32] are active areas of interest. With the ability to penetrate many common paints [33], polymer coatings [34], and organic materials [35], terahertz waves are well suited to non-destructive evaluation of industrial products [36]. With sub-millimetre resolution, defects in the structures of composite materials, shown in Fig. 1.2(b), can be readily detected [22, 37]. The research over the previous decades has been primarily focused on reporting these contrast mechanisms without strong consideration for building practical terahertz imaging systems, though in recent years this has changed, with rapid improvements in imaging times

and system footprint [38]. Here, various imaging modalities are reviewed with a focus on limitations and potential improvements.

Focused Beam Imaging

The most rudimentary imaging systems make use of a single source, a single detector, and an optical system to project a focused beam onto a target [39]. Then, either the target or the imaging system is physically moved to scan this focused beam over the target. The lateral resolution of this system is limited by the larger of the spot size of the terahertz beam or the step size of the scanning system. The theoretical limit of the resolution is half the wavelength, where a system is described as diffraction limited. Traditionally, the sample has been moved using a multi-axis stage to achieve a 2D image, with the depth information reconstructed via direct time domain spectroscopy or the inverse Fourier transform in the case of a frequency domain measurement. In this case the depth resolution is limited by the bandwidth of the system. Today, high precision stages are commercially available and rarely inhibit the resolution, though critically they still limit the image acquisition time. Additionally, this scheme requires a cooperative target that is small enough to be mounted to the stage. Though the imaging times for scanned systems have improved in recent years, they are still typically on the order of hours, even for relatively small centimetre-scale targets. To address this, there has been growing interest in beam-steered systems based upon, galvanometers [38], rotating mirrors [23, 40], Risley prisms [41, 42], and telecentric lenses [43] which can rapidly scan focused beams onto a target. These systems are much faster than traditional multi-axis stage systems but often have associated distortions and limited scanning ranges. In spite of this, focused beam imaging still remains the dominant imaging modality, and produces high resolution images with good signal-to-noise ratios [44].

Synthetic Aperture Radar

To address the limitations of focused beam imaging, terahertz synthetic aperture radar has emerged. Here the optical system is removed, and through a process of mathematical correlation, full 3D scene reconstruction is possible by simply moving the source, detector(s), or sample relative to each other [45–47]. While physically this system is much simpler than traditional lens based systems, it is instead computationally intensive, requiring time or high-performance computers to reconstruct images. With enough computing power, the data acquisition and processing time can be less than the time required for focused beam imaging.

Single Pixel Imaging

Alongside these approaches, single shot imaging techniques such as coded aperture arrays or radar based upon frequency scanning antennas have emerged. Coded aperture imaging techniques employ spatial light modulators to vary the illumination of the target [48, 49], while measuring the response, then through algorithmic means the shape of the object can be reconstructed. Here no mechanical parts or beam steering are required, which results in more compact imaging systems. Though, the burden is shifted to the spatial light modulator, which also may limit the performance. Similarly, to avoid mechanical beam steering, and in the absence of solid-state beam-formers, the frequency scanning properties of leaky-wave antennas can be used to build radars [50, 51]. Here the antenna performance becomes critical to determining the imaging performance. These single shot imaging techniques are still emerging and while the preliminary results do not compare to the high resolution images produced by focused beam systems, the image acquisition time is significantly better, on the order of seconds or less, making them suitable for real-time monitoring of time-varying targets.

Terahertz Cameras

Terahertz focal plane detector arrays, so-called terahertz cameras, have emerged as a scalable solution to the issue of imaging with a single detector [52–56]. Instead of individually sampling points, hundreds of thousands of pixels may be simultaneously detected promising to drastically reduce imaging

times. However, this is an entirely new modality of imaging for the terahertz domain. Though it is physically analogous to visible light photography there are key distinctions to be made. First, without strong natural sources, room-temperature terahertz cameras are reliant on the use of a dedicated source to illuminate the scene. Second, unlike at optical frequencies most of the reflection experienced is specular, and most materials do not diffusely scatter terahertz waves, resulting in poor lighting conditions for imaging. In this case, beam homogenising illumination systems must also be implemented to achieve effective lighting [57]. Many reports of imaging with a terahertz camera make use of back lighting, essentially imaging the silhouette of an object placed in front of a terahertz source [58, 59]. In some cases, for example with cooperative targets in an airport, this may be practical, but in many cases this is simply impossible. With this in mind, the utility of the imaging modality is limited. Additionally, though mega-pixel terahertz cameras are available, the physical size of the sensors remain small. This poses issues for imaging, consider that in a full-frame optical camera the sensor is typically 36×24 mm, with 6048×4024 pixels, or a pitch of $6 \mu\text{m}$, or approximately 10 free-space wavelengths. At terahertz frequencies where the wavelengths are on the order of 1 mm, to achieve the same spacing would require a $6 \text{ m} \times 4 \text{ m}$ sensor. Instead, in terahertz cameras by maintaining small sensor sizes, despite the large number of pixels the imaging is simply diffraction limited, producing blurred images at low terahertz frequencies. On top of these constraints, bolometer based cameras are unable to detect the phase information of the received signal, so new signal processing techniques, such as interferometric or holographic [60] techniques, are required to recover the depth information, which incidentally is readily available in time-domain spectrometer or coherent detector systems. At present, the quality of imaging available with camera based systems is hardly comparable to focused or synthetic aperture based systems. There is still a disconnect between the images that are visible in the literature, sometimes acquired over hours with a focused beam system, and what is practically achievable in real-time with existing cameras. While the arrival of terahertz cameras is a significant step towards practical terahertz imaging, the technology is still developing, and dedicated research is still required to attempt to address the limitations.

1.3 State of Terahertz Technologies

In the previous section, the various applications of terahertz technology were discussed. Underpinning both streams of application are state-of-the-art components; sources, detectors, and functional components. Broadly, there are two approaches to realising terahertz technologies, those that are dependent on electronic principles, effectively scaling down microwave devices, and those that are photonics inspired. In modern systems, there are typically both electronic and photonic components, forming hybrid systems, employing various semiconductor platforms, photonic sources, and electronic detectors. Next, the state of the underlying hardware is surveyed. Here, the focus is on integrated technologies, with strong preference for technologies that have prospects for widespread use, so compact, room-temperature, devices are preferred, while bulky, cryogenic devices are excluded. Additional considerations such as cost, fabrication infrastructure, and commercial availability are also important considerations for constructing practical terahertz systems.

1.3.1 Sources

Terahertz sources are a technological bottleneck. There is a perennial dearth of high power and high efficiency sources owing to fundamental limitations in scaling mature technologies to the terahertz range. In recent years there has been continuous marginal gains in semiconductor based sources, frequency multipliers, and resonant sources, which will be expounded upon in the following sections.

Photonic Generation

Photonic generation of terahertz waves employs non-linear rectification of the optical signal to produce terahertz waves, a process of frequency down-conversion. A variety of non-linear devices including photo-conductive antennas [63, 64], PIN diodes [65], non-linear crystals [66], and photo-diodes [61, 67], depicted in Fig. 1.3(a), can be used to achieve this. These devices have the advantage

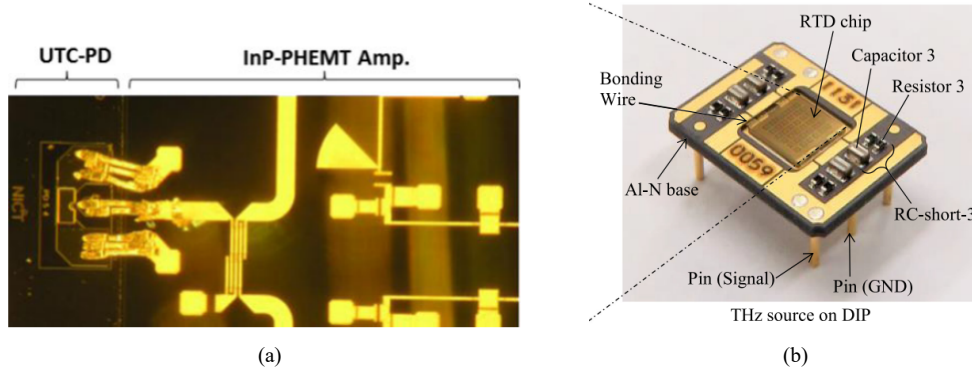


Figure 1.3: State-of-the-art terahertz sources. (a) Uni-travelling carrier photo-diode terahertz source, adapted from [61], © 2016 IEEE. (b) Resonant tunnelling diode array capable of generating 10 mW at 450 GHz, adapted from [62], © 2022 IEEE.

that they can leverage mature optical technologies; optical resonators, mode-locked lasers, optical modulators, and fibre amplifiers. Though the conversion efficiency is typically low, high-power lasers can be used to generate terahertz power on the order of milliwatts [68, 69]. Of course, such high power lasers are impractical for everyday use, while more modest laser power may be sufficient for short-range applications. Alongside the lasers themselves, the full suite of photonic integrated devices also becomes available. This includes electro-optic modulators for producing phase- and amplitude-modulated terahertz signals [10]. One key advantage of these sources is their phase stability as, through the use of mode locked lasers and optical resonators, the produced terahertz waves are remarkably stable, which is beneficial for communications applications [19]. As such, photonic terahertz sources are widely used for communications demonstrations with many of the highest aggregate data rate demonstrations employing high-order phase modulation schemes which are dependent on this phase stability [20].

Frequency Multiplication

From microwave electronics, frequency multipliers employ non-linear effects to up-convert the input frequency to the terahertz range. This is typically achieved through a multiplier chain [70, 71] realised in the form of an integrated circuit, resulting in compact sources. Additionally, both microwave and terahertz amplifiers can be integrated along the multiplication chain to produce output powers on the order of 10s to 100s of milliwatts. However, through this process of multiplication the phase noise of the system is amplified, proportional to $N \log N$, where N is the multiplication factor. Unfortunately, this phase noise is detrimental to communications systems employing phase-modulation. As some of the most mature terahertz devices, they are commercially available and are widely used across imaging and communications.

Resonant Sources

Beyond frequency conversion, terahertz waves can be generated directly through fundamental oscillators, namely through the use of resonant tunnelling diodes [72]. These semiconductor sources are compact, require low bias voltages, are frequency tunable [73], and compatible with amplitude modulation [74]. Additionally, they can also function as sensitive envelope or coherent detectors [75]. The power of single resonator is limited but through array-based techniques as shown in Fig. 1.3(b), based techniques the total output power can reach 10 mW [62]. Though the output power diminishes as the operating frequency increases, resonant tunnelling diodes up to 2 THz have been reported [76]. Together these factors have seen resonant tunnelling diodes used across communications [77] and sensing [78] applications.

1.3.2 Detectors

While the available power from compact sources has remained low, there has been increasing emphasis on compensating for this through sensitive detectors. As such detectors across a wide range of

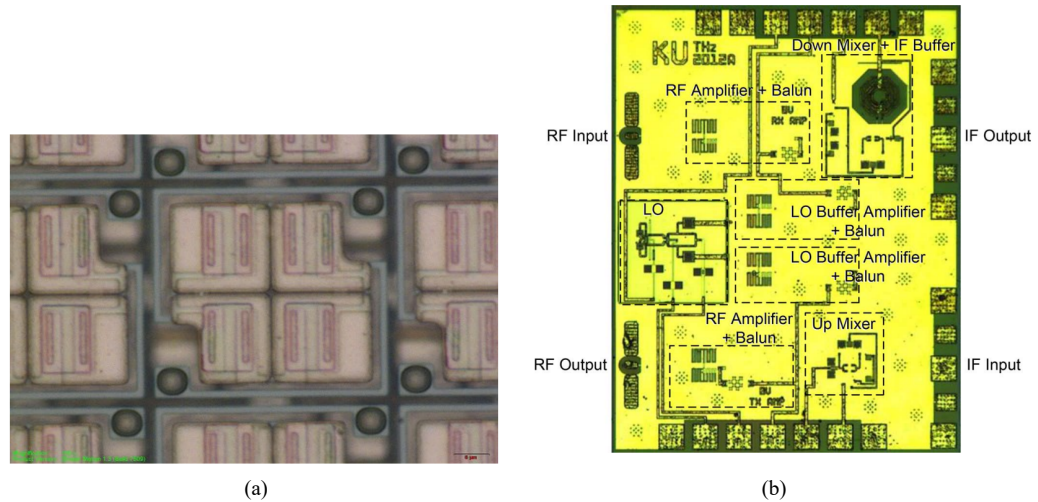


Figure 1.4: State-of-the-art terahertz detectors. (a) Terahertz bolometric detector, adapted from [55], reproduced with permission from Springer Nature. (b) Terahertz heterodyne receiver, adapted from [80], © 2014 IEEE.

mechanisms have been developed. Mirroring sources, these detectors draw upon established optical and microwave detection methods; photo-conductive antennas, bolometric detection, heterodyne detection, and envelope detection. Broadly these methods may be characterised as coherent or incoherent detectors [79], where the defining characteristic is the preservation (or lack thereof) of phase in the detected signal.

Incoherent Detectors

Incoherent detectors, or sometimes called power detectors, respond to the power incident on the detector and as such the phase and amplitude of the incident wave are lost. These detectors have found widespread use in the terahertz domain where coherent detection can prove challenging owing to the added complexity of heterodyne or electro-optic sampling. Instead compact and cost-effective incoherent detectors are often employed where the complexity is prohibitive or avoidable. The two most common incoherent detectors are bolometers and envelope detectors.

Bolometric detection is based upon measuring the change in temperature that is incurred by the absorption of the incident wave. As such, these detectors are generally comprised of an absorber coupled to a thermometer circuit or probe. Here, the absorber can be tailored for frequency dependence to reduce cross-talk as the thermal detection itself is indiscriminate, allowing for narrow or wideband detection [81]. The detection itself is most commonly performed by measuring the change in resistance that occurs due to Joule heating, often with either amorphous silicon [82] or with a vanadium oxide [83]. Typically, these bolometers are compact and can operate at room temperature, making them attractive for detector arrays, to form so-called terahertz cameras [55, 58]. Relying on thermal modulation, the response times of these detectors are typically slow, on the order of kilohertz at room temperatures [84], with the fastest operating at tens of megahertz [85]. Fast bolometric detection is possible at cryogenic temperatures with hot electron bolometers available up to 4.7 THz [86], though the need for cryogenic cooling typically precludes these devices for practical applications [87, 88]. Nevertheless, their simplicity and low cost ensures that bolometers are widely used detectors in cases where slow-detection is acceptable.

As a fast alternative to bolometric detectors, envelope detectors based upon self-mixing inside of diodes have emerged. Envelope detectors are frequently used in the terahertz domain to detect and demodulate amplitude modulated signals. Most these receivers are instantiated with a zero-biased Schottky barrier diode [89] (SBD). Though recently Fermi-level managed barrier diodes [90] have emerged as a competitive alternative and more generally other non-linear diode with a fast response time, such as resonant tunnelling diodes [91], may be purposed as detectors. Schottky detectors are

commercially available up to 1.7 THz, with output bandwidths up to 40 GHz and responsivities on the order of 2000 V/W [92], making them excellent receivers for communications applications [93]. The output bandwidth of the module is rarely limited by the diode detector itself but rather the external electrostatic discharge protection and amplifiers necessary to protect the sensitive junction from damage. Though the receiver itself is incoherent, through additional digital signal processing the phase can be recovered through the implementation of a Generalized Kramers-Kronig receiver so long as the modulated signal is analytic [94]. The high responsivity and broad output bandwidth have made these envelope detectors an indispensable part of most laboratories conducting terahertz telecommunications research. With few drawbacks, beyond incoherence and some non-linearity, these compact and sensitive room temperature detectors are very practical and can be readily integrated to form systems on compact chips for widespread adoption.

Coherent Detectors

In contrast to incoherent detectors, coherent detectors preserve the amplitude and phase information of the detected signal. This has advantages in communications applications where the phase is critical for many common modulation schemes and in sensing applications where the phase information is conventionally used to imply range or complex permittivity information. Further, coherent detectors can provide fine spectral resolution through precise tuning of the local oscillator frequency [95]. These advantages do come at a cost though, with coherent receivers requiring many, more complex components compared to the simpler incoherent detectors, as well as the supply of a local-oscillator signal. In the terahertz range two coherent detection schemes are commonly employed, electro-optic sampling and heterodyne receivers.

Electro-optic sampling makes use of ultra-short optical pulses, typically a femtosecond laser, to gate the detection of the incoming terahertz signal using a photo-conductive antenna [96] or another optical rectification element such as a ZnTe crystal [97]. In this way the instantaneous magnitude of the electric field is imparted onto the pulsed laser which is detected with a photo-diode. Then by delaying the optical pulse, the detection gate is passed over the terahertz wave to indirectly reconstruct the signal in the time domain. This process forms the basis for time-domain spectroscopy where broadband pulses can be accurately measured [98]. It is important to note that though this detection is coherent, it is relatively slow, relying on a physical delay to construct the time domain response, which renders it impractical for most communications applications. Nevertheless, electro-optic sampling is still widely used in laboratory settings, and with the arrival of more compact fibre coupled electro-optic sampling engines these devices are certainly more practical than they once were [99, 100].

As an alternative to electro-optic sampling, heterodyne receivers can be employed as is common in microwave systems. Heterodyne receivers are centred around the concept of down-conversion using a mixer aided by a local oscillator [101, 102] and augmented with various filters [103], amplifiers, and demodulators, to form the recognisable superheterodyne architecture [104]. At terahertz frequencies, many of these components suffer from significant losses in passive devices and poor conversion efficiency in active devices. Additionally, to reduce the load on the baseband hardware typically a high frequency local-oscillator is used, requiring a dedicated source, typically a signal generator connected to a series of frequency multipliers. En face, this seems to result in complexity approaching that of electro-optic sampling but in practice, advances in monolithic millimetre integrated circuits (MMICs) have produced impressive, compact heterodyne receiver modules [80, 105] as depicted in Fig. 1.4(a), though the efficiency is still improving. While many of the conversion losses are unavoidable, the use of planar metallic waveguides, while convenient for monolithic integration, does introduce significant attenuation.

1.3.3 Platforms for Systems

Alongside the sources and detectors, various candidate waveguiding platforms have emerged. Waveguides are the foundation of integrated technologies, facilitating the connection of various components. Though it may be intuitive to simply select a waveguiding platform that is compatible with the source or detector, these materials often result in high losses. However, considering the

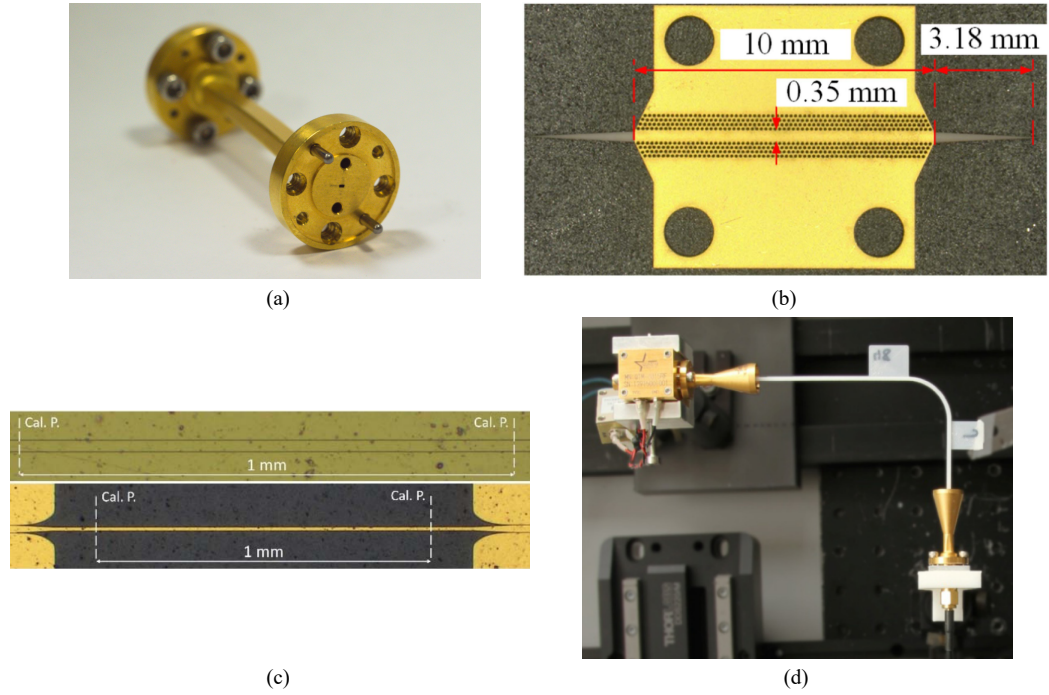


Figure 1.5: State-of-the-art terahertz waveguides. (a) Hollow metallic waveguide. (b) Substrate integrated non-radiative guide, adapted from [106], © 2023 IEEE. (c) Co-planar waveguide, adapted from [107], © 2021 IEEE. (d) 3D printed cyclic-olefin copolymer (COC) waveguide, adapted from [108], © 2024 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement.

low-available power, these high waveguide losses are untenable. As such a hybrid integration modality has emerged, where sources and detectors are embedded within external waveguiding platforms where the efficiency, design flexibility, or physical robustness is improved.

Hollow Metallic Waveguides

Today, the most commonly used waveguides in laboratory sub-terahertz systems are hollow metallic waveguides. Their flanged interfaces, visible in Fig. 1.5(a), make them convenient for building modular, reconfigurable systems by hand, while with micromachining broadband waveguides with relatively low loss can be achieved. The leading cause of loss in these waveguides is Ohmic loss, and as such this loss depends on the metal of choice. In addition to this, surface roughness loss also contributes additional loss, so the surface finish of the internal walls is critical. For metalisation, high conductivity metals, such as gold or copper, are preferred to reduce losses. This is because, unlike at microwave frequencies, the thin oxidation layer that arises on silver components begins to contribute additional dielectric losses. The fabrication of these waveguides is primarily achieved in three ways; 3D printing [109–113], milling [114, 115], and through micromachining [116–118]. Of these, 3D printing, either directly with metals or with polymers and subsequent surface metalisation results in the poorest surface finish and hence the highest loss, on the order of 3 dB/cm in the 220–330 GHz range with additional polishing [109]. Similarly, mechanical milling is usually performed on aluminium to build split-blocks which are then gold coated, and assembled to form the completed waveguide. These waveguides have reported losses on the order of 0.6 dB/cm in the 500–750 GHz range [116]. Finally, to achieve the best surface finish, deep-reactive ion (DRIE) of several silicon wafers which are then bonded and metalised, with low losses in the range 0.2–0.8 dB/cm in the 220–325 GHz range [117]. These three techniques represent three drastically different costs and fabrication complexities. A polymer 3D-printer can be operated by a lay-person and costs on the order of hundreds of dollars, while a precision CNC mill may require a dedicated technician and dedicated infrastructure. In contrast, the DRIE etch fabrication infrastructure is highly specialised, and the fabrication of these waveguides requires the etching and

bonding of multiple wafers with micro-scale precision. This places the fabrication complexity on-par with semiconductor waveguides. As such, most commercially available hollow metallic waveguides are milled split-block form. Beyond this frequency band, the losses continue to scale with frequency as surface roughness is exacerbated relative to wavelength. Today, these waveguides are widely used by the terahertz community with a wide array of sources [119], detectors [120], active components [121], passive devices [113], and antennas [122], housed within or coupled to, hollow metallic waveguides. Part of the value is the modularity afforded by the flanged interface, allowing systems to be temporarily arranged from a library of components manually by lay-people. While this capability is invaluable in an experimental setting, it is not critical for widespread adoption, where device footprint and efficiency are more highly valued. This trend is evident in microwave electronics where planar waveguiding technologies and monolithic integrated circuits dominate today. However, to compete with this mature technology, the same range of components with improved performance must be available.

Planar Metallic Waveguides

Planar waveguides are the basis for modern integrated technologies, where many devices are compiled on a single monolithic structure. As such, there have been attempts to scale microwave planar waveguides to terahertz frequencies. As in hollow metallic waveguides, the presence of metals leads to unavoidable Ohmic losses. However, here there are also additional substrate losses to consider. There has been an active search to find suitable dielectric substrates with low loss at terahertz frequencies, ideally within the range of existing microwave substrates, but so far it seems that many widely available substrates contribute considerable losses [123]. In spite of this, a wide array of terahertz transmission lines based upon planar metallic waveguides have been demonstrated including, co-planar waveguides (CPW) [107, 124–126], micro-strip lines [51, 127, 128], substrate integrated guides (SIW) [106, 129–131] depicted in Fig. 1.5(b), and Goubau lines [124, 132, 133] depicted in Fig. 1.5(c). Generally, the loss of these waveguides is significantly higher than the aforementioned hollow metallic waveguides, with loss typically exceeding 1 dB/cm, but can be higher than 10 dB/cm.

Though the transmission losses of these waveguides are excessive, planar metallic waveguides are commonly combined with high-electron mobility transistors (HEMT), to form monolithic microwave integrated circuits (MMIC). Owing to the convenience of the homogeneous integration these circuits have emerged as the dominant modality for active devices in the terahertz range. Utilising traditional semiconductor manufacturing techniques, MMICs can be used to integrate frequency multipliers [134], detectors [135], filters [136], mixers [134], modulators [137], and amplifiers [138, 139] monolithically. To date, many typical semiconductor platforms, including silicon, indium gallium arsenide, indium phosphide and gallium nitride, have been explored in the sub-terahertz range. Though the efficiency is low, the primary benefit of this scheme is functionality. Owing to low efficiency, these chips are typically dense, and once the functional elements are realised the wave is coupled to another, more efficient waveguiding platform such as a hollow-metallic waveguide [140, 141]. The functionality afforded by these semiconductor integrated circuits is indispensable to modern terahertz science and is unlikely to be replaced in the future. Still, frequent and substantial improvements in the efficiency and cut-off frequency of these components are being made as semiconductor devices are optimized for terahertz operation and fabrication quality improves. Nevertheless, to realise efficient terahertz systems the amount of planar metallic waveguiding should be minimised to avoid these significant losses.

Dielectric Waveguides

So far, the waveguides considered have employed metals to confine and guide the wave. As discussed, this introduces unavoidable frequency scaling losses, which diminish the efficiency. Beyond the terahertz range, in optics, these effects are amplified further, so outside free-space transmission, the dominant waveguiding modality has long been dielectric waveguides [142]. While the most recognisable dielectric waveguide is the now ubiquitous optical fibre [143], there has been accelerating interest in planar dielectric waveguides for application in photonic integrated circuits (PIC) [144–146]. In line with this reasoning, terahertz planar dielectric waveguides and fibres emulating these optical waveguides have emerged as an alternative to metallic guides. Though electromagnetically these devices scale in

size naturally, and fabrication is often more forgiving at the micro than the nano scale, the material choice must be re-evaluated as devices are migrated from optical wavelengths to terahertz frequencies. As an example, silicate glasses, are commonly used for optical fibres and as substrates for silicon on insulator (SOI) planar waveguides, as they are almost loss-less at 1550 nm, but exhibit significant loss at terahertz frequencies [147]. As such, a wide variety of alternate materials have been trialled to replace lossy optical materials with suitable terahertz materials.

For low permittivity materials, typically used as optical fibres and substrates, the properties of many polymers and glasses have been measured, with loss tangents on the order of 10^{-2} [123, 148–153], making them too lossy for waveguiding over an appreciable distance. A notable exception is cyclo-olefin-copolymer (COC), which has a frequency stable permittivity of 2.34 and a loss tangent less than 5×10^{-3} across the terahertz band [108]. Nevertheless, many low-index terahertz fibres, such as the one shown in Fig. 1.5(d), have been demonstrated, with broadband, low-loss performance [154–159]. Still, while the low-loss, broadband performance of the fibres is impressive, their general utility is limited due to the limited range of integrated devices which can be embedded and difficulties with input and output coupling. Additionally, on a technological level, as a long-distance transmission lines they are outclassed by optical fibres. There have been demonstrations of low permittivity planar waveguides but the weak mode confinement generally makes them inferior to high permittivity guides.

High-permittivities are generally preferable for planar waveguides as the contrast between the waveguide and the surrounding free-space leads to strong confinement. This has lead to widespread utilisation of intrinsic semiconductors and ceramic materials. Of these, intrinsic, high-resistivity, float-zone, silicon has been the most widely used owing to its minimal loss and low-dispersion, which in high-resistivity samples has been measured at 3×10^{-5} [160]. As such, intrinsic silicon is the natural choice for low-loss terahertz waveguides, and various architectures including silicon-on-insulator, and more recently substrateless guides have emerged as premier technologies, with losses significantly lower than even the best hollow metallic guides. Beyond silicon, ceramics such as alumina [161], zirconia [162], titanium dioxide [163], and low-temperature co-fired ceramics (LTCC) [123] have been profiled, with some waveguiding demonstrations. Though generally the losses here exceed those of silicon, there may be practical benefits to ceramic waveguides. Particularly the ability to 3D-print ceramics, leads to greater design freedom than the strictly planar silicon guides.

For highly efficient terahertz integrated circuits, dielectric waveguides are necessary to mitigate the unavoidable metallic losses, though the choice of material is critical to ensure that the Ohmic losses are not simply substituted for dielectric losses. Here, as in optics, silicon is a natural choice for planar waveguiding, with minimal loss, a moderate permittivity, and low dispersion [164]. All-silicon waveguides will be discussed at depth in the following chapter.

Evaluation of Terahertz Waveguides

The waveguide is the foundation of integrated technologies. As such, due consideration is needed to select the most appropriate modality, with a summary of the waveguides reviewed in this section presented in Table 1.1 and depicted in Fig. 1.6. In the microwave range, hollow and planar metallic guides are dominant and provide excellent performance well into the millimetre-wave regime. Further, Ohmic losses continue to scale with frequency and eventually, as in optics, dielectric waveguides become a necessity for highly efficient waveguiding. Beyond efficiency, practical considerations including fabrication complexity and the availability of sources and detectors are important considerations. As such, the inclusion of metals will always be necessary for source, detector and active device integration due to the need for electrical contacts. This suggests that hybrid systems, comprised of active metallic components and dielectric passive components is a promising candidate for efficient, functional, terahertz integrated circuits.

Table 1.1: Comparison of terahertz waveguide platforms.

Waveguide Platform	Centre Frequency (GHz)	3-dB Fractional Bandwidth	Attenuation (dB/cm)
3D Printed Cu Hollow [109]	275	40%	8
Split-block Al Hollow [114]	342	10%	2
DRIE Au Hollow [117]	275	40%	0.2
Au CPW on PET [124]	925	38%	6.8
Au CPW on BCB [126]	420	38%	27
Au Microstrip on COC [51]	275	40%	3.7
Cu MSTL on SiO ₂ [128]	250	40%	3.5
Au SIW on GaAs [129]	400	-	3.9
Au SIW on Si [131]	275	40%	4.3
Au SIW on Al ₂ O ₃ [130]	285	31%	0.75
Au Goubau on PET [124]	925	38%	1.3
COC Strip [158]	120	-	0.63
Si on Silica [165]	585	15%	0.5
Si on BCB [166]	540	15%	0.46
Substrateless Si PhC [167]	330	1%	0.04
Substrateless Si TIR [168]	275	40%	0.05

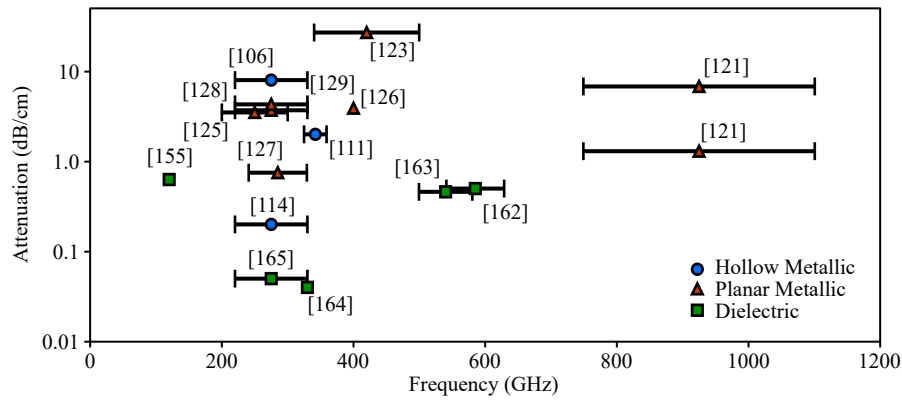


Figure 1.6: Comparison of terahertz waveguide platforms, using data in Table 1.1. Error bars represent the reported bandwidth.

1.4 Outline of Thesis

As terahertz technologies mature, integrated technologies must emerge to translate laboratory capability to widespread adoption. The limited available power from compact terahertz sources, and frequency scaling free-space and Ohmic losses, necessitate the efficiency be a primary concern of candidate integrated platforms. As such, dielectric waveguides, formed from low-loss silicon without a substrate, have emerged to fill the role.

This thesis is divided into 3 parts, which are subdivided into 10 chapters. In Part I, context for the following parts is provided in 2 chapters. This chapter is a broad review of the state of terahertz technology, and second, a focused review of substrateless silicon waveguides. Part II, composed of 4 chapters, contains original contributions relating to integrated waveguiding and components. Part III, composed of 2 chapters, contains original contributions relating to imaging and sensing techniques that are compatible with integrated technologies. The final chapter provides a conclusion and outlook. The outline of each chapter is as follows,

Chapter 2 (Context) is a review of substrateless silicon waveguides, previous demonstrations and outlook. This chapter identifies gaps in the existing literature, separating under-researched components from fundamental constraints. From this, four areas are identified to be addressed in Part II of this thesis: unwanted evanescent coupling, wideband waveguides, unrealised components, and frequency-scanning antennas.

Chapter 3 (Original Contribution) presents substrateless terahertz extreme skin-depth waveguides. To overcome unwanted evanescent coupling that arises in unshielded dielectric waveguides, anisotropic cladding can be introduced to tightly confine the guided mode to the core and suppress the evanescent fields. Here, this technique is applied to substrateless silicon waveguides at terahertz frequencies. These waveguides are fabricated, and the loss, dispersion, and coupling suppression characteristics are experimentally verified. The contents of this chapter are published in [169].

Chapter 4 (Original Contribution) presents terahertz rib waveguides. In photonic integrated circuits, rib-waveguides are widely used for their fabrication simplicity and wide single-mode bandwidth. Rib waveguides from 3D-printed alumina are designed and experimentally validated. Though the dielectric losses exceed those of silicon waveguides, the loss is lower than planar metallic waveguides, and many hollow metallic waveguides. Here, 3D-printed alumina is used for its practical advantages and as a foundational waveguide for future truly 3D devices.

Chapter 5 (Original Contribution) is focused on the development of integrated components. The extreme skin-depth waveguide from Chapter 3 is used to build a compact and efficient arbitrary ratio power divider, exploiting the evanescent coupling suppression. This device is published in [169]. Next, a silicon delay line and coupled to a thermo-electric heater to realise a thermal delay line. These components address critical deficiencies. Finally, the 3D-printed alumina rib waveguide from Chapter 4 is used to build a ring resonator. Here, the ring itself doubles as a well for a liquid analyte such that it is functionally a liquid sensor.

Chapter 6 (Original Contribution) presents two terahertz antennas. First, a frequency scanning leaky-wave antenna based upon slab-mode leakage is designed, fabricated, and experimentally demonstrated. This device is published in [170]. Second, a rib-waveguide, this time in silicon, is used to construct a wideband antenna, based upon an integrated Galilean Telescope architecture. Here, wideband, integrated optics and the wide single-mode bandwidth of the rib waveguide are employed to realise an antenna with simulated 3-dB bandwidth of 220–500 GHz, spanning two traditional metallic waveguide bands. The antenna is fabricated and experimentally characterised over the 220–330 GHz band.

Chapter 7 (Original Contribution) presents leaky-wave radar techniques. This chapter comprises a theoretical and an experimental component. The theoretical contribution, is an analysis of the depth and angular resolutions of leaky-wave radar, proposing a more strict limitation than that which exists in the literature. Then, utilising the antenna proposed in Chapter 6, leaky-wave radar experiments are performed, including multi-target tracking, simultaneous liquid sensing of two targets,

and multi-target vibrometry. These results are published in [170].

Chapter 8 (Original Contribution) presents liquid sensing with terahertz swept-source coherence tomography. At present, many of the compact, integrated detectors available do not capture the phase information, as such to differentiate targets at different depths, coherence tomography techniques are required. Here, analysis of in-container liquids is used as an example of the ability to recover material properties at depth without access to the phase information in the reflected signal. The underlying principles outlined are broadly applicable to terahertz imaging beyond integrated technologies, including terahertz cameras. These results are published in [171].

Chapter 9 (Summary and Outlook) concludes the thesis.

Chapter 2

Substrateless Silicon Waveguides

Abstract

Substrateless silicon waveguides have emerged as a viable pathway towards terahertz integrated circuits that can exploit the vast, underutilised terahertz bands with high efficiency. For this reason, in recent years there has been rapid development at all levels; the foundational waveguides, passive components, tuneable devices, and the development of fully integrated systems with hybrid integrated sources and detectors. In this chapter the state of the substrateless silicon waveguide platform is reviewed. The focus of this review is contextualising the subject by identifying the fundamental physical limitations of silicon as a material and how it has been leveraged to this point. The various waveguiding schemes available are described, along with an overview of the passive components that have been already achieved on the platform. Next the outlook for tuneable silicon waveguides is given, with an overview of various physical effects that could be employed to further these capabilities. Finally, state-of-the-art terahertz integrated circuits are examined, with a particular interest in the integration of sources and detectors on the platform to build stand-alone systems. This review and the limitations of the research hitherto, inform the research directions expounded in Part 2 of this thesis.

2.1 Introduction

2.1.1 Silicon

Silicon has become one of the most widely used materials in modern electronic and photonic systems, with widespread uses across power, micro, and nano-electronics. As such there exists vast fabrication infrastructure dedicated to the manufacture of crystalline silicon and silicon devices, in facilities known as foundries. Today, intrinsic silicon is readily available in crystalline form as a wafer, with a plethora of n-type, p-type, and intrinsic carrier concentrations. At room temperature and under atmospheric conditions it is a stable solid and only forms a 3 nm oxidation layer [172] which is negligible compared to the millimeter scale wavelengths considered in this thesis. For waveguiding applications its dielectric properties are of critical interest. Importantly, in the terahertz range it is almost completely non-dispersive, with a very stable permittivity of 11.68 [160] at room-temperature. The electromagnetic attenuation is dependent on a variety of factors, including temperature, dopants, and the presence of imperfections, but is principally determined by the free carrier concentration, typically on the order $1.45 \times 10^{10} \text{ cm}^{-3}$ at ambient temperatures [173]. To produce very high purity monocrystalline silicon the float-zone process [174] is employed, resulting in wafers with resistivities exceeding $20 \text{ k}\Omega \text{ cm}$, corresponding to loss tangents on the order of 3×10^{-5} at terahertz frequencies [160]. This exceptionally low loss and stable permittivity makes silicon a near ideal dielectric for waveguiding. In this case, the majority of losses arise from coupling and device insertion losses, determined by design choices.

In this section the existing literature on terahertz substrateless silicon waveguides is reviewed. While

much of the existing literature is oriented towards devices operating in the 220–400 GHz range, the WR3.4 and WR2.8 bands, these techniques generally scale well to higher frequencies, as the properties of silicon remain stable well above 2 THz. The preferred fabrication method is deep-reactive ion etching, which employs photolithographic techniques to pattern the wafer, as such features down to the micron scale are possible. The limiting factor is generally not patterning resolution but rather wafer thickness, with thicker wafers requiring longer etch times to produce small features, which leads to significant over-etching of large features. As the operating frequency scales, the permissible wafer thickness shrinks, in turn facilitating smaller feature sizes. At present, the highest frequency experimental demonstration of all-silicon waveguiding is in the WR1 band [175], spanning 750–1100 GHz, though in principle even higher frequencies are possible. As such, I emphasise that all-silicon waveguides are not just a practical solution in the sub-terahertz bands, but more generally for terahertz systems.

2.1.2 Evolution from Silicon on Insulator Waveguides

The favourable properties of silicon have seen it become one of the most widely used materials in optical photonic integrated circuits, particularly in the telecommunications bandwidth centred at 1550 nm [176]. Here thermal oxidation of the silicon can be used to grow a thin layer of Silica Glass (SiO_2) [177] which can form a substrate for the waveguide. At 1550 nm, the loss of the silica is negligible and forms a near ideal substrate material, mechanically supporting the silicon waveguide which is formed by etching away the silicon wafer to form nano-scale structures [178]. However, at 275 GHz, this substrate loss is no longer negligible, as is evident in a variety of terahertz silicon on insulator waveguides [165, 166, 179, 180] and time domain spectroscopy of silica glass [147]. For this reason terahertz substrateless silicon waveguides [164] have emerged, leveraging the properties of silicon without the additional losses from the substrate material, to realise extremely low loss terahertz waveguides.

2.2 Waveguide Variants

To realise a substrateless waveguide two conditions must be simultaneously met, first a method of confining the propagating wave to the waveguide core, and second, the core must be mechanically supported. In this section various schema for achieving these objectives which have been presented in the literature are discussed. These techniques are not mutually exclusive and combinations of these waveguides may be present within a single monolithic system, employed where their individual properties are most suitable.

2.2.1 Slab

The most elementary waveguide, depicted in Fig. 2.1(a), is simply a thin slab of material, such as a silicon wafer, by which the wave is confined out-of-plane by total internal reflection and the wave is unconstrained in-plane [181]. This mode must be managed through collimation, allowing for use in beam-forming [182], and for other devices such as beam-splitters [183]. These are achieved through the design of integrated optics [184], regions of effective medium that are used to emulate traditional free-space refractive devices. The simplicity of the slab waveguide and its broadband nature make them useful in many cases. With this in mind, the primary drawback is the physical footprint; as in free-space optics in order to maintain a collimated slab mode its beam waist must be sufficiently large, resulting in large centimetre scale devices [185]. As such these devices sit between free-space devices and true waveguides, whereby they are monolithically integrated, but it is still difficult to integrate many components.

2.2.2 Band-Gap Photonic Crystal

The earliest substrateless silicon waveguides were based upon band-gap photonic crystals, periodic structures composed of air and silicon which inhibit wave propagation of the slab mode [186]. This

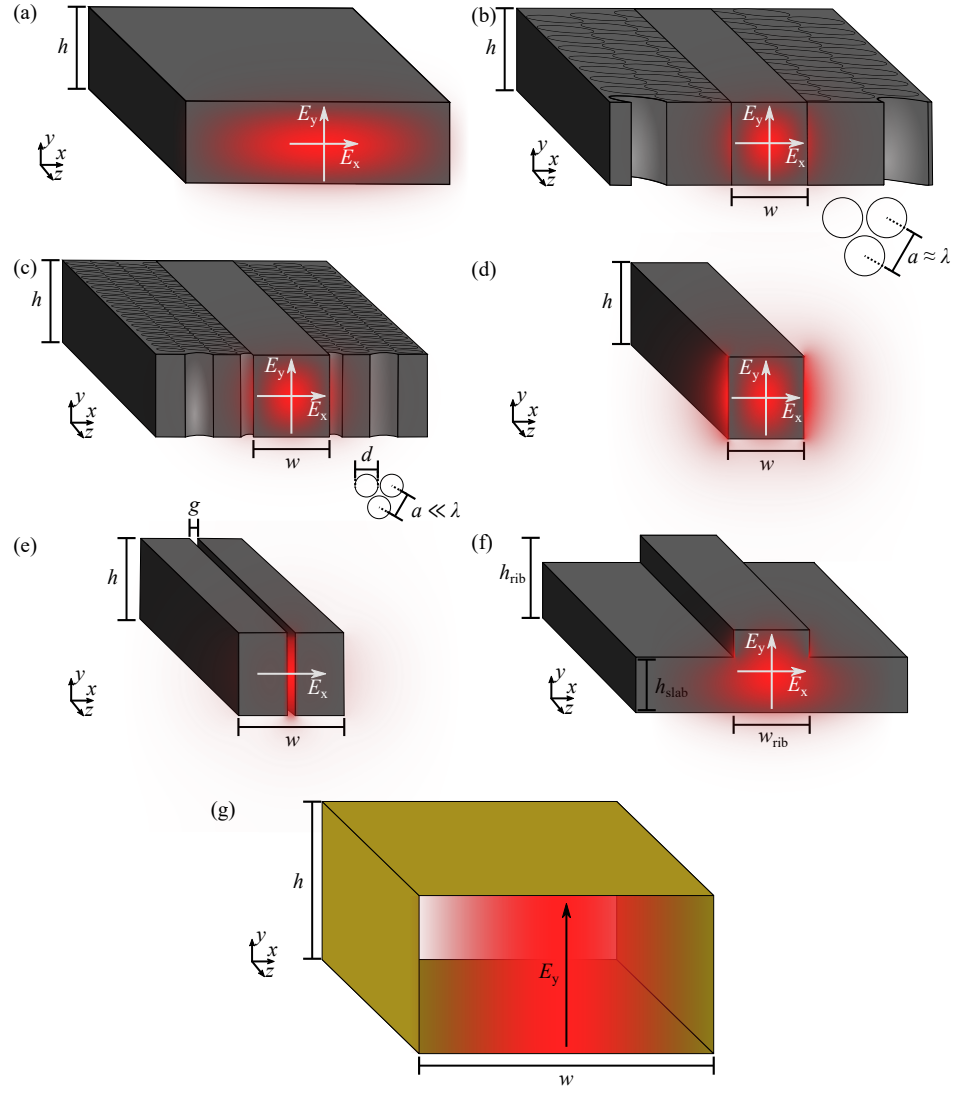


Figure 2.1: Variants of all-silicon terahertz waveguides. (a) Slab waveguide, defined by the thickness of the slab. (b) Band-gap photonic crystal, defined by the thickness of the slab, the core width, the lattice period, and the hole diameter. (c) Effective-medium clad waveguide, defined by the thickness of the slab, the core width, the lattice period, and the hole diameter. (d) Unclad waveguide, defined by the thickness of the slab and the core width. (e) Slot waveguide, defined by the core width, the slot width, and the thickness of the slab. (f) Rib waveguide, defined by the rib height, the rib width, and the slab thickness. (g) Hollow rectangular waveguide, defined by the width and height of the rectangular waveguide, drawn to scale.

photonic crystal confines the propagating wave to the waveguide core which is formed from a defect in the photonic crystal lattice as illustrated in Fig. 2.1(c) [167, 187]. Thus, the operating bandwidth of the waveguide is constrained by the band-gap of the supporting lattice structure, which is typically a fractional bandwidth no greater than 20% [188] and is accompanied by strong dispersion. The band-gap is strongly dependent on the lattice parameters, and often this is highly restrictive for realising complex devices as there are limited avenues for tuning the device which do not compromise the mode confinement. Nevertheless, there have been demonstration of routing components, evanescent couplers, and filters [189]. Most recently, so called topologically protected waveguides have emerged [190, 191], with very similar performance and properties to the prior band-gap photonic crystals based on hexagonal lattices. Here however, the criteria required to generate the waveguide is even more restrictive, severely limiting the range of possible components that can be realised, while presenting few practical advantages, notably tight bends and back-scattering protection, over other waveguiding schemes.

2.2.3 Effective-medium Clad

Similar to the band-gap photonic crystal waveguide, the core of the waveguide can be clad by an air-silicon lattice structure as in Fig. 2.1(d). However, distinct from the band-gap photonic crystal the period of this lattice is deeply sub-wavelength such that it is experienced as an effective medium [192]. This effective medium then facilitates field confinement to the core via the refractive index contrast between the silicon core and the cladding [193]. Crucially, this effect applies in the broadband, so long as the operating wavelength is sufficiently large. The effective permittivity of this lattice is anisotropic and dependent on the ratio of air to silicon in the lattice, controlled by the hole radius and lattice period. To realise a waveguide, these variables should be selected such that the refractive index contrast between the silicon core and the surrounding medium is sufficient to promote total internal reflection, with the strongest confinement achieved when the index contrast is maximised [194]. Though strong confinement is advantageous this contrast need not always be maximised, leaving some flexibility to tune the permittivity of the cladding for the realising devices. The dimensions of the waveguide are often selected to ensure single-mode propagation across the operating band, with the upper frequency limit defined by the onset of the higher order mode. As a dielectric waveguide, there is no strict lower frequency cutoff for the fundamental mode, in contrast to hollow metallic waveguides. Instead, as the frequency decreases the mode confinement becomes ever weaker, and when the mode is weakly confined it will be readily radiated. Typically, by appropriately choosing the dimensions the fractional bandwidth of the waveguide will approach 40%, able to cover entire hollow metallic waveguide bands. Additionally, if the height and width of the waveguide core is approximately equal, two orthogonal modes will be supported, allowing for polarisation multiplexing and dual polarisation devices [168]. As such these effective-medium clad waveguides have all but superseded the band-gap photonic crystals as the design freedom and broadband operation makes them more suitable for most operations. However, these two schemes need not be mutually exclusive; while the waveguide clad with effective medium is generally superior, regions of band-gap photonic crystal can still be utilised where required to achieve frequency selectivity.

2.2.4 Unclad

The previously discussed waveguides rely on complete cladding of the waveguide. However, silicon is mechanically strong enough such that it is self-supporting even for microscale ribs which can be tethered to other supporting structures to form the unclad waveguide shown in Fig. 2.1(f). An early instantiation of this approach was to use ribs to physically support a ribbon waveguide [195]. The ribs should be selected such that their spacing is sub-wavelength to avoid incidental Bragg-grating effects, though even with sub-wavelength spacing the effect of scattering is non-negligible. Instead, the ribbon waveguide can be tethered to an effective-medium clad waveguide which effectively frames the now unclad ribbon waveguide [196]. This is advantageous as the high index contrast between the silicon core and the surrounding air results in strong field confinement to the waveguide core, but also grants significant design freedom without having to conform to a lattice cladding structure.

2.2.5 Slot

In the previous sections the focus has been on the cladding material of the waveguide, but the core of the waveguide can also be modified to adjust the propagating mode. In these waveguides the solid core confines the mode, with limited evanescent fields in the surrounding air and cladding regions. If intense fields in air are desired, such as for sensing applications, a slot waveguide, depicted in Fig. 2.1(e), can be realised by maintaining the cladding material and simply splitting the core to realise a narrow air gap [197]. The propagating mode of this waveguide is such that it is concentrated in this air gap, with field intensities beyond the evanescent field intensities observed in other waveguides. This property can be useful for sensing applications [198] or for point source emulation [185]. Additionally, the dispersion of this waveguide is also different from other waveguides and can be simply tuned by adjusting the width of the narrow slot.

2.2.6 Rib Waveguides

Unlike the index-contrast guides described previously, wave propagation inside the rib, or occasionally referred to as ridge, waveguide depicted in Fig. 2.1(b), is maintained through the index contrast between the fundamental rib mode and the fundamental mode of the surrounding slab. Additionally, the guide is protected from higher-order modes by this mechanism, as higher order modes are readily leaked into the surrounding slab [199]. As such the single-mode bandwidth of this waveguide can exceed that of the total-internal reflection guides of the previous sections. However, this confinement mechanism is weaker than the waveguides previously mentioned, requiring gentle gradients between waveguide sections and large bend radii, leading to large device footprints to avoid significant radiation losses. This waveguide can be realised through the partial etching of a wafer [200]. Though, to realise this waveguide as well as other structures, which require complete etching simultaneously, multiple etching stages are required, complicating the fabrication process. The partial etching leads to a 2.5D device with out-of-plane asymmetry, which stand in contrast to the strictly planar waveguides mentioned previously.

2.3 Passive Components

Beyond the waveguide itself, the functionality of the platform is determined by the range of available components. These components are used to manipulate the guided mode to achieve various functions; routing, frequency selectivity, polarisation control, and interfacing with external systems either through coupling interfaces or antennas. In this section a review of the range of previously demonstrated components is presented.

2.3.1 Coupling to Hollow Metallic Waveguides

Currently, the dominant waveguiding modality is that of the hollow metallic waveguide. Most commercially available components come with hollow metallic waveguide ports, as they are physically robust and can be simply used to construct modular systems. As such for characterisation of waveguides in a laboratory setting and for future packaging of devices, a transition to hollow metallic waveguides is a necessity. As such, most demonstrations of substrateless waveguides propose the use of a spike taper, depicted in Fig. 2.2(a–b), to interface between the two [164]. The efficiency of the coupling is dictated by the length of the tapered rod, where a longer rod results in a more gradual taper, and hence better broadband index matching. Ideally, the tip of the taper is infinitesimally small, but in practice the tip is more reliably fabricated if a finite tip width is included. One notable feature of these tapers is their fragility, as they are long and very thin, they are prone to breaking when the waveguide is handled, or when the taper is manually inserted into the waveguide without due care. As a result, there has been an effort to realise alternative coupling structures, one such approach is illustrated in Fig. 2.2, where the rod is truncated, and an additional matching structure is used to improve coupling [201]. Though these structures typically narrow the operating bandwidth, they are significantly more robust, with similar coupling efficiency.

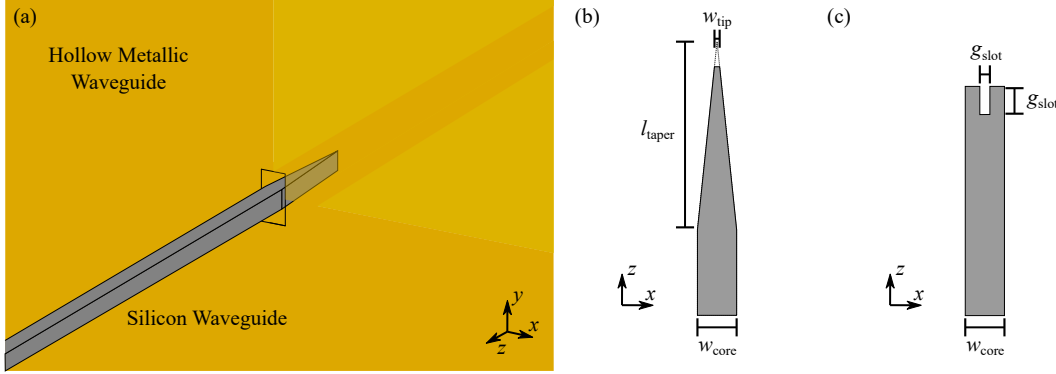


Figure 2.2: Coupling all-silicon waveguides to hollow-metallic waveguides. (a) Insertion of a coupling taper into a hollow metallic waveguide. (b) Standard linear taper coupling spike. (c) Truncated coupling structure, as in [201].

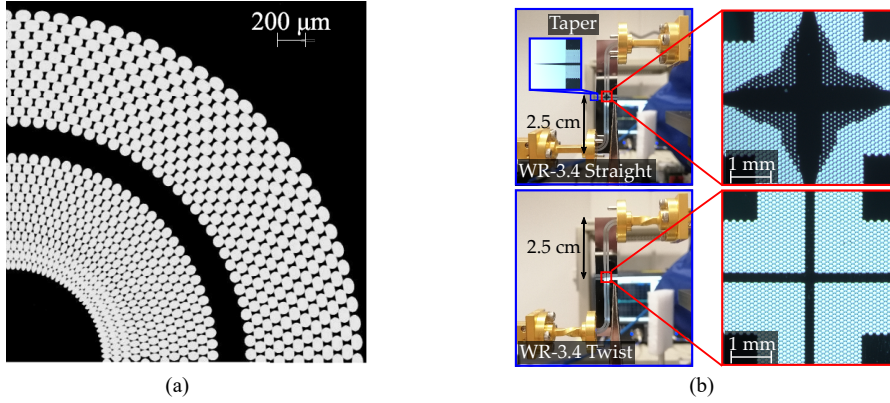


Figure 2.3: All-silicon routing components. (a) Effective medium clad circular bend, adapted from [168] © 2021 IEEE. (b) Effective medium clad waveguide crossings, with permission from [202] ©Optical Society of America.

2.3.2 Routing

For dense integration, routing components are necessary for connecting functional components. The most essential of these is the bend, but also in some cases additional crossings may also be necessary.

Bending

The most essential routing component is the waveguide bend, as it is nigh impossible to construct compact systems without them. At the same time the act of bending the guided wave is also foundational for many other components including ring resonators amongst others. Typically, circular bends, depicted in Fig. 2.3(a), are employed [168], presumably as they are the most simply designed, although they have been shown to be sub-optimal for compact, low-loss waveguides bends [203]. Nevertheless, the minimum bending radius of the platform should be selected such that the bending loss is minimised while considering that extremely large bends will result in increasing material losses. For silicon waveguides where the material losses are nearly negligible, often the minimum bending radius is selected for reasons of compactness, noting that the device footprint is strictly limited by the wafer size acceptable by the foundry. Bending loss arises from radiation losses from the outer edge of the waveguide, and is typically related to the mode confinement of the waveguide. For total internal reflection guides, the bending loss is dependent on the core-cladding contrast, while for band-gap photonic crystals tight bends can be readily achieved as the slab mode is prohibited from propagating [190]. Investigations have shown that bends with radii on the order of 10 guided wavelengths can be achieved with minimal bending loss.

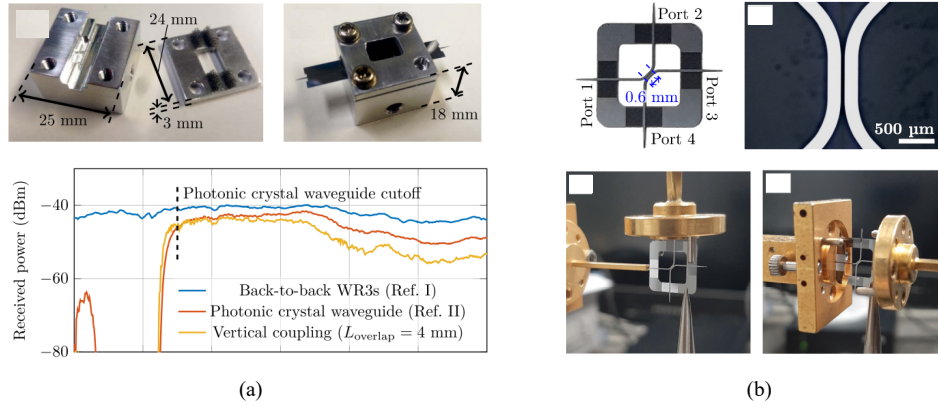


Figure 2.4: All-silicon evanescent couplers. (a) Out-of-plane evanescent coupler, adapted from [204], ©2019 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement. (b) In-plane evanescent coupler, adapted from [196], ©2020 IEEE.

Crossing

A more niche routing component is the waveguide crossing, which facilitates the intersection of two waveguides, with suppressed crosstalk between the waveguide. For planar circuits, as the density of components increases it may become necessary to include crossings to avoid labyrinthian circuit routing. Fortunately, compact crossings, such as the one depicted in Fig. 2.3(b), with insertion loss less than 1 dB, average crosstalk less than 39 dB, and a footprint of 4λ can be readily included by leveraging effective medium techniques [202].

2.3.3 Evanescent Couplers

The un-shielded nature of dielectric waveguides makes them naturally susceptible to evanescent coupling, the phenomenon by which a wave propagating in a waveguide may tunnel into an adjacent waveguide via its evanescent field [205]. This phenomenon is dependent on the dimensions of the two adjacent waveguides, as well as the operating frequency. As such this phenomenon is frequently used to build frequency diplexers [189, 196, 206] as depicted in Fig. 2.4(a), as a broadband input signal can be divided losslessly based upon which frequencies couple to the adjacent waveguide and which remain in the original waveguide. Typically, this has been demonstrated in-plane, though this effect can also be used to couple between two waveguides separated out of plane [204], as shown in Fig. 2.4(b). Though in optical integrated circuits evanescent couplers can be used to realise compact power dividers, owing to the frequency dependence of the coupling effect this scheme does not scale well to terahertz frequencies where the fractional bandwidths are typically much larger. More broadly, evanescent coupling as a phenomenon plays a vital role in many other functional components which are expounded upon in the following sections.

2.3.4 Resonators

Resonant structures are one way on introducing frequency selective behaviours to a broadband platform, critical for filtering and frequency-division multiplexing, but also can be useful for enhancing light-matter interactions for sensing. Until now the focus has been on two specific resonators, 1D photonic crystal cavities and disc, or ring, resonators, with many variants of these principles demonstrated.

Photonic Crystal Cavities

To realise a photonic crystal a periodic array of air holes can be etched in silicon. As in the cladding of a band-gap photonic crystal waveguide, the periodicity of these holes creates a band-gap

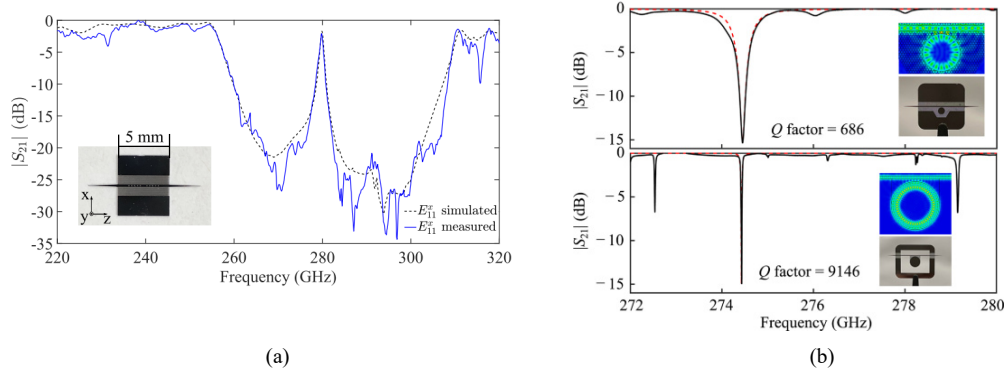


Figure 2.5: All-silicon resonators. (a) 1D photonic crystal cavity, adapted from [207], ©2021 IEEE. (a) Ring resonator, with permission from [208] ©Optica Publishing Group

which inhibits the propagation of select frequencies through the photonic crystal region, resulting in a band-stop effect. By creating a defect in this array, a resonant cavity is formed allowing a narrow band of frequencies to pass through the photonic crystal via tunnelling, resulting in a very narrow band-pass filter as in Fig. 2.5(a) [207, 209, 210]. These filters are extremely compact, with footprints completely inside the core of the waveguide, and lengths of only a few guided wavelengths. The limitation of this technique is that the rejected wave is not separated from the initial waveguide and is simply reflected back to the input. This reflection should be carefully managed as the strong reflected power may lead to damage in some cases. Nevertheless, the low intrinsic loss of the silicon allows for very high Q -factor resonances to be realised with photonic crystal cavities, producing narrowband band-pass-filters with minimal insertion loss.

Ring Resonators

Ring resonators exploit evanescent coupling effects to draw power out of the input waveguide into a large disc or ring, where resonant modes are excited. At the resonant frequency the field drawn into the ring interferes with the field which remains in the waveguide, constructively interfering resulting in a stop-band effect visible in Fig. 2.5(b), which is analogous to a multi-pass interferometer [211]. This stop band effect is frequency periodic, with the resonance period, known as the free-spectral range, dependent on the circumference of the resonator. Unlike the 1D photonic crystal cavity the ring resonator can be augmented such that the rejected frequencies can be siphoned from the main line by introducing a second waveguide tap to the disc resonator. The output of the second waveguide, observed over a single resonance resembles that of a photonic crystal cavity, with a narrow pass band. This device then acts as a natural frequency multiplexer, though it is essential to note that the multiplexed frequencies are narrowband and periodic [212]. The width of the resonance, measured by the Q -factor, is dependent on resonator circumference but is affected by balancing the coupling coefficient between the waveguide and the ring with the losses arising from the ring through a process known as critical coupling [213]. Due to the low intrinsic loss of silicon, and the tight bending available on total internal reflection based waveguides, compact, high- Q resonators can be realised [208]. Other substrateless ring resonators based on rib waveguides have also been proposed, albeit with significantly lower Q -factors owing to the increased bending losses [214–216]. Though there has been demonstrations of simple ring resonator architectures at terahertz frequencies, there also exists a significant body of more complex architectures which could be readily adapted from 1550 nm photonic integrated circuits [217], for realising more complex functionality.

2.3.5 Filters

The aforementioned resonators result in narrowband frequency selective behaviour, but broadband frequency selectivity is also important, most critically for telecommunications to reduce inter-channel interference on the receiver, and for standard compliance on the transmitter [220]. Though, the

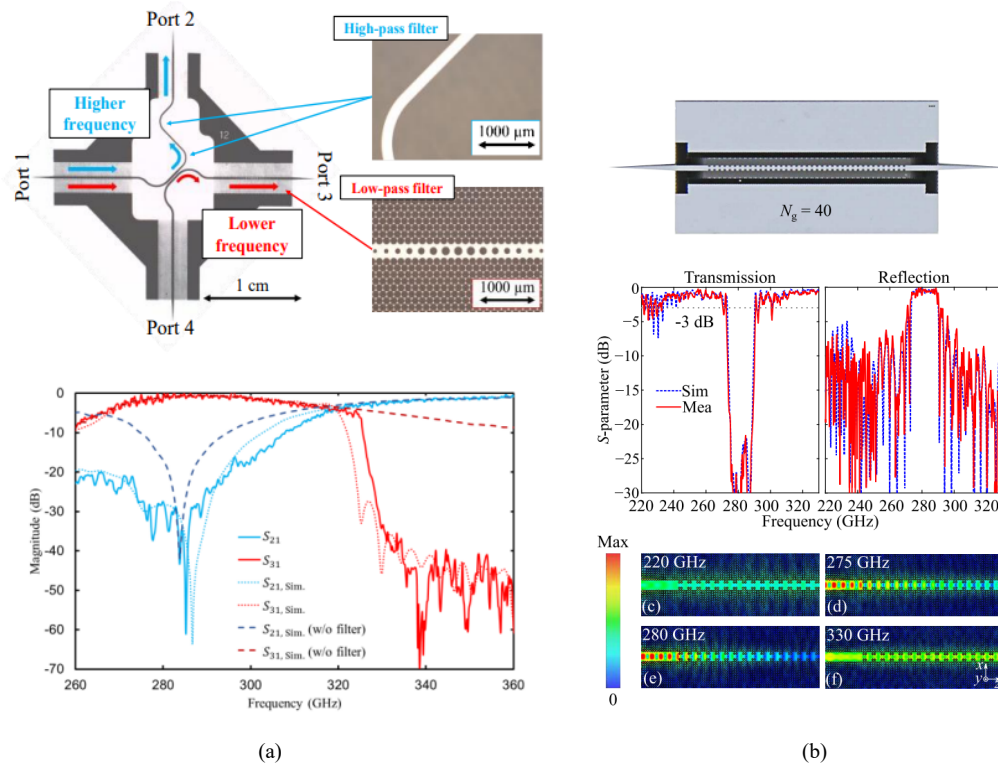


Figure 2.6: All-silicon filters. (a) Filter based upon evanescent coupler, adapted from [218]©2023 IEICE. (b) Bragg grating filter, adapted from [219].

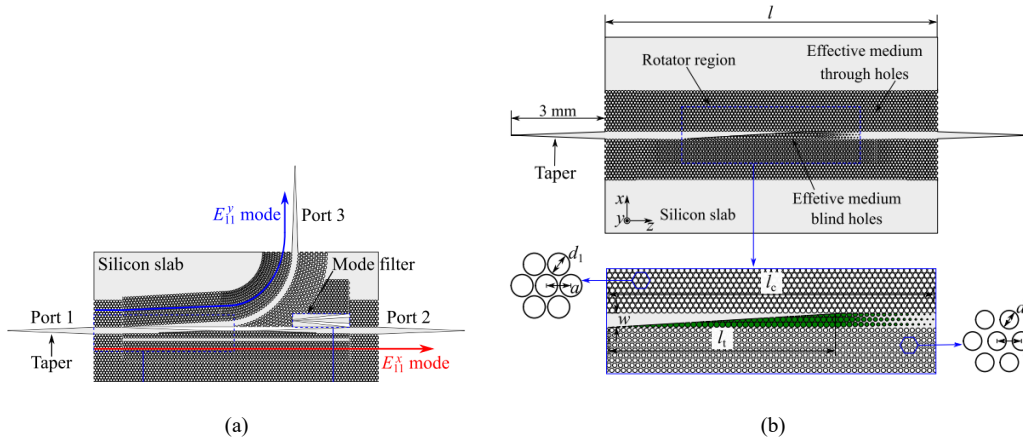


Figure 2.7: All-silicon polarisation manipulating devices. (a) Broadband polarisation multiplexer, adapted from [225], ©2021 IEEE. (b) Broadband polarisation rotator, adapted from [226], ©2023 IEEE.

evanescent couplers seemingly fulfil this role, they often have very slow frequency roll-off rates. So, typically they are combined with resonant cavities or other filters to enhance their performance, as in Fig. 2.6(a) [218]. To expand from diplexing to multiple channels, evanescent coupling to a nearby slab can be used, relying on the dispersion of this effect to form frequency channels [221, 222]. For channelisation widely tunable bandpass and bandstop filters are critical. To realise this Bragg-grating filters, shown in Fig. 2.6(b), have been employed [219, 223], as their structure combined with the flexibility of effective-mediums facilitates vast flexibility for designing filters with varying bandwidths and centre frequencies. As with 1D photonic crystal cavities a Bragg grating filter alone is unable to recover the rejected frequencies and this is still an ongoing area of research, though in optics, system architectures to overcome this limitation have been proposed [224].

2.3.6 Polarisation Control

As both effective-medium clad and unclad waveguides support dual-polarisation propagation, it is necessary to design devices to manage and control the two modes. Most importantly in order to make use of both modes simultaneously, they must be separated through a process of de-multiplexing. Attempts using evanescent couplers often result in narrowband performance, owing to the previously discussed frequency dependence [227, 228]. Conveniently, the anisotropy of the effective-medium cladding facilitates some degree of polarisation control by ensuring the two fundamental modes propagate with distinctive modal indices. This can be leveraged to realise a polarisation multiplexer [225, 229], depicted in Fig. 2.7(a). Similarly, a broadband polarisation rotator would be a valuable component, though traditionally these devices have been realised with 2.5D devices, to introduce asymmetry to the waveguide core, a process which would require multiple etching stages [230]. Though this is not a physical limitation, this process would introduce significant fabrication complexity which is otherwise necessary. For now, only simulated results for a proposed polarisation rotator, shown in Fig. 2.7(b), are available [226].

2.3.7 Antennas

Whether it is for telecommunications or imaging applications, antennas are indispensable components as they form the interface between guided waves and free-space transmission. For terahertz antennas the primary focus has been broad-bandwidth, high-directivity and high-efficiency to utilise widebands, offset the unavoidable losses, while preserving the limited power available from current terahertz sources. For systems based around hollow metallic waveguides, this has led to the wide-spread use of horn antennas, with gain typically on the order of 25 dBi [235]. Alternatively, many sources are often directly coupled to hemi-spherical lens antennas with similar gain profiles [236].

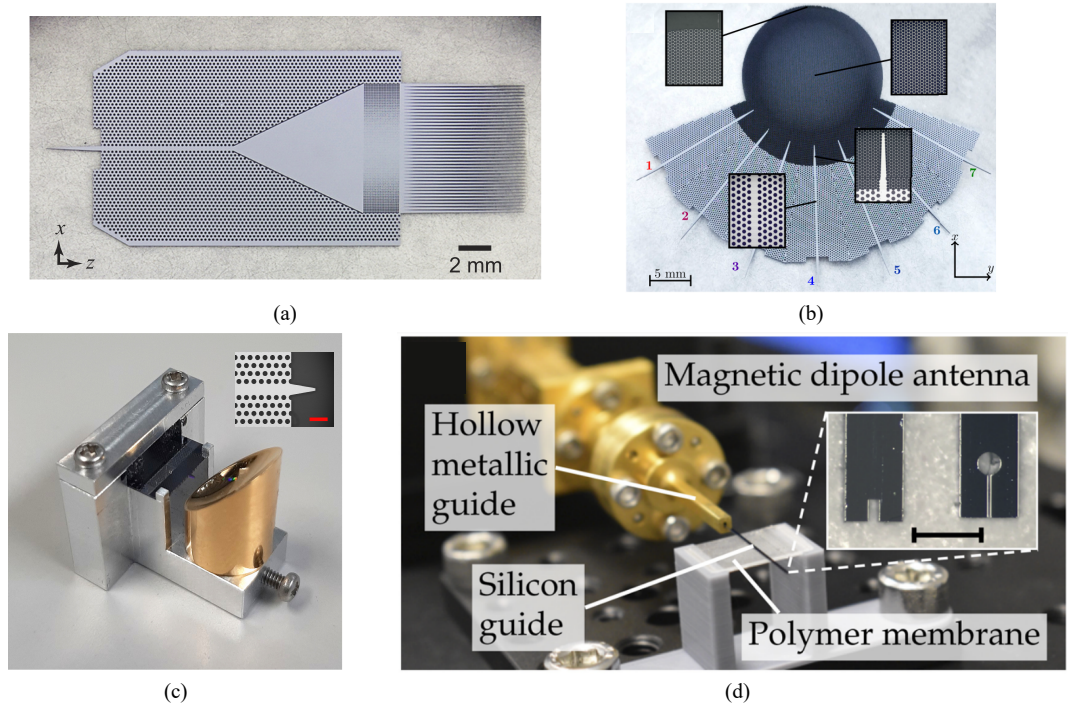


Figure 2.8: All-silicon antennas. (a) Rod array antenna, adapted from [231]. (b) Luneberg lens antenna, adapted from [232]. (c) External optic antennas, adapted from [233], ©2020 IEICE. (d) Truncated rod antenna, with permission from [234], ©Optica Publishing Group.

Hence, waveguide integrated antennas have sought to emulate this performance through integrated optics, with large planar apertures, depicted in Fig. 2.8(i–ii), to maximise the gain [231, 232]. The planar aperture does present an obstacle to building high gain waveguide integrated antennas, as the 1D aperture limits the aperture size, resulting in a fan beam. To correct for this an auxiliary optic, such as the parabolic mirror in Fig. 2.8(c), is introduced [233, 237]. In this configuration the low gain silicon antenna acts as the divergent lens of a Galilean telescope. If an auxiliary lens is acceptable then a large integrated antenna is redundant and the silicon footprint can be reduced. Then, the focus of the antenna design can be shifted to designing compact antennas, as in Fig. 2.8(d), despite their lower gain [234]. Looking forward, as the focus of integrated antenna design transitions from gain maximisation, antennas with additional functionality such as frequency scanning, ultra-wide bandwidth, or tunable beam-forming become of interest.

2.4 Tunability

Though a wide range of functions can be achieved with passive components, advanced capabilities are enabled by tunable components. Tunability refers to the ability to reconfigure or adjust the performance of the fabricated device with an external stimulus. It is important to distinguish between two primary use cases of tunability, low speed tuning with speeds on the order of seconds to microseconds, and high speed tuning, with speeds of microseconds to nanoseconds. Of course high-speed switching is always preferable, but it may not always be necessary. For example, an equaliser used to balance amplitude and phase of a communications channel may only need to change slowly to adjust to changing channel environments. However, for a modulator the maximum modulation speed is directly determined by the switching speed. Tunability of the device may be achieved by modulating the phase, the amplitude, or both independently, to achieve so-called vector modulation. Typically, these effects are typically entangled, and most modulations will result in an effect on both the amplitude and phase. Most often, this is detrimental and interpreted as a phase shift at the cost of an unwanted attenuation. At present, high-efficiency phase shifters are of particular interest to the community as they are enabling devices

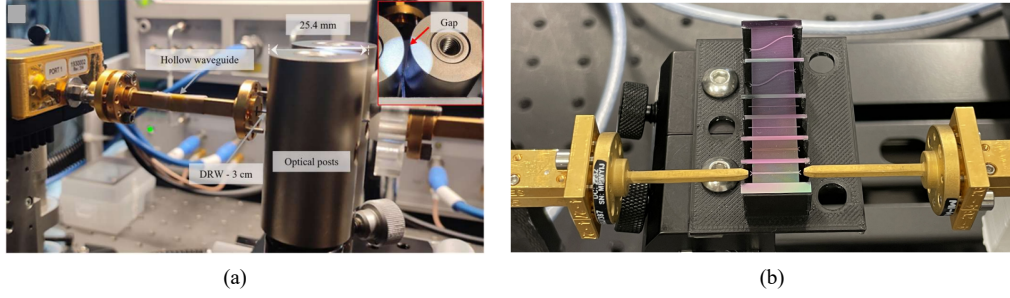


Figure 2.9: All-silicon mechanically tuned devices. (a) Mechanically tuned polariser, adapted from [238], ©2022 IEEE. (b) MEMS phase shifter, adapted from [239], ©2023 IEEE.

for high value applications, particularly beam-forming. The avenues for tunability are determined by the material properties of silicon. In this section various methods of tuning substrateless silicon waveguides are discussed.

2.4.1 Mechanical

The simplest form of tunability is mechanical tuning, physically moving elements of the system to achieve tuning. The relative fragility of the substrateless silicon waveguides makes mechanical tuning a delicate act. Theoretically, mechanical tuning is achievable through mechanical adjustment using external piezo-electric motors. The high drive voltages, typically on the order of tens of volts, and micro-scale displacements make realising these systems practical is an ongoing challenge. Nevertheless, if these practical challenges are overcome, they could be used to realise tunability at speeds on the order of 0.1 ms, or on the kilohertz scale. In laboratory environments, various mechanically tuned components have been demonstrated, such as the mechanical polarizer in Fig. 2.9(a) though their scalability to practical applications may be limited [238, 240]. Instead, more success has been realised with micro-electrical mechanical systems (MEMS), which are compatible with the fabrication systems already in use to fabricate the waveguides. Typically, the silicon MEMS device is used in concert with a traditional rectangular waveguide to realise a tunable phase shifters [241, 242], switches [243], and filters [244]. Recently, there have been demonstrations, such as those depicted in Fig. 2.9(b), which simultaneously use MEMS based devices as waveguide and actuator [239, 245, 246]. The experimental performance is promising, with low loss and wide tunable ranges. Though the speed of these terahertz switches is unreported, microsecond [247] to nanosecond [248] switches have been reported.

2.4.2 Electro-optic Effect

There is no Pockel's effect in bulk, unstrained silicon. As such the avenues for direct tuning of all-silicon components with electric fields is limited without the introduction of electro-optic materials to enhance this effect. Additionally, while electro-optic modulators are well established in optical photonics [249], these devices, which exploit very small changes in refractive index, can be massive relative to the wavelength, and yet remain physically only millimetres in size [250]. To directly scale these devices to the terahertz domain would result in truly massive devices, on the order of meters, which are absolutely unfabricable with existing foundry infrastructure. Still, despite significant challenges, the electro-optic effect may be one of the few potential pathways to a direct terahertz modulator owing to the speed of the effect, though suitable materials with high electro-optic coefficients would need to be investigated further.

2.4.3 Thermo-optic Effect

Crystalline silicon is an excellent thermal conductor with a high melting point. Under heating the crystalline lattice expands, leading to a thermo-optic effect, whereby the modal index of the

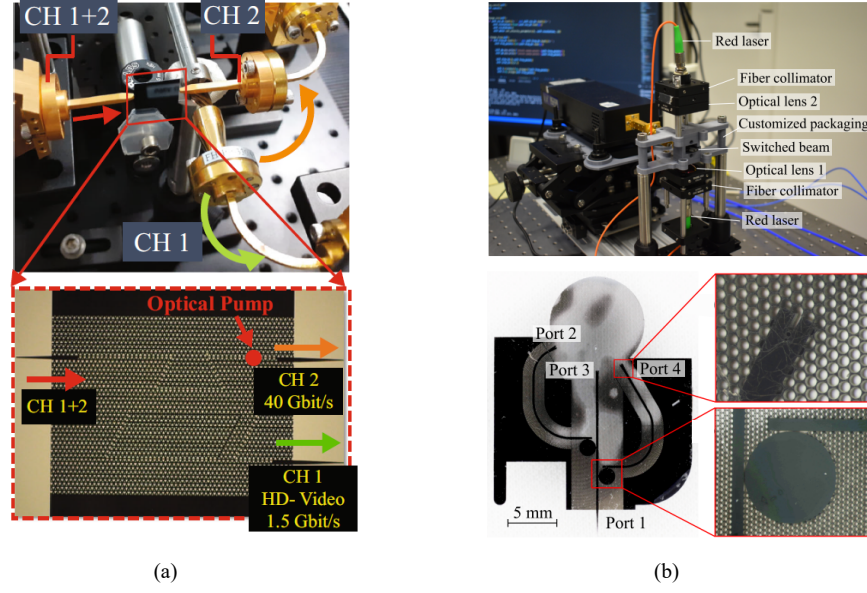


Figure 2.10: All-silicon devices tuned by photo-excitation. (a) Tuned-resonator switch, adapted from [255], ©2024 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement. (b) 1-to- N switch, adapted from [212], ©2023 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement.

waveguide is changed in response to heating. In the 450–660 GHz range the thermo-optic coefficient has been measured around $1.40 \times 10^{-4} K^{-1}$ [251], while at 150 GHz a value of $1.26 \times 10^{-4} K^{-1}$ was measured [252]. In addition to this thermal expansion, as the temperature changes the intrinsic carrier concentration, and hence the resistivity also changes leading to some excess loss. Typically, heating effects are slow as they rely on conduction to heat and cool the device. This is exacerbated on the millimetre scale, but typically even in 1550 nm thermo-optic devices are limited to response times on the order of milliseconds [253]. This slow response is primarily a result of heat management. To operate quickly the temperature must be readily controllable, which requires the ability to generate and dissipate heat quickly. Owing to its high thermal conductivity silicon is comparably well suited to thermal tuning. However, such a high thermal conductivity also makes it difficult to localise the tuning, especially in a monolithic structure as is typical of a substrateless waveguide. One terahertz thermo-optic shifter demonstrated a limited range of phase shift [254], though the short waveguide limited the phase shift. Still, at present, there is limited investigation into the true ceiling of silicon thermo-optic devices in the terahertz range.

2.4.4 Photo-electric Effect

Silicon has a bandgap of 1.12 eV, corresponding to photons with a wavelength less than 1107 nm. Hence, visible light can be used to stimulate bound electrons inside the crystal lattice into their conduction band, a process of electron emission known as photo-doping. The processes of converting photons into free carriers, results in an increase in the free-carrier concentration inside the silicon equal to the photon flux. This increase in free-carriers modulates both refractive index and resistivity, as is described by the Drude model [256, 257]. Unfortunately, the plasma resonance of the photo-induced carriers is in the terahertz range, exacerbating the losses induced [258]. Thus, this effect is always a simultaneous phase and amplitude modulation, and the two cannot be de-coupled. Although an optical modulator can be used to rapidly modulate the light source which stimulates free carriers, the modulation in free-carrier concentration is constrained by the carrier-lifetime, the rate at which liberated electrons are re-captured. In silicon at near intrinsic carrier densities has been measured on the order of 500 μs [48]. Additionally, the localisation of this effect is governed not by the spot size of the laser used to invoke the photo-electric but rather the carrier lifetime and the carrier velocity. Previous numerical studies indicate that excited electron diffusion is typically on the order of millimetres [259].

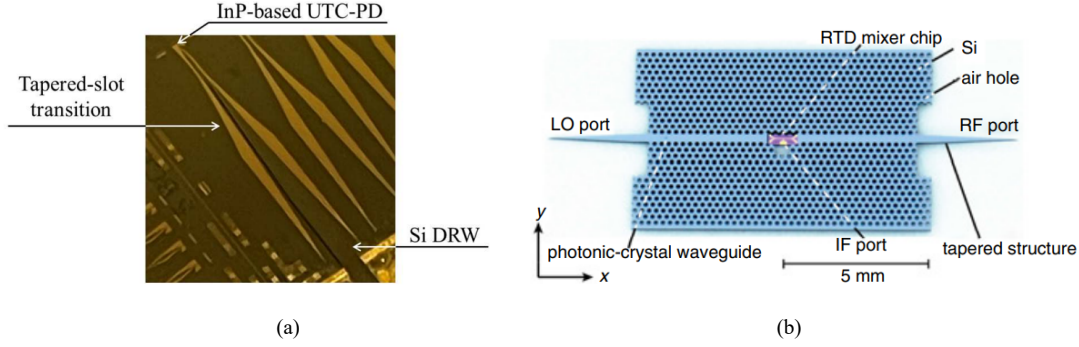


Figure 2.11: Hybrid integration of sources and detectors with all-silicon waveguides. (a) Coupling of uni-travelling carrier photodiode to all-silicon waveguide via slot-mode converter, adapted from [266], ©2023 IEEE. (b) Integration of a resonant tunnelling diode to an all-silicon waveguide, adapted from [267].

Additionally, this carrier dispersion acts to form a gradual transition from the intrinsic silicon to the photo-excited region, limiting the in-plane reflectivity achievable. For free-space devices, the air-silicon interface provides a natural sharp boundary such that the reflectivity can be controlled [260]. There is an intrinsic trade-off; for deep modulation the carrier lifetime must be long to limit recombination, but this results in slower switching speeds, and less control of localisation. Thus, techniques like surface passivation can be used to increase the carrier life-time if deep modulation is required, at the expense of switching speed [261]. For in-plane localisation of this effect, photo-excited and un-excited regions must be physically separated to disable the diffusion of carriers between regions. In the presence of a substrate, mesa like structures can be used to isolate regions [262], but it is complicated to translate this idea to a substrateless platform, where a physical connection is necessary to maintain the self-supported structure. Nevertheless, there has been significant investigation into photo-electric effect based tunable integrated terahertz devices to realise, single switches [195, 255] depicted in Fig. 2.10(a), 1-to- N add-drop switches [212] depicted in Fig. 2.10(b), and variable attenuators [263]. It is important to note here that all of these devices exploit the enhanced absorption induced by the excess free-carriers, with the switches employing resonances to further enhance this effect resulting in narrowband devices. Similar to thermal tuning, this effect may be suitable for low-frequency tuning of devices, especially amplitude equalisation, but is an unlikely path towards realising a broadband, high efficiency, phase shifter.

2.5 Hybrid Integration of Sources and Detectors

With a variety of passive and tunable components available, rudimentary integrated systems can be realised, however they are still reliant upon external receivers and detectors. To address this there has been active research into hybrid integration of compact semiconductor sources based upon other semiconductor technologies such as indium phosphide (InP) [264] or gallium nitride (GaN) [265], which are more conducive to realising these devices. In this section prior work on hybrid integration of sources, with an eye towards fully integrated terahertz systems, is reviewed.

2.5.1 Hybrid Integrated Sources

Of the available terahertz sources, the most compact, room-temperature sources are uni-travelling carrier photodiodes (UTC-PD) [65, 268], PIN diodes [65], and resonant tunnelling diodes (RTD) [62, 72].

The UTC-PD is a photonic terahertz source, making use of photo-mixing to generate terahertz waves and as such can readily make use of existing 1550 nm infrastructure, including high speed IQ modulators and tunable lasers. This can be employed to generate complex modulated signals, with tunable carrier frequencies over hundreds of gigahertz, often limited more by the out-coupler

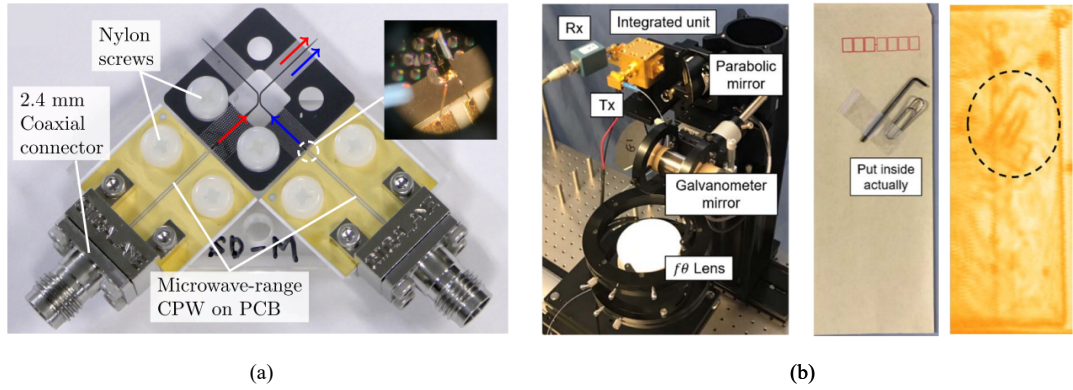


Figure 2.12: Integrated systems based upon all-silicon waveguides. (a) Silicon waveguide transceiver module, adapted from [273], ©2022 IEEE. (b) Imaging system with integrated beam-splitter, adapted from [183], ©2020 IEICE.

than the photo-diode itself [269]. These capabilities are invaluable for communications applications. However, the typical output power from such a device is on the order of microwatts to milliwatts [68]. The hybrid integration of these sources with silicon rod waveguides has been demonstrated via the slot-mode converter depicted in Fig. 2.11(a), which matches the microstrip line to the silicon rod with high efficiency [266]. With the concurrent development of 1550 nm photonic integrated circuits and terahertz integrated circuits, it can be envisioned that hybrid integrated photonic-terahertz circuits could one day provide compact, self-contained terahertz communications systems.

In contrast to the UTC-PD, the resonant tunnelling diode is an electronic source capable of generating milliwatts of power [62, 72], significantly higher than the UTC-PD. The operating frequency is determined by the resonant structure and is tunable [270], the tunable range is on the order of 100 GHz [271], enough to nearly cover a rectangular waveguide band. Previously RTDs have been integrated through backside coupling [272, 273] or through a mode-converter [274] to substrateless silicon waveguides to form compact transmission modules with a simple SMA interface [218, 275].

2.5.2 Hybrid Integrated Detectors

In some cases the same sources can also be used as detectors. Notably the RTD can serve as either a source and detector due to its nonlinear terahertz response [276]. Beyond this, Schottky barrier diodes have also been integrated onto silicon waveguides via flip-chip bonding, as in Fig. 2.11, where it serves as a sub-harmonic mixer [267, 277]. In this case, the terahertz signal acts as the local oscillator in order to demodulate an incoming modulated signal, which can then be probed via bias lines connected to the RTD. These demonstrations show that it is possible to conveniently integrate state-of-the-art detectors onto substrateless silicon waveguides.

2.6 Integrated systems & Applications

With a range of components, sources, and detectors available, it is logical that application demonstrations are beginning to emerge. Of the most interest are imaging, sensing, and communication systems. Currently, the cost of sources and detectors is still restrictive and as such it is not viable for every demonstration to use integrated sources and detectors, although the technology exists. As such coupling to sources embedded within hollow metallic waveguides is still the most common technique, but as mentioned this an economic not a technological decision. In this section applications oriented integrated systems are reviewed.

2.6.1 Integrated Sensing Systems

Integrated sensors are used to detect and differentiate between analytes. Often, this is achieved through contact with the waveguide to induce a phase or amplitude change in the guided wave. The simplest integrated sensor is simply a straight waveguide augmented with external micro-fluidics, where the transmitted phase and amplitude can be used to infer the properties of the analyte [278]. The sensitivity of this kind of sensor is dependent on the strength of the evanescent fields, where stronger fields result in enhanced interaction effects. Where weak evanescent fields are present, a long waveguide may be required to detect a measurable phase change, resulting in bulky structures and large required analyte volumes. At the same time, for aqueous analytes which are often lossy, long interaction lengths will result in significant attenuation to the signal and sensitive detectors must be employed. Alternatively, sensing based on reflection can be performed, where an interface between the guided mode and the analyte is formed and the reflection from the interface is measured [185]. This has the advantage that the interaction length is very short, and hence lossy analytes may be sensed with less sensitive detectors. In both of these cases the magnitude and phase of the signal must be measured to reconstruct the complex permittivity of the analyte. For compact sensors, for which only the magnitude spectrum must be measured, resonant structures can be employed to enhance the interaction without increasing the footprint [198, 279]. In this case the properties of the resonance, namely, the resonance frequency and resonance depth, are used to infer the complex permittivity of the analyte. As a low-loss waveguide silicon can be used to construct compact resonators with very high Q -factors, and hence very high sensitivity.

2.6.2 Integrated Imaging Systems

Imaging systems are used to collect spatial information about a sample under-test, most commonly in a reflection configuration. At terahertz frequencies, scanned focus beam imaging systems are widespread. Being comprised of discrete free-space components these systems often occupy a large footprint. Here, integrated devices can be used to replace some elements of a bulky imaging system. Particularly, by integrating the source, detector, and beam-splitter onto a single chip the system footprint can be reduced significantly [183]. In this configuration it is difficult to integrate the lenses as large apertures are necessary to generate tight focal spots, the source of imaging resolution. However, low-gain antennas are advantageous for generating rapidly diverging beams, significantly reducing the optical path lengths required before a collimating lens. As an alternative to focused beam systems, near field imaging can also be performed [280]. Here integrated technologies are invaluable, as without the obligatory lenses the systems can be made to be extremely compact with integrated sources and detectors. However, both of these systems require raster scanning the sample, a time-consuming process, with scan times often on the order of hours, and multi-axis stages required to manage the scanning. Here there is an opportunity, inspired by microwave radar techniques, to reduce image acquisition times significantly, utilising antennas with functionality beyond that of the existing end-fire antennas.

2.6.3 Integrated Communication Systems

Integrated communications systems are likely the application of terahertz waves with the most immediate value. With the announcement of IEEE standard 802.15.3d [220] the future of terahertz communications is being defined. To date, many impressive terahertz communications demonstrations have focused on achieving high aggregate data rates without considering channelisation or bandwidth constraints [281], while making use of offline techniques to process huge volumes of data. As such the hardware is often stripped back to just a high gain antenna connected directly to a source, with amplifiers to maximise received power at the receiver [282]. These communication systems often make use of incredibly large, expensive, and powerful real-time-oscilloscopes to directly measure incoming data. More modest communications demonstrations using substrateless silicon components are abundant [185, 193, 196, 218], with a focus on demonstrating their general suitability for communications. The data rates in these cases are rarely limited by the silicon devices themselves but due to the external

equipment; modulators, oscilloscopes, detectors and the like. For practical applications, hardware, and particularly integrated components will play an increasingly important role in breaking down the data stream such that it can be processed on portable hardware. For this reason, multiplexers and filters will be of particular importance. On the transmission side, while power available from each source remains low, the aggregate channel power can be improved through the use of multiple sources, also requiring multiplexers. For now, these postulations remain theoretical, though preliminary investigations have been performed [222].

2.7 Conclusion

In the last decade substrateless silicon waveguides have emerged as a promising avenue for unlocking the potential of terahertz technologies. Primarily, this is due to silicon as a material providing exceptionally low material losses and dispersion in the terahertz range, along with moderate permittivity for field confinement. Its mechanical strength and compatibility with high precision manufacturing techniques have enabled micro-patterning critical to provide the flexibility to realise a wide range of devices. Though a comprehensive library of components have been demonstrated there are still unexplored avenues, with select passive components, power dividers, and antennas with broader operating bandwidths and frequency-scanning radiation still unavailable, these missing components will be critical to future integrated systems. Beyond this, there are still more foundational matters to address including the compactness of the platform. With most discrete components occupying millimetre scale footprints we should endeavour to develop techniques to shrink devices and decrease footprints where possible such that future integrated systems can be fabricated with existing foundry infrastructure. In this thesis I seek to address these shortcomings through proposing a variety of passive components alongside a new variant of the silicon substrateless waveguide and an investigation of 2.5D devices with alumina, a ceramic alternative to silicon. To compliment this, contributions to imaging and sensing techniques compatible with the integrated sources and detectors are made.

Part II

Terahertz Integrated Circuits

Chapter 3

Extreme Skin-Depth Waveguides

Abstract

All-silicon substrateless waveguides have become a leading contender for terahertz device integration owing to their broad operating bandwidth and exceptional efficiency. However, without metallic confinement these un-shielded waveguides are susceptible to evanescent coupling, requiring that waveguides be placed sparsely to resist unwanted interactions. This sparsity remains a critical obstacle to compact devices and integrated systems. To counter this, substrateless extreme skin-depth waveguides are proposed, utilising a self-supporting anisotropic cladding that markedly reduces the evanescent field penetration into the surrounding cladding, and hence suppresses cross-coupling between waveguides. Here we achieve 20 dB cross-talk suppression across the WR3.4 band, 220–330 GHz, a 40% fractional bandwidth, with less than half a free-space wavelength separations and coupling lengths exceeding 10 free-space wavelengths. Integrable with existing all-silicon devices, I foresee these techniques enabling the dense integration of terahertz systems with substrateless silicon waveguides.

3.1 Introduction

Dielectric confinement mechanisms, either photonic band-gap or total internal reflection, permit strong evanescent fields outside the waveguide core which enables evanescent coupling between adjacent waveguides. In many cases this phenomenon can be harnessed to realise useful devices; uni-directional couplers [204, 218], ring resonators [212] or in-slab beam-formers [283]. However, strong evanescent fields come at the cost of integration density. To avoid these unwanted evanescent coupling, waveguides must be placed sparsely, on the order of multiple wavelengths, leading to enlarged system footprints and limited opportunities for the realisation of devices where sub-wavelength waveguide spacing is critical, such as antenna arrays. Though undesirable, enlargement is tolerable in visible or infrared optics where wavelengths are on the order of 1 μm and packaged devices are on the order of 1 mm, but at terahertz frequencies directly scaling these same devices would result in a footprint of 1 m, which is completely impractical. Beyond this, the long-term commercial viability of a platform is dependent on the device yield per wafer, which in turn reduces the cost per device as the devices get smaller. For these reasons, coupling suppression strategies for integrated circuit technologies at terahertz frequencies will become essential as the system complexity and fabrication volume increases.

Since Marcatili's initial description of the dielectric waveguide coupler [194], coupled mode theory [205] emerged to describe complex coupled systems. Arising from this, various schemes for coupling suppression have been proposed including photonic crystal fencing [284], superlattice techniques [285], and adiabatic elimination [286]. Though these techniques provide solutions to the problem of unwanted evanescent coupling under specific conditions, they do not address the underlying cause of coupling, i.e. the strong evanescent field that exists outside the waveguide core. A more general solution is an all-dielectric waveguide that strongly suppresses the evanescent field such

that two identical waveguides can exist in proximity without significant coupling.

The primary mechanism for evanescent coupling is the physical overlap between the evanescent field and the coupled waveguide, and so the decisive factor in suppressing evanescent coupling is the concentration of evanescent fields as close as possible to the guide's core—away from the core of an adjacent guide. The evanescent field distribution is affected by a range of parameters including core dimensions relative to wavelength, confinement mechanism, and cladding material. Waveguides with cores that are large relative to wavelength have stronger wave confinement compared to smaller ones, but to ensure single-mode operation the core enlargement must be balanced against the onset of higher-order modes. For a single-mode guide, a recent analysis revealed that cladding anisotropy can enhance the field confinement further for in-plane-polarised modes [287]. In nano-photonics, this led to the development of the so-called extreme skin-depth, or E-Skid, waveguides, which exploit total internal reflection confinement with an anisotropic cladding, suppressing the evanescent field beyond the level expected for the index contrast. Here, the term skin-depth is used atypically, referring to the penetration of the evanescent field into the dielectric cladding, not to the skin-effect in conductive materials. Usually, this anisotropy is realised through a sub-wavelength periodic grating of microbeams that runs parallel to the waveguide core [288–292]. Previously, in nano-scale waveguides these microbeams have been mechanically supported by the substrate. However, as discussed previously in Chapter 1, in silicon on insulator waveguides at terahertz frequencies the quartz or silica substrates result in additional losses, with waveguide losses measured as 0.46 dB/cm [166] and 0.40 dB/cm [179] respectively, more than 8 times the loss of the substrateless structures. Previously, silicon microbeams tethered to effective-medium lattices have been shown to be mechanically self-supporting [196], forming a pathway to realise extreme skin-depth waveguides on a substrateless waveguide platform. Here I design and fabricate, single-mode, substrateless, extreme skin-depth waveguides and experimentally validate their transmission properties and resistance to evanescent coupling.

3.2 Theory and Design

3.2.1 Coupling Suppression with Anisotropic Cladding

A comprehensive analysis of the effect of anisotropy on evanescent coupling is available in the supporting information of [287]. Here, for completeness, I reproduce some key results in the context of our substrateless platform. Consider the waveguide depicted in Fig. 3.1(a) supporting the fundamental E_x^{11} mode, with in-plane-polarisation, propagating in the z direction of an infinite rectangular dielectric waveguide constructed from a core with width w , and isotropic permittivity $\varepsilon_{\text{core}}$. The waveguide is surrounded by an anisotropic homogenous dielectric with permittivity tensor $\varepsilon = (\varepsilon_x, \varepsilon_y, \varepsilon_z)$. The x -component of the electric field is given by,

$$E_x(x, z) = \frac{\beta}{\omega \varepsilon_0} \cdot \begin{cases} \frac{A}{\varepsilon_{\text{core}}} \cos(k_{x,\text{core}} x) e^{-j k_z z}, & |x| < w/2 \\ \frac{B}{\varepsilon_x} e^{-k_{x,\text{cladding}} x} e^{-j k_z z}, & |x| > w/2 \end{cases} \quad (3.1)$$

where $k_{x,\text{core}}$ and $k_{x,\text{cladding}}$ are the wavenumbers in the core and the cladding respectively. These parameters, which determine the modal distribution, can be determined by applying boundary matching and continuity conditions at the core-cladding interface, resulting in the following equations which can be solved simultaneously,

$$k_{x,\text{core}}^2 + k_{x,\text{cladding}}^2 \frac{w^2 \varepsilon_x}{4 \varepsilon_z} = \frac{k_0^2 w^2}{4} (\varepsilon_{\text{core}} - \varepsilon_x), \quad (3.2)$$

$$k_{x,\text{core}} = \frac{\varepsilon_z}{\varepsilon_x} k_{x,\text{cladding}} \tan(k_{x,\text{cladding}}). \quad (3.3)$$

According to Eq. (3.1), $k_{x,\text{cladding}}$, should be maximised to maximise the decay of the evanescent fields, and thus minimise coupling. Critically this parameter depends on the in-plane-anisotropy, i.e., ε_x and ε_z , of the cladding material. Through the simultaneous solution of Eq. (3.2) and Eq. (3.3) it was established that high parallel permittivity, ε_z , relative to perpendicular permittivity, ε_x , leads to strong

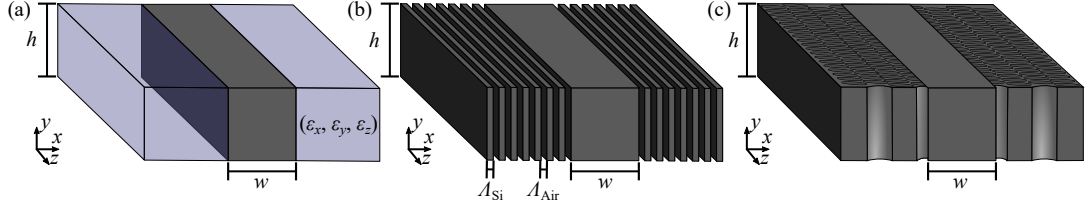


Figure 3.1: Substrateless terahertz waveguides. (a) Illustration of a dielectric waveguide clad with artificial, homogenous anisotropic effective medium. (b) Schematic drawing of the extreme skin-depth waveguide with realised anisotropic cladding. (c) Schematic drawing of the effective medium clad waveguide with in-plane-isotropic hexagonal lattice effective medium cladding [168].

evanescent field decay [288]. This result is underpinned by the concept of relaxed total internal reflection in anisotropic materials, by which mode confinement is solely induced by the permittivity contrast between the core permittivity, ϵ_{core} , and the perpendicular component of the cladding permittivity, ϵ_x . As this condition is independent of the parallel component of the cladding permittivity, ϵ_z , mode confinement can be achieved with cladding materials with high parallel permittivities, inducing rapid evanescent field decay.

Though the innate anisotropy of common materials is minimal, and is all but absent in silicon, anisotropy can be introduced through sub-wavelength patterning to form effective mediums [293]. One such anisotropic effective medium, as in Fig. 3.1(b), can be formed by interleaving parallel strips of two materials to form an effective medium with the requisite in-plane-anisotropy. This anisotropy can be understood through various effective medium theories [192, 294] such as Rytov's original formulation of stratified media [295], quasi-static effective medium theory, as in [293], or the Maxwell-Garnett effective medium theory, as in [288], which predicts the permittivities parallel, ϵ_z , and perpendicular, ϵ_x , to the waveguide core as,

$$\epsilon_z = \epsilon_y = \epsilon_{Si}\rho + \epsilon_{Air}(1 - \rho) , \quad (3.4)$$

$$\epsilon_x = \frac{\epsilon_{Si}}{\rho + (1 - \rho)\epsilon_{Si}} , \quad (3.5)$$

where ρ is the silicon filling factor,

$$\rho = \frac{\Lambda_{Si}}{\Lambda_{Si} + \Lambda_{Air}} , \quad (3.6)$$

and Λ_{Si} and Λ_{Air} are the stripe widths of the two constitutive materials, air and silicon. In Fig. 3.2(a), we compare the effective permittivity tensors of two effective medium configurations, the anisotropic alternating strips depicted in Fig. 3.1(b) and the hexagonal lattice proposed in [168] and depicted in Fig. 3.1(c). I note that, in both cases, a wide range of permittivities can be achieved by varying the fill factor. In Fig. 3.2(a) I highlight the in-plane-anisotropy that occurs in the strip effective medium, compared to the complete isotropy of the hexagonal lattice medium. Critically, in Fig. 3.2(b) I calculate the evanescent field decay rate for both cases, noting the significantly higher decay rate for the anisotropic case, in line with the findings of [287]. Here I follow the convention of [288] in applying Maxwell-Garnett approximations, but to interrogate this convention I compared the Maxwell-Garnett approximation to Rytov's formulation which explicitly considers stratified media [295], only to find that in this case they are identical. In accordance with Fig. 3.2(a), I select a fill factor of 0.5, or $\Lambda = \Lambda_{Si} = \Lambda_{Air}$, to maximise the anisotropy and hence the evanescent decay rate. In this case the precise values of Λ are a free variable so long as it is deeply sub-wavelength, but fabrication considerations place a lower limit on this variable at $\Lambda = 20 \mu\text{m}$. This device is simulated using the commercially available FIT solver CST Studio 2023. In Fig. 3.2(a) a cross-section of the modal distribution at 220 GHz is shown for the fundamental mode, while Fig. 3.2(b) shows the intersection of the cross-section with the $y = 0$ plane, compared to equal size waveguides clad with effective medium cladding as depicted in Fig. 3.1(c). Highlighting the rapid decay of the evanescent fields within a core width of either side of the waveguide core.

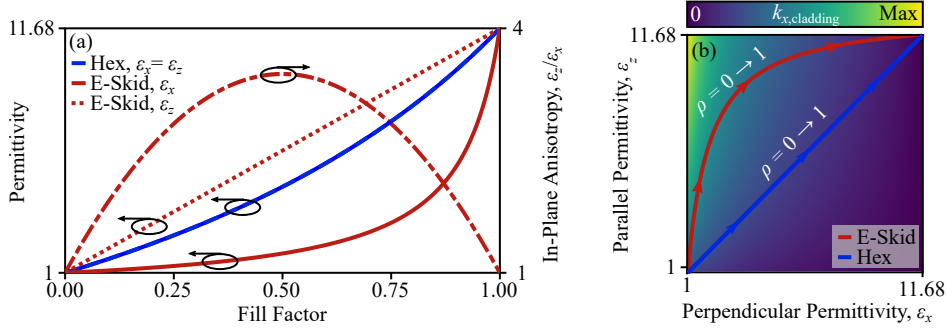


Figure 3.2: Analysis of the effect of cladding anisotropy on evanescent field decay. (a) Comparison of the permittivity tensors of hexagonal lattice, in Fig. 3.1(c), and alternating strip, in Fig. 3.1(b), effective mediums (left axis) and in plane anisotropy ratios, ϵ_z/ϵ_x , for the alternating strips (right axis). (b) Evanescent field decay rate in colourplot and manifested as $k_{x,cladding}$. This decay rate is a function of the in-plane-permittivities, ϵ_z and ϵ_x , or the parallel and perpendicular permittivities. Line traces are for the permittivities of the hexagonal lattice (blue) and extreme skin-depth (red) claddings as the silicon fill factor is varied from 0 to 1. In these calculations the waveguide core has a height, h of 250 μm and a width, w of 225 μm , such that these results are comparable to previous substrateless silicon waveguides designed for the same frequency range.

3.2.2 Supporting Effective Medium

As there is no substrate material, the micro-beam structure must be mechanically tethered to a frame to provide mechanical support. Previously in [196], this frame was an effective-medium clad waveguide [168]. Here ‘hex’, refers to the hexagonal lattice of cylindrical through holes which clads the waveguide core, as depicted in Fig. 3.4(a). Though this is generally effective, in this case the modal discontinuity between the effective medium waveguide and the extreme skin-depth waveguide does introduce coupling loss on the order of 1–2 dB at low frequencies where the field is most weakly confined to the core. Here I propose an alternative structure to mitigate the coupling loss while maintaining mechanical support.

Ideally, to transition between dissimilar waveguides as depicted in Fig. 3.4(a–c), the modal index and modal distribution of the two waveguides should be as similar as possible to avoid reflections and scattering. The modal distribution of the extreme skin-depth waveguide is distinctly different from that of the effective-medium clad waveguide, in particular due to the strong electric fields that exist in the air gaps between the silicon strips. To mimic this effect while creating a self-supporting lattice at the same time, I introduce linkages between micro-beams with subwavelength spacing, as illustrated in Fig. 3.4(c). It is critical that the linkage spacing be sub-wavelength to avoid Bragg grating effects. With these linkages a distorted hexagonal lattice is formed, which is self-supporting. I refer to this cladding lattice as ‘pill’, as the shape of the air-holes resemble a typical pharmaceutical product. Modal analysis presented in Fig. 3.4(d) shows that this waveguide supports a fundamental mode with a similar modal index to the hexagonal lattice clad waveguide, as the silicon volume proportion of the two waveguides is similar. This implies that the modal index discontinuity remains, this is unavoidable as the introduction of the linkages introduces additional silicon which loads the propagating mode. However, as shown in Fig. 3.2(b) the waveguide mode more closely resembles that of the extreme skin-depth waveguide, improving the coupling between the frame and the waveguide. A comparison of full-wave simulations in Fig. 3.4(f–g), highlights this effect, with scattering visible in the hex to E-skid transition, but is suppressed in the ‘pill’ to E-skid transition. I note that introduction of the linkages partially compromises the anisotropy of the cladding which reduces the coupling suppression properties of the cladding, though it still out-performs isotropic cladding. Nevertheless, the primary advantage of this pill cladding is as a frame it can significantly reduce the coupling loss while providing mechanical support.

3.3 Results

Sample waveguides, shown in Fig. 3.5(a), are fabricated from 250 μm high-resistivity ($>20 \text{ k}\Omega\cdot\text{cm}$) float-zone silicon wafers through deep-reactive ion etching (DRIE). Measurements are performed with

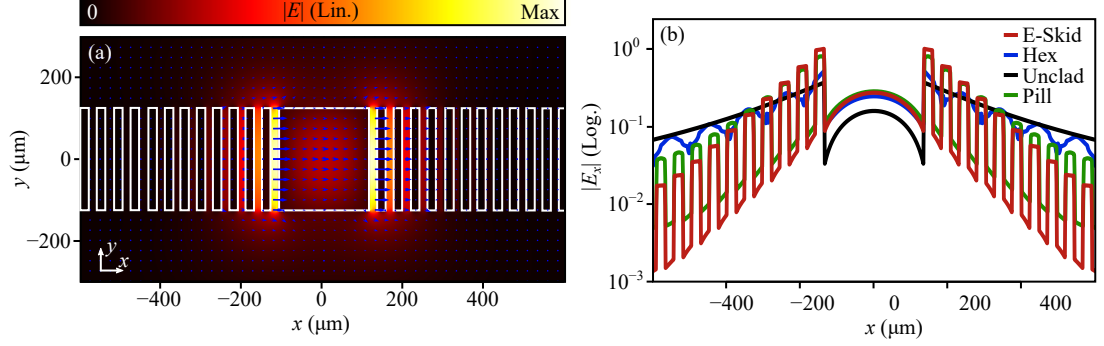


Figure 3.3: Modal distributions of extreme skin-depth waveguide. (a) Electric field distribution of the extreme skin-depth waveguide at 220 GHz. (b) Cross-section of (a) in logarithmic scale, with comparisons to the modes of unclad, hexagonal lattice, and 'pill' lattice effective medium clad waveguides of the same dimensions.

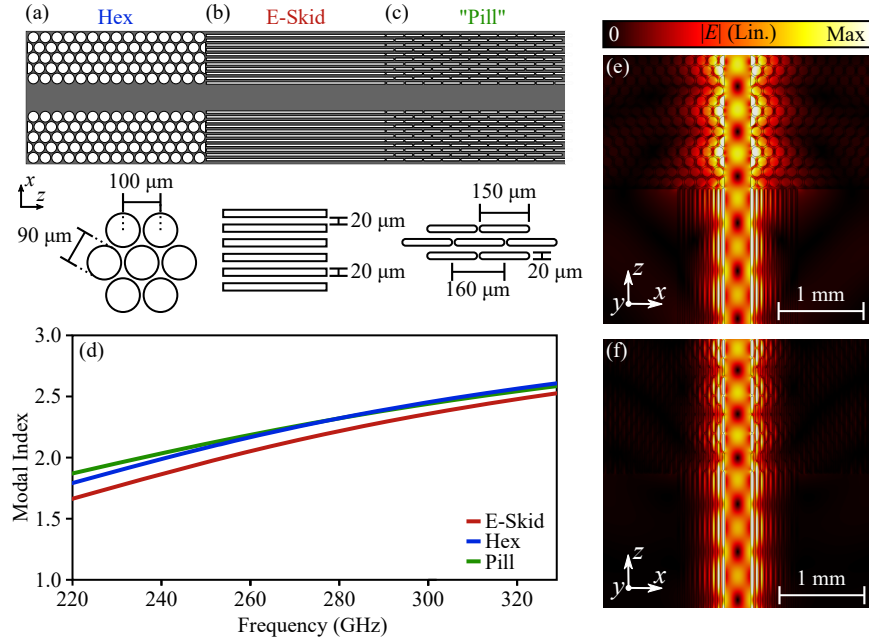


Figure 3.4: Mechanical support for extreme skin-depth waveguides. (a) Effective medium clad waveguide based upon a hexagonal lattice effective medium. This cladding is in-plane-isotropic and is mechanically self-supporting. (b) Extreme skin-depth waveguide with in-plane-anisotropic cladding. This cladding must be mechanically supported by tethering the ends of the waveguides to another waveguide. (c) Proposed mechanically self-supporting cladding which more closely resembles the anisotropic cladding of the extreme skin-depth waveguide. (d) Modal indices of each of the waveguides described in (a-c). The simulated E -field distributions at the junction between the extreme skin-depth waveguide and (e) hexagonal lattice and (f) proposed alternative supporting lattice at 220 GHz. I highlight 220 GHz, as at this point where the wave is most weakly confined to the core, so the choice of cladding has the largest impact. Here I note the mode conversion and scattering induced by the mismatch between the two waveguides in (e) and the smooth transition between waveguides in (f).

a Keysight N5222B Vector Network Analyser with WR3.4 VDI extension modules. Data is recorded after 40 consecutive measurements are made with the in-built averaging functionality of the vector network analyser. An IF bandwidth of 100 kHz was used. The extreme skin-depth waveguides are mechanically supported by an effective medium clad waveguide frame and terminated with a linear tapered rod. The silicon waveguide is coupled to the hollow metallic waveguides by inserting the tapered end of the silicon waveguide into the hollow waveguide aperture. As shown in Fig. 3.5(b), samples are placed into an alignment jig 3D printed from polylactic acid (PLA), which supports only the frame of the waveguide leaving the waveguide itself suspended in air, such that the jig does not interfere with the wave propagation. Then micrometer stages are used to manually align the waveguide in order to maximise the coupling. All measurements are normalised to a reference measurement of the metallic waveguides in a back-to-back configuration. For this back-to-back measurement of flangeless waveguides, the micrometre stages are used to align them such that the transmission is maximised. I acknowledge that misalignment in this back-to-back measurement will exaggerate the transmission performance of the silicon waveguides. However, the results remain valid for cross-coupling analysis, which is the focus of this work. Measured results are compared to simulations performed in the commercially available CST Studio Suite 2023, using a permittivity, $\epsilon_{\text{Si}} = 11.68$ and loss tangent $\tan\delta = 3 \times 10^{-5}$ [160].

3.3.1 Propagation Properties

Straight waveguides with 10 mm, 15 mm, and 20 mm extreme skin-depth waveguide sections are measured in order to extract the complex propagation constant of the waveguides through a process of de-embedding. As depicted in Fig. 3.5(a), these waveguides are fabricated with a standard effective-medium clad frame as in [196], such that these results are comparable to previous all-silicon waveguide measurements [167, 168, 196]. In Fig. 3.5(c), the measured transmission results are shown. Due to the low loss of silicon, the losses incurred over 5 mm of propagation are small, in fact magnitudes smaller than the fluctuations arising from multiple reflections generated during coupling. The measured amplitude is thus the superposition of these multiple reflections, giving rise to interference fringes. As the period of these interference fringes changes with waveguide length, they are not annulled by the cut-back method, leading to sections of apparent gain, or negative attenuation. Nevertheless, in Fig. 3.5(d) I calculate the propagation loss of the waveguide. As expected, I observe strong variance, but the overall trend is aligned well with simulated results, and an underlying absorption coefficient on the order of 0.1 dB/cm is calculated. This result is also aligned with previous measurements of other all-silicon waveguides [167, 168, 196], indicating that the anisotropic cladding does not produce any unexpected losses. With the uncertainty in these results, I cannot definitively state the attenuation coefficients of these waveguides. Longer waveguides are required, so the cumulative attenuation is greater than measurement uncertainty. Additionally, in Fig. 3.5(e), the phase constant is calculated. Although, the phase constant at 220 GHz is unknown, I plot the measured results offset to match the mode simulation, and observe that the de-embedded value is closely matched to the value calculated with a numerical mode-solver in this case, though we acknowledge that in reality these curves could be further offset.

Though the observed propagation loss is low, as is evident in Fig. 3.5(c), I observe strong coupling loss from the hexagonal lattice frame, particularly at low frequencies. To demonstrate the efficacy of the proposed alternative distorted hexagonal lattice frame, two 10 mm samples, depicted in Fig. 3.6(a–b) are fabricated to compare the performance of the two framing techniques. In Fig. 3.6(c), improved return loss is observed, by suppressing the reflections which arise from the frame. Hence, the coupling loss is reduced at low frequencies and the transmission is improved on the order of 1 dB, as visible in Fig. 3.6(d). Based upon the value of the absorption coefficient measured above, the coupling loss for these samples can be estimated at < 1 dB for the pill design, and < 2 dB for the hex design at 220 GHz, and close to 0.1 dB at 330 GHz for both designs. This simple enhancement ensures that the absolute transmitted power of the waveguide is high and comparable to other all-silicon waveguides.

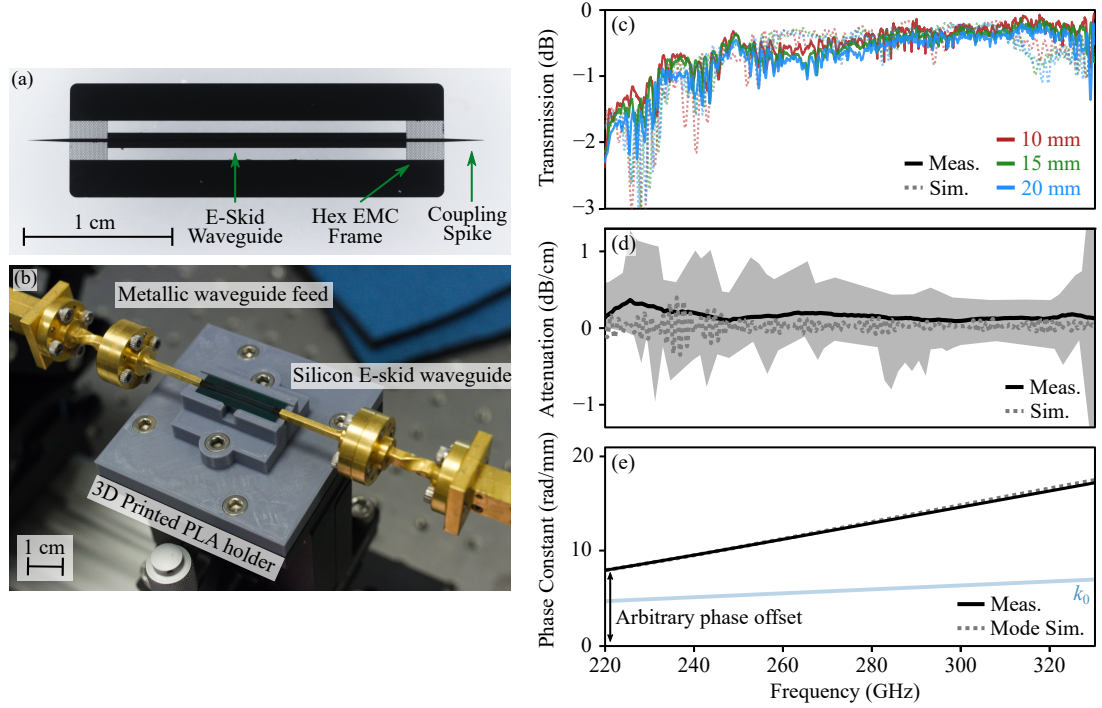


Figure 3.5: Fabrication and measurement of straight extreme skin-depth waveguides of various lengths. (a) Photograph of 20 mm extreme skin-depth waveguide sample, highlighting the waveguide itself, the hex lattice effective medium frame, and the coupling spike which is inserted into the WR3.4 waveguide. (b) Photograph of experimental setup, showing the feed metallic WR3.4 waveguides coupled to the silicon waveguide under test. The twists are necessary to feed the waveguide with the in-plane-polarised TE mode. The silicon waveguide is packaged inside a 3D-printed PLA holder. (c) Measured transmission coefficients for waveguides of various lengths. (d) Estimation of attenuation coefficient implied by (c), the solid line estimates the mean attenuation, while the grey region displays the variance of the attenuation. I attribute this strong variance and negative attenuation to error introduced from the manual alignment between the silicon and metallic waveguides. (e) Phase constant de-embedded from the measurement of multiple waveguides. Due to the unknown phase offset at the minimum frequency, there is an offset between our measured result and the mode simulation. I plot our de-embedded value offset to match the mode simulation.

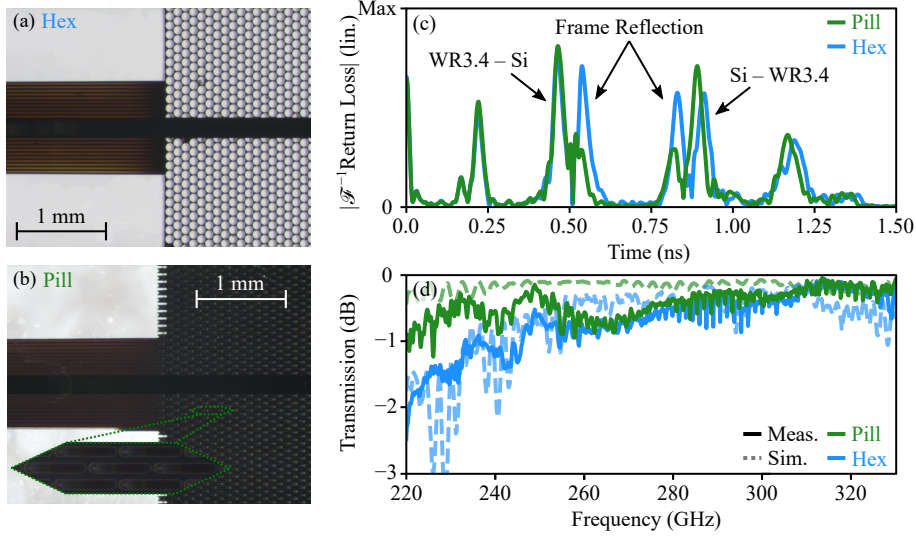


Figure 3.6: Fabrication and measurement of extreme skin-depth waveguides with different structural supporting waveguides. (a) Micrograph of extreme skin-depth waveguide framed with hexagonal lattice effective medium. (b) Micrograph of extreme skin-depth waveguide framed with the proposed pill shape effective medium. I note that the etched regions are partially blind resulting in poor optical contrast between the etched and un-etched regions. (c) Reflections from the waveguide presented in the time domain to highlight the reduction in the reflections arising from the mismatch between the frame and the extreme skin-depth waveguide. (d) Transmission coefficients of the waveguides shown in (a) and (b). These are compared to the result from full-wave mode simulation.

3.3.2 Coupling suppression

Next, the coupling suppression properties are experimentally validated. The two 2×2 uni-directional couplers in Fig. 3.7(a–b) are fabricated with a coupling length of 10 mm and waveguide separation of $420 \mu\text{m}$ ($0.46 \lambda_0$ at 220 GHz), the first with extreme skin-depth waveguides and the second with un-clad waveguides. To measure these multi-port devices with our 2-port vector network analyser, sequential measurements must be made. Here, two opposite ports are coupled to the metallic waveguide ports of the vector network analyser, and the remaining ports are left with coupling spikes. These coupling spikes match the silicon waveguide silicon to free space, where the power radiates and gets partially absorbed by nearby absorbers. As such, these ports can be considered as though they are approximately matched loads. In Fig. 3.7(c–d), the through and cross transmission results are presented. The unclad coupler shows the strong frequency-dependent response typical of a uni-directional coupler, with frequencies centred around 245 GHz coupling strongly to the cross-port whilst higher frequencies are retained in the through port. As in Fig. 3.7(d), the extreme skin-depth waveguide shows strong coupling suppression, on the order of -25 dB or 0.3% of the original coupled power, maintaining strong, broadband transmission across the operating band. This key result shows the feasibility of substrateless extreme skin-depth waveguides for achieving broadband coupling suppression in all-dielectric waveguides. We observe blue-shifting of the coupling frequency arising from unintentional over-etching of the waveguide. I note that above 310 GHz, the cross-coupling of the extreme skin-depth guide exceeds the unclad guide, this arises from scattering at the frame interface, which results in spurious fields inside of the cladding. These fields are not readily radiated or absorbed, and eventually re-enter the waveguide where they are eventually measured as cross-talk. In contrast, the unclad waveguide has no such cladding to capture and propagate the scattered field.

3.4 Conclusion

In this chapter, I experimentally demonstrate substrateless extreme skin-depth waveguides at terahertz frequencies. The presented waveguides operate over the same band and with comparable loss to previously all-silicon waveguides which have been clad with isotropic effective mediums or air,

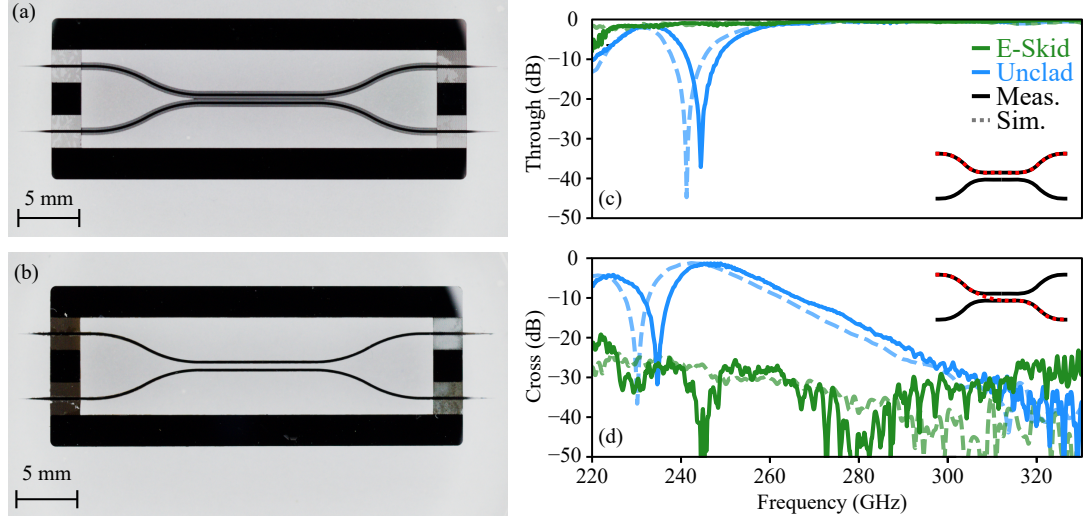


Figure 3.7: Fabrication and measurement of evanescent couplers. (a) Micrograph of extreme-skin-depth waveguide evanescent coupler. (b) Micrograph of unclad waveguide evanescent coupler. These couplers are framed with effective-medium clad waveguides. Measured and simulated transmission at the (c) through and (d) cross ports of the evanescent coupler. A blue-shift in the coupling frequency of the unclad coupler is observed, which is attributed to unintentional over-etching during the fabrication process.

while suppressing the evanescent coupling between adjacent waveguides $0.46\lambda_0$ spacing with crosstalk suppression above 20 dB. This level of suppression should be sufficient for most applications, ensuring that intended transmission is almost unaffected across the operating bandwidth, and most importantly removing strong transmission loss due to evanescent coupling. Importantly, these waveguides open a pathway towards the dense integration of broadband components on the substrateless all-silicon waveguide platform, without incurring Ohmic losses from metallic shielding or the bandwidth limitations of photonic bandgap effects. This circuit density is critical for reducing the footprint of devices and increasing the device yield for wafer, factors which are critical for widespread adoption.

Chapter 4

Rib Waveguides

Abstract

The rib, or ridge, waveguide has been a staple at optical wavelengths for decades owing to its large single mode bandwidth and simple fabrication, but has been scarcely utilised in the terahertz domain. The strictly planar substrateless waveguides discussed to this point are advantageous due to their strong, broadband mode confinement and high efficiency, but the bandwidth achievable with these waveguides is fixed due to the onset of higher order modes as the frequency increases. In this chapter, rib waveguides are employed to expand the single-mode operating region beyond the achievable range with previously described waveguides. Beyond this, the 2.5D nature of these waveguides opens additional design freedoms through adapting the height. To assess the practicality of this scheme, metallic waveguide coupling, bending, and slab thickness transitions are explored. Finally, terahertz waveguides manufactured with 3D-printed alumina are experimentally characterised over the 220–330 GHz range.

4.1 Introduction

In many cases, the substrateless waveguides discussed previously are sufficiently broadband, typically a 40% fractional bandwidth, that they are not the bandwidth-limiting factor. Notably, they can cover a single traditional metallic waveguide band, which is convenient for coupling to waveguide coupled sources and detectors. However, optical sources, such as the uni-travelling carrier photo-diode, can operate over far broader bandwidths than a single metallic waveguide band, and so ultra-broadband devices serve a special utility in this case. Ultra-broadband integrated systems are of interest for both sensing and communications applications. In sensing, the broadband absorption information can be used for spectroscopy to identify spectroscopic signatures or in radar applications where the depth resolution is directly proportional to the system bandwidth. For communications, ultra-broadband devices, particularly front-end devices such as antennas, act as the interface between free-space and the integrated circuit, where passive signal processing can be employed to receive the broadband signal.

To date, ultra-broadband waveguiding has been achieved through the use of over-moded rod waveguides [266, 296], which support higher-order modes. Typically, the utility of these rods is limited, as any asymmetry in the guide readily excites these higher order modes which are then difficult to suppress. As an alternative to this, I propose that rib waveguides are a more practical approach to the realisation of a single-mode ultra-broadband integrated waveguide platform.

Beyond their broadband single-mode propagation, rib waveguides are also of interest as they are 2.5D devices, in contrast to the strictly 2D waveguides discussed previously. This additional degree of design freedom is useful in devices that require out-of-plane asymmetry such as polarisation rotators. Of course, this advantage comes at a cost, notably that to manufacture these waveguides through DRIE, multiple stages of lithography and etching are required, increasing the complexity and cost.

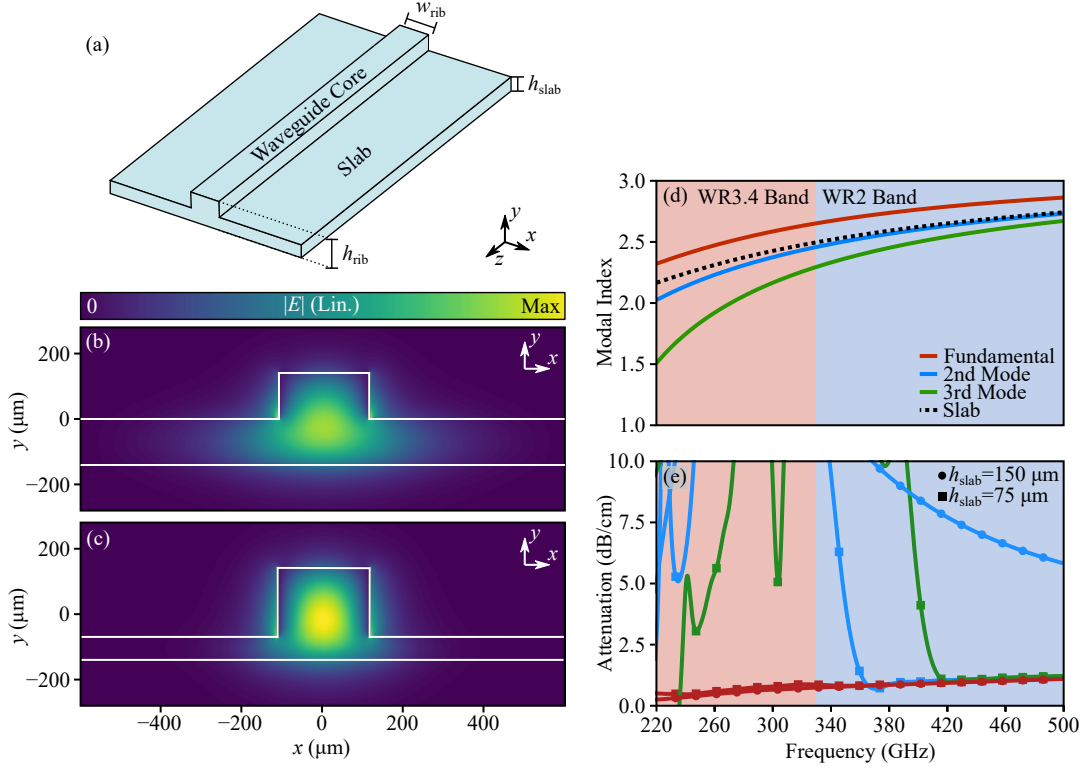


Figure 4.1: Schematic of the rib waveguide. (a) Isometric drawing of the rib waveguide. Electric field distributions of the rib waveguide with (b) $h_{\text{slab}} = 150 \mu\text{m}$ and (c) $h_{\text{slab}} = 75 \mu\text{m}$ and the same rib height of $300 \mu\text{m}$. (d) Modal analysis of the rib waveguide, highlighting that only the fundamental mode propagates with a higher modal index than the slab mode, leading to single mode propagation. (e) The simulated attenuation of each mode in waveguides with $75 \mu\text{m}$ and $150 \mu\text{m}$ slabs, showing that in the thicker slab the attenuation of the second mode is strong even at 500 GHz , while in the thinner slab, leakage of the higher-order modes is weak above 350 GHz .

Some foundries employ a dual-etch process for DRIE of relatively thick silicon wafers and in this case this process can be employed for the fabrication of rib waveguides without additional complexity. With this in mind, there is interest in exploring alternative fabrication techniques, notably additive manufacturing for manufacturing waveguides. Although the polymer materials typically associated with additive manufacturing are poor choices, recently ceramics such as alumina have become available, which are physically strong, have a moderate and stable permittivity, and critically, have competitive attenuation [161]. Previously, silicon based rib waveguides have been demonstrated [297, 298]. So the focus of this chapter is the realisation of rib waveguides with 3D-printed alumina and broadband analysis. That said, the analysis and designs contained are generalisable to both alumina and silicon waveguides, with slight parameter changes to compensate for the change in permittivity.

In this chapter, ultra-broadband terahertz rib waveguides are designed alongside the fundamental components required to form an integrated circuit. An analysis of coupling to metallic waveguides and bending is presented over the $220\text{--}500 \text{ GHz}$ range, spanning two traditional rectangular waveguide bands, a fractional bandwidth of 75%. These waveguides are then fabricated from 3D-printed alumina and experimentally characterised over the $220\text{--}330 \text{ GHz}$ band, with estimations of the attenuation coefficients and propagation constants extracted from these measurements.

4.2 Analysis

4.2.1 Modal Analysis

The rib waveguide, depicted in Fig. 4.1(a), has long been a mainstay of optical dielectric waveguides owing to its simple fabrication and robust performance [199, 299]. The waveguide is controlled by

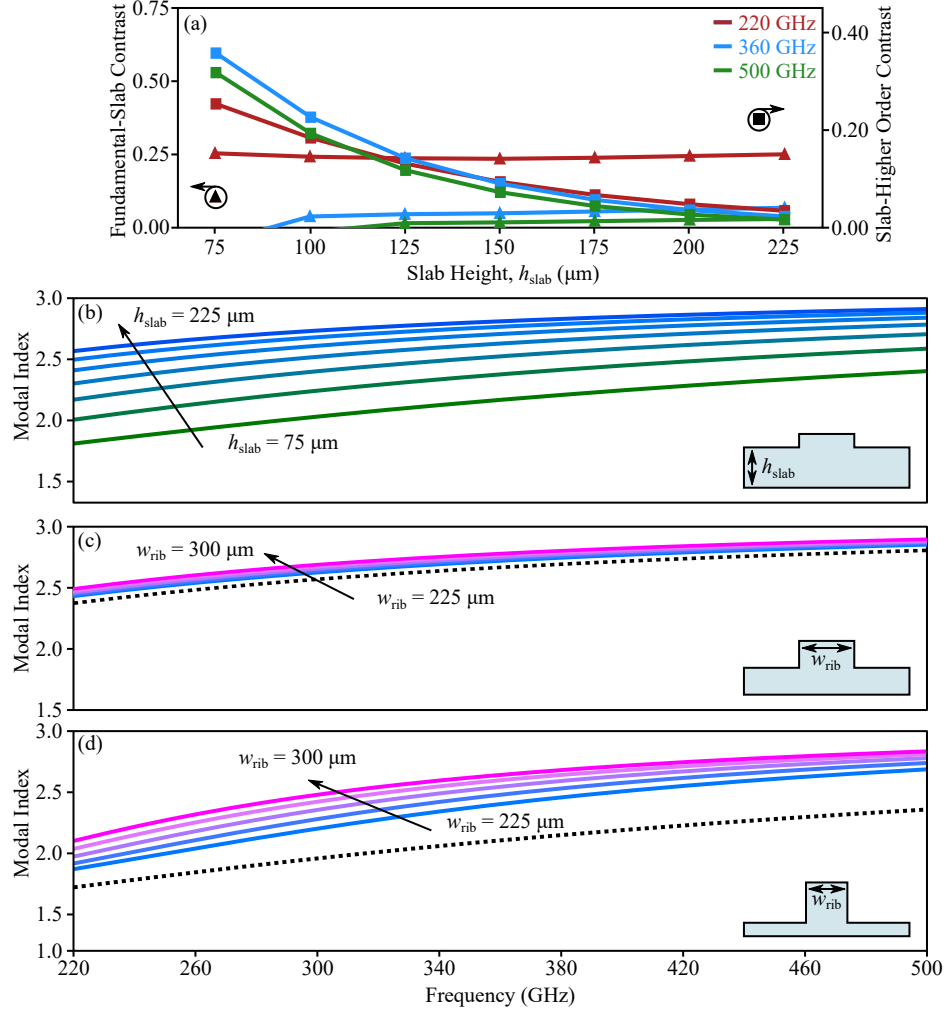


Figure 4.2: Modal analysis of alumina rib waveguides. (a) Modal index contrast between the fundamental mode and the slab, indicated by square markers, and the higher order mode and the slab mode, indicated by triangle markers. This highlights the trade-off between fundamental mode confinement and protection from higher order modes as the slab height is varied. (b) Modal index as the thickness of the slab is swept in the range 75–225 μm , with rib width and rib height 300 μm . (c) Modal index as the rib width is swept from 200–300 μm , with rib height 300 μm and slab thickness of 150 μm . The dash line represented the slab mode of the surrounding slab. (d) Modal index as the rib width is swept from 200–300 μm , with rib height 300 μm and slab thickness of 75 μm .

three determining parameters, the thickness of the slab, the width of the rib, and the height of the rib. By carefully selecting these parameters, a single mode waveguide is realised [300]. The fundamental mode, shown in Fig. 4.1(b–c), is confined to the core by total internal reflection, so even though the mode may propagate in the surrounding slab, the contrast between the fundamental and slab mode maintains the confinement. Intuitively, higher order modes are unable to propagate in the waveguide as they lack this contrast and are progressively leaked into the surrounding slab. This understanding is supported by full-wave modal analysis of the structure presented in Fig. 4.1(d), where it is clear that the fundamental mode is the only mode that exists above the slab mode of the surrounding membrane, resulting in the continuous leakage of higher order modes into the surrounding slab in the case they arise. As shown in Fig. 4.1(e), this higher order mode protection depends on the slab thickness, with thicker slabs providing stronger leakage at higher frequencies, while for thin slabs the leakage may only exist across a single waveguide band. In Fig. 4.2(a) we show the relationship between slab height, fundamental mode confinement and higher-order modes. Although a thin slab results in stronger contrast between the guided mode and the slab mode and hence stronger mode confinement, the protection from higher-order modes is concurrently reduced, indicated by the weak contrast between the slab mode and the second-order modes, an effect that is exacerbated at higher frequencies. For devices manufactured additively, the thickness of the slab can be adjusted across the design without incurring additional fabrication steps, allowing high modal index contrast to be realised when necessary such as for bending, whilst thicker slabs can be used on straight sections. For single-mode operation over the 220–330 GHz band we select a rib width and height of 300 μm . In Fig. 4.2(b–d) the effect of slab thickness and rib width on propagation properties are analysed with full-wave simulation in CST Studio 2023. The material properties of 3D-printed alumina are taken from previously published experiments, with an alumina permittivity, $\epsilon_{\text{alumina}} = 9.5$ and a loss tangent, $\tan \delta = 7.5 \times 10^{-4}$ [161]. In Fig. 4.2(c–d), we show the ability to tune the modal index by varying the rib width and slab height. Based upon these results, I concentrate on waveguides with $w_{\text{rib}} = 300 \mu\text{m}$, $h_{\text{rib}} = 300 \mu\text{m}$ and $h_{\text{slab}} = 75 - 150 \mu\text{m}$. In this range, the fundamental mode is well confined to the rib and the thin slab is fabricable.

4.2.2 Coupling to WR3.4 Waveguide

At present, many commercially available sources and detectors are housed within micro-machined packages that offer an external terahertz-range interface in the form of a hollow metallic waveguide. As such it is necessary to couple to hollow metallic waveguides for characterisation of the waveguide. In conventional ribbon waveguide platforms, this is achieved by a tapered spike that is inserted into the metallic waveguide to gradually match the two waveguides [164, 301]. This is effective for waveguides where the propagating mode exists mainly within the core of the waveguide. However, in the case of the rib waveguide where the mode is significantly larger than the width of the rib, this spike fails to launch the mode efficiently, owing to the sudden introduction of the slab, effectively introducing a step transition from a ribbon to a rib waveguide. Instead, as depicted in Fig. 4.3(a), a two stage solution is required, first a spike is used to transition from the hollow metallic waveguide to a ribbon waveguide, then in the second stage the slab is gradually introduced to launch the fundamental mode of the rib waveguide. This edge coupler is parameterised by three variables; the length of the spike, the length of the slab taper, and the width of the slab taper. The width of the slab taper should be sufficiently large that the edge of the mode does not interact with the edge of the slab as the mode is launched, and at 220 GHz where the mode is the largest, 2000 μm is sufficient to meet this criterion. It is intuitive that the longer the spike and the slab taper, the more gradual the transition will be and hence the lower the coupling loss will be. However, longer length will incur additional material losses, and additionally a long spike becomes increasingly fragile. Together these factors define an optimisation problem. To address this fragility we constrain the maximum length of the spike to 2000 μm and examine the coupling loss as the length of the slab taper is varied, with results presented in Fig. 4.3(c). Based upon these results we conservatively select a slab taper of length 3600 μm , corresponding to a coupling loss of 0.3 dB per taper, compared to almost 1 dB per taper with just the spike.

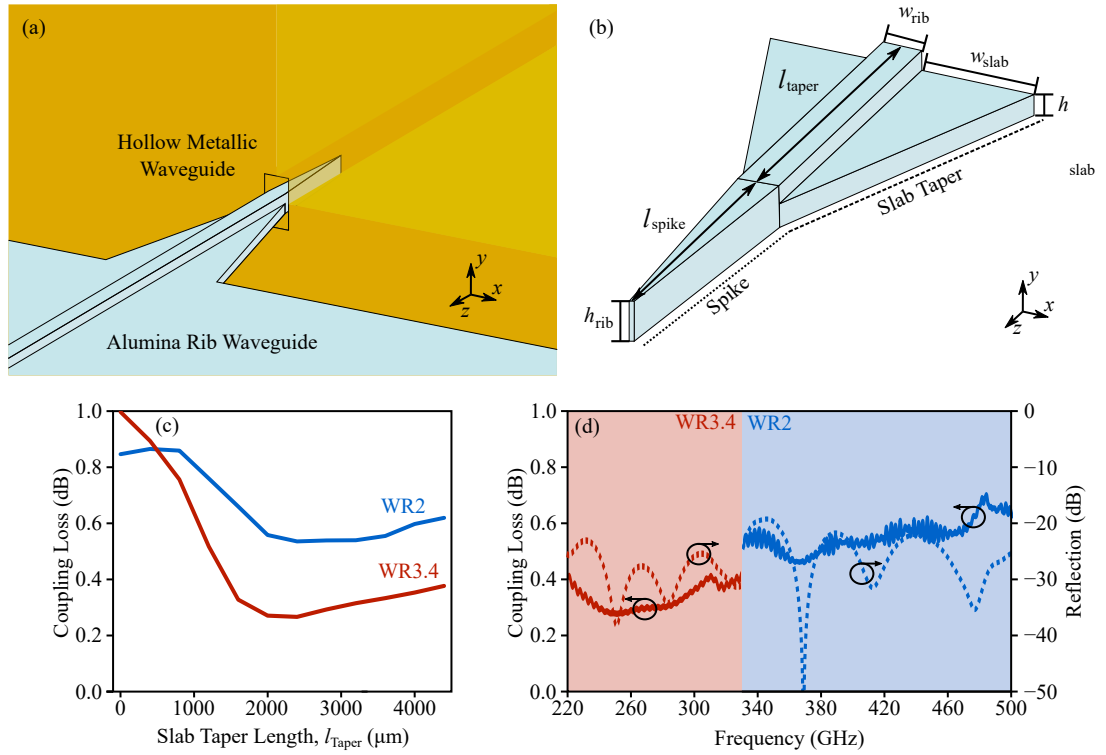


Figure 4.3: Schematic of WR3.4-alumina rib coupler. (a) Conceptual drawing, showing the tapered coupler inserted into a WR3.4 waveguide. (b) Schematic of the coupler, highlighting design parameters. (c) Mean coupling loss as the length of the tapered rib is swept, at spike length of 2000 μm , with slab width of 850 μm , rib width and rib height of 300 μm , and a slab thickness of 150 μm . (d) Coupling loss and reflection from a tapered structure with length 3600 μm , at spike length of 2000 μm , with slab width of 850 μm , rib width and rib height of 300 μm , and a slab thickness of 150 μm .

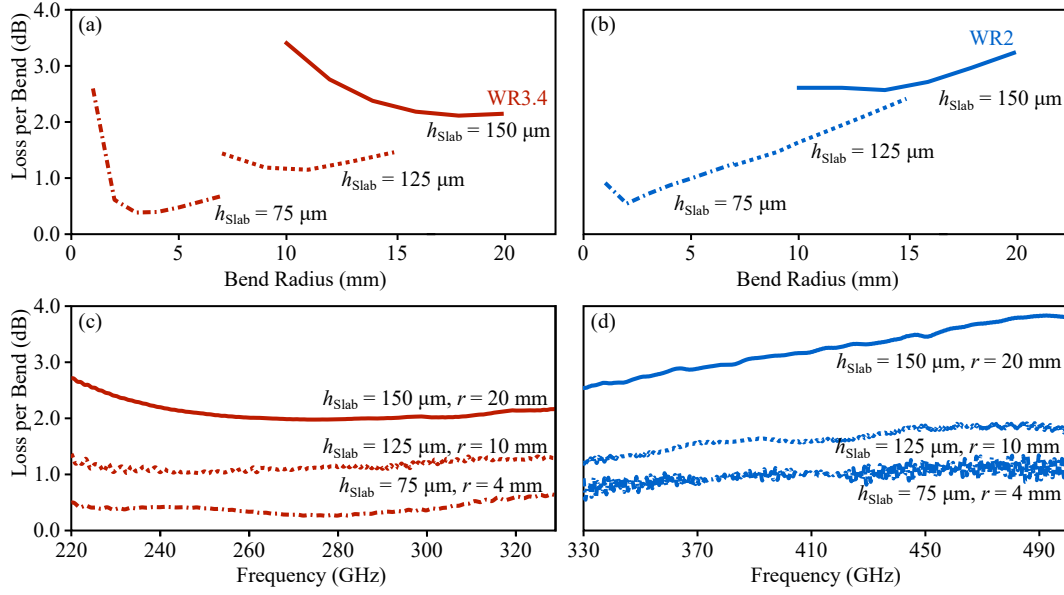


Figure 4.4: Bending loss of alumina rib waveguides. Mean loss per bend of rib waveguides with varied slab thickness in the (a) WR3.4 and (b) WR2.2 frequency bands. (c–d) Frequency dependent loss of selected bends from (a–b).

4.2.3 Bending

One disadvantage of the rib waveguide compared to other waveguide configurations is its bending loss [302]. Owing to the modest modal index contrast between the fundamental mode and the surrounding slab mode, the waveguide will readily leak into the slab at bends. This effect is exacerbated at low frequencies where the confinement is weakest, and when the bend radius is small. These losses can be mitigated by simply increasing the bending radius, sacrificing compactness for efficiency, as is illustrated in Fig. 4.4. However, owing to material losses, the loss per bend also gradually increases concurrently [203, 303], leading to a lower boundary for the bending loss, irrespective of bending radius. These competing factors lead to the existence of an optimal bend radius, and a non-monotonic trend in the bending loss. Alternatively, the bending performance can be improved by decreasing the slab thickness, increasing the contrast between the guided and slab modes. By increasing the contrast, the mode confinement to the rib is increased, reducing the radiation losses throughout the bend. However, this may permit higher order modes at sufficiently high frequencies, as previously discussed. Moreover, this technique is not typically employed as it requires multiple etching stages, which would otherwise be necessary, increasing the fabrication complexity. In this case, additive manufacturing addresses the second issue as the fabrication readily facilitates multiple slab thicknesses without additional cost. As previously discussed in Section 4.2.1, even with slabs as thin as 75 μm the single mode condition is maintained over the 220–330 GHz region for waveguides with heights and rib widths of 300 μm . For these reasons the bending loss of waveguides with slab thicknesses of 75 μm , 125 μm , and 150 μm are presented in Fig. 4.4. For slab thickness of 75 μm the permissible bending radius can be as small as 2500 μm or $2\lambda_0$, while a bending loss of less than 1 dB per bend is incurred, with little advantage in increasing the bend radius beyond this point.

To realise the above-described bend, a slab-thickness transition, as depicted in Fig. 4.5(a), is necessary. As in Fig. 4.5(b), the two regions cannot be simply concatenated without introducing additional loss. As such a gradual transition is necessary. During fabrication the structure is assembled by the sequential deposition of 19 μm -thick layers, which after shrinkage during sintering become 15 μm layers, ensuring that the transition must be discretised. For a transition from 150 μm to 75 μm , 4 additional layers must be introduced. As in the case of bending there is an upper limit to the transition length owing to the material losses, I determine that 400 μm per layer is sufficient, with an average loss per height transition of 0.12 dB in the WR3.4 band and less than 0.20 dB in the WR2.2

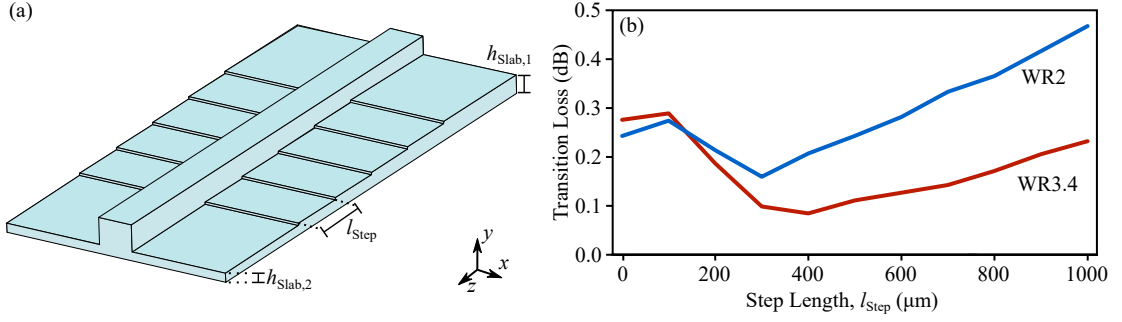


Figure 4.5: Design of transition between two rib waveguides with varying slab thickness. (a) Schematic drawing of the transition including key parameters. The step height is determined by the layer thickness of the 3D-printer, in this case 15 μm . (b) Transition loss for 75 μm to 150 μm slab thickness transition as the length of each step is varied.

band. This loss is far below the loss incurred from bending with thick slabs, and the footprint of the transition is only 1200 μm , ensuring that compact bends with minimised loss are achievable.

4.3 Experimental Characterisation

Samples are fabricated through a lithography-based ceramic manufacturing (LCM) technique. A Lithoz CeraFab 7500 printer [304] in combination with Lithalox 360 [305] slurry are used to create the samples. The printer has a pixel size of 25 μm and a layer height of 19 μm . After printing, the samples are cleaned and sintered at 1600°C over a period of 10 days. To correct for deformation during the sintering process, the samples are ironed by pressing the sample between two flat plates and heating to 1500°C. Following fabrication the sample waveguides are characterised. Measurements are performed with a Keysight N5222B vector network analyser (VNA) with Virginia Diodes WR3.4 VNAX extension modules. The VNA with extension modules was calibrated with a manufacturer provided calibration kit using the TRL method as only a single transceiver and a receiver are available. For characterisation, five straight waveguides of varying lengths are fabricated, as well as an S-bend depicted in Fig. 4.6(a), which include the coupling tapers, bends, and a straight waveguide section. The straight waveguides were designed with rib widths and rib heights of 300 μm and a slab thickness of 150 μm , while the S-bend samples had designed slab thickness of 75 μm . After fabrication these dimensions were measured with an optical microscope. For both the straight and S-bend samples, the measured rib width is 310 μm , slightly larger than designed. For the straight samples the measured slab height is 145 μm and the rib height is 285 μm , slightly smaller compared to the designed height. Similarly, in the S-bend samples, the measured dimensions are smaller than designed, with a rib height of 240 μm and a slab height of 80 μm . I attribute these discrepancies to shrinkage that occurs during the sintering process and anticipate that this issue could be improved with further calibration and pre-compensation for these sintering effects. Electromagnetically, I expect that these reduced heights will degrade the low-frequency performance of the waveguides, particularly in the case of the S-bend samples where leakage to the slab is increased. The fabricated waveguides are held with a package 3D-printed from polylactic acid (PLA), as shown in Fig. 4.6(b). This supporting structure is designed such that this support does not interact with the guided wave. In Fig. 4.6(c), I present the transmission amplitude over the measured band, showing the 3 dB bandwidth exceeds the measurable bandwidth. These measurements are normalised to the transmission magnitude of the metallic waveguides in back-to-back configuration. To make this measurement, flangeless waveguides are aligned with micrometer stages. To de-embed the attenuation constant, α , and phase constant, β , of the alumina waveguides, I compare the amplitude and phase change of the various lengths of the waveguides, presenting the mean and standard deviation of all combinations. I observe that the relative loss of some waveguide combinations is negative, which I attribute to variance in the fabricated couplers. In the future, alternative coupling structures to the spike [201] could be employed to improve the fabrication consistency. Nevertheless, I observe attenuation on the order of 0.2 dB/cm and a propagation constant of 14 rad/mm at 275 GHz, as in Fig. 4.6(d) and (e) respectively, albeit with significant uncertainty. The propagation constant is

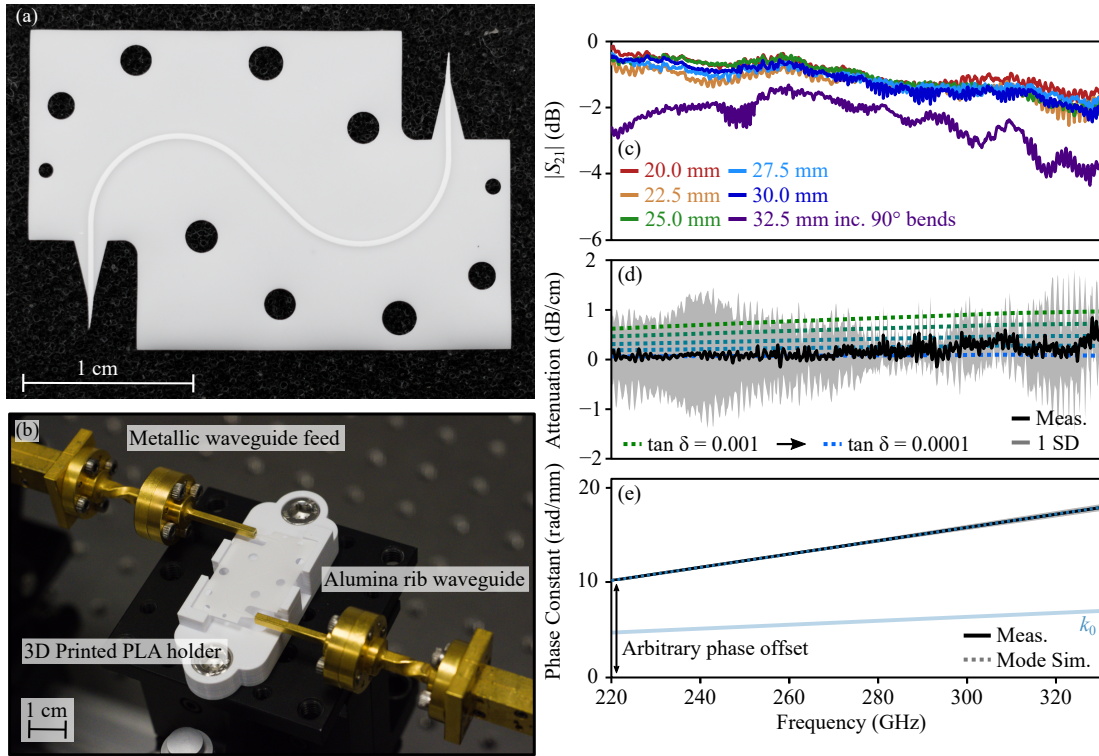


Figure 4.6: Measurement of fabricated alumina rib waveguides. (a) Micrograph of a fabricated sample. (b) Waveguide under measurement, supported by a 3D-printed holder, and coupled to hollow metallic waveguides. (c) Measured transmission for waveguides of various lengths. (d) Attenuation coefficient calculated from (c), these results are compared to simulations, dashed lines, with varying Alumina loss tangents. (e) Phase constant calculated from the measured phase of the waveguides. The measured and simulated phase profiles overlap completely. Here k_0 is the phase constant in air.

approximately linear, indicating low dispersion across the WR3.4 band, this is typical of rib waveguides, for which the constitutive material is non-dispersive, though the dispersion is expected to increase at higher frequencies [306]. I observe that the loss in our measured samples is lower than our simulated results based upon the loss tangent extracted from previous experiments [161]. I understand that one cause of loss in 3D-printed alumina is remnant polymer that is not expelled during the sintering process. Furthermore, I speculate that in these thin samples there is little remnant polymer and hence the material losses are lower than expected, but this requires further investigation. From these results I can also infer that the bending loss is on the order of 1 dB per bend, in line with the simulated result in Fig. 4.4.

4.4 Conclusion

The fundamental components of a terahertz rib waveguide platform fabricated from 3D printed alumina have been analysed and experimentally demonstrated. The loss of these waveguides is measured on the order of 0.2 dB/cm, lower than most planar metallic waveguides and comparable to the ubiquitous hollow metallic waveguide. This loss is >4 times the loss of comparable silicon waveguides but the practical advantages and lower fabrication costs, could compensate this for applications where small additional losses are not critical. Further, optimisation of the printing process may reduce losses further. The moderate permittivity and loss characteristics of alumina allow 3D-printing to be leveraged to build 2.5D integrated circuits, which are difficult to fabricate with semiconductor based manufacturing. In the future I anticipate the development of true 3D devices, further leveraging the capabilities of 3D-printing to develop high gain antennas, polarisation rotators, and other high value devices that are typically difficult to realise on strictly 2D waveguide platforms. Beyond 3D-printed alumina, silicon rib waveguides can be used to span multiple traditional waveguide bands with single-mode operation, providing extra utility when compared to over-moded rod waveguides that are currently employed.

Chapter 5

Guided Wave Components

Abstract

Guided-wave components bring necessary functionality to a waveguide platform allowing for complex functional, manipulation of the wave. To date, many passive components have been developed for substrateless waveguide platform. Having demonstrated extreme skin depth waveguides and analysed rib waveguides in the previous chapters, here I seek to leverage their advantages to realise new components. In this chapter three components are proposed. First, I propose that the coupling suppression afforded by the extreme skin depth waveguide in tandem with isotropic effective medium techniques can be employed to realise efficient, arbitrary ratio power division. Then, a low-loss, thermo-optic phase shifter is proposed based upon an Archimedean spiral waveguide coupled to a resistive heater. Finally, utilising the rib-waveguide, a ring resonator is designed for use as a liquid sensor where the rib membrane acts as a liquid well to better contain the analyte. These components are simulated, fabricated, and experimentally tested, validating their performance. These components are the building blocks of future all-integrated terahertz systems.

5.1 Arbitrary Ratio Power Divider

Having demonstrated the low-loss and coupling suppression of the extreme skin-depth waveguide in Chapter 3, we look to exploit these and other advantages to build compact passive components. Power division is one of the most elementary functions of a waveguide platform, allowing for a single source to be used to feed many channels as is common in large antenna arrays [307], or for a reference signal to be siphoned from a main signal for channel monitoring in communications applications [308] or for chip-integrated interferometry [309]. In nano-photonics, uni-directional couplers [310] and multi-mode interferometers [311–313] are mature implementations of this functionality. For uni-directional couplers, their aforementioned frequency dependence makes them unsuitable for broadband power division in the fractionally broad terahertz bands, where they are more commonly employed as frequency diplexers than as power dividers [218]. Similarly, multi-mode interferometer based power dividers can be used to realise arbitrary ratio power division across a narrow fractional bandwidth, though design with either parametric optimisation [314–316] or inverse design [317], requires a time-consuming optimisation for each required extinction ratio. A broadband alternative with intuitive design is a simple Y-branch. However, without modification only equal power division is possible with a symmetric junction. Additionally, significant radiation losses, particularly at low frequencies, can be incurred when tight bends are used to create a compact structure [196]. We propose an extreme skin-depth waveguide Y-branch for compact and broadband power division leveraging the suppressed bending loss, with an additional modification to enable arbitrary ratio power division.

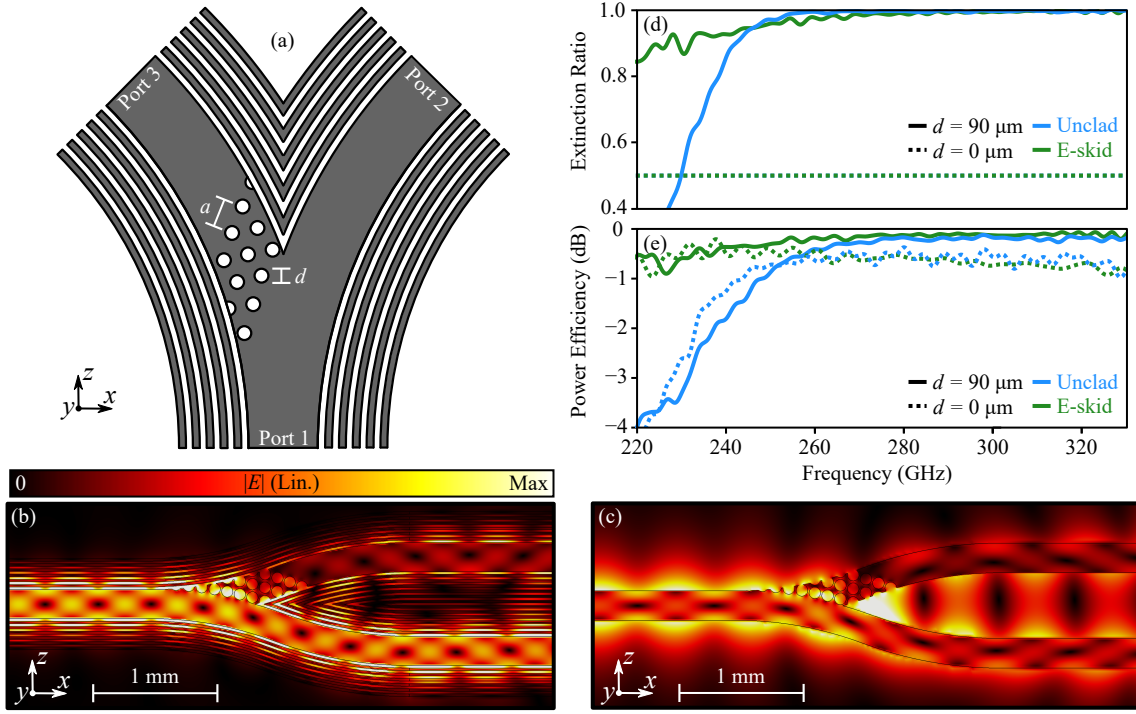


Figure 5.1: Schematic diagram of arbitrary ratio power divider. The extinction ratio between the two ports can be tuned by adjusting the ratio of the hole diameter and lattice period d/a . Electric-field at 220 GHz for (b) extreme skin-depth power divider, and (c) unclad power divider. (d) Extinction ratio of each power divider defined as $|t_{21}|^2/(|t_{21}|^2 + |t_{31}|^2)$. (e) Power efficiency defined as $|t_{21}|^2 + |t_{31}|^2$.

5.1.1 Design

In order to enable arbitrary ratio power division, the symmetry of the Y-branch must be broken, which in this case is achieved by the introduction of a partially transparent obstruction to one port as shown in Fig. 5.1(a). This obstruction, an effective medium region formed from a sub-wavelength hexagonal lattice of cylindrical exclusions, serves a dual function. First, to partially limit power from coupling into one port, and second, to guide the deflected power into the second port. With this technique the extinction ratio can be tuned by adjusting the fill factor of the hexagonal lattice effective medium, defined as $\zeta = (\pi d^2)/(2\sqrt{3}a^2)$, by changing the hole diameter, d , relative to the lattice period, a . Practically, this ratio is limited by two factors, first, the minimum fabricable hole diameter, in this case $20 \mu\text{m}$, and second, the diameter of the holes must be smaller than the lattice period. The importance of the extreme skin-depth cladding is highlighted when comparing the simulated E -field distributions in Fig. 5.1(b-c), where we observe that in the unclad case, the mode is not obstructed by the inclusions, and simply couples across the air gap immediately following the divider. In Fig. 5.1(d-e), we describe the splitters in terms of two properties derived from the linear transmission magnitude $t = |S|$, first the extinction ratio which quantifies the proportion of power that enters the primary port,

$$\text{Extinction Ratio} = \frac{|t_{\text{main}}|^2}{|t_{\text{main}}|^2 + |t_{\text{side}}|^2}, \quad (5.1)$$

and second the power efficiency,

$$\text{Power Efficiency} = |t_{\text{main}}|^2 + |t_{\text{side}}|^2. \quad (5.2)$$

We observe that, at low frequencies, where evanescent coupling is most pronounced, the extreme skin-depth coupler outperforms the unclad coupler owing to suppressed leakage.

5.1.2 Fabrication & Experimental Verification

To validate our design, power dividers as in Fig. 5.2(a), without an obstruction, shown in Fig. 5.2(d), and with obstructions of 25 and 45 μm , shown in Fig. 5.2(b–c), are fabricated to characterise their performance. As with previous samples, the extreme skin-depth waveguide power divider is framed by an effective medium for structural support. To facilitate the measurement, the ports must be separated by a significant distance, to give clearance for the coupling hollow metallic waveguide. Hence, the fabricated power dividers are not as compact as those presented in Section IV-A. Nevertheless, this is sufficient for experimental validation of the compactness advantage presented in Fig. 5.1. To characterise each sample, 3 measurements are made, the reflection generated by the divider, the transmission to the primary port, t_{main} , and the transmission to the secondary port, t_{side} . Due to practical constraints, these measurements are not made simultaneously, but rather they are measured sequentially for each sample, with some manual realignment required between each measurement. In Fig. 5.2(e), we observe that the measured extinction ratio is consistent with those obtained through full-wave simulation, with an achievable range between 50:50 and 95:5, with minor frequency dependence across the 110 GHz operation bandwidth. The power efficiency, presented in Fig. 5.2(f), is comparable to that of an equal length straight waveguide and aligns well with expectations from simulation. The maximum insertion loss is less than 1 dB for equal power splitting, while this insertion loss becomes negligible for higher extinction ratios. The back-scattering arising from the power divider is also measured. To isolate the reflections from the dividing structure, time gating is applied to the time domain spectrum shown in Fig. 5.2(g) to determine the frequency domain response shown in Fig. 5.2(h). We observe additional reflections from the inclusion of the power divider, especially at low extinction ratios, though at higher extinction ratios these reflections become negligible.

5.2 Thermo-optic Phase Shifter

To-date, many passive components have been proposed covering a wide range of capabilities. In contrast, there have been very few tunable devices developed for terahertz silicon waveguides. As discussed at length in Section 2.4, this is likely due to the fact that there are very few viable mechanisms for tuning silicon. The most thoroughly explored avenues for tuning are mechanical [238, 240] and photo-excitation [207, 212], neither of which have produced practical phase shifters to-date. With this in mind, thermo-optic tuning is relatively under-explored.

Thermo-optic phase shifters employ the change in modal index incurred as the temperature of the waveguide is changed to generate a tunable phase shift. In bulk silicon, the room-temperature permittivity is on the order of 11.68, while the first-order thermo-optic coefficient is on the order of $1.40 \times 10^{-4} \text{ K}^{-1}$ [251]. Though the thermal coefficient is small, over a long propagation distance the effect can be appreciable. To demonstrate this, I calculate the temperature-varying modal index of the in-plane mode through full-wave simulation, across a 50 K temperature change. These simulations, presented in Fig. 5.3(a), are performed across the 220–330 GHz range to measure the frequency dependence. Though the change in bulk index is broadband, the effect on the modal index varies with frequency, as the field distribution changes with frequency. Based upon the calculated modal index, the phase accumulated through waveguide with length l is given by $\phi = -\beta l$. In Fig. 5.3(b), I show the relative phase change at 275 GHz resulting from the temperature change. These theoretical results show that a continuously tunable, broadband, terahertz phase shifter with a 360° tuning range is achievable within a modest footprint and reasonable temperature range.

Though temperature change is inherently slow, the temperature could be accurately and efficiently controlled with a thermostat and a compact heater, producing an economical tunable device. Recently, a thermo-optic phase shifter was produced and used to form a two-element antenna array, but these waveguides were far too short to introduce large phase shifts [254], resulting in a narrow steering angle. Naturally, this phase shift can be increased by simply extending the length of the waveguide. To achieve this compactly, a space-filling curve can be implemented to maximise the path-length for a given footprint. Theoretically, any space filling curve is suitable, but to minimise the bending loss, an augmented, double Archimedean spiral is a natural choice which has been widely employed in optics.

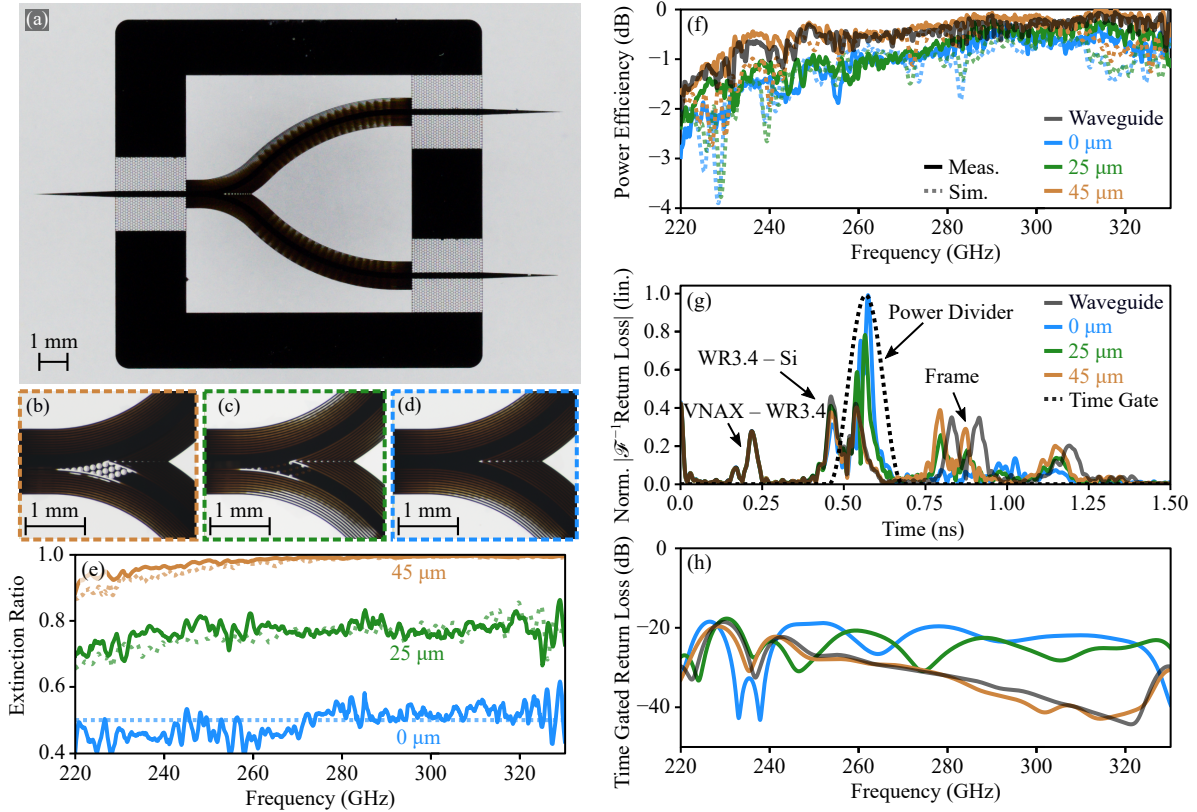


Figure 5.2: Experimental characterisation of integrated power dividers. (a) Photograph of fabricated 1×2 power divider. Micrographs of the junction region for (b) $r = 45 \mu\text{m}$, (c) $r = 25 \mu\text{m}$, and (d) $r = 0 \mu\text{m}$. (e) Extinction ratio of each power divider defined as $|t_{\text{main}}|^2 / (|t_{\text{main}}|^2 + |t_{\text{side}}|^2)$. (f) Power efficiency defined as $|t_{\text{main}}|^2 + |t_{\text{side}}|^2$. (g) Time domain response of the reflection coefficient highlighting the contribution from the power dividers. (h) Time gated reflection coefficient of each sample.

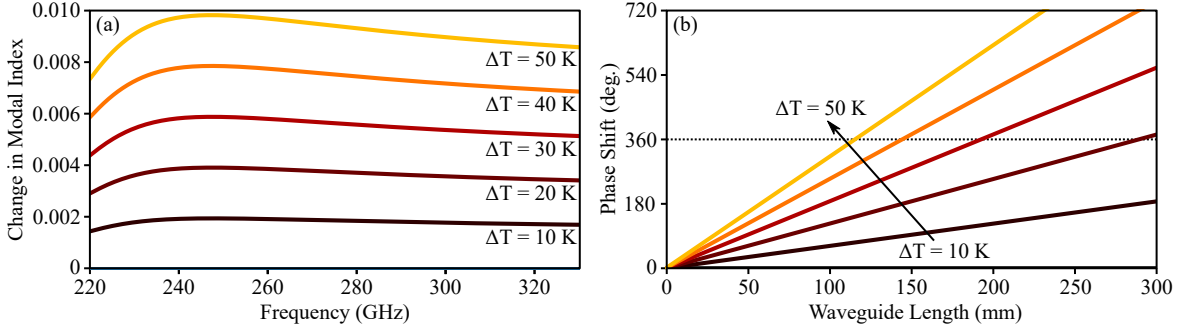


Figure 5.3: Thermo-optic effect on unclad silicon waveguides. (a) Change in modal index in response to a temperature change. (b) Thermally induced phase shift at 275 GHz.

In this section, a double Archimedean spiral waveguide with a path length of 25 cm is fabricated and experimentally demonstrated. This spiral is thermo-coupled to a resistive heater, and the phase shift is measured experimentally. To address the limitations of this initial design, improvements are proposed for future designs.

5.2.1 Augmented Double Archimedean Spiral Waveguide

The Archimedean spiral was first described in 225 BCE [318] as a spiral with a constant separation between concentric arms, and is commonly described mathematically in polar coordinates as $r = b\theta$. Here, the variable b controls the distance between concentric points on the spiral, and as b approaches 0, the curve becomes space-filling. For waveguiding, the principal concern of employing this spiral directly is bending loss. At the centre of the spiral, the curvature of the spiral approaches infinity and this is impractical, so the spiral is usually truncated at the minimum bending radius, $r_{\min}$. To produce a delay line, the spiral is then inverted to form the exit path, as depicted in Fig. 5.4(a), which is connected in the centre by an S-bend. To increase the path length, the spiral is then cut along one axis and extended by inserting straight sections of length l . The augmented spiral depicted in Fig. 5.4(a) is no longer a true Archimedean spiral, but a discrete approximation. I define this spiral by the minimum bending radius, $r_{\min}$ and the straight section length l . The variable b is replaced by the separation between the arms of the spiral d , which have a waveguide width w . Then the path length of the augmented spiral L , is given by the equation,

$$L = L_s + 2 \sum_{i=0}^N (2\pi r_i + l) , \quad (5.3)$$

where N is the number of rotations, L_s is the length of the central S-bend,

$$L_s = \frac{\pi r_{\min}}{2} , \quad (5.4)$$

and r_i is determined recursively by the equation,

$$r_{i+1} = r_i + d + w , \quad (5.5)$$

and the initial value is $r_0 = r_{\min} + \frac{d+w}{2}$. The footprint of the spiral is given by the equation, $A = (2r_N + D) \cdot (2r_N + l)$. Of these variables, two are fixed by the properties of the waveguide. The separation distance d should be selected to avoid cross-coupling between waveguides, while the smallest bend radius $r_{\min}$ should be selected to avoid bending losses. Then the straight section length l and the number of loops N can be selected to tune the length of the delay line. With this in mind, the most compact spiral, with compactness defined as L/A , is achieved when d and $r_{\min}$ are minimised. As a proof of concept, an unclad waveguide spiral is fabricated with, $w = 225 \mu\text{m}$, $r_{\min} = 1500 \mu\text{m}$, $d = 660 \mu\text{m}$, $l = 17000 \mu\text{m}$, and $N = 3$, providing a path length of 302 mm inside a $10.3 \text{ mm} \times 26.4 \text{ mm}$ footprint. According to Fig. 5.3(b), this length should be sufficient to achieve a 360° phase shift with as little as 20 K temperature change.

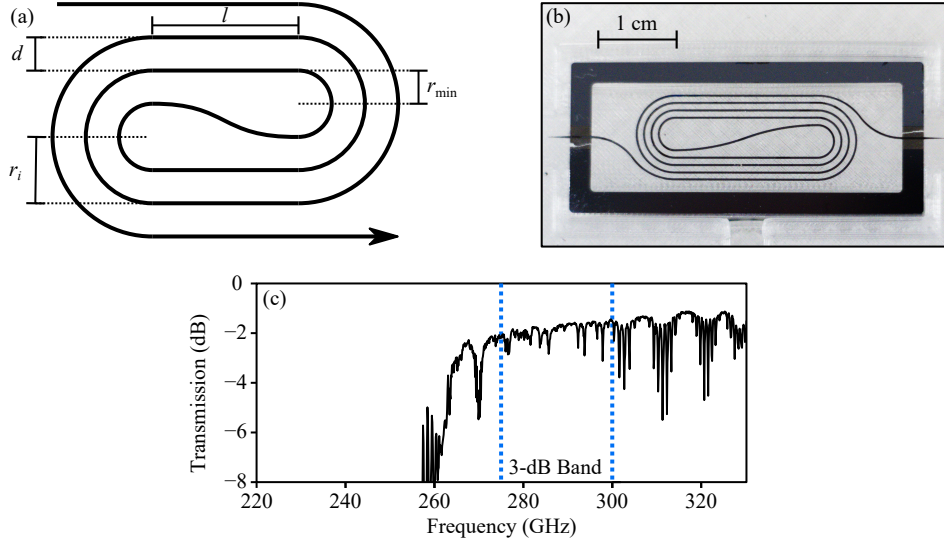


Figure 5.4: Augmented Archimedean spiral. (a) Design of the augmented Archimedean spiral, depicting the key design parameters. (b) Fabricated spiral waveguide, indicating damaged regions. Measured transmission parameter of the spiral waveguide. (c) The measured transmission of the spiral waveguide, with the largest 3-dB bandwidth highlighted.

5.2.2 Resistive Heater Phase Shifter

The fabrication of this waveguide is performed through the DRIE of a high-resistivity silicon wafer with thickness $250\text{ }\mu\text{m}$. I note that this fabrication is challenging due to the extremely long, thin waveguide which is attached to the frame at only two positions and as such is very fragile. This fragility, combined with incidental over-etching resulted in damage to the fabricated sample. Nevertheless, this fabricated sample could be measured but only with the support of a substrate. To act as a substrate a 3D printed mount COC mounting plate is produced and the sample is carefully placed upon it. Although the additional loss from the substrate is not negligible, it is minimised through 3D-printing by producing a mount with low infill percentage, in this case 15%. In Fig. 5.4(b), the fabricated sample is depicted. Measurements, shown in Fig. 5.4(c) are made over the 220–330 GHz range with a Keysight N5222B vector network analyser (VNA) in combination with Virginia Diodes WR3.4 VNAX extension modules. Flangeless waveguides are used to launch the in-plane polarised fundamental mode. Due to the strong evanescent coupling between the adjacent unclad waveguides, the lower frequency cutoff of the prototype is 270 GHz, as the strong cross-coupling between adjacent lines leads to poor transmission. I note the resonances above 300 GHz arise from misalignment of the waveguide causing resonances to appear where the coupling spike touches the inner surface of the hollow metallic waveguide. This is unavoidable considering the damage to the frame of the sample. Nevertheless, the average insertion loss, in the ranges unaffected by coupling or misalignment, is low. The combined loss of the long waveguide, the coupling loss, and the additional substrate loss, is on average 2 dB.

To realise a thermo-optic phase shifter the prototype spiral waveguide is thermo-coupled to a $12\text{ }\Omega$ resistor which functions as a heater. To achieve this, the 3D-printed mount is adapted to include a CNC milled aluminium block can be inserted to thermo-couple the frame of the silicon waveguide to the resistor, as shown in Fig. 5.5(a). The assembled module is shown in Fig. 5.5(b). This is necessary as the 3D-printed mount itself functions as a thermal insulator. A source-meter (SMU) is used to supply 6 V and 0.5 A, corresponding to 3W of dissipated power. I note that this arrangement is not thermodynamically optimised and relies on the physical contact between the elements. Though the aluminium via and the silicon waveguide are good thermal conductors, the contact could be further improved through the use of a thermal adhesive. The consequence of this is slow heating and cooling of the sample and as such, a slow response time. The measurement procedure described previously is

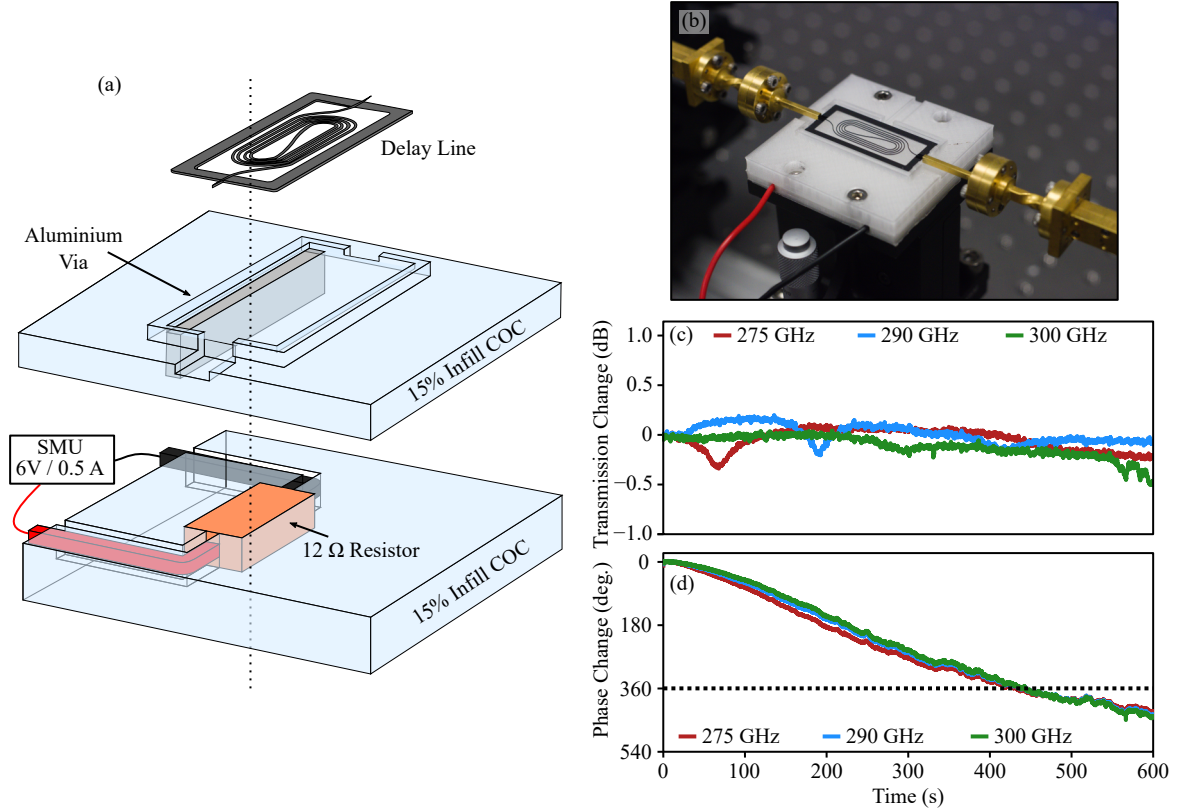


Figure 5.5: Thermo-optic phase shifter. (a) Schematic drawing of the assembled thermo-optic phase shifter. (b) Photograph of the assembled thermo-optic phase shifter under measurement. (c) Amplitude change under heating from ambient temperature. (d) Phase change under heating from ambient temperature. In (c) and (d), a 20 sample moving average is applied to reduce the sample-to-sample noise.

repeated with the assembled phase shifter module, and measurements are made at a rate of 15 Hz as the sample is heated over a period of 10 minutes, until the device reaches thermal equilibrium. In Fig. 5.5(c–d), the phase and amplitude change as the module heats from room-temperature is shown. The phase change between ambient and maximum temperatures is greater than 360° , while the additional loss compared to the ambient spiral is less than 1 dB. Though the exact temperature of thermal equilibrium is unknown, based upon the previous calculations in Fig. 5.3(b), I suggest that it is in the range of 20–30 K above the ambient temperature. These results indicate that low-loss, broadband phase-tuning is achievable through thermo-electric tuning of all-silicon waveguides.

Though this result is encouraging, there are several obvious flaws in this design. First, the bandwidth is limited by the evanescent coupling between adjacent unclad waveguides and the unclad waveguides themselves are fragile and are prone to breaking. Both of these issues may be addressed by replacing the unclad waveguide with the extreme skin-depth design proposed in Chapter 3. Though the extreme-skin depth waveguide design would provide maximal coupling suppression, the structural instability remains, and fabricating such long thin ribs has proven to be challenging. Alternatively, the pill cladding would provide structural support while simultaneously improving the coupling suppression. Additionally, the prototype result shows phase change in excess of the necessary 360° , indicating that the length could be reduced to further improving the footprint. Further, thermodynamic improvements should also be made including an investigation of the use of micro-Peltiers in combination with smaller resistive elements which can be directly thermo-coupled to the silicon waveguide via the frame. This would remove the need for the aluminium via which contributes significant thermal mass, damping the thermal response of the system.

In this section a thermo-optic phase shifter based on an augmented Archimedean spiral is proposed, fabricated, and experimentally tested. Though the thermal tuning is slow, the phase shift is larger than

360°, while the insertion loss is below 1 dB, opening the way for future low-loss terahertz phase tuning. To improve upon this initial demonstration, modifications are proposed to increase the response time, the bandwidth, and the physical robustness of the device. I emphasise that thermo-optic tuning is enabled by the extremely low-loss of silicon waveguides, whereas replication of a similar design, such a metallic waveguide filled with a thermo-optic material, may incur severe losses over the propagation distance.

5.3 Ring Resonator for Liquid Sensing

Ring resonators make for convenient sensors as information about both the real and imaginary components of the permittivity can be deduced from the amplitude spectrum [319]. The 2.5D nature of the rib waveguide from Chapter 4 makes it well suited to use as a liquid sensor, as the ring resonator can serve a dual purpose, both as the waveguide and as a well for the analyte as illustrated in Fig. 5.6(a). This exists in contrast to purely 2D ring resonators which cannot physically contain the analyte [208]. The ring resonator is parameterized by two key variables, the ring radius and the separation from the feeding waveguide, which we denote as r_{ring} and d_{sep} respectively in Fig. 5.6(b). The radius of the resonator is constrained by the minimum bending radius of the waveguide but is ultimately determined by the desired free-spectral range (FSR) of the resonator, with larger radii resulting in smaller free-spectral ranges [217], as determined by the equation,

$$\text{FSR} = \frac{c^2}{n_g L f^2}, \quad (5.6)$$

where n_g is the modal refractive index, f is the frequency, L is the path-length of the ring, and c is the speed of light in free-space. For liquid sensing applications the desired FSR is determined by the analytes of interest, as the FSR limits the maximum change in resonance frequency for unambiguous detection. We select a resonator radius of 5000 μm , which corresponds to a FSR of 3 GHz in simulation and a well volume of 17.1 μL . To achieve a high Q factor resonance the critical coupling condition should be sought [213], which is achieved by tuning the separation between the waveguide and the ring such that the transmission through the resonator is equal to the circulation losses of the ring. If the separation is too small, then the resonator will be over-coupled, while too large a separation results in under-coupling. Both cases result in diminished Q -factor. This is an important consideration for sensing, where a narrow, high Q resonance is required in order to measure subtle changes in the resonant frequency.

Due to the 25 μm resolution of the 3D-printer, we simulate separations of -25 , 0 , and 25 μm with ethanol in the well of the resonator, where a negative separation implies the structures are overlapping. These simulated results are presented in Fig. 5.6(c), and to have a critical coupling point close to the centre frequency of 275 GHz we select a minimal separation distance, of -25 μm . The fabricated ring, depicted in Fig. 5.7(a), is measured in the same way as other waveguiding structures presented in this thesis. We compare the measured and simulated results in Fig. 5.7(b), and observe the expected series of resonances with the designed free spectral range. though we note some red-shifting which we attribute to fabrication tolerances. Additionally, the critical coupling point is highly sensitive to all fabrication tolerances and material properties, such as the permittivity and loss tangent of the material, and as such it is expected that the measured critical coupling point is shifted relative to the simulation. The Q -factor, calculated as $f_c/\Delta f_{3\text{-dB}}$, of the critically coupled resonance at 223.75 GHz is 880 when the resonator is empty, and 216 at 274 GHz when loaded with ethanol, a decrease that is expected due to the dampening effects of the analyte. This Q -factor is comparable to some reported integrated ring resonators realised with silicon, especially those with rib waveguides, $Q = 355$ [214], $Q = 305$ [215], and $Q = 1210$ [216], despite the additional material losses. However, this value is much lower than state-of-the-art integrated silicon resonators which have achieved measured Q -factors of 9146 [208] and 57700 [210], while non-integrated resonators can reach Q -factors of 15000 [320].

To measure the sensitivity of our ring resonator sensor we select two analytes with very similar complex permittivities, ethanol and isopropyl-alcohol (IPA), previously reported as $2.70 - 0.76j$ [321]

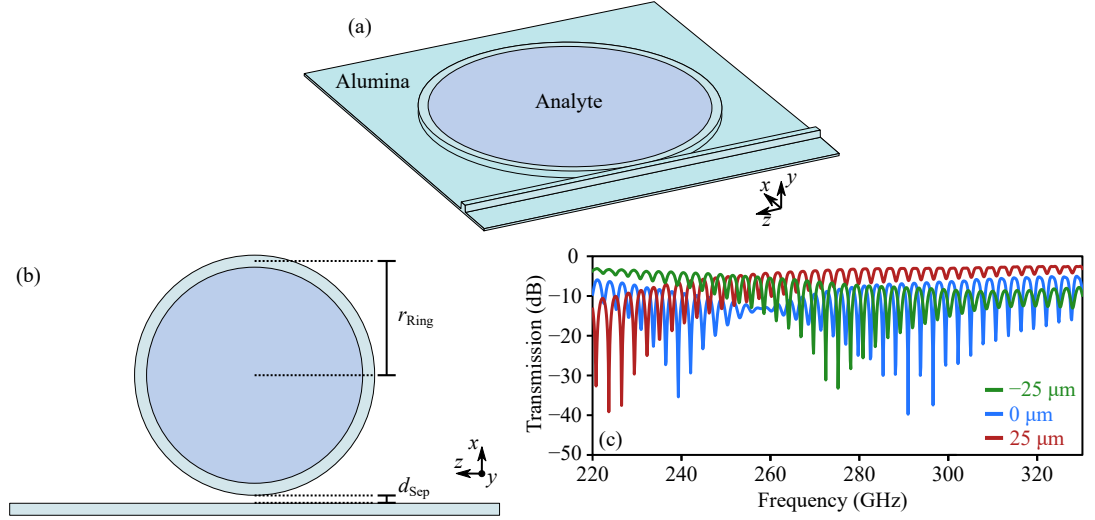


Figure 5.6: Design of alumina ring resonator. (a) Conceptual drawing of ring resonator with an integrated liquid well filled with analyte. (b) Schematic view of ring resonator with critical parameters identified. (c) Simulated transmission through the ring resonator with a ring radius r_{ring} of 5 mm and ring separations of -25 , 0 , and $25 \mu\text{m}$. We observe that at the centre frequency, with $25 \mu\text{m}$ the resonator is under-coupled, while at $0 \mu\text{m}$ the resonator is over-damped.

and $2.61 - 0.29j$ [322] respectively at this frequency range. We note that the real component of the permittivities are similar, while the absorption resulting from the imaginary component is more pronounced. Hence we expect a small change in resonance frequency and a more pronounced shift in critical coupling point. A pipette is used to dispense a single drop, approximately $20 \mu\text{L}$, of the analyte into the centre of the ring resonator and the VNA is used to measure the spectrum, though in this case the number of measurement points is increased to 9009, to achieve a frequency resolution of 12 MHz. To further test the sensitivity, we mix ethanol and IPA to form an even mixture of the two. In Fig. 5.7(c), we observe a large shift in the critical coupling point, but we can also distinguish the two liquids on the basis of the very slight difference using a single peak as in Fig. 5.7(d). We observe a resonance shift of 110 MHz, representing a sensitivity of 2.44 GHz/RIU, and a critical coupling shift of 10.85 GHz.

5.4 Conclusion

In this Chapter three guided-wave components are proposed, fabricated, and experimentally demonstrated. These components span both passive and tunable devices, across different underlying waveguides. In principle, each of these components are compatible with each other, all realisable on an all-dielectric waveguide platform, whether that is silicon or alumina. The primary advantage of these components is their efficiency, with an emphasis on minimising the device insertion loss, such that the efficiency of the underlying waveguides is preserved. These components join a growing library of all-dielectric terahertz devices, which can be combined to form integrated terahertz systems for high-performance sensing and communications applications.

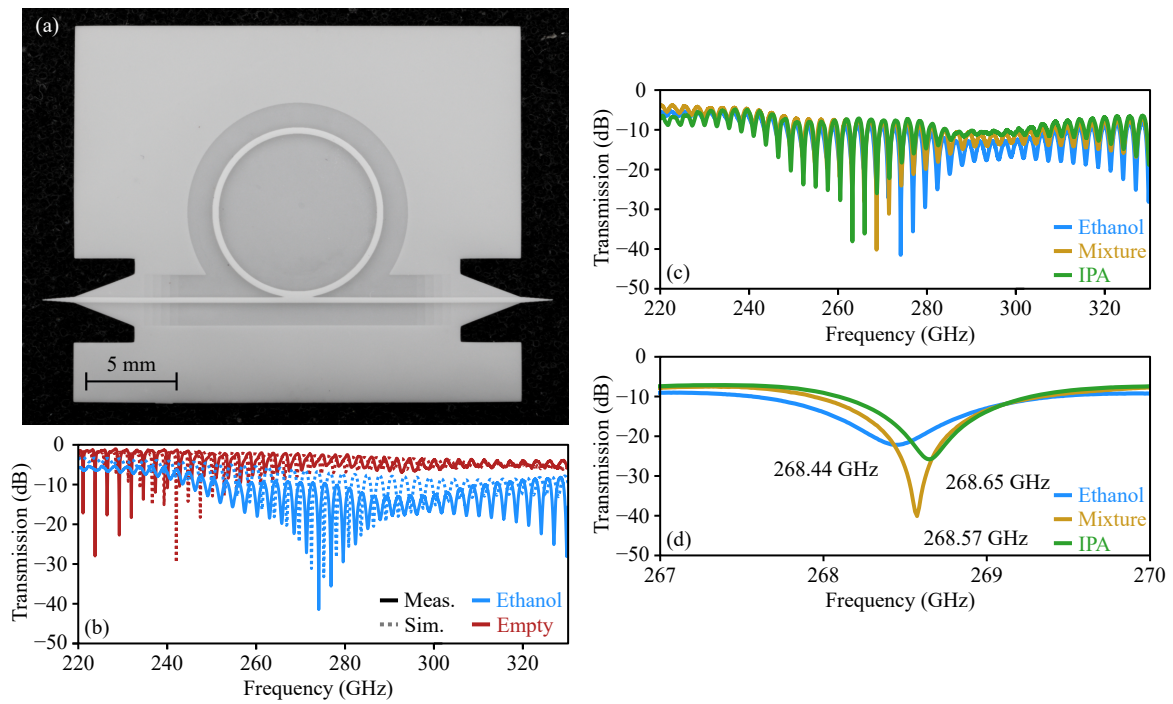


Figure 5.7: Measurements of alumina ring resonator. (a) Photograph of the fabricated sample. (b) Comparison between measured and simulated transmission for empty resonator and resonator filled with ethanol. (c) Transmission spectra for resonator filled with ethanol, isopropyl-alcohol and a mixture thereof, observing the shift in critical coupling points across the 3 measurements. (d) Close-up of a single resonance, showing the shift in the resonance frequency as the analyte changes.

Chapter 6

Antennas

Abstract

Antennas are the interface between integrated circuits and free-space, and as such at least one antenna is present in almost all wireless systems. To date, the focus of antennas on the substrateless silicon platform has been high-gain endfire antennas with bandwidth covering the single mode operating region of the underlying waveguide. These high-gain antennas are well suited for communications applications where point-to-point links are desired, but without mechanical actuation, the antennas do not provide coverage of an area for radar applications. To realize this capability, a frequency scanning leaky-wave antenna is proposed, based upon fast-wave leakage from a silicon waveguide into an adjacent slab, from which it is radiated into free-space via a progressive index-matching structure. On the other-hand, while existing antennas cover traditional rectangular waveguide bands, modern photonic sources such as uni-travelling carrier photo-diodes can provide excitation over far broader bands, and as such there is desire for multi-band antennas which can support these sources. Traditionally, over-moded rod waveguides have been used. However, a delicate feed design is required to ensure single mode antenna excitation, and furthermore, the gain of these antennas is limited. Instead, an integrated Galilean Telescope based upon slab-mode integrated optics fed by a single-mode rib waveguide is proposed to operate over the 220–500 GHz band, equivalent to two waveguide bands, i.e. WR3.4 and WR2.2. These antennas are described, simulated, and experimentally characterized over the 220–330 GHz band. These two original antenna designs are distinctly tailored for their intended final applications, the Galilean Telescope for communications and the leaky-wave antenna for radar applications.

6.1 Leaky-wave Antenna

Previously, terahertz leaky wave antennas have been proposed for a variety of platforms, including hollow metallic waveguides [50], terahertz microstrip line [323], parallel plate waveguides [324, 325], spoof surface polariton waveguides [326], all silicon [327, 328], silicon on insulator [329], 3D-printed cyclic olefin co-polymer (COC) [159], 3D-printed alumina [330], and indium-phosphide [127, 331, 332]. Many of these antennas utilize metals for mode confinement, hindering the maximum realized gain due to Ohmic losses incurred. Those that do not include metals are narrow band due to frequency dependent coupling mechanisms [327–329], or reliance on photonic crystals [330]. Alternatively, waveguides realized monolithically from high-resistivity float-zone silicon could be utilized to instantiate a leaky wave antenna. In recent years, substrateless silicon waveguides [164, 168, 188], have been used to realize a range of passive components [219, 333] including a variety of high gain end-fire antennas [231, 232, 334]. This approach is attractive as the intrinsic material losses of these devices are nearly negligible ensuring very high radiation efficiency so long as coupling to free space is managed carefully. In this context, I aim to consolidate the practical advantages of frequency scanning antennas for radar applications with a high efficiency dielectric waveguide platform, focusing on the development of a high gain, frequency

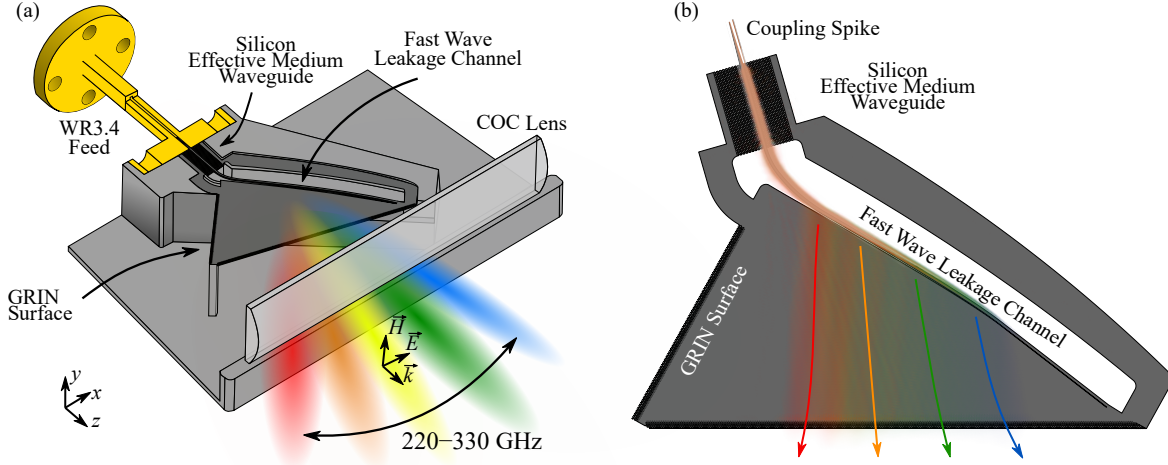


Figure 6.1: Proposed leaky-wave radar module. A schematic drawing of the proposed leaky wave radar package, highlighting the various components, including the fast-wave leakage channel, the GRIN anti-reflection coating, and the auxiliary cyclic-olefin-copolymer (COC) lens. These elements are mounted in a fixture, 3D printed from polylactic acid (PLA), designed such that it does not interfere with the device operation.

scanning antenna.

The proposed antenna, illustrated in Fig. 6.1, utilizes continuous fast-wave leakage between a dielectric waveguide and an adjacent dielectric slab [283, 335–337]. This negates the need for scattering elements typical of a periodic LWA. This is critical for a substrateless, dielectric, leaky-wave antenna where the lack of a metallic ground plane for shielding makes it difficult to suppress the undesired symmetry that arises from the radiating elements, which results in a halving of the power radiated in the desired direction. In infrared photonics, this can be partially addressed through the use of apodised grating structures [336], though to realize this asymmetry a multi-stage etching process would need to be employed, increasing the fabrication complexity.

Here, I provide information about the design of this all-dielectric leaky-wave antenna, design an auxiliary lens, and experimentally validate its performance. The antenna is intended for mono-static radar applications, as such gain should be maximised to increase both received and transmitted signal power and the operating frequency should be broad to improve the depth resolution.

6.1.1 Antenna Design

Previously, an integrated frequency division multiplexer was developed based upon in-slab beam-forming of slab modes launched by fast-wave leakage from an unclad dielectric waveguide into an adjacent dielectric slab [283]. In this case, the leakage rate and radiation angle are controlled by the separation between the waveguide core and the slab. As the guided waves propagate in the dielectric waveguide, they undergo phase change with respect to distance in addition to gradually leaking power. This translates to a wide aperture distribution with linearly ramped phase. In the cited work, in-slab focusing at a desired point is achieved by compensating for this change in phase by progressively shortening the distance from the slab edge to that point, resulting in convex curvature. Thus, the leaked terahertz waves that enter the slab via this convex-curved boundaries will constructively interfere at the aforementioned point, forming a focus. Critically, due to the dispersion of both the waveguide and slab modes the location of this focus is frequency-dependent, resulting in a frequency-scanning focus that may be collected at different points in the slab, thereby achieving frequency-division multiplexing. By placing the focus in the far-field, a collimated frequency-scanning beam, depicted in Fig. 6.1(b), is launched, rather than a focused beam, and this is scanning-mechanism of the antenna.

The antenna is composed of 3 connected stages as depicted in Fig. 6.1. The leakage channel is a dielectric waveguide which guides the fundamental E_x^{11} mode as it is continuously leaked into an adjacent dielectric slab. On the other side, this slab is bordered by a GRIN anti-reflection structure

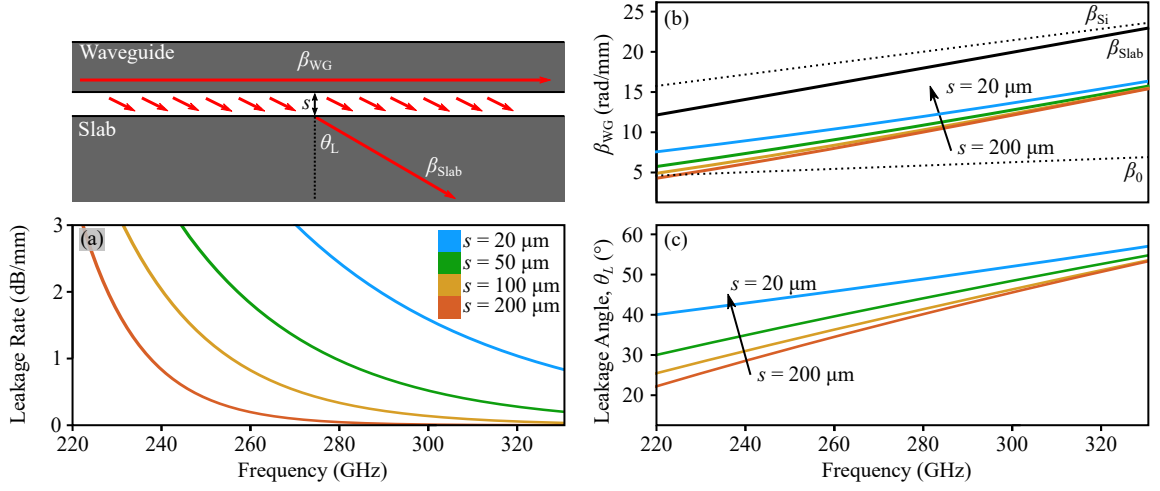


Figure 6.2: Characteristics of waveguide-slab leakage. (a) Leakage rate from guided to slab mode for various waveguide-slab separations. (b) Phase constant of waveguide mode when loaded by slab at various separations. (c) Launch angle of the slab mode arising from leakage from the waveguide.

realized by etched holes in the silicon slab, to facilitate the conversion of the slab mode into free-space. Then an external astigmatic lens is used for H -plane collimation, designed to enhance the far-field gain of the antenna package. The following sub-sections describe the design of each component individually.

Uniform Leakage Wave Tunneling

A slow-wave waveguide will not leak energy into free space without radiating elements that introduce a discontinuity, as is commonly utilized in scatterer based, periodic leaky-wave antennas [338]. In lieu of scattering elements, an intermediary medium is required to induce power leakage, and in this case a dielectric slab serves this purpose. This slab is capable of supporting its own guided slab mode with a slower wave speed than the channel waveguide mode, which induces a gradual power transfer from the waveguide mode, into the slab mode, by a process of evanescent coupling, also known as wave-tunnelling.

It is intuitive that, as the separation between the waveguide and the slab is reduced, the degree of overlap of the evanescent fields will increase, accelerating the rate of leakage and increasing modal index of the waveguide which is now loaded by the nearby slab. Previously, a theoretical analysis of the leakage between a dielectric waveguide and adjacent slab was presented to quantify these relations, and was later verified by full-wave simulation [339, 340]. In Fig. 6.2(a–c) the critical outcomes of this analysis for the E_x^{11} waveguide mode are presented for a high-resistivity float-zone waveguide core of width 200 μm and adjacent slab, both with a thickness of 250 μm , with separations varying from 20–200 μm . Here, I adopt a realistic permittivity of 11.68, and neglect material losses as the loss tangent, $\tan\delta$, is known to be less than 1.5×10^{-5} at these frequencies [160].

The leakage profile is indicative of the effective aperture of the antenna—a larger aperture corresponds to a higher gain. In this case, a uniform-leakage profile is desired, with an aperture of 14.5 mm. This design process is performed at the center frequency, 275 GHz, and as such the performance degrades as the operating frequency deviates from this point. From Fig. 6.2(a), at low frequencies the rate of leakage accelerates rapidly, causing rapid leakage and thus a poor aperture is formed. At high frequencies, the rate of leakage is limited, leading to residual power in the guide even with long trailing channels at the minimum fabricable separation, 20 μm , limiting the efficacy of the antenna at these frequencies.

In Fig. 6.2(b), the dispersive nature of this leakage mechanism is observed, and from the phase constants of the slab and the waveguide loaded by the nearby slab, the leakage angle as shown in

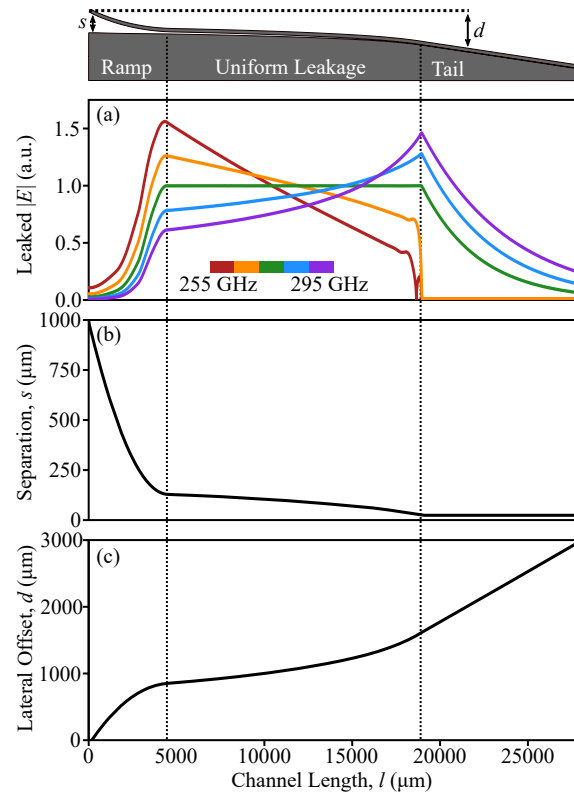


Figure 6.3: Design of the continuously leaking waveguide. (a) Desired leakage profile for the formation of a uniform aperture at 275 GHz. The separation between the waveguide and the slab (b) and the lateral offset (c) are designed such that the leakage profile in (a) is achieved while desired focus is in the far-field.

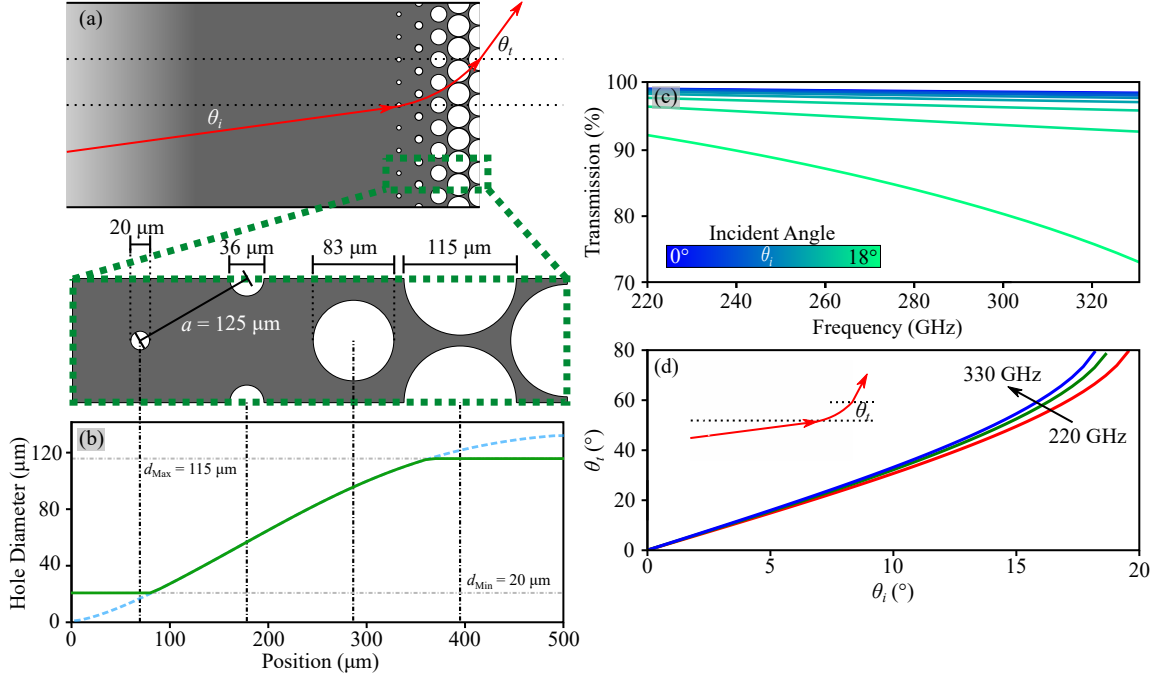


Figure 6.4: GRIN anti-reflection structure design overview. (a) Effective medium GRIN anti-reflection coating used to match the slab mode into free space. (b) Quintic gradient curve used to design this anti-reflection structure, showing the cropping due to fabrication constraints. (c) Broadband transmission and (d) transmission angle of the GRIN structure derived through discretized ray tracing method.

Fig. 6.2(c) is derived as,

$$\sin \theta_{\text{Leakage}} = \frac{\beta_{\text{Waveguide}}}{\beta_{\text{Slab}}}. \quad (6.1)$$

The combination of these factors limits the maximum achievable bandwidth of this scheme.

Using the relationship between separation, leakage rate, and leakage angle, the iterative design algorithm described in [283] can be implemented to determine the necessary separation and waveguide curvature required to project a beam into the far-field. The separation between the waveguide and the slab is designed in 3 sections in order to achieve the leakage profile shown in Fig. 6.3(a). First, the waveguide is gradually introduced to the slab to avoid a sudden index discontinuity, while allowing low frequency components to leak. Then the separation is tailored to induce a uniform leakage profile, to achieve this the separation is gradually decreased until the minimum possible separation is reached. Finally, a long trailing section with the minimum viable separation is introduced, as this is critical to improve performance at higher frequencies where slow leakage results in residual power in the waveguide after the uniform leakage region. The separation between the waveguide and adjacent slab across the length of the channel is shown in Fig. 6.3(b). Beamforming is achieved by a lateral offset of the waveguide relative to the feed as shown in Fig. 6.3(c). This offset compensates the accumulated phase as the wave propagates along the feed waveguide, ensuring that the phase profile of the leaked wave is ramped, generating a collimated beam at the output which is essential for realising high farfield gain.

GRIN Anti-Reflection Structure

In this antenna, the dielectric slab acts as an intermediary medium for broadband, scatterer-free leakage, but ultimately acts as an obstacle to the effective transfer of terahertz power from the waveguide to free space. The Fresnel losses at the edge of slab increase with the incident angle, until ultimately total internal reflection occurs, at the critical angle $\theta_c \approx 18^\circ$, calculated as $\theta_c = \arcsin(n_0/n_{\text{Si}})$ by assuming the slab modes shares the same modal index as bulk silicon. To overcome this, the boundary

of the slab is angled such that the centre frequency is normally incident, ensuring that across the operating band the incident angle remains below the critical angle and Fresnel losses are minimized. However, still these losses are still not negligible, even at small incident angles. Compounding this, the component of the beam that is reflected at this interface will continue to propagate internally, until it is eventually radiated forming undesirable side lobes, or is dissipated at the input as additional reflection loss. For these reasons, an anti-reflection scheme is essential.

In optics, a related problem arises in the design of solar cells. In order to couple light into high-index dielectrics as the sun passes through the sky varying the incident angle, GRIN structures are utilized to overcome weak transmission at oblique incident angles [341–343]. Specifically, quintic index transitions have been shown to be a simple, compact, and effective mechanism to realize efficient matching over a broad range of incidence angles. In this case, a gradient index can be realized through the perforation of the silicon slab with cylindrical holes arranged in a hexagonal lattice, as long as the lattice period has a deeply sub-wavelength period, hence the lattice period, $a=125\text{ }\mu\text{m}$ is selected. The Maxwell-Garnet approximations [192] in combination with the transcendental solution for the slab mode index [344] can be used to derive the range of achievable indices. Then, using these values the quintic gradient index distribution can be calculated [342]. Due to fabrication constraints, the minimum possible hole diameter is $20\text{ }\mu\text{m}$, and in order to maintain the mechanical stability of the structure, the maximum diameter is limited to $115\text{ }\mu\text{m}$. At 275 GHz these correspond to modal indices of 3.00 and 1.28 respectively, incurring some residual discontinuity between the slab mode, the GRIN structure, and free space. In Fig. 6.4(a), this matching scheme is outlined with a single unit cell of the GRIN anti-reflection coating highlighted, with hole diameters corresponding to the gradient in Fig. 6.4(b).

To validate the performance of this design, a ray-tracing model is implemented to simulate the transmission of slab mode through the gradient index structure at various incident angles. The GRIN structure is discretized into 30 segments modeling the transition from silicon into free-space via the GRIN structure, with each segment's refractive index corresponding to the modal index of a silicon slab perforated uniformly with holes of diameter shown in Fig. 6.4(b). Then Snell's Law and Fresnel coefficients are applied iteratively at each interface to calculate the final transmission magnitude and transmitted angle. This process is repeated at each frequency to account for the slab mode dispersion, yielding results shown in Fig. 6.4(c-d) respectively. Here, transmission efficiency is in excess of 95% for incident angles up to 17° , corresponding to a maximum transmitted angle after refraction of 70° , incidentally expanding the field-of-view of the antenna.

3D-Printed COC Lens

Whilst in-plane the antenna aperture is wide, and hence directive, the out-of-plane radiation pattern of the all-dielectric leaky-wave antenna is fundamentally limited by the small physical aperture created by the thin edge of the silicon wafer. This results in a so-called fan-beam, typical of other antennas which use the slab's edge as a radiating aperture [231, 232, 334]. For many applications this is undesirable for two reasons; firstly, it limits the maximum achievable gain of the antenna, and secondly, the out of plane power can easily result in spurious reflections from the environment, leading to multipath interference. To compensate for this, the transverse aperture is expanded with free space optics to form a module with a two-dimensional radiating aperture [233]. In this case, a cylindrical plano-convex lens is designed with a bespoke ray-tracing algorithm and manufactured from 3D printed cyclic-olefin-copolymer (COC) [42, 345]. This lens is designed to correct the fan-beam effect in the out-of-plane dimension while maintaining the frequency scanning beams in plane, and so a cylindrical lens is the natural choice to correct this astigmatism. In this design process I assume COC is a lossless, dispersion-less material with a permittivity $\epsilon_{\text{COC}} = 2.31$, in line with previously reported results [346]. Though the focal length of this lens is a free-variable, for many applications a compact module is desirable, so a lens cross-section of 12 mm and a focal length of 15 mm is selected. These values were determined by observing the field distribution 15 mm from the antennas radiation centre in full-wave simulation. Further, the numerical aperture of the lens should be moderate to minimise the effect of defocusing due to the migrating phase centre of the silicon antenna. In this case, simulations indicate that the phase centre migrates axially on the order of 20 mm across the $220\text{--}330\text{ GHz}$ range. In this

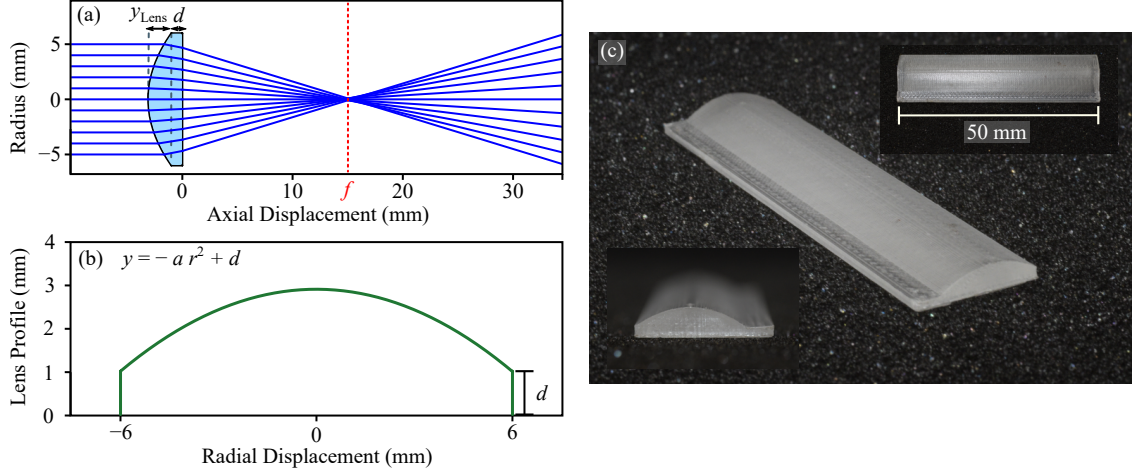


Figure 6.5: Auxiliary 3D-printed COC lens. (a) Output from optimization of the parabolic surface via a ray tracing algorithm, with a focus at 15 mm. (b) Optimized lens profile comprising a quadratic surface and a fixed offset, $d = 1$ mm, where $a = 0.0583$. (c) Photograph of cylindrical lens 3D printed from COC.

case the Rayleigh length is 2 mm, significantly smaller than the apparent phase centre migration, so the performance may be degraded at the edges of the band due to defocusing. This can be mitigated with a longer focal length lens if needed. Then, 2D ray-tracing is applied to optimize the parabolic lens profile y , by varying a in the expression $y = ar^2 + d$. Here a parabolic lens is used to avoid spherical aberrations. The Nelder-Mead method is used to minimize an objective function which considers weighted factors arising from the ray-tracing algorithm; the distance between the mean of all ray intersections and the desired focus, and the thickness of the lens.

In Fig. 6.5(a), the outcome of this optimization process is presented. As the desired lens is cylindrical, the optimized lens profile is simply extruded to form a 3D solid. The in-plane resolution of this process is limited by the width of the 0.4 mm extrusion nozzle, while the printing layer height is set to 50 μm . In Fig. 6.5(c), the surface and internal finish of the lens are imperfect resulting in a cloudy appearance. It has been shown that this has a small impact on lens performance, as this cloudiness arises from the presence of air in the printed material which results in the aggregate refractive index [347, 348], though this can be compensated for during the lens design process.

6.1.2 Leaky-wave Antenna Characterization

Measurement Setup

To validate this design, the device is fabricated from a 250 μm float-zone, high-resistivity, silicon wafer with a single mask, deep reactive ion etch process. Experiments are performed with a Keysight N5222B Vector Network Analyser with WR3.4 VDI frequency extension modules. The largest dimension of the physical aperture of the antenna is 35 mm without the lens and 51 mm with the lens, implying a Fraunhofer distances of 1.1 m and 4.8 m respectively. Due to practical limitations, and the lack of a 2D near-field scanning system, the radiation pattern is not measured in the far-field. Instead, I measure the radiation pattern in the radiative near-field at a distance of 200 mm. As shown in Fig. 6.6(a), the antenna module is placed atop a rotating stage such that the phase centre of the antenna is centered above the rotating axis. Figure 6.6(b) shows the fabricated silicon device supported by the 3D printed fixture and coupled to the metallic waveguide feed and COC lens. A computer is used to synchronize the VNA and rotating stage to automatically measure the radiation pattern as the antenna is rotated. In Fig. 6.6(c), the fabricated device is shown with inset micrographs highlighting the key features of the antenna. To measure the realized gain, S_{21} is measured across the frequency range at each transmission angle with the silicon antenna as the transmitter and another diagonal horn antenna with known gain, in the range 22–25 dBi across the measured range, as a receiver. This measurement is

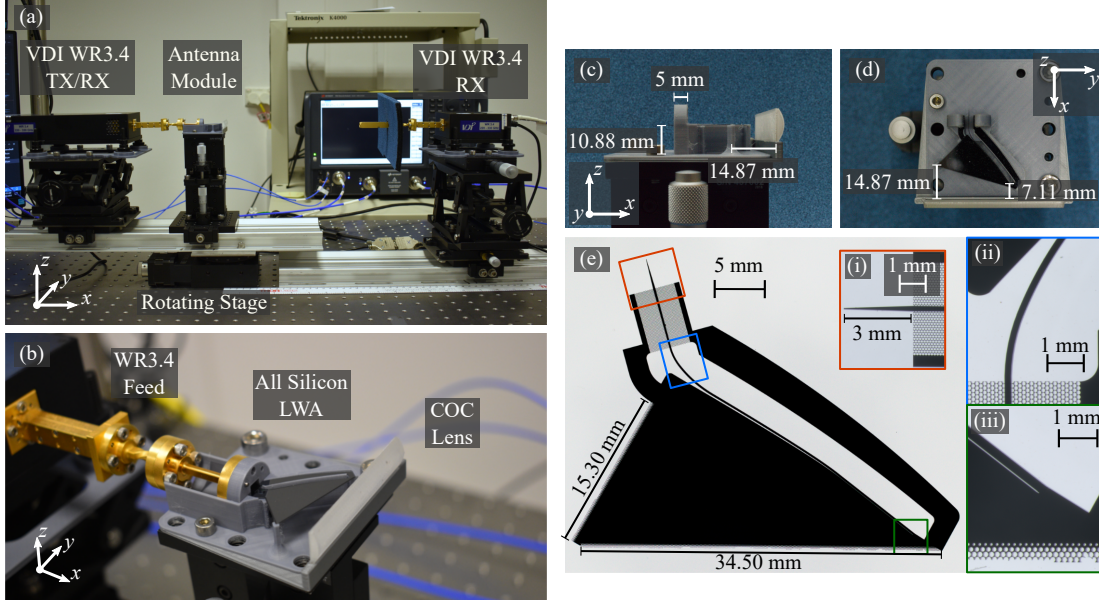


Figure 6.6: Experimental setup for antenna characterization. (a) Overview of experimental setup, showing VDI extension modules aligned with antenna module on top of motorized rotating stage for automated radiation pattern measurements. (b) 3D printed antenna module with packaged antenna, integrated COC lens, and rectangular waveguide alignment flange. For practical reasons, the antenna is packaged in a 3D printed polylactic acid (PLA) mount, such that the alignment to the feed waveguide and external lens are fixed in place. The mount is designed such that the PLA does not interfere with the electromagnetic wave guiding. (c) Side view of radar module, highlighting key parameters. (d) Top view of radar module, highlighting the distance from the antenna to the lens. Note that the radiation center of the antenna exists within the slab, such that the edge of the slab is not at the focal length of the lens. (e) Macroscopic image of fabricated sample with micrographic inserts, (i) feeding taper to be inserted into rectangular waveguide for efficient coupling, (ii) unclad waveguide section, (iii) fine resolution features including the leakage channel and anti-reflection structure—with some damage visible arising from incidental over-etching during fabrication.

compared to a reference measurement in which the same measurement is performed with a diagonal horn antenna in place of the leaky-wave antenna. The realized gain is calculated as,

$$G(f, \theta) = |S_{21, \text{LWA}}(f, \theta)| - |S_{21, \text{Horn}}(f, 0)| + G_{\text{Horn}}(f, 0) + 20 \log_{10} \frac{d_{\text{LWA}}}{d_{\text{Horn}}} \quad (\text{dB}), \quad (6.2)$$

where, $S_{21, \text{LWA}}(f, \theta)$ is the measured transmission with the proposed antenna as a transmitter at a distance of d_{LWA} from the receiver, while $S_{21, \text{Horn}}(f, 0)$ is the measured transmission with a horn antenna with gain, $G_{\text{Horn}}(f, 0)$, at a distance of d_{Horn} . These measured results are compared to full-wave simulation in the commercially available CST Studio Suite 2023, but only in the case without the lens as the lens' large electromagnetic size makes full-wave simulation impractical.

Results

In Fig. 6.7(a), I present the measured reflection, which is below -10 dB across the measured band, highlighting good coupling between the feed and the silicon antenna with reflections in line with the simulated results. Notably, there is no significant increase in reflection due to the inclusion of the external lens. This is expected as the index of COC is low resulting in low reflection amplitude, and compounding this the divergent beam is primarily reflected away from the antenna aperture. Figure 6.7(b) is the realized gain map of the antenna, showing the frequency sweeping characteristic of leaky wave antennas, with select frequencies plotted in polar coordinates in Fig. 6.7(c). Then, Fig. 6.7(d) contains the maximum gain at each frequency with and without the inclusion of the COC lens. With the COC lens, an average increase in gain of 6.5 dB is observed suggesting that this lens is effective at collimating the H -plane component as intended. Although the Rayleigh length of the COC lens is narrow, there appears to be little evidence of de-focusing due to the migrating phase centre

Table 6.1: Comparison of experimentally demonstrated leaky-wave antennas and this work.

Waveguide Platform	Max Gain (dBi)	Fractional Bandwidth	Centre Frequency (GHz)	Field of View	Integrated	External Lens
Hollow Metallic [50]	-	-	415	51°	Yes	No
Silicon Photonic Crystal [327]	-	2%	325	-	Yes	No
Silicon Slab [328]	-	2%	320	-	Yes	No
Silicon Rib [329]	-	1%	194	-	Yes	No
COC Rib [159]	-	-	120	-	Yes	No
Alumina Photonic Crystal [330]	-	10%	105	-	Yes	No
Microstrip Line [51]	18	32%	275	38°	Yes	No
Parallel Plate [325]	-	-	225	35°	No	No
Spoof Plasmon Polariton [326]	16	41%	182.5	30°	Yes	No
Substrate Integrated [331]	15.4	15%	60	18.2°	Yes	No
Indium Phosphide [127]	11	16%	275	40°	Yes	No
Indium Phosphide [332]	23	16%	275	33°	Yes	Yes
This Work	25	19%	275	34.3°	Yes	Yes

of the silicon antenna, as evidenced by the stable frequency response. The maximum gain of 25 dBi is on-par with that of a standard horn antenna. In Fig. 6.7(e), the approximately linear frequency scanning behavior is described.

Here I note the fabricated sample shows minor deviation from the simulations, namely a 3-dB bandwidth of 53.5 GHz as compared to 61.7 GHz in simulation, while the field-of-view is then compressed to 34.3° compared to 40.0° in simulation. I ascribe these effects to fabrication tolerances, notably incidental overetching leading to a narrower than designed waveguide and oversized holes in the GRIN structure. As a result, this changes the dispersion relation at the core of the design methodology. A thinner waveguide drives faster leakage from the waveguide as the phase constant of the waveguide diminishes while the relative dispersion between the slab and waveguide is also changed—hence these changes to the leakage profile and scanning angle outside of the design frequency. As visible in Fig. 6.6(c,iii), overetching also results in some damage to the anti-reflection structure which may hinder the matching at oblique angles, further suppressing the realised gain. However, generally the measured simulations confirm the antennas ability to generate a high gain beam with quasi-linear frequency scanning.

In Table 6.1, this antennas performance is compared to other experimentally demonstrated leaky-wave antennas in the literature. Of these antennas in this table, the antenna presented in this thesis has the highest gain. This is attributed to two factors; the use of silicon results in high-efficiency, and an auxiliary lens enhances the directionality, together resulting in high-gain. Though the measured 3-dB bandwidth is less than simulated, and less than the best performing antenna in the table [51], the roll-off is slow, and the less stringent 10-dB bandwidth is close to the full WR3.4 band, from 240–330 GHz. Similarly, the 3-dB field-of-view is constrained, but the linear frequency scanning is maintained across a broader range, from 240–330 GHz, across a close to 70 degree field of view. Though the 3-dB level is an accepted standard for comparison, it may not reflect the actual performance limit. This is especially true in sensing, where so long as the recieved power is above the noise floor, some information can be recovered. In the following chapter, a thorough examination of antenna performance in sensing applications is presented.

An all-dielectric leaky-wave antenna module is designed, fabricated, and experimentally characterised. The key utility of this antenna is its frequency scanning radiation pattern that presents beam-forming capability without the need for mechanical actuation, or phase shifters which have proven difficult to realise efficiently at terahertz frequencies. The silicon antenna is combined with a 3D-printed lens, to form an economical and compact module without compromising the performance.

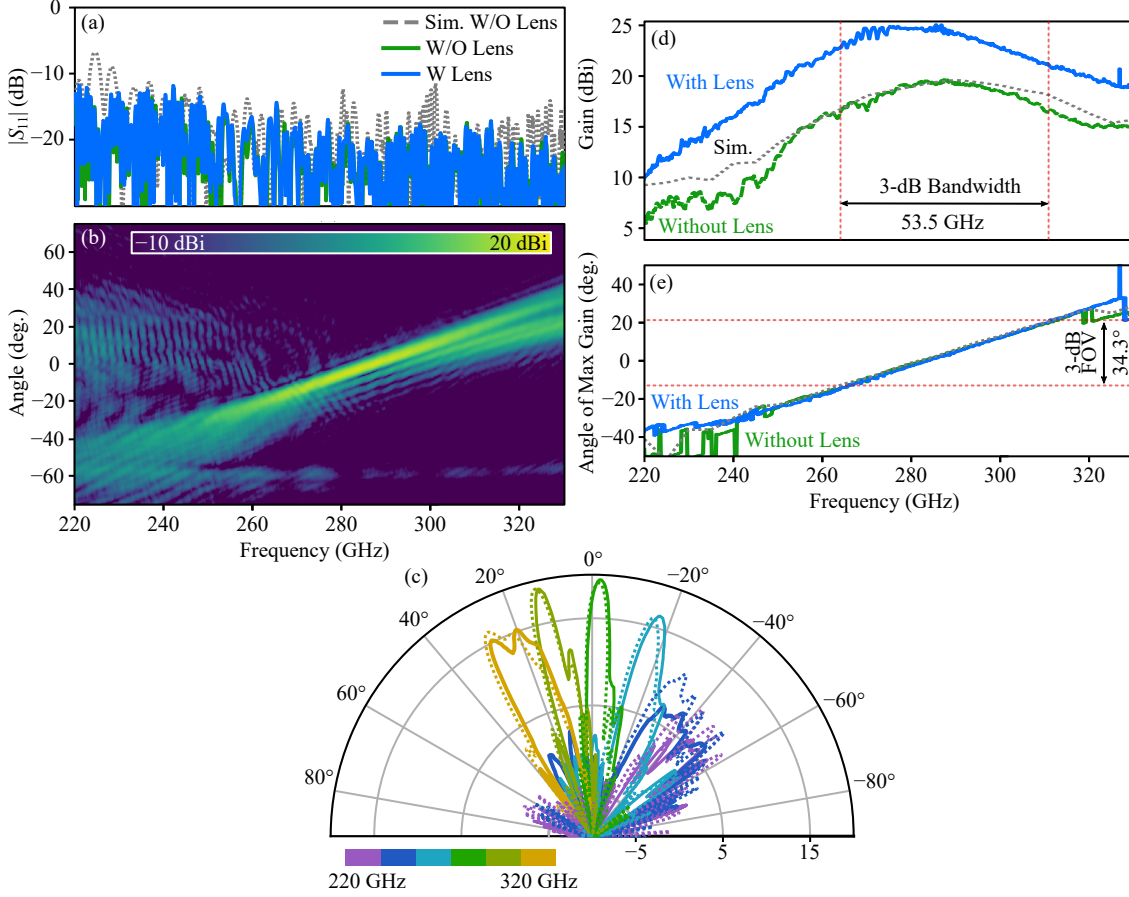


Figure 6.7: Experimental characterization of the proposed antenna. (a) Measured reflection coefficients to demonstrate efficient coupling to free space over the measured frequency range. (b) Radiation pattern measurement without lens over frequency and angle of interest showing frequency scanning behavior. (c) Radiation pattern measurements at selected frequencies across the operating band. (d) Maximum gain over frequency, with and without the external COC lens. (e) Angle of the maximum gain over frequency describing the angular frequency scanning behavior, at either end of the operating band the relationship between angle and frequency breaks down, resulting in the sudden discontinuities observed in this plot, as a similar gain is observed across a wide range of angles.

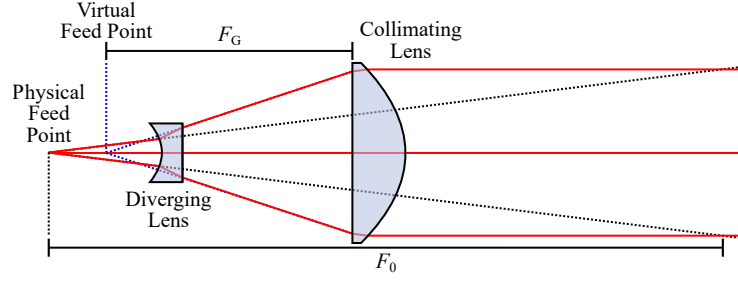


Figure 6.8: Schematic of Galilean telescope. The three stages of the antenna are depicted; the feed point, the diverging lens, and the collimating lens. The role of the diverging lens is highlighted by the comparison of F_G to F_0 the focal length of the collimator in a Galilean system and in a single lens system respectively, showing that a much larger aperture can be achieved with a smaller footprint.

In Chapter 7 this antenna is employed to realize a leaky-wave radar.

6.2 Galilean Telescope Antenna

In Chapter 4, a broadband rib waveguide with a single-mode bandwidth of 220–500 GHz was proposed. However, beyond the waveguide itself, ultra-wideband components are also necessary to make use of the expanded bandwidth. To date, typically over-moded rib waveguides are used for these ultra-wideband systems [266, 296], and tapered rods make for simple low-gain antennas. The gain of these travelling wave antennas is tied to the length of the rod, and so to enhance the gain, the rod must be made longer, simultaneously increasing the fragility. Previously, for other silicon guides this issue has been addressed through the use of integrated endfire antennas, either in the form of lens antennas [231, 232] or planar horns [334]. These antennas provide enhanced gain through a 2D-aperture and are formed in three sections; a waveguide feed, a divergence region, and a phase-correction to collimate the beam before it is radiated. In principle, this scheme scales well to ultra-broadband use as the antenna employs the slab-mode, which is single-mode in broadband. However, to ensure operation in broadband, the frequency dependent effects of each element must be compensated appropriately. In this section I propose an ultra-wideband endfire antenna based upon a integrated Galilean Telescope, instantiated with a rib waveguide feed and effective-medium integrated lenses. The elements of this antenna are described, simulated, and a prototype of this antenna is fabricated and experimentally characterised over the 220–330 GHz band. The antenna could not be experimentally characterised in the 330–500 GHz band due to the lack of available facilities.

6.2.1 Antenna Design

The Galilean Telescope, depicted in Fig. 6.8, is a two-element, refractive optical system, comprised of a successive diverging and converging lens, used to provide magnification of distant objects. The diverging lens increases the illuminated area of the larger converging lens, providing a compact, large aperture system. In essence, this system is a high-gain optical antenna, providing highly directional imaging. To realise the integrated instantiation of this antenna depicted in Fig. 6.9, each of the elements is designed and combined to form a monolithic silicon module.

Rib Waveguide Feed

The gain of an endfire antenna is determined by its aperture relative to wavelength. So, to provide an even gain across a broad bandwidth, the effective aperture must vary with frequency. To realise this, frequency dependence must be introduced as the modal dispersion of the slab-mode alone is not sufficient to compensate for the required change in apertures. With this in mind, I elect to use a tapered rod-feed to launch the slab mode from the rib waveguide. Tapered rods are dispersive elements, with the lowest frequencies readily radiated, while the highest frequencies remain confined until the end of the rod as depicted in Fig. 6.10(a-c). Thus, the length of the tapered rod can be used to

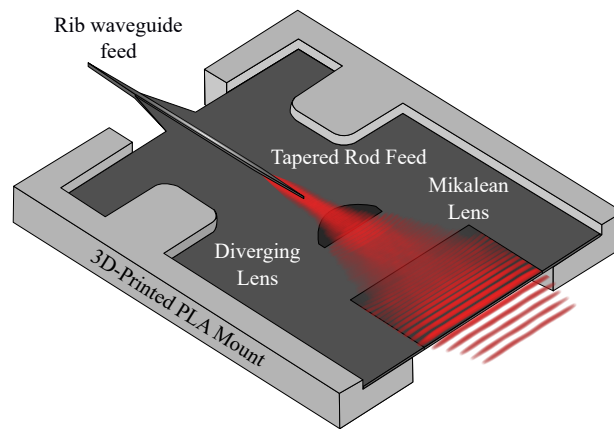


Figure 6.9: Proposed Galilean telescope Antenna. The three stages of the antenna are depicted; the tapered feed, the integrated diverging lens, and the Mikaelian lens.

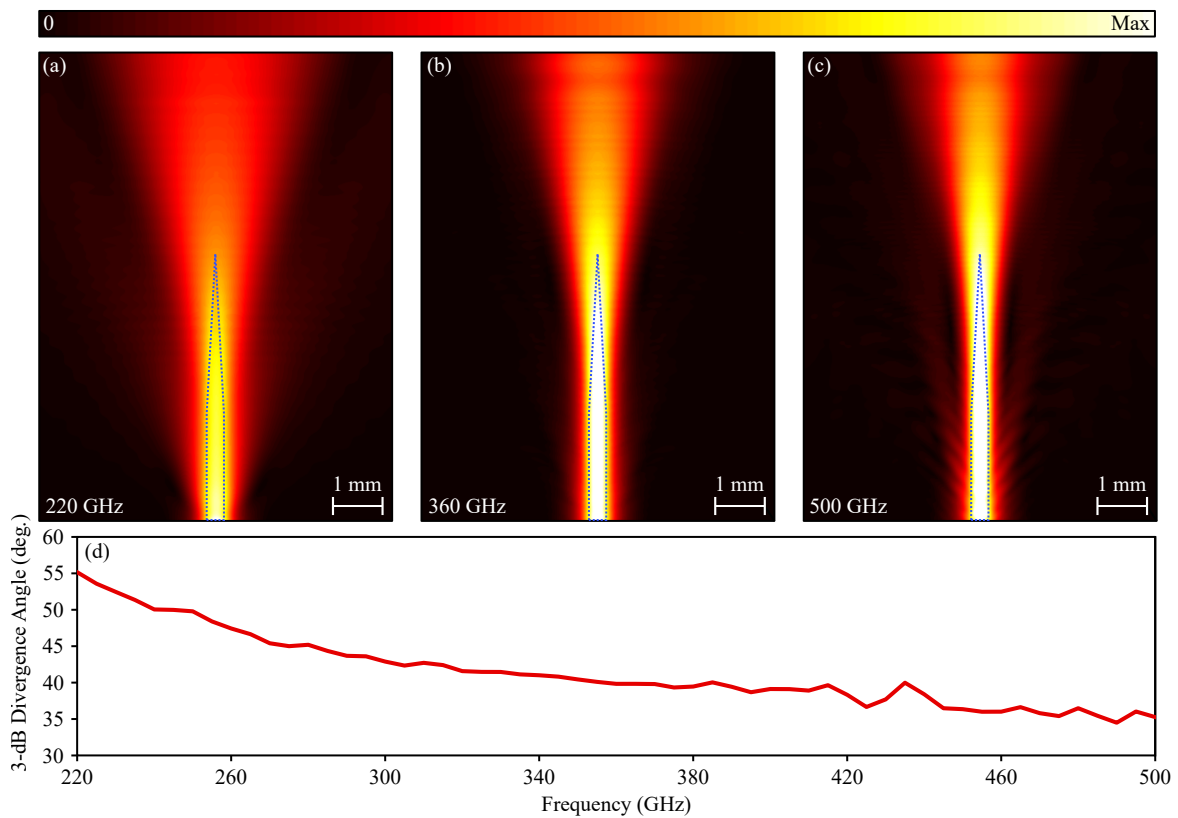


Figure 6.10: Design of tapered rod feed. Simulated electric-field at (a) 220 GHz, (b) 360 GHz, and (c) 500 GHz for a tapered rod of length 3 mm. (d) 3-dB divergence angle of the tapered rod feed across the 220–500 GHz range.

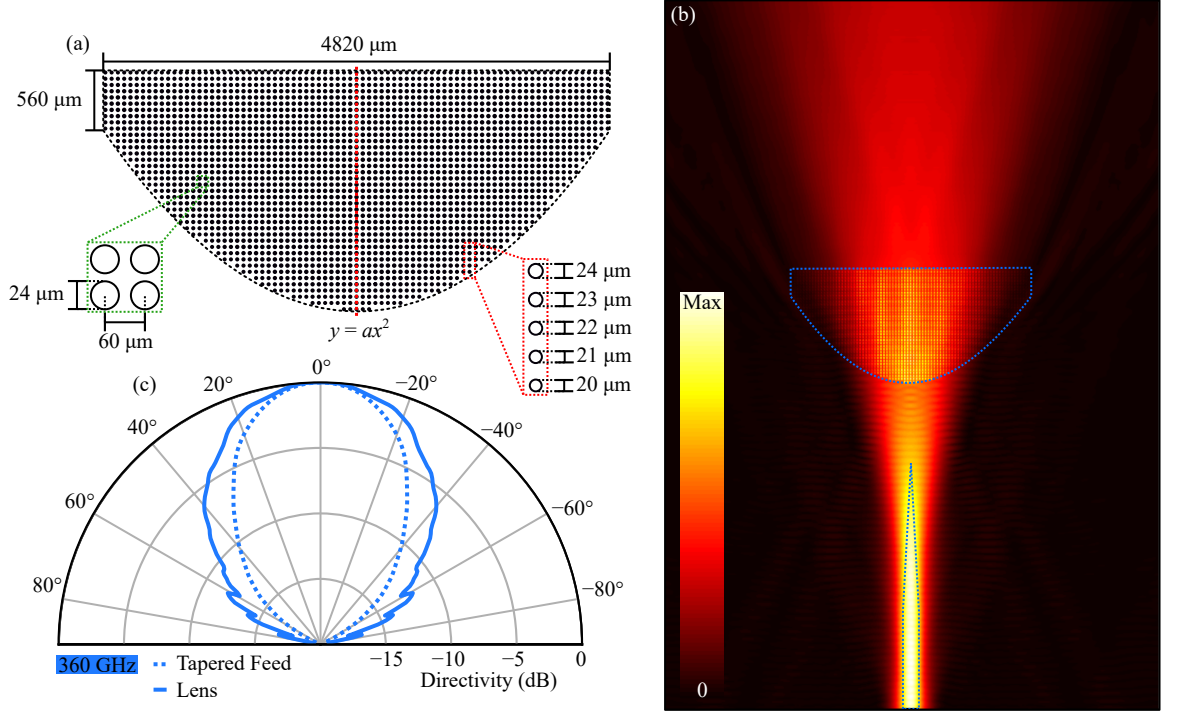


Figure 6.11: Design of integrated diverging lens. (a) Lens schematic. (b) Simulated E -field pattern of the combined tapered feed and diverging lens. (c) Launched slab-mode patterns with and without the diverging lens at 360 GHz, each normalised to their respective maximums.

tune this effect to provide the frequency dependent aperture required for an even gain profile. The waveguide feed is a silicon rib waveguide with rib width of $325\ \mu\text{m}$, a rib thickness of $250\ \mu\text{m}$, and a slab thickness of $175\ \mu\text{m}$. The taper length is $3000\ \mu\text{m}$, and has a tip width of $20\ \mu\text{m}$. This results in a launched slab mode with a divergence angle ranging from 35° at $220\ \text{GHz}$ to 55° at $500\ \text{GHz}$, as shown in Fig. 6.10(d). Alongside this change in divergence angle, the phase centre of the launcher migrates towards the tip of the taper, from $300\ \mu\text{m}$ from the base of the taper at $220\ \text{GHz}$, to $1000\ \mu\text{m}$ from the base of the taper at $500\ \text{GHz}$. This change in phase centre reduces the dispersion of this element, by resulting in further expansion of the launched mode at $220\ \text{GHz}$, as it is launched first, while at $500\ \text{GHz}$ the mode is confined for longer, but diverges more rapidly once launched.

Integrated Diverging Lens

The first lens after the feed is the diverging lens. This lens functions to enhance the divergence of the feed, which facilitates a more compact antenna by reducing the feed-length while maintaining the wide aperture necessary for high-gain. To produce divergence through refraction, an effective medium region is introduced by perforating the silicon with through-holes in a sub-wavelength lattice. The modal index of the slab mode can be solved numerically as described in [232]. The refractive power of the lens is proportional to the difference between the indices of the slab-mode in the perforated and un-perforated region. On the other hand, this difference determines the resultant reflection at the interface. To facilitate high refractive power with suppressed reflections, a gradient index transition is introduced, analogous to an anti-reflective coating in an optical system. The minimum hole size is constrained by fabrication to $d = 20\ \mu\text{m}$, while the largest holes in this lens are $d = 25\ \mu\text{m}$. The lens profile is defined by the quadratic with the equation $z = 2280 - (3 \times 10^{-4})x^2\ \mu\text{m}$. In Fig. 6.11(a), the lens with anti-reflection structure is depicted. The lens is placed $3\ \text{mm}$ from the tip of the tapered feed, with the curved face towards to the feed. The simulated E -field of the combined elements is depicted in Fig. 6.11(b). In Fig. 6.11(c), the propagation pattern of the launched slab mode with and

without the additional lens is included to show the enhanced divergence.

Impedance Matched Mikaelian Lens

In principle, any converging lens can be used to collimate the diverging slab mode before it is radiated. A curved surface is simple, but introduces strong reflections at the interface between the platform and free space without additional anti-reflection. Though anti-reflective structures were developed in Section 6.1.1, these rely on a small angle of incidence to avoid total internal reflection. Additionally, the curved surface also provides a fragile overhang which is prone to breaking. For these reasons, I prefer Mikaelian lenses [349] as they are more physically robust without sacrificing performance. Previously, Mikaelian lenses were employed with profiles derived from phase-front correction. These lenses are designed by calculating the phase profile of the beam at the aperture, and then imposing a transmissive phase mask to correct for the heterogeneity. The principle drawback of this approach is that it does not provide innate index matching, so additional reflections are unavoidable. In [231], the reflection is simply incurred on the feed side, while a rod array is used to provide index matching on the radiating end. In [334], a numerically optimised lens was used to reduce the reflections, but an analytic technique was not proposed. Here, I outline an analytic technique for deriving an integrated Mikaelian lens with anti-reflective matching layers. An overview of this lens, which occurs in three contiguous stages as depicted in Fig. 6.12(a), with the function of each stage visible in simulated electric fields presented in Fig. 6.12(b).

As with other Mikaelian lenses, the design begins by considering the phase profile of at the input to the lens, commonly given by the equation,

$$\phi_{\text{feed}}(x) = -\beta(\sqrt{F^2 + x^2} - F) + \phi_0, \quad (6.3)$$

where β is the propagation constant of the slab mode, F is the focal length of the lens, in this case the distance from the lens to the feed, and ϕ_0 is a normalizing factor, which represents the phase accumulated over the length of the feed at the centre of the lens, given by,

$$\phi_0 = \beta F. \quad (6.4)$$

Previously [231], the propagation profile of the corrective lens is given by,

$$\beta(x) = -\frac{\phi(x)_{\text{feed}}}{L}, \quad (6.5)$$

where L is the thickness of the corrective lens, under the assumption that the phase profile is homogenous along the propagation direction. It is this homogeneity that does not permit for the inclusion of anti-reflection layers. Instead, I propose that the homogeneity can be broken by iteratively calculating the phase change as the wave propagates in the lens, and then constraints may be implied on the range of permissible β to produce an overall gradually-changing structure that is innately robust to the undesired reflections produced by index mismatch. To describe this process, I begin by defining the thickness of the corrective lens, L , and discretising this length into N slices, each with a thickness of a , such that $L = Na$. The slice thickness a corresponds to the lattice period of the effective medium used to implement the gradient index structure. Then, as the wave propagates through each slice, it accumulates a phase change,

$$\phi_i(x) = -\beta_i(x)a, \quad (6.6)$$

such that over the the entire lens, the wave accumulates the aggregate phase change,

$$\phi_{\text{lens}} = \sum_{i=1}^N \phi_i(x). \quad (6.7)$$

By appropriately selecting $\beta_i(x)$ a corrective lens can be developed. The simultaneous optimization of $\beta_i(x)$ for all rows is complicated, instead the process can be performed iteratively, on each slice sequentially, by tracking the residual phase change after propagation through each row,

$$\phi_{\text{residual},i+1} = \phi_{\text{residual},i}(x) - \phi_{\text{lens},i}, \quad (6.8)$$

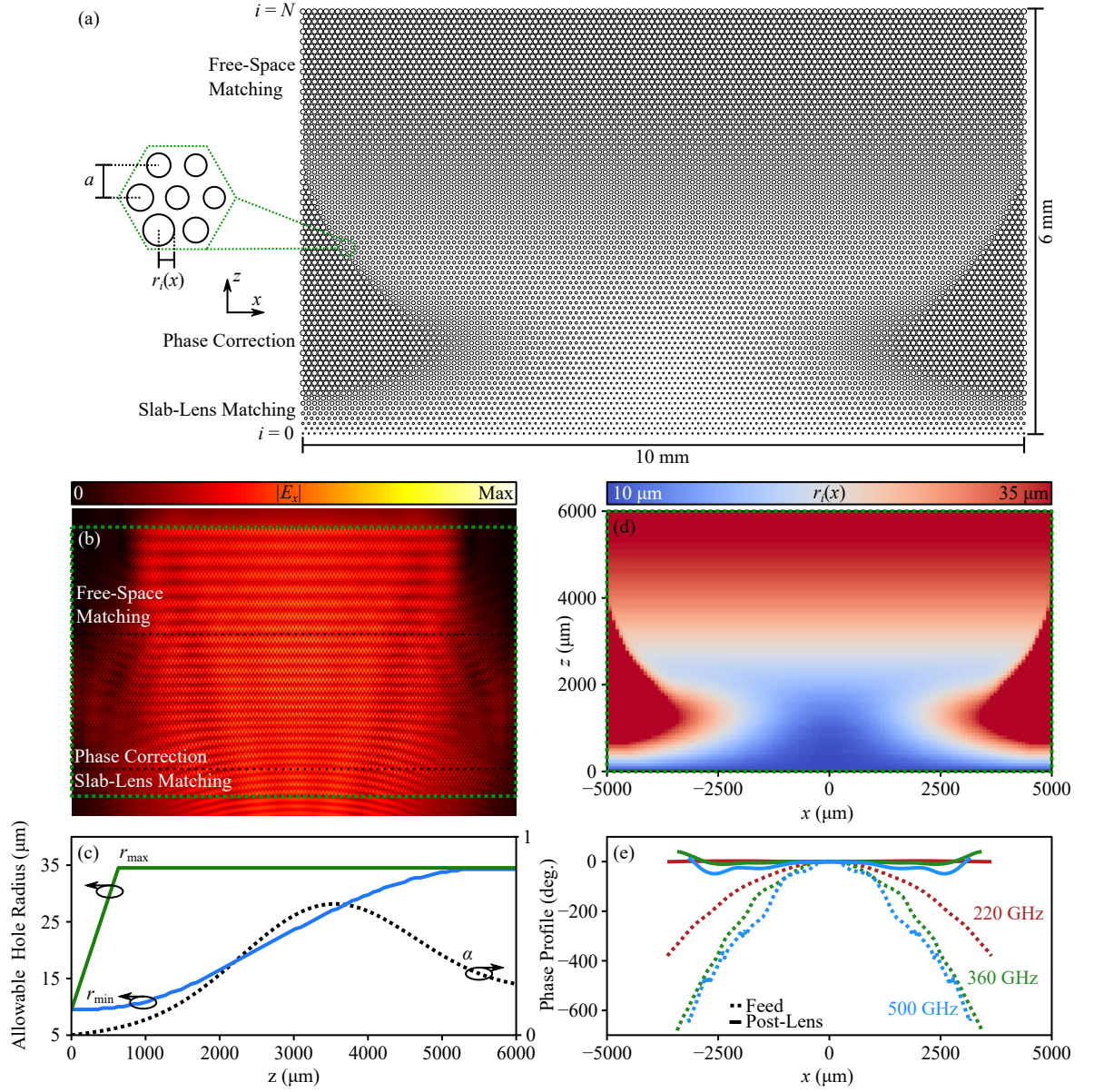


Figure 6.12: Design of impedance matched Mikaelian lens. (a) Lens overview, highlighting the transition, correction, and matching regions. (b) Simulated E-field pattern as the wave propagates through the lens. (c) Weighting function, maximum and minimum hole radius constraints over the length of the lens. (d) Resultant gradient index profile. (e) Simulated residual phase response at the lens aperture.

then desired β of the next row is determined as,

$$\beta_{\text{desired},i}(x) = -\frac{\alpha}{a}\phi_{\text{residual}} , \quad (6.9)$$

where α is a weighting term. This weighting is introduced to avoid rapid changes, essentially limiting the gradient of the profile. This term can be any distribution. In this case I selected a skewed Gaussian distribution, shown in Fig. 6.12(c), to force a large proportion of the phase correction to the centre of the lens, leaving the edges oriented towards index matching. To force index matching at the start and end of the lens, the range of β is constrained by limiting the hole radius of the effective medium, as shown in Fig. 6.12(c). On the feed side, the maximum value is constrained to force index matching from the silicon slab to the effective medium region. On the opposite end, the minimum value is constrained to force the gradual transition from the effective medium to free-space. The resulting limits are applied following the calculation of $\beta_{\text{desired},i}$ to yield β_i . This process is repeated for each row to produce the propagation constant profile of the entire lens, which in-turn is used to calculate the gradient index distribution.

To calculate this profile the various input parameters should be selected. First, the row constant a , is determined by the lattice constant of the effective medium, in this case the lattice constant is selected as 80 μm such that this value is smaller than the slab-mode wavelength at 500 GHz, so the separation between rows is $a = 80\cos(\pi/6)$ μm . The length of the lens is, in principle, a free variable but should be sufficiently long to avoid sharp changes in β , in this case $L=6$ mm. The width of the lens is selected as 10 mm to provide a sufficiently large aperture. The focal length, F , is determined by simulating the antenna with various values to find the optimal length, in this case the optimal value is determined as 10 mm. Due to the negative focal length of the diverging lens and the migrating phase centre of the feed, this distance is not simply fixed across frequency or the point-to-point distance from the lens to the feed, which is 11.5 mm, highlighting the footprint contraction brought by the addition of the lens. With these values, the gradient index profile is calculated, and is presented in Fig. 6.12(d). The lens is simulated from the feed through the aperture, and the phase profile is measured at the start of the lens and in the free-space immediately after the lens aperture, depicted in Fig. 6.12(e). Here, I observe that the phase correction is imperfect but the non-uniformity is significantly reduced to less than 100° across the 220–500 GHz range. Since the optimization is performed at a single frequency, 360 GHz, dispersive effects are the primary cause of non-uniformity in this case. In this case, 360 GHz is selected as it is the mid-band frequency. However, optimisation at 300 GHz, the frequency that represents the mid-point of the waveguides modal refractive index, may have been more appropriate.

6.2.2 Prototype Measurements

The antenna is fabricated from a 250 μm high-resistivity silicon wafer using a two stage DRIE etch process. First, the through-holes are etched on one side to a depth of 175 μm . Then the wafer is flipped, and the entire wafer, except for the ribs, is etched to a depth 75 μm . The antenna is placed in a mount, as shown in Fig. 6.13(a), 3D-printed from poly-lactic acid (PLA), ensuring that a suitable gap is left to separate the functional elements of the antenna from the PLA. In this case experimental demonstration is limited to the 220–330 GHz range by the availability of equipment. Nevertheless, a Keysight N5222B vector network analyser in combination with WR3.4 Virginia Diodes vector network analyser extension modules is used to make measurements across this band. As in previous Chapters, the silicon device is fed by hollow rectangular waveguides, which are manually aligned to couple the silicon and metallic waveguides. The reflection coefficient is measured, as shown in Fig. 6.13(b), showing decreased reflection compared to simulation, well below -10 dB across the measured frequencies. I attribute this to incidental overetching of the GRIN lens, which causes improved impedance matching from silicon to free-space. However, this improved transition compromises the phase compensation, so is ultimately undesirable. The antenna mount is placed on a rotating stage, with the radiation centre of the antenna, approximately the position of the tapered feed, placed at the rotation centre of the stage. The receiver, terminated with a standard WR3.4 diagonal horn antenna with known radiation characteristics, is placed 20 cm from the silicon antenna, further than the Fraunhofer distance

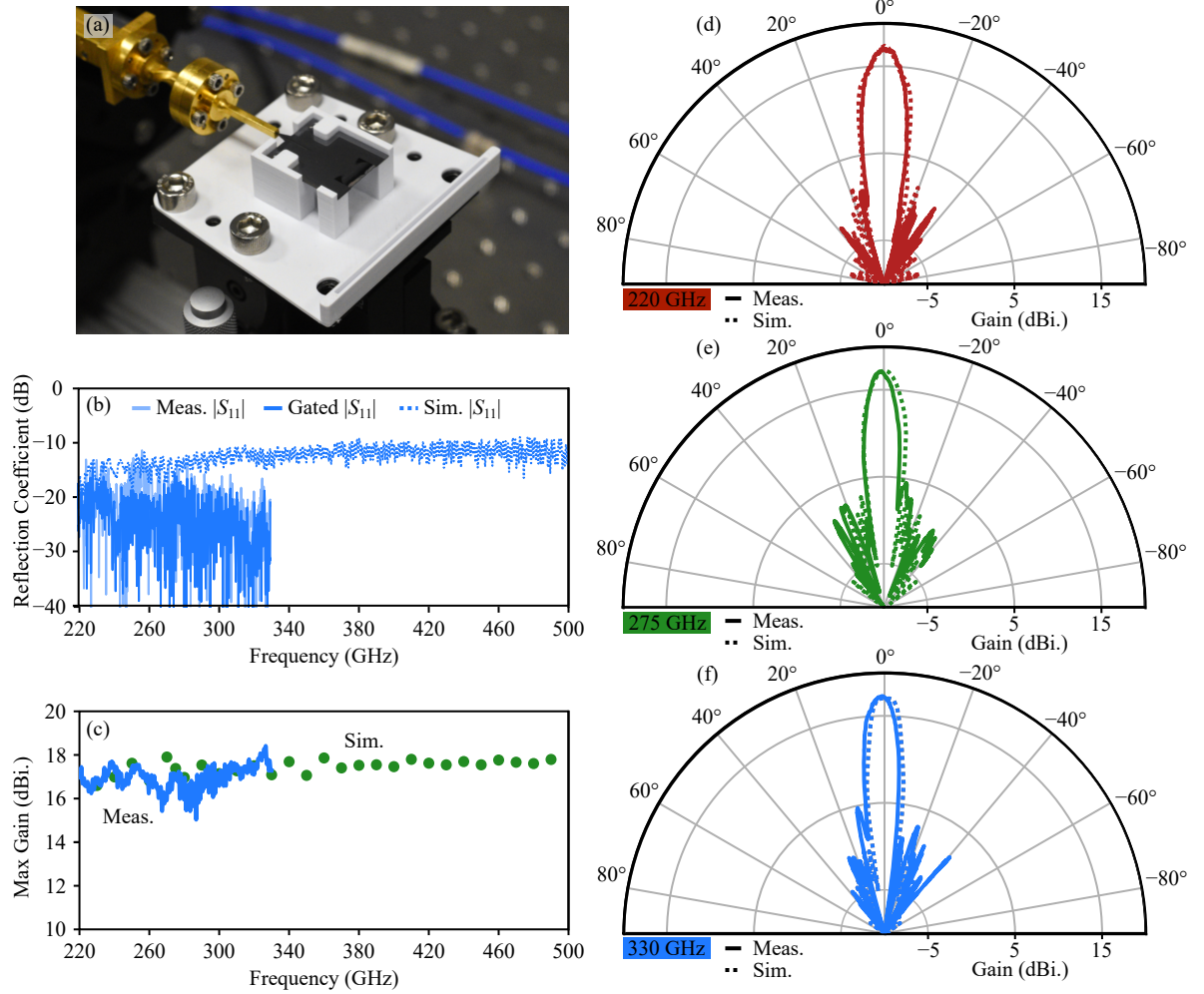


Figure 6.13: Fabricated Galilean Telescope Antenna. Simulated data spans 220–500 GHz, measurements are constrained by available equipment to 220–330 GHz. (a) Photograph of the fabricated sample. (b) Measured and simulated antenna reflection coefficient. (c) Measured and simulated gain over frequency. (d-f) Measured and simulated radiation patterns.

of 17.8 cm, calculated using the illuminated lens aperture at 330 GHz. Python code is used to control the rotating stage and vector network analyser to automate the radiation pattern measurement. The gain is calculated as described in Section 6.1.2. In Fig. 6.13(c), the maximum gain measured across the WR3.4 band is shown, while Fig. 6.13(d) shows the radiation patterns at 220–330 GHz, noting the highly directional patterns with low side-lobes. There is good alignment between measurement and simulation in this band.

6.3 Conclusion

Two all-silicon terahertz antennas are proposed, fabricated, and experimentally demonstrated. These antennas move beyond the previous generation of single-band end-fire antennas that have been demonstrated previously, bringing ultra-wideband performance and passive beam-forming through frequency-scanning, while maintaining the high-gain through high-efficiency that is inherent to all-silicon antennas. While these antennas function as standalone components, the next step is to employ their integrability to fully realize their potential by integrating them with sources, detectors, and other passive components to built fully integrated systems for communications and imaging applications.

Part III

Techniques Towards Applications

Chapter 7

Leaky-wave Radar

Abstract

To circumvent the problem of realising terahertz beam steering without mechanical actuation, so called leaky-wave radars have emerged. Conceptually, by using the frequency-scanning beam of a leaky-wave antenna, the angular position of objects can be determined by correlating the frequency-dependent reflections from targets with the known spatial-spectral mapping of the antenna’s beam pattern. To determine the axial position or the range, an inverse-fast-Fourier transform is applied, building a 2D position map of objects. These two properties can be obtained with a single frequency sweep over the operating bandwidth, which with modern frequency multiplier sources can be performed on the order of milliseconds, enabling real-time acquisition. Previously, to infer the angular position from the received signal, a process of frequency windowing based on a linear approximation of the frequency scanning behaviour has been used. In this Chapter, I propose that instead, the measured radiation pattern of the antenna can be used to more-appropriately correlate the measured reflection. Additionally, the Chapter includes a theoretical analysis of leaky-wave radar, deriving the relationship between the field of view and operating bandwidth of the antenna and the angular and depth resolution of the realised radar. This analysis reveals an intrinsic relationship between the angular resolution, depth resolution, field-of-view, and operating bandwidth of the leaky-wave radar, which places an upper-bound of the achievable performance of leaky-wave radar systems. Finally, these principles are employed in a series of experimental demonstrations including multi-target tracking, liquid sensing and vibrometry, all using the all-silicon leaky-wave antenna proposed in Chapter 6.

7.1 Introduction

The use of terahertz frequencies for radar applications offers unique opportunities in terms of resolution and object penetration. Specifically, the shorter wavelength compared to traditional microwave radar enables resolutions on the order of millimetres as opposed to meters. Additionally, terahertz waves have the ability to penetrate non-metallic, dry materials, many of which are typically opaque to light detection and ranging (LIDAR) [350]. The combination of these properties defines a niche where terahertz waves are uniquely suited for the detection of small targets which are optically hidden from the viewer.

The earliest terahertz radars were based upon terahertz time domain spectroscopy [351, 352], using optically pumped photo-conductive antennas in combination with a mechanical delay line to realise ultra-broadband systems with depth resolution on the order of microns. However, there exist several fundamental barriers to the practical deployment of these systems. First, they rely on mechanical actuation to realise in-plane beam scanning, which when combined with long integration times, results in impractically long acquisition times for real-time tracking. Second, these systems are typically bulky and far from portable, while only producing microwatts of terahertz power, which is rapidly dispersed

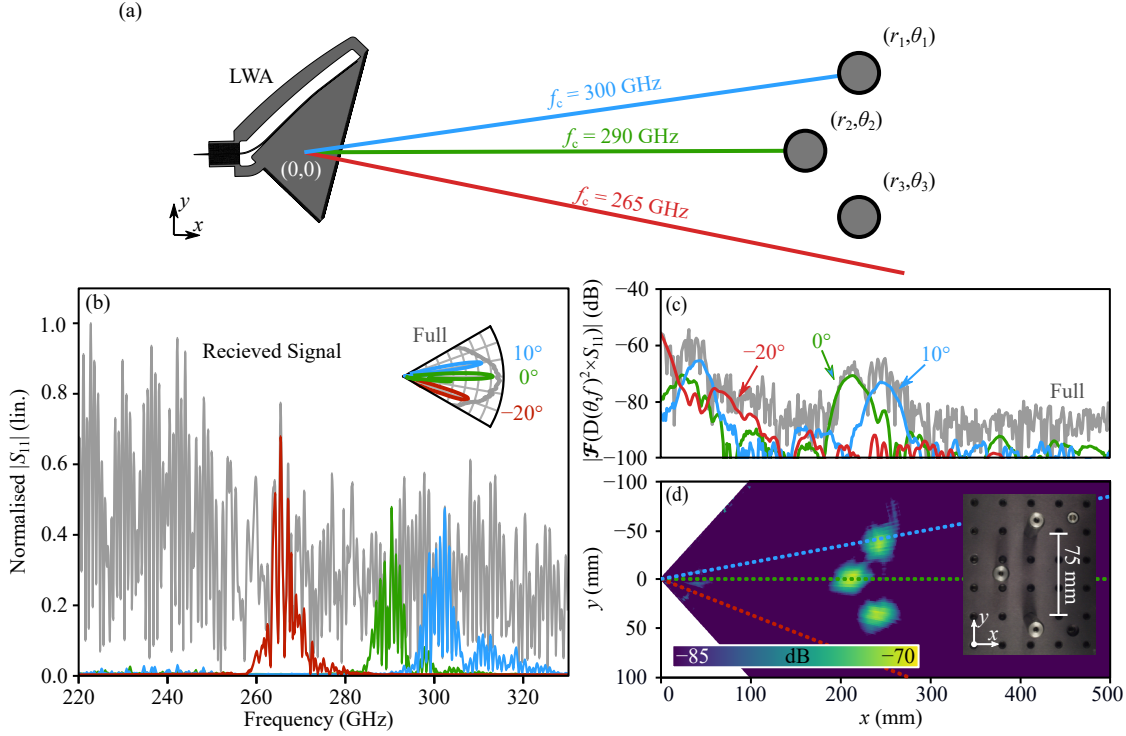


Figure 7.1: Visual description of the spatial mapping process used for single shot radar image retrieval. (a) Illustration of the physical setting showing the coordinate reference. (b) Magnitude of received signal windowed by the directivity measured at each angle to map the components of the received signal to direction. (c) Inverse Fourier transform is then applied to each complex-valued, windowed component of the received signal to estimate the time domain signal arriving from each angle. In this case one component shows an empty spectrum (red), while the other component shows a peak at 225 mm (green) and 250 mm (blue). (d) 2D map in Cartesian coordinates, built from this process applied for all angles and then converted from polar to Cartesian coordinates. Here the recovered radar image is shown alongside the corresponding ground truth, 3 optical posts arranged in a triangle.

due to path loss, stringently limiting the effective range. The combination of these factors makes the prospect of widespread adoption of such a system for ranging and localisation improbable.

In competition with terahertz time domain spectroscopy, terahertz frequency modulated continuous wave radars have emerged [353–355], capable of improved range due to higher output powers at the expense of bandwidth, and hence depth resolution. To realise beam steering, a quasi-optical reflector is typically mechanically actuated with a piezo-electric or otherwise mechanical stage. This mechanism is much faster than raster-scanning but still results in an inherent trade off between achieved resolution and measurement times. Specifically, the range is proportional to the chirp time, which then limits the speed that the beam can be scanned. Additionally, phase noise becomes increasingly critical for high-accuracy systems [356].

These points were addressed through the use of leaky-wave antennas in combination with a frequency swept terahertz transceiver as a terahertz radar [50, 357, 358]. Without mechanical parts, the size and complexity of the system is significantly reduced whilst the innate frequency scanning of leaky-wave antennas enables single shot imaging of a single plane with wide field of view—a critical capability in the terahertz regime where broadband, efficient, and integrated phase-shifters for the realisation of phased arrays are still elusive. Hence, for applications where reduced resolution is permissible, particularly for localisation, the practical advantages of an integrated system are significant.

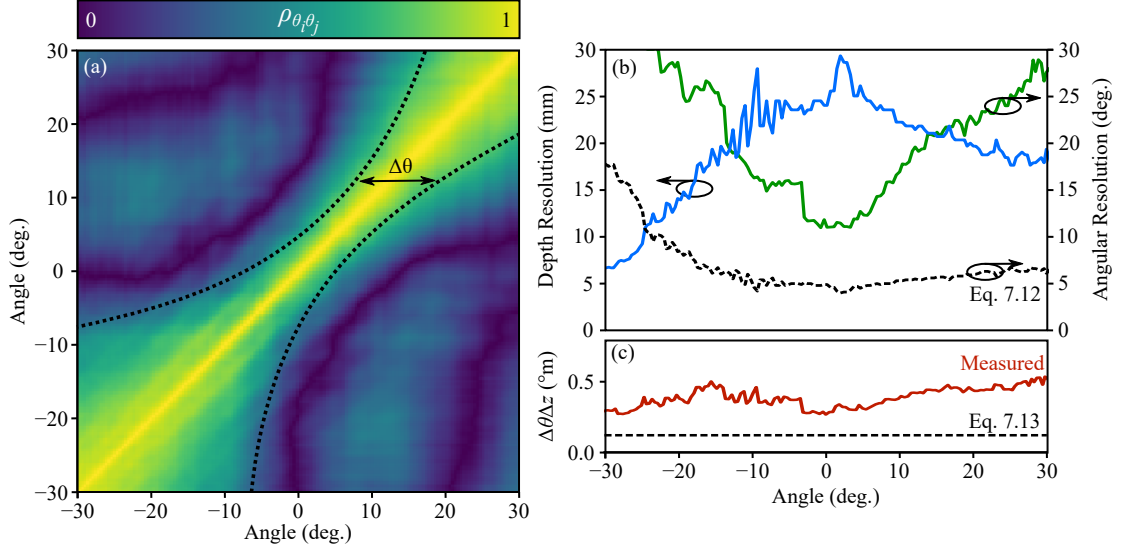


Figure 7.2: Radar resolution parameters calculated from the all-silicon leaky-wave antenna. (a) Correlation between the gain measured at each angle and the gain measured at every other angle, describing the angular resolution of the system. In this case, a strong correlation with other angles indicates poor angular resolution as the signal at a given angle is poorly distinguished from other angles. (b) Depth resolution as defined in Eq. 7.3 and the angular resolution defined as range of angles for which the similarity between the central angle and the surrounding angles is greater than 0.5. (c) Product of the depth and angular resolution.

7.2 Theoretical Analysis of Performance

Fundamentally, leaky-wave radar is underpinned by the correlation between the received reflections and the mapping between frequency and beam angle. In previous works [359, 360], the received frequency-domain spectra were discretized with fixed windows in order to derive the spatial mapping. Importantly, this approach highlights the fundamental trade-off between depth and angular resolution, with narrower frequency domain windows resulting in higher angular resolution at the expense of range resolution, which is derived from the bandwidth of the window. In [50], the angle of the target is mapped by calculating the frequency at which the maximum change in reflection occurs. In both cases, the range is determined by inverse-Fourier-transform. I propose that the directivity of the antenna can be used to window the received reflection in the frequency domain in order to achieve angular resolution limited by the beam angle and depth resolution limited by the dispersion of the antenna. In this way, the spatial mapping can be expressed as,

$$A(\theta, d) = \mathcal{F}^{-1}(D^2(\theta, f) \cdot S_{11}), \quad (7.1)$$

where $A(\theta, d)$ is the 2D radar mapping and $D(\theta, f)$ is the antenna directivity.

In Fig. 7.1(a), an example S_{11} measurement is shown with the corresponding measured reflection in Fig. 7.1(b), this value is multiplied by the radiation pattern shown in Fig. 6.7(b) and the inverse Fourier transform is applied to form the range map for each angle, with two angles shown in Fig. 7.1(c), which when applied to all angles results in the 2D mapping in polar coordinates as shown in Fig. 7.1(d).

Based upon this approach the angular and depth resolutions are estimated based on the antenna's radiation pattern. In Fig. 7.2(b), the depth resolution is calculated from the 3-dB bandwidth, BW, at each angle with the equation as per depth resolution of an OCT system [361],

$$\Delta z = \frac{2\ln 2}{\pi} \frac{c}{\text{BW}(1 - \frac{\text{BW}^2}{4f_c^2})}. \quad (7.2)$$

And when the fractional bandwidth available at each angle is limited this can be further simplified to,

$$\Delta z = \frac{2\ln 2}{\pi} \frac{c}{\text{BW}}. \quad (7.3)$$

In order to achieve the finest possible angular resolution, the frequencies propagated in each direction must be unique such that they can be distinguished from all other angles. In other-words, frequency provides a one-to-one mapping to angle. Conversely, to achieve the best possible depth resolution, the entire available bandwidth should be directed uniformly across the field of view, as broad bandwidth is required to distinguish between subtle differences in time delay. This is a fundamental limitation of leaky-wave radar; a direct and unavoidable tradeoff between angular and depth resolution. I attempt to quantify this trade-off by analysing the cross-correlation between received signals to retrieve an intuitive definition of the angular resolution of the system. In Fig. 7.2(a), the similarity matrix of the radiation pattern is depicted, defined as,

$$\rho_{\theta_i \theta_j} = \frac{\sum_{f_k} D(f_k, \theta_i) \cdot D(f_k, \theta_j)}{\sqrt{\sum_{f_k} D(f_k, \theta_i)^2} \sqrt{\sum_{f_k} D(f_k, \theta_j)^2}}, \quad (7.4)$$

where a strong correlation between signals when $i \neq j$ implies poor distinguishability and hence poor angular resolution. From this, the angular resolution is defined as the range of angles for which the correlation between the centre angle and adjacent angles exceeds 0.5, as highlighted in Fig. 7.2(a). In Fig. 7.2(b), I compare the depth and angular resolution and observe their inverse relationship, postulating that the product of the depth and angular resolution as shown in Fig. 7.2(c) should be approximately constant, approaching a theoretical limit in the operating region of the antenna.

To quantify the interrelation between depth and angle resolution, first consider the frequency scanning behaviour as a linear relationship between the angle of transmission θ and the central frequency, f_c such that,

$$f_c = (\theta - \theta_{f_{\text{Min}}}) \frac{df_c}{d\theta} + f_{\text{Min}}, \quad (7.5)$$

where $\frac{df_c}{d\theta}$ is the rate at which the central frequency changes with respect to beam angle. In actuality, this relationship is implicit in Eq. 6.1 for small angles, though as observed in Fig. 6.2, the relationship over this frequency range is approximately linear. Then, the radiation pattern of the antenna is approximated such that at each angle it is a unity-amplitude Gaussian in the frequency domain with width w_0 such that the FWHM is equal to the channel bandwidth BW, then,

$$D(\theta, f) = \exp\left(-\frac{1}{2} \frac{(f - f_c)^2}{w_0^2(\theta)}\right), \quad (7.6)$$

where,

$$w_0 = \frac{\text{BW}}{2\sqrt{2\ln 2}}. \quad (7.7)$$

Then, assuming a constant beam width with respect to centre frequency, the directivity at one angle can be expressed as the directivity at any other angle, with the centre frequency shifted such that,

$$D(\theta_i, f) = D(\theta_j, f + \Delta f_c). \quad (7.8)$$

Then, the similarity between the radiation pattern at any two angles, θ_i and θ_j is contained within the auto-correlation function of $D(\theta_i, f)$, denoted as $D(f) \star D(f)(\Delta f_c)$, which can be calculated as,

$$D(f) \star D(f)(\Delta f_c) = \int D(f) D(f + \Delta f_c) df, \quad (7.9)$$

where Δf_c then comes to represent the difference in centre frequency between any two angles. Continuing by expanding Eq. 7.9,

$$\begin{aligned} D(f) \star D(f)(\Delta f_c) &= \int \exp\left(-\frac{1}{2} \frac{f^2}{w_0^2}\right) \exp\left(-\frac{1}{2} \frac{(f + \Delta f_c)^2}{w_0^2}\right) df, \\ &= \exp\left(-\frac{1}{2} \frac{(f + \Delta f_c)^2}{(\sqrt{2}w_0)^2}\right). \end{aligned} \quad (7.10)$$

From here, the full width at half maximum, which is defined as the boundary for similarity, can be easily extracted from the auto-correlation as it is similarly a Gaussian function,

$$\text{FWHM}(f_c) = \sqrt{2} \text{BW}. \quad (7.11)$$

This can be interpreted as the distance from the central frequency required to reduce the auto-correlation to less than 0.5. Hence, by inverting Eq. 7.5, this expression can be linked to the angular resolution, whereby the received signals at each angle are sufficiently distinguishable from adjacent angles. Re-writing this in terms of scanning angle yields an equation linking the bandwidth to the angular resolution $\Delta\theta$,

$$\Delta\theta = \frac{d\theta}{df_c} \sqrt{2} \text{BW}. \quad (7.12)$$

Finally, as the depth and angular resolution can both be derived from the bandwidth and central frequency, it is natural to combine them. Then, by combining Eq. 7.3 and Eq. 7.12, when the channel bandwidth is sufficiently small, the product of the depth and angular resolutions becomes,

$$\Delta z \Delta\theta = \frac{2\sqrt{2}\ln 2}{\pi} \frac{d\theta}{df_c} c, \quad (7.13)$$

or, consider this condition in terms of device bandwidth and field of view,

$$\Delta z \Delta\theta = \frac{2\sqrt{2}\ln 2}{\pi} \frac{\text{FOV}_{\text{LWA}}}{\text{BW}_{\text{LWA}}} c. \quad (7.14)$$

This intuitive result implies that, in order to achieve the best possible resolution product, the ratio of bandwidth to field-of-view should be maximised, and so the only way to expand the field-of-view without degrading the resolution is to simultaneously increase the operating bandwidth.

Here I arrive at a consistent but stricter limitation for the depth-angle uncertainty than previously presented [51], as I apply a more-stringent depth resolution criterion and consider the differentiability of each angular component from the broadband signal. I note that the presented condition is still the best achievable value under ideal leaky-wave frequency scanning, as variable bandwidth, non-linear frequency scanning, non-Gaussian gain profiles, and the presence of side lobes all degrade the performance. In Fig. 7.2(b-c), I observe the impact of these effects by comparing the theoretical values derived here to measured values. I postulate that the presence of side lobes in the antenna radiation pattern is the primary cause of this difference as these effects are not accounted for under ideal conditions.

7.3 Multi-Target Tracking

The most elementary application of a terahertz radar module is for the detection and ranging of objects. In contrast to a microwave radar, the shorter wavelength enables the detection of small objects, while maintaining the ability to penetrate some common obstructions such as plasterboard or thin screens which may block monitoring with LIDAR or an ordinary camera. Due to the previously outlined limitations, this technique is not suitable for multi-layer imaging of fine structures typically associated with terahertz technologies. The system is shown in Fig. 7.3, and is comprised of the aforementioned leaky-wave antenna coupled to the calibrated VNA with attached VNAX transceiver module. The VNA performs a continuous 1001 point frequency sweep across the 220–330 GHz band at

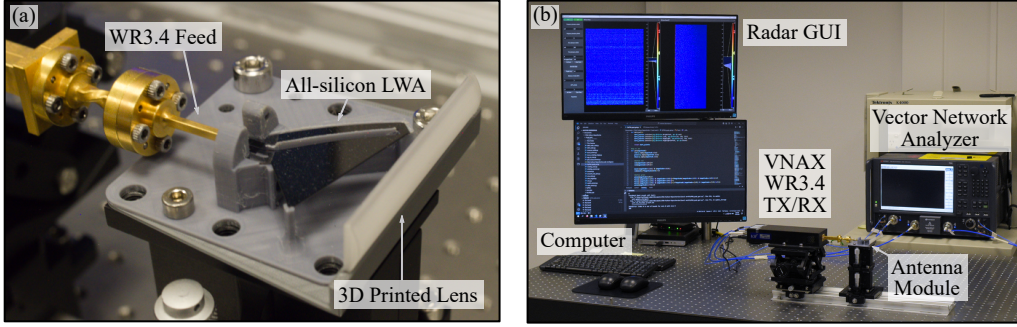


Figure 7.3: Overview of leaky-wave radar system. (a) Photograph of all-silicon leaky-wave antenna, packaged with 3D-printed COC lens and coupled to WR3.4 waveguide. (b) Annotated photograph of laboratory system.

a rate of approximately 15 Hz. The IF bandwidth of this sweep is 100 kHz. Radar data processing as described in Section 7.2 is performed on the computer using Python code, and is displayed in real-time on the GUI. Here, I produce a simple system demonstration; tracking multiple moving targets simultaneously. As shown in Fig. 7.4(a), 4 metallic optical posts with diameter of 12 mm are placed on a rotating stage at varying radii from the rotation centre. Then measurements are made continuously through a full 360° range of motion, with speeds ranging from 0.5° to 10° per second. This demonstrates suitability for real time tracking. In Fig. 7.4(b–e), a selection of the single-shot frames captured throughout the rotation show that, throughout the scan, multiple objects at various depths and angles can be simultaneously resolved clearly. To quantify the localisation accuracy, a 2D peak finding algorithm is applied to each frame to find the position of each post, and the positions determined are shown in Fig. 10(f–g). In Fig. 10(h), this information is used to calculate the localisation error of each post. The error is dependent on the angular position of the post, with higher errors at the edge of the field of view, in line with the angular resolution calculated in Fig. 7.2(b). Within the 3-dB field-of-view, the localisation error is below the diameter of the post, but beyond this range, the localisation accuracy is degraded due to the effect of image smearing as the linear relationship between angle and frequency breaks down. Finally, the mean and standard deviation of the error are calculated at various motor speeds, up to the limit of our rotation stage, showing only a small increase in error at these low velocities. To accompany this demonstration, I supply a video showing real-time tracking of an optically obscured object, visible in Supplementary Material 1 of [170]. In this video, an optical post is hidden behind a sheet of paper. In this case both the obstruction and the optical post can be localised.

7.4 Liquid Sensing

A second potential application is in a front-line test for the differentiation of liquids that appear identical under visual inspection or are obscured by an opaque container. In contrast to common chemical analysis this technique is non-destructive, and as the radiation is non-ionizing this technique can be applied without the need for shielding. Reflectometry is a common technique for quickly differentiating liquids based upon contrast in their reflection or transmission characteristics. Here, I apply this technique qualitatively to mixtures of two common liquids [321, 362, 363]; ethanol, $n_{\text{Ethanol}} = 1.70 - 0.21j$, and water, $n_{\text{Water}} = 2.52 - 1.11j$ contained within High Density Polyethylene (HDPE) film canisters [364], $n_{\text{HDPE}} = 1.53$. Without the depth resolution to distinguish the reflection from the air-HDPE interface from the HDPE-liquid interface, the measured amplitude must be considered as the sum of the two individual reflections from each surface. In line with previous work on this topic [171, 321, 362, 363] I model the normalised reflection magnitude as,

$$\frac{E_R}{E_0} = |\rho_{0,\text{HDPE}}| + |\tau_{0,\text{HDPE}}\tau_{\text{HDPE},0}\rho_{\text{HDPE},\text{Sample}}|, \quad (7.15)$$

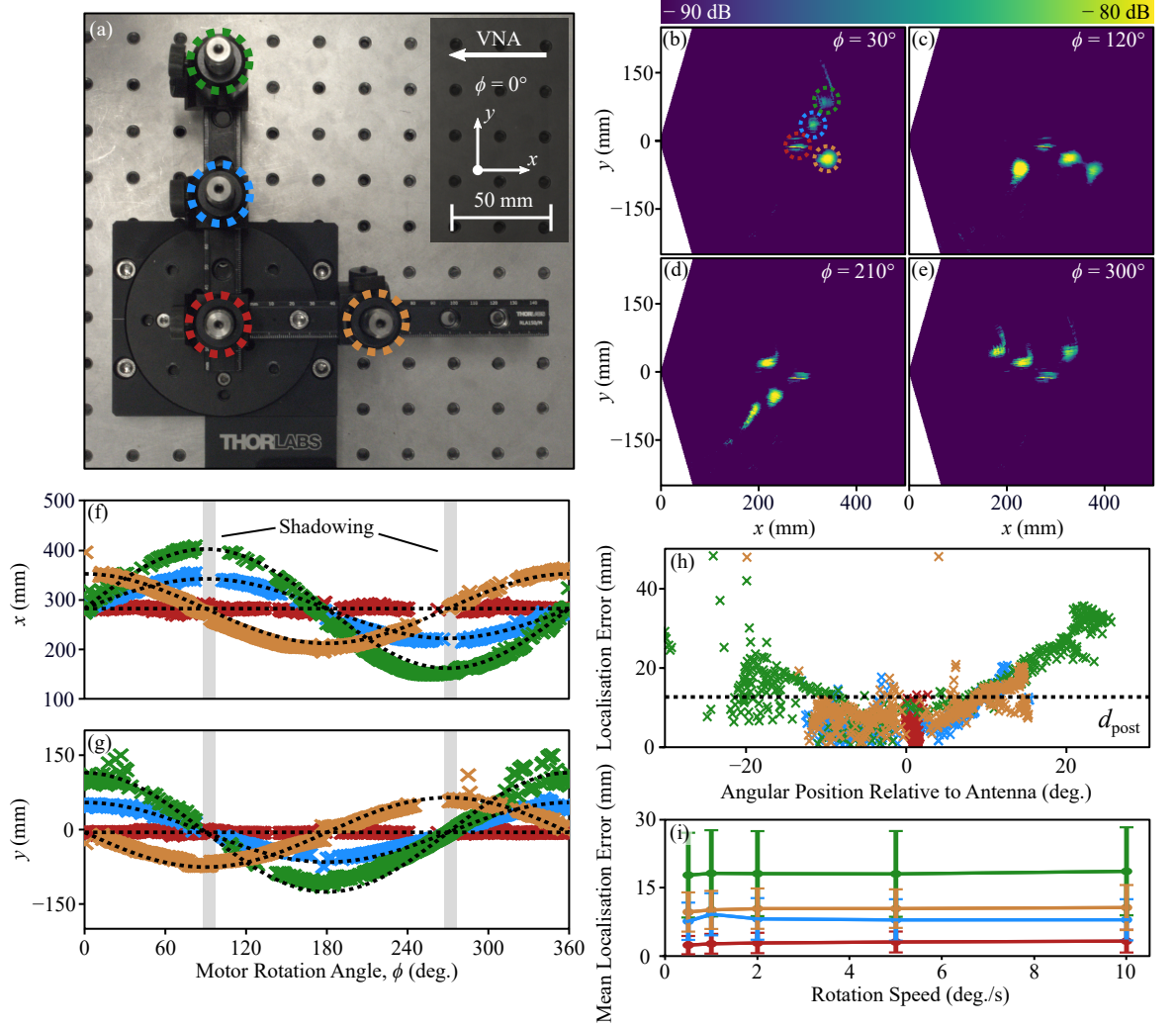


Figure 7.4: Demonstration of multi-object tracking with leaky-wave radar. (a) Experimental setup for demonstration of multi-object tracking. (b–e) Recovered reflection profiles obtained in real time as the posts are rotated around a common axis, where ϕ is the rotation stage angle. (f–g) x and y coordinates of each post, recovered from the radar data using a 2D peak finding algorithm. Black dashed lines represent the actual position of the posts, determined by their known radius and angle. Discontinuities in the measured data occur where a post is shadowed by another post. (h) Error between the recovered and actual positions. I note that this dependency on angle is consistent with the angular resolution determined in Fig. 9(b). (i) Position error with increasing motor speeds, noting that for the measured speeds the error is unchanged.

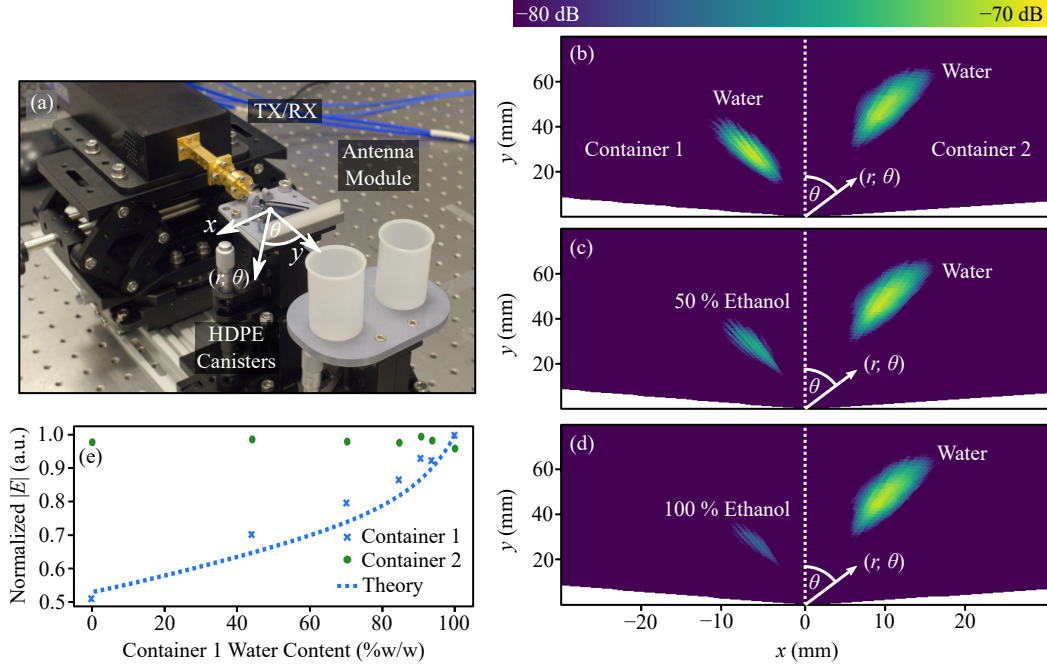


Figure 7.5: Demonstration of liquid differentiation with leaky-wave radar. (a) Experimental setup for demonstration of ability to differentiate between in container liquids. (b) Reflection profile of two HDPE containers, both containing water. (c) Reflection profile when one container contains a 50%v/v ethanol solution and the other contains water. (d) Reflection profile when one container contains ethanol and the other contains water. (e) The peak amplitudes of each container as the water/ethanol proportion of Container 1 is varied.

where the first term represents the reflection from the air-HDPE interface at the outer surface of the container, and the second term the reflection from the inside surface of the container. The Fresnel coefficients $\rho_{i,j}$ and $\tau_{i,j}$ are the Fresnel reflection and transmission coefficients respectively calculated as,

$$\rho_{i,j} = \frac{\hat{n}_i - \hat{n}_j}{\hat{n}_i + \hat{n}_j}, \quad \tau_{i,j} = \frac{2\hat{n}_i}{\hat{n}_i + \hat{n}_j}. \quad (7.16)$$

I assume that the loss from transmission through the thin HDPE is negligible and ignore the curvature of the container. I model the aqueous ethanol solutions with an empirically derived triple Debye model [363]. To determine the maximum sensitivity of our system, various mixtures of ethanol and water are measured. As shown in Fig. 7.5(b-d), one container is filled with pure water, while the second container is filled with various mixtures of water and ethanol. The ethanol proportion is varied non-linearly to assess the minimum step size that can be differentiated with steps from 50% to 2.5% by volume. In Fig. 7.5(e) the results of this measurement are presented. Container 1 contains water (green marks), while Container 2 contains various ethanol-water mixtures (blue marks). These results are normalised to the maximum amplitude observed. I observe experimental results in line with Eq. 7.17 and a minimum differentiable step of 5%. With further calibration I believe this result could be improved.

7.5 Vibrometry on Multiple Targets

Due to the speed of acquisition, I propose that a niche where leaky-wave radar may be advantageous is the monitoring of time-varying systems, such as object tracking or vital sign monitoring, where the angular resolution is not as critical as in applications such as security screening. Previously, a leaky-wave radar was used to monitor a single target over time [50], I seek to extend this ability to monitor multiple targets simultaneously. To this end, I present a proof of concept demonstration, using a leaky-wave antenna to monitor the time-varying reflection of two targets simultaneously.

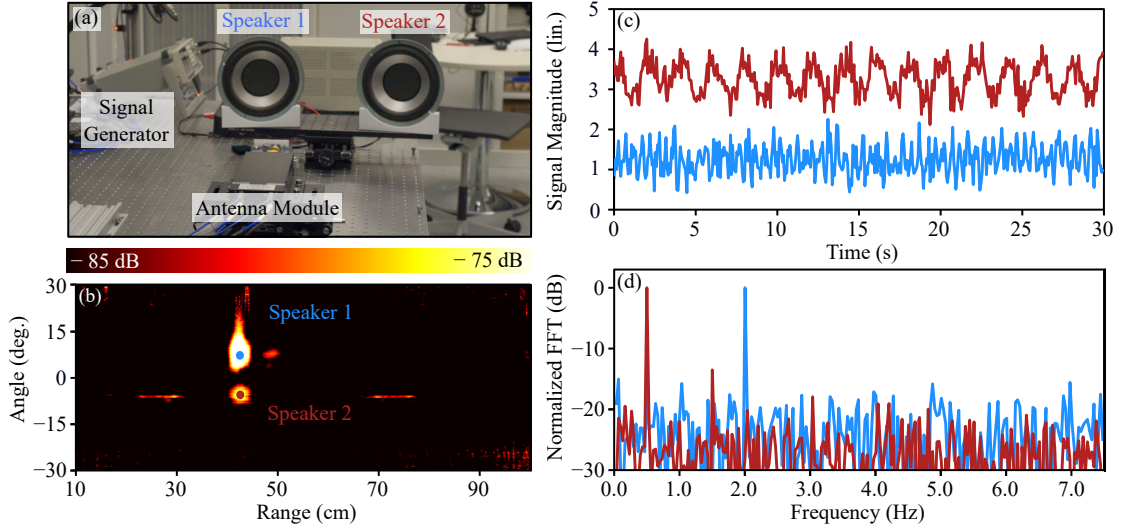


Figure 7.6: Simultaneous monitoring of time-varying targets with leaky-wave radar. (a) Photograph of the experimental setup, showing the antenna module facing towards two speakers. (b) Recovered angle-depth map of the scene. (c) Trace of the signal over time at the two angles of interest. (d) Fast-Fourier transform of (c) showing that the source of the two signals can be discriminated.

As a proof-of-concept, I arrange two speakers, fed independently by two channels of a signal generator as targets. As shown in Fig. 7.6(a), the speakers are placed 40 cm in front of the antenna module, and are separated by 35 cm. The measurement procedure described in Section 7.1 is performed, and the scene in Fig. 7.6(b) is recovered, showing the two targets at the expected 40 cm from the antenna. As an example, I feed one speaker with a 0.5 Hz sinusoid and the other with a 2 Hz sinusoid, then monitor these signals continuously over a 30-second period at the aforementioned rate of 15 samples per second with the leaky-wave radar, with the time domain response in Fig. 7.6(c), showing the reproduced sinusoidal signals. The FFT of these two signals is produced in Fig. 7.6(d), showing signal-to-noise ratios on the order of 20 dB, and the expected 0.5 Hz and 2 Hz frequency peaks.

I present a proof-of-concept demonstration for the monitoring and localisation of time-varying signals, arriving from multiple targets with leaky-wave radar despite limited angular and depth resolution. Moving forward, this work should be expanded to assess the feasibility of remotely detecting vital signs on human targets, where movement and the irregular shape of the torso will further degrade the signal-to-noise ratio. Additionally, though typically the breath cycle is approximately sinusoidal and does not exceed 4 Hz, for other vital signs, such as ECG or EEG, where the pulse shape is more complex, the sample rate will need to be improved for accurate signal recreation. One method for achieving this is through the use of more coarse sweeps once a vibrating target is found, this will allow for faster acquisition. In the case where the range of the target is not of interest, single tones corresponding to the specific angle of arrival can be used to further reduce the data acquisition time.

7.6 Conclusion

Leaky-wave radar is a viable technique for the short range monitoring of a scene in real time owing to its millisecond scale scene acquisition time. This rapid acquisition comes at the cost of depth and angular resolution, in both respects it is deficient when compared to state-of-the-art mechanically steered systems. The analysis here stipulates that this is due to the interrelation between field-of-view, operating frequency, depth, and angular resolution. Critically, I propose that the depth-angle resolution product can only be improved by reducing the field of view or by increasing the operating bandwidth. Owing to these factors, the use cases for leaky-wave radar is not a direct substitute for mechanically steered systems, but is best used for tracking multiple targets in real-time, as demonstrated experimentally here, where multiple small targets can be observed in real-time. More generally, similar analysis could

be applied to other systems which employ leaky-wave antennas, critically to communication systems, where an analogous derivation for the relationship between antenna factors and carrier capacity may be possible.

Chapter 8

Terahertz Swept Source Coherence Tomography

Abstract

For on-site measurements, large, expensive, conventional terahertz pulse time domain systems for non-destructive evaluation will potentially be superseded by compact electronic-based terahertz systems. However, common incoherent electronic detectors are not capable of detecting the phase of received signals, complicating the characterisation of multilayer samples. I propose a practical method for the characterisation of in-container liquid samples using swept-source terahertz coherence tomography in reflection configuration. I demonstrate this technique in the 220–330 GHz frequency band to quantify the principal components of common alcoholic beverages, namely, water, sugar, and ethanol, with sensitivity to ethanol concentration below 0.4%v/v, whilst simultaneously recovering information about the container. Additionally, the method allows real-time observation of dilution in the mixtures. The proposed method facilitates measurement with significantly reduced experimental overhead and critically, is compatible with incoherent terahertz cameras for quantitative imaging.

8.1 Introduction

In recent years, terahertz non-destructive evaluation has received significant interest from industry for its suite of advanced applications including, security screening [365], biomedical imaging [32], analysis of pharmaceutical products [366], agricultural inspection [367], and even archaeology [368]. To this end, terahertz time-domain spectroscopy (THz-TDS) has been the regularly employed [369], driven by ultra-short lasers these systems are capable of measuring time-resolved responses over exceptionally broad frequency bands, yielding high spatial and depth resolution for sub-millimetre multi-layer applications [36, 370, 371]. Additionally, the application of the Fourier transform also facilitates frequency domain analysis, with the unique spectral signatures of materials over broad bandwidths offering simple contrast mechanisms for frequency domain imaging [372]. However, as widespread adoption of terahertz technologies approaches, the cost and complexity of these laser-based systems becomes prohibitive for portable applications.

To address these hindrances, integrated semiconductor technologies have emerged as a competitive alternative, with a range of bolometers [373], photo-diodes [374], resonant tunnelling diodes [72, 375], and Schottky diodes [183, 376] acting as versatile, compact terahertz sources and detectors. Complimentary to this, recent advances in terahertz CMOS have facilitated the integration of bolometers [377] or field effect transistors [56, 378] into vast detector arrays to realise terahertz cameras capable of real-time imaging with practical resolutions [379, 380]. These incoherent cameras motivate the development of new data processing techniques capable of recovering crucial depth information without the presence

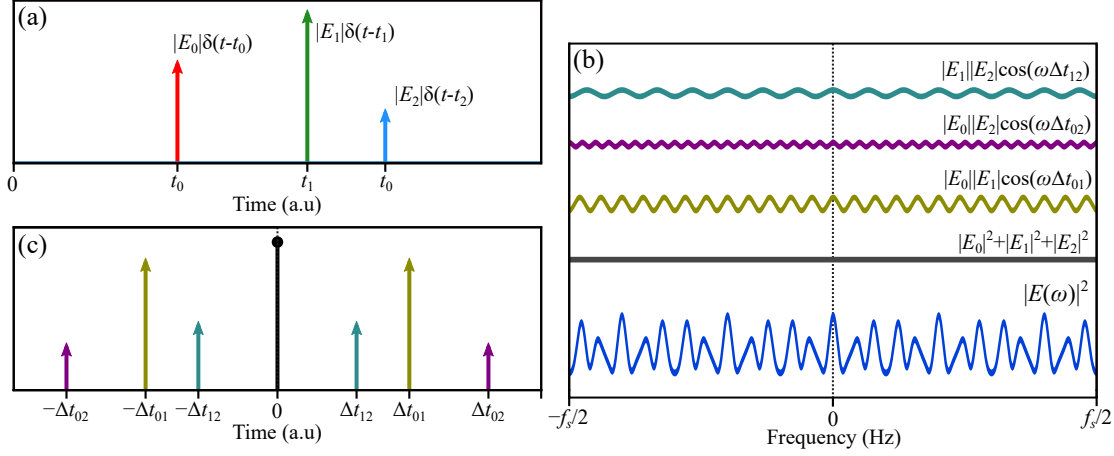


Figure 8.1: Visualisation of the band-unlimited profile in the time domain arising from a series of 3 interfaces, demonstrating the mathematical foundations of optical coherence tomography. (a) Series of 3 Dirac-Delta functions in the time domain, analogous to the reflection from a series of Fresnel interfaces under illumination by a band-unlimited pulse as described in Eq. 8.1. Only the primary reflections are considered. (b) Magnitude of Fourier transform of (a) as described in Eq. 8.3, $|E(\omega)|^2$, decomposed into its principal components, revealing a series of cosine functions in the frequency domain with phase determined by the time delay between Dirac-Delta functions in (a). (c) Inverse-Fourier transform of $|E(\omega)|^2$ as described in Eq. 8.4, highlighting the recovered Dirac-Delta functions

of the phase information.

In optics, such phase-less analysis is commonly implemented through coherence tomography [381–384] or other interferometric techniques. In the terahertz domain, demonstrations of coherence tomography can be divided into two categories, time-domain, and frequency-domain coherence tomography. The first utilises a phase-varied reference path and a narrow-band source to produce an interference profile over a range of phase delays. Then, this profile can be used to recover the depth profile of the target [385]. Alternatively, a fixed phase delay can be implemented and instead, the frequency can be tuned to produce a frequency domain interference profile. Then through use of the inverse-Fourier transform the depth profile can be recovered in a technique known as swept-source optical coherence tomography [50, 386–389]. Importantly, the absence of efficient terahertz phase-shifters limits time-domain terahertz coherence tomography to mechanically tuned phase delays. Instead, focussing on frequency-domain terahertz coherence tomography, where a swept-frequency source and incoherent detector array could instead be used to realise a compact non-destructive evaluation module, without the need for mechanical or electrical actuation. Further, in the past the focus of such systems has been for imaging, here I extend the analysis to quantifying the component proportions of the sample under examination, making the monitoring and evaluation of multi-layer samples feasible without a large laser-based system.

I propose a technique based on swept-source optical coherence tomography combined with Fresnel analysis for extracting key information from multi-layer systems. This technique only requires measurement of reflection magnitude in the frequency domain with a frequency-tunable terahertz source. Section 8.2 provides an illustrative derivation of the Fresnel model of a simple reflectometer. In Section 8.3 this technique is applied experimentally in the 220–330 GHz band, to the inspection of aqueous ethanol solutions in-container to demonstrate the sensitivity of the system and comparable performance to a common phase sensitive technique.

8.2 Sample Characterisation with Frequency-Domain Terahertz Coherence Tomography

8.2.1 General concept of Swept-Source Terahertz Coherence Tomography

Frequency-domain coherence tomography refers to the process of extracting depth and material information about target from the absolute value of the frequency domain signal. To outline this method, first consider a band-unlimited profile in the time domain arising from a series of N interfaces, results in a finite sum of Dirac-Delta functions with amplitude $|\hat{E}_i|$ at time step t_i , where t_i encapsulates the phase due to propagation, as depicted in Fig. 8.1(a),

$$\hat{E}(t) = \sum_{i=0}^{N-1} |\hat{E}_i| \delta(t - t_i) . \quad (8.1)$$

This equation neglects the phase responses at the interfaces for simplicity. Then consider $\hat{E}(\omega)$, the Fourier-transform of $\hat{E}(t)$,

$$\hat{E}(\omega) = \sum_{i=0}^{N-1} \hat{E}_i(\omega) = \sum_{i=0}^{N-1} |\hat{E}_i| \exp(-j\omega t_i) . \quad (8.2)$$

With knowledge of the complex spectrum, the inverse-Fourier transform can be applied to provide a direct mapping between the frequency and time domains, with each sinusoidal component in the frequency domain corresponding to a Dirac delta function in the time domain. However, if only the magnitude of this spectrum is measured, then such a direct Fourier mapping does not exist. Alternatively, important information can still be recovered from the inverse-Fourier transform of the magnitude spectrum. To demonstrate this, first, the closed form of the magnitude spectrum can be derived from Eq. 8.2 as,

$$|\hat{E}(\omega)|^2 = \sum_{i=0}^{N-1} |\hat{E}_i|^2 + 2 \sum_{i=1}^{N-1} \sum_{j=0}^{i-1} |\hat{E}_i| |\hat{E}_j| \cos(\omega \Delta t_{ij}) , \quad (8.3)$$

where Δt_{ij} is the time difference between peak i and peak j . This is visually described in Fig. 8.1(b). Then applying the inverse Fourier transform to Eq. 8.3,

$$\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\} = \delta(t) \sum_{i=0}^{N-1} |\hat{E}_i|^2 + 2 \sum_{i=1}^{N-1} \sum_{j=0}^{i-1} |\hat{E}_i| |\hat{E}_j| \delta(t \pm \Delta t_{ij}) . \quad (8.4)$$

This result can be decomposed into two groups of components, first each physical interface contributes to the peak measured at $t = 0$ and second each interface pair results in a corresponding peak at the phase difference between the two reflections, $t = \Delta t_{ij}$, and with amplitude, $2|\hat{E}_i| |\hat{E}_j|$, twice the product of the two generating interfaces. In other words, any pair of reflections interfere with each other and gives rise to a new peak as shown in Fig. 8.1(c). In practice, Gaussian-like pulses are observed in place of Dirac delta functions in the time domain and hence the ability to distinguish between adjacent peaks is limited by the width of the received pulse, as determined by the operating bandwidth of the system. This constraint is expressed by the well known optical coherence tomography axial resolution equation [381],

$$\Delta z = \frac{2 \cdot \ln 2}{\pi} \frac{c}{4n f_{\min} f_{\max}} \frac{(f_{\max} + f_{\min})^2}{f_{\max} - f_{\min}} , \quad (8.5)$$

where n is the refractive index of the medium and $f_{\min}$ and $f_{\max}$ are the lower and upper bounds of the system bandwidth respectively. These relationships provide a limited mapping between the time and frequency domains, in the absence of phase information.

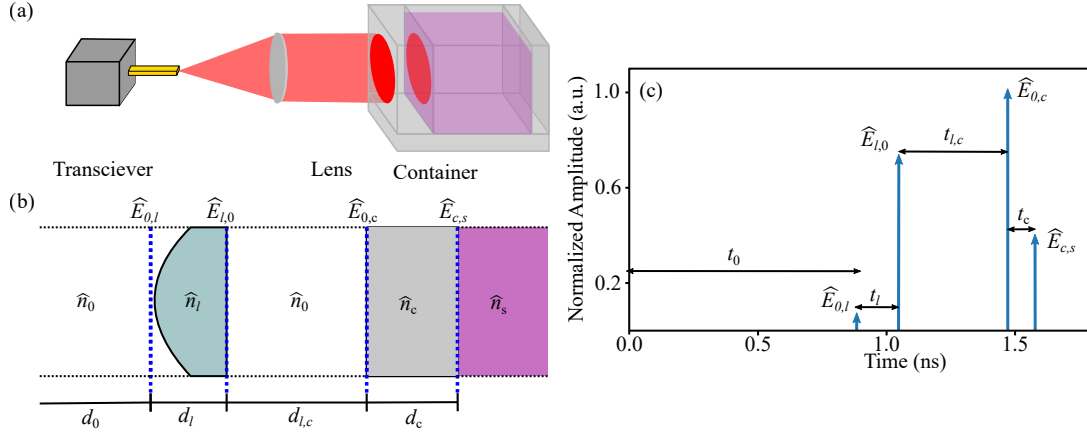


Figure 8.2: Description of the container system under analysis. (a) Simple normal incidence terahertz reflectometer consisting of a transceiver, a lens to collimate the beam, and the sample under test. (b) System described in (a) decomposed into a series of Fresnel interfaces. A plano-convex lens with refractive index, $\hat{n}_l$, and thickness, d_l is used to illuminate a liquid sample with refractive index, $\hat{n}_s$, inside a container with thickness, d_c and refractive index, $\hat{n}_c$. Generally, the distances and the refractive index of the lens and container can be obtained in advance while the refractive index $\hat{n}_s$ is to be determined through this process. (c) Time-domain signal derived from Fresnel equations with realistic variable values.

8.2.2 Characterisation of In-container Liquid with Known Phase Information

First, the relationship between material properties and reflection profile are derived through normal-incidence Fresnel analysis of the complex valued reflection profile [390]. This process is well-known [362] and summarised here only to provide some background for the optical coherence tomography process in Section 8.2.3. Consider the system described in Fig. 8.2(a,b), the reflection profile consists of four primary reflections, arising from the four interfaces, air-lens, lens-air, air-container, and container-sample.

$$\hat{E}(\omega) = \hat{E}_{0,l}(\omega) + \hat{E}_{l,0}(\omega) + \hat{E}_{0,c}(\omega) + \hat{E}_{c,s}(\omega) . \quad (8.6)$$

Interfaces past the sample can be ignored under the assumption that the sample is sufficiently absorptive, and sufficiently thick. In this illustrative analysis, secondary reflections are ignored, though I note that their inclusion does improve model accuracy. Further, it is presumed that the curvature of the nominally convex face of the lens is negligible, and instead assume normal incident conditions. Given that the lens is located at distance, d_0 , from the transceiver these components can be expressed as,

$$\hat{E}_{0,l}(\omega) = \hat{E}_0(\omega) \rho_{0,l} \exp(-2jk_0 d_0 \hat{n}_0) , \quad (8.7a)$$

$$\hat{E}_{l,0}(\omega) = \hat{E}_0(\omega) \tau_{0,l} \rho_{l,0} \tau_{l,0} \cdot \exp(-2jk_0(d_0 \hat{n}_0 + d_l \hat{n}_l)) ,$$

$$\hat{E}_{0,c}(\omega) = \hat{E}_0(\omega) \tau_{0,l}^2 \tau_{l,0}^2 \rho_{0,c} \cdot \exp(-2jk_0(d_0 \hat{n}_0 + d_l \hat{n}_l + d_{l,c} \hat{n}_0)) ,$$

$$\hat{E}_{c,s}(\omega) = \hat{E}_0(\omega) \tau_{0,l}^2 \tau_{l,0}^2 \tau_{0,c} \rho_{c,s} \tau_{c,0} \cdot \exp(-2jk_0(d_0 \hat{n}_0 + d_l \hat{n}_l + d_{l,c} \hat{n}_0 + d_c \hat{n}_c)) .$$

Here, $\hat{E}_0$ is the input signal and ρ and τ are the normal-incidence Fresnel coefficients at the relevant interfaces given by the proceeding equations,

$$\rho_{0,l} = \frac{\hat{n}_0 - \hat{n}_l}{\hat{n}_0 + \hat{n}_l} \quad (8.8a)$$

$$\rho_{l,0} = \frac{\hat{n}_l - \hat{n}_0}{\hat{n}_l + \hat{n}_0} \quad (8.8b)$$

$$\rho_{0,c} = \frac{\hat{n}_0 - \hat{n}_c}{\hat{n}_0 + \hat{n}_c} \quad (8.8c)$$

$$\rho_{c,s} = \frac{\hat{n}_c - \hat{n}_s}{\hat{n}_c + \hat{n}_s} \quad (8.8d)$$

$$\tau_{0,c} = \frac{2\hat{n}_0}{\hat{n}_0 + \hat{n}_c} \quad (8.8e)$$

$$\tau_{c,0} = \frac{2\hat{n}_c}{\hat{n}_0 + \hat{n}_c} \quad (8.8f)$$

$$\tau_{0,l} = \frac{2\hat{n}_0}{\hat{n}_0 + \hat{n}_l} \quad (8.8g)$$

$$\tau_{l,0} = \frac{2\hat{n}_l}{\hat{n}_0 + \hat{n}_l} . \quad (8.8h)$$

Hence, from the ratio of Eqs. 8.7(c) and 8.7(d), so long as only $\hat{n}_s$ is unknown, the reflection coefficient, $\rho_{c,s}$ and complex refractive index, $\hat{n}_s$, can be determined as,

$$\rho_{c,s} = \frac{\hat{E}_{c,s}}{\hat{E}_{0,c}} \frac{\rho_{0,c}}{\tau_{c,0}\tau_{0,c}} \exp(2jk_0 d_c \hat{n}_c) . \quad (8.9)$$

$$\hat{n}_s = \hat{n}_c \frac{1 - \rho_{c,s}}{1 + \rho_{c,s}} , \quad (8.10)$$

where $\hat{E}_{c,s}$ and $\hat{E}_{0,c}$ can be isolated from the complex frequency-domain spectrum through time gating as described previously. The equation above allows us to accurately calculate the complex frequency-dependent refractive index of the sample, given that complex refractive index of the container is known a priori.

8.2.3 Characterisation from Absolute Reflections Spectrum (Swept-Source Terahertz Coherence Tomography)

Estimation of sample properties

In conventional implementations of coherent tomography, a reference path and Mach-Zehnder interferometry is used to gauge absolute distances [385]. However, for applications where only the thickness or material properties are of interest this is ‘absolute’ range from the receiver is superfluous information, and the ‘relative’ distance from the inverse-Fourier-transform can be used to characterise the desirable information. Next, it is demonstrated that part of this information can be recovered from only the amplitude of this spectrum. Through Eq. 8.4 I observe that, the desirable reflections, $|\hat{E}_{0,c}|$ and $|\hat{E}_{c,s}|$, can be recovered from the amplitude spectrum as,

$$\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{0,c}|l,0} = 2|\hat{E}_{l,0}||\hat{E}_{0,c}| , \quad (8.11)$$

$$\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{c,s}|l,0} = 2|\hat{E}_{l,0}||\hat{E}_{c,s}| . \quad (8.12)$$

Such that,

$$\frac{|\hat{E}_{c,s}(t)|}{|\hat{E}_{0,c}(t)|} = \frac{\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{c,s}|l,0}}{\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{0,c}|l,0}} . \quad (8.13)$$

Eq. 8.13 can be used to recover the refractive index as in Eq. 8.9 and 8.10. I note that through analysis of the magnitude spectrum, only the amplitude of the reflected peaks are recovered such that,

$$|\rho_{c,s}| = \frac{|\hat{E}_{c,s}|}{|\hat{E}_{0,c}|} \frac{|\rho_{0,c}|}{|\tau_{c,0}||\tau_{0,c}|} |\exp(2jk_0 d_c \hat{n}_c)| = \frac{|\hat{n}_s - \hat{n}_c|}{|\hat{n}_s + \hat{n}_c|} . \quad (8.14)$$

Through Eq. 8.14 alone, a direct mapping to refractive index of the sample, $\hat{n}_s$ is not possible without further assumptions. For example, in the case that both container and the sample have negligible absorption, i.e., $n_s \gg \kappa_s$ and $n_c \gg \kappa_c$, then the equation becomes invertible such that,

$$\hat{n}_s = \hat{n}_c \frac{1 - |\rho_{c,s}|}{1 + |\rho_{c,s}|} . \quad (8.15)$$

Though, in practice this assumption is not widely applicable. However, for practical applications the knowledge of the innate refractive index is not important so long as a robust correlation between reflection coefficient, $|\rho_{c,s}|$ and mixture content can be empirically developed as is common in near-infrared or mid-infrared spectroscopy [391–393].

Estimation of container properties

Finally, the only prerequisite is knowledge of the container refractive index, $\hat{n}_c$, and thickness, d_c . In practice, the refractive index of most common container materials could be readily catalogued, and a thickness measurement can be readily obtained. Nevertheless, a viable estimate of the container properties can be derived from the sample measurement itself. To develop this information, the interference between the fixed optic and the air-container reflections can be used. The magnitude of the container reflection coefficient, $|\rho_{0,c}|$, is derived from Fresnel analysis, from Eqs. 8.7(b) and 8.7(d) such that,

$$|\rho_{0,c}| = \frac{|\rho_{0,l}|}{|\tau_{0,l}|^2 |\tau_{l,0}|^2} \frac{|\hat{E}_{0,c}|}{|\hat{E}_{l,0}|} = \frac{|\hat{n}_c - \hat{n}_0|}{|\hat{n}_c + \hat{n}_0|}, \quad (8.16)$$

where,

$$\frac{|\hat{E}_{0,c}(t)|}{|\hat{E}_{l,0}(t)|} = \frac{\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{c,s|0,c}}}{\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{l,0|c,s}}}. \quad (8.17)$$

Then, assuming the container material is dispersion-less and given the container thickness, d_c , is known, the real component of n_c can be estimated from the location of the interference peak arising from the container.

$$\mathcal{R}(\hat{n}_c) = \frac{c\Delta t_{c,0|c,s}}{2d_c}. \quad (8.18)$$

Then from Eq. 8.16,

$$\mathcal{I}^2(\hat{n}_c) = \frac{(\mathcal{R}^2(\hat{n}_c) - 1)(|\rho_{0,c}|^2 - 1) + 2\mathcal{R}(\hat{n}_c)(|\rho_{0,c}|^2 + 1)}{1 - |\rho_{0,c}|^2}. \quad (8.19)$$

Unlike the sample index, these complex properties of the container can be estimated from the amplitude-only data, because the information of the wave traversing and being reflected from the container is fully available.

Impact of Secondary Reflections

In the previous sections only the primary reflections are considered, though secondary reflections can be observed in the time domain spectrum at a delay corresponding to the thickness of the container plus the round trip distance between the lens and the container. While the magnitude of these reflections is small, their impact can be observed in Fig 8.7, where the swept-source terahertz coherence tomography measurements are systematically reduced in comparison to the complex spectrum analysis. Through Fresnel analysis these reflections are described as,

$$\hat{E}_{0,c,l,c}(\omega) = \hat{E}_{0,c}(\omega)\rho_{0,l}\rho_{0,c}\exp(-2jk_0d_{l,c}\hat{n}_0), \quad (8.20a)$$

$$\hat{E}_{c,s,l,c}(\omega) = \hat{E}_{c,s}(\omega)\rho_{0,l}\rho_{0,c}\exp(-2jk_0d_{l,c}\hat{n}_0), \quad (8.20b)$$

Then the peak at $t = \Delta t_{l,0|0,c} = 2d_{l,c}/c$ is expanded due to the interference from these secondary peaks, from Eq. 8.13 this is derived as,

$$\begin{aligned} \mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{l,c}/c} &= \mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{l,0|0,c}} + \mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{0,c|0,c,l,c}} + \mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{c,s|c,s,l,c}} \\ &= 2|\hat{E}_{l,0}||\hat{E}_{0,c}| + 2|\hat{E}_{0,c}||\hat{E}_{0,c,l,c}| + 2|\hat{E}_{c,s}||\hat{E}_{c,s,l,c}| \\ &= 2|\hat{E}_{l,0}||\hat{E}_{0,c}| + |\rho_{0,l}||\rho_{0,c}|(|\hat{E}_{0,c}|^2 + |\hat{E}_{c,s}|^2), \end{aligned} \quad (8.21)$$

This impacts the recovered reflection coefficient as $|\hat{E}(\omega)|^2|_{\Delta t_{l,0|0,c,s}}$ is unaffected while $|\hat{E}(\omega)|^2|_{\Delta t_{l,0|0,c}}$ is increased, and hence the reflection coefficient is suppressed. The impact of the secondary peaks is

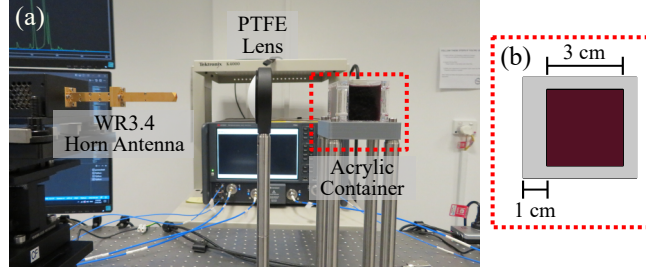


Figure 8.3: Annotated photograph of experimental setup. (a) Terahertz path containing a diagonal horn antenna attached to VDI WR3.4 extension module, a single Thorlabs PTFE LAT075 plano-convex lens, and the sample container supported by a 3D printed housing. (b) Dimensions of the PMMA sample container used throughout this work. While the system is phase-sensitive only the amplitude data is processed in this demonstration.

dependent on three factors, the refractive index of the lens and the container, which can be determined, but also the refractive index of the sample, which is not immediately determinable. To quantify the impact, I analyse the ratio of the peak with and without the inclusion of secondary reflections,

$$\begin{aligned}
 \frac{\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{l,c/c}}}{\mathcal{F}^{-1}\{|\hat{E}(\omega)|^2\}|_{\Delta t_{l,0}|_{0,c}}} &= \frac{2|\hat{E}_{l,0}||\hat{E}_{0,c}| + 2|\rho_{0,l}||\rho_{0,c}|(|\hat{E}_{0,c}|^2 + |\hat{E}_{c,s}|^2)}{2|\hat{E}_{l,0}||\hat{E}_{0,c}|} \\
 &= 1 + |\rho_{0,l}||\rho_{0,c}| \left(\frac{|\hat{E}_{0,c}|^2}{|\hat{E}_{l,0}||\hat{E}_{0,c}|} + \frac{|\hat{E}_{c,s}|^2}{|\hat{E}_{l,0}||\hat{E}_{0,c}|} \right) \\
 &= 1 + |\rho_{0,l}||\rho_{0,c}| \left(\frac{|\hat{E}_{0,c}|}{|\hat{E}_{l,0}|} + \frac{|\hat{E}_{c,s}|^2}{|\hat{E}_{l,0}||\hat{E}_{0,c}|} \right) \\
 &= 1 + |\tau_{0,l}||\tau_{l,0}|(|\rho_{0,c}|^2 + |\tau_{0,c}||\rho_{c,s}||\tau_{c,0}|^2 \exp(-4jk_0 d_c \hat{n}_c)) .
 \end{aligned} \tag{8.22}$$

Evaluating Eq 8.22 with the lens and container refractive indices used throughout this work,

$$\frac{|\hat{E}(\omega)|^2|_{\Delta t_{l,c/c}}}{|\hat{E}(\omega)|^2|_{\Delta t_{l,0}|_{0,c}}} = 1.029 + 0.41|\rho_{c,s}|^2 \tag{8.23}$$

From here, it follows that the secondary reflections lead to a systematic under-estimation of peak ratio and hence and under-estimation of reflection coefficients.

8.3 Application to In-Container Liquids

One potential application of this technique is for the monitoring of ethanol content during the fermentation, bottling, and storage of alcoholic beverages. During the production process the ethanol content is measured frequently to monitor the rate at which sugars are converted to ethanol. These routine measurements are commonly performed manually, requiring sample extraction, then either specific gravity testing, or infrared spectroscopy are used to determine ethanol concentration. In the bottling process, water is frequently used to flush pipes while switching varieties. Though, residual water leads to dilution in the end-product immediately following this flushing. To mitigate this, sample bottles are repeatedly removed to test for dilution, reducing the overall production efficiency. Here, a series of experiments are conducted, applying the previously described techniques to detect variation in ethanol content with three different sample types, aqueous ethanol solutions, ethanol-grape juice solutions, and finally dilution of wine with water. All measurements presented are the average of 40-consecutive measurements, with zero-padding, and data processing performed offline.

To verify the theoretical framework outlined in the Section 8.2.3, I apply this technique experimentally. A Keysight N5222B Vector Network Analyser equipped with VDI WR3.4 extension

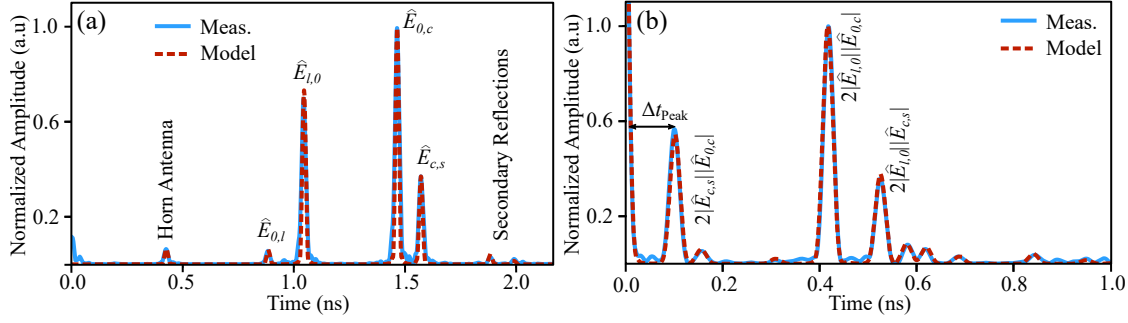


Figure 8.4: Comparison of Fresnel model to measured data for drinking water. (a) Time-domain information recovered with inverse-Fourier-transform from complex valued spectrum, as described by Eq. 8.1. (b) Time-domain information retrieved from the magnitude of the spectrum, as described by Eq. 8.4. The model derived previously is extended to contain most significant secondary reflections and reflection from the horn antenna for completeness. Amplitudes of both models are normalised to the largest peak. The container and sample are assumed to be dispersionless.

modules is used to acquire S_{11} , the complex-valued frequency-domain reflection spectrum over the frequency range 220–330 GHz. The transmitted output power of this system is 1 dBm. After 40 consecutive measurements, the dynamic range is 85 dB, measured from the noise floor to the system maximum. The system is arranged as shown in Fig. 8.3(a), and after the lens, the resulting collimated beam has a measured width of 28.5 mm at 220 GHz and 22.5 mm at 330 GHz. With reference to Eq. 8.5, this operating frequency corresponds to a free-space depth resolution of 1.25 mm, with a Fourier time-domain resolution (c/f_s , where $f_s = 660$ GHz is the effective sampling frequency, equal to double the maximum measurable frequency) of 0.45 mm. The container and sample are assumed to be dispersionless. Time gating is applied to the complex spectrum to remove artefacts arising from the vector network analyser, then the phase information is discarded to perform the swept-source terahertz coherence tomography. It should be noted that such artefacts from an electronic-based system can be calibrated out in practical scenarios. Additionally, I reiterate that this VNA system is not representative of a compact or portable terahertz system, but is an illustrative tool for highlighting a technique which could ultimately be realised with a less-sophisticated system based around a swept source, such as a tunable resonant tunnelling diode [73] and an incoherent detector array.

The sample, depicted in Fig. 8.3(b), is placed into a 3D-printed housing and mounted on a motorised rotating stage, these aid the precision alignment of the sample while ensuring a consistent position over many measurements. To validate the model previously outlined, the container is filled with water and a measurement made. Previously, the average refractive index of water in this frequency range was found to be $\hat{n}_s = 2.52 - 1.11j$ [363]. Fig. 8.4 demonstrates there is strong agreement between this model and the experimentally measured data. The peak labelled $\hat{E}_{l,0}$ has been manually scaled to account for the curved surface of the plano-convex lens, though this reflection is not used in any further analysis.

Based on the physical geometry and normal incidence assumption, this technique will be naturally sensitive to alignment. Note that in this case a relatively thick, $d_c = 1$ cm, rectangular container is used which exacerbates this effect. In practice, liquid containers are often round, with sub-millimeter thickness, which alleviates some of this sensitivity. Nevertheless, Fig. 8.5, highlights an admissible misalignment tolerance of approximately ± 1 degree either side of normal incidence, where the ratio between the two signals of interest is relatively stable.

The relationship between ethanol concentration and refractive index in the terahertz band has been analysed previously [321, 363]. Here, mixtures with ethanol concentrations ranging from 0–100%v/v are created from bottled drinking water and laboratory grade ethyl alcohol using a volumetric pipette. In Fig. 8.6(a), I show the measured frequency domain signal, and in Fig. 8.6(b-c), the time-domain information recovered from the complex and absolute valued spectrums respectively. In Fig. 6(a), I present the measured frequency-domain signal, and in Fig. 8.6(b-c), the time-domain information recovered from the complex and absolute valued spectrums respectively. In this case, the

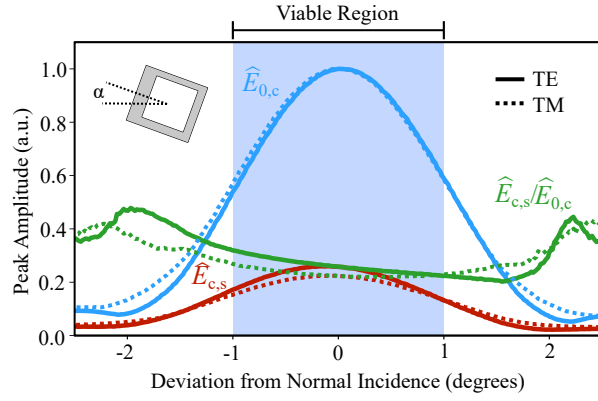


Figure 8.5: Experimentally measured peak amplitudes as a function of angle of incidence. The ratio of peaks (green) is consistent within a 1 degree deviation from normal incidence. There is some asymmetry in this measurement which is attributed to a slight asymmetric curvature in the surface of our acrylic container.

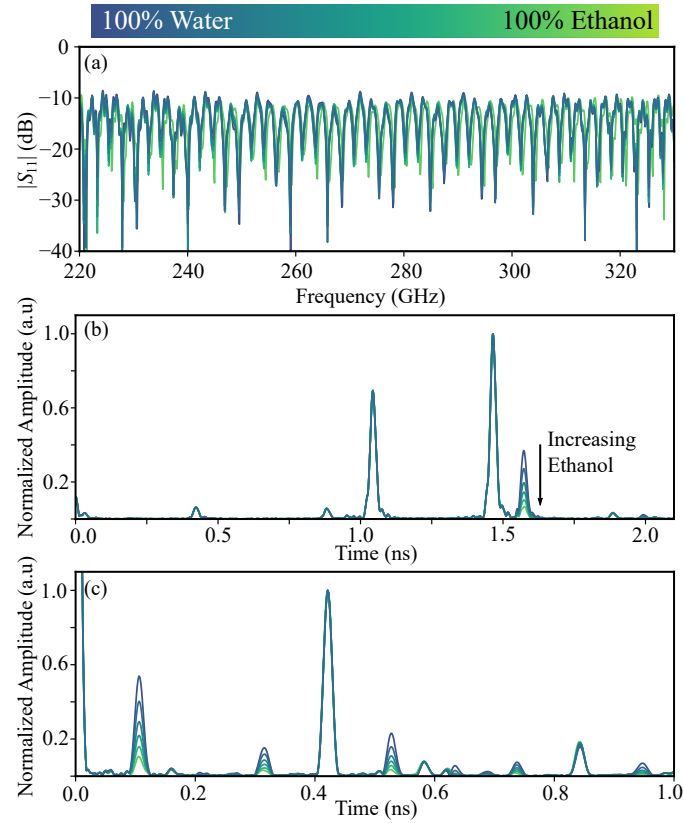


Figure 8.6: Measured reflection profiles as the proportion of water to ethanol is adjusted. (a) Measured frequency-domain reflection amplitude. (b) Measured time-domain information recovered with inverse-Fourier-transform from complex valued spectrum. (c) Measured time-domain information retrieved from the magnitude of the spectrum.

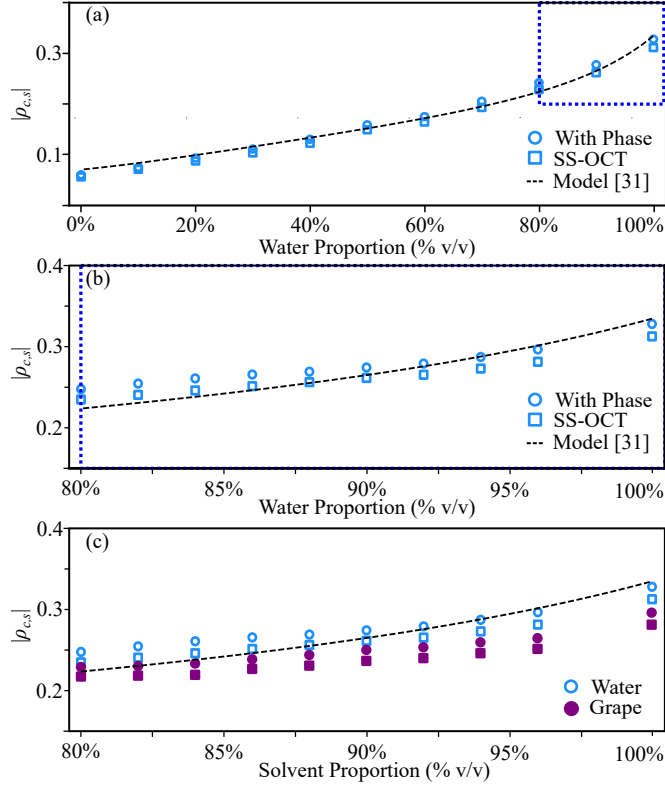


Figure 8.7: Reflection coefficient extracted from measurement of aqueous ethanol solutions. (a) Aqueous ethanol solutions in the water proportion range 0–100%. (b) Aqueous ethanol solutions in the water proportion range 80–100%. (c) Ethanol solutions dissolved in water (blue) and grape juice (purple).

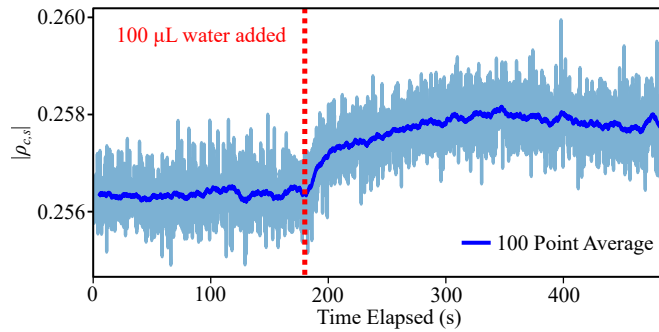


Figure 8.8: Reflection coefficient arising from an in-container sample of wine measured in real time at a sampling rate of 10 Hz. At 180 seconds elapsed, 100 μL of water is added to the 25 mL wine sample, and the diffusion of water through the sample is observed, in turn increasing the reflection coefficient before the system stabilizes to its final state.

weakest reflection of interest occurs at 100%v/v ethanol concentration, with a magnitude of -45 dB. In Fig. 8.7(a), measurements are taken at 10%v/v intervals, demonstrating the strong physical relationship between ethanol concentration and measured reflection. There is strong alignment between traditional and measurements derived through swept-source terahertz coherence tomography. Fig. 8.7(b) highlights sensitivity in the low ethanol proportion region, where most common fermented beverages exist. In this region, there is a systematic discrepancy between with-phase and swept-source terahertz coherence tomography arising from the impact of secondary reflections, as discussed previously. In Fig. 8.7(a-c), these measurements are compared to the phenomenological model proposed in [363] and observe general agreement with these results. However, I note that this phenomenological model was derived from the average result of measurements in the range 0.15–1.0 THz, and hence I expect the measurements to exceed this model as the permittivity of both ethanol and water decrease with increasing frequency, resulting in suppressed reflection coefficient.

This experiment is repeated with grape juice as the solvent in place of water. The impact of the presence of sugars in the solution was previously described in [363], where the imaginary component of sugary solutions was significantly decreased compared to purely aqueous solutions. In line with this change in index it is expected that the presence of sugars will decrease the measured peak at the container-sample interface, and hence suppress the extracted reflection coefficient. Fig. 8.7(c) reinforces these findings. Note that, while in this case the amplitude-only measurement does not facilitate the determination of both the real and imaginary components of the sample refractive index necessary to determine the proportions of water, sugar, and ethanol, for fermentation monitoring or dilution detection, only relative deviation from the baseline is necessary.

To demonstrate dilution detection capability a 25 mL sample of wine (var. Cabernet Sauvignon, stated ethanol concentration 13.5%v/v) is measured, and then add 100 μ L of water with a volumetric pipette, equivalent to 0.4%v/v of the total sample. This sample is measured in real-time at a rate of 10 Hz, limited by the time taken for the VNA to acquire the necessary 1001 frequency points to achieve an unambiguous free space range of 2.73 m, to monitor the reflection coefficient over time. The results in Fig. 8.8 show that the addition of this small volume of water is clearly detectable, and the diffusion of the added water through the sample is measured as a gradual change in the reflection coefficient. This demonstration shows that this technique could be applied to real-time, in-line, process monitoring with high sensitivity.

8.4 Conclusion

In recent years, terahertz non-destructive evaluation has received significant interest from industry but significant cost and slow acquisition speeds have dampened mass adoption. In response to this terahertz cameras comprised of incoherent detector arrays have emerged as a cost-effective, high speed, imaging solution but without access to the complex valued spectrum. As such, multi-layer imaging based on time domain discrimination of each reflection becomes impossible. I propose a technique based on swept-source optical coherence tomography combined with Fresnel analysis for extracting key information from multi-layer systems. This technique only requires measurement of reflection magnitude in the frequency domain with a frequency-tunable terahertz source. This technique is verified with experimental results and I present a comparison to modelled results.

To highlight the potential applications I apply this technique to the analysis of in-container liquids, where the relationship between reflections at multiple interfaces can be used to derive information about the contents without destructive evaluation or chemical testing. I present measurements of aqueous ethanol samples at low ethanol concentration, mimicking common alcoholic beverages, and demonstrate the ability to discriminate between these samples with changes to the mixture composition under addition of water in volumes as small as 0.4%v/v, as well as observe the effect of the addition of sugar.

In the future, this technique could be applied to a terahertz camera paired with a frequency-tunable source to realise high resolution, fast-acquisition, multi-layer terahertz imaging. This extension will allow rapid quantitative analyses of liquid content and its uniformity, and therefore potentially be a

promising alternative to traditional destructive approaches.

Part IV

Conclusion

Chapter 9

Conclusion

Abstract

This chapter concludes this thesis, providing an overview of the presented works and offering outlooks for future developments in each part. The chapter ends with concluding remarks.

9.1 Thesis Summary

The utilisation of terahertz frequencies offers a pathway to high-speed wireless communications and valuable non-destructive imaging techniques. Although these applications have all been demonstrated in the decade prior, they have not been widely adopted due to the prohibitive bulk and expense of existing systems. To address this, I suggest that compact and cost-effective integrated systems, alongside compatible techniques, must be developed before terahertz technologies will be widely adopted. To this end I present this thesis in two interrelated parts.

The first part of the thesis presents an exploration of terahertz integrated circuits, presenting an array of new devices including foundational waveguides, functional tunable and passives components, as well as antennas. These compact devices all share an all-dielectric foundation, using low-loss silicon and alumina to avoid Ohmic losses and maximise the device efficiency, while employing cost-effective and scalable fabrication techniques suitable for mass-manufacture. Importantly, these devices address current deficiencies, expanding the capabilities of all-dielectric terahertz waveguides toward a fully functional system with tunable elements, beamforming capabilities, and routing elements.

The second part of the thesis focuses on applications of terahertz technologies. Here I improve upon existing capabilities by proposing economic systems, with specialised hardware and data-analysis techniques to reduce cost and size. Difficulties with terahertz beam-forming may be overcome through the use of leaky-wave radar, and I expand this field through demonstrations and theoretical analysis of the performance. Simultaneously, I propose that, in multilayer imaging applications, knowledge of the phase information can be supplemented by analysis of the amplitude through swept-source coherence tomography in the terahertz domain. This is a great advantage as the capability to directly extract the phase comes at a significant cost. I note that these techniques are directly related to the previous part, as by simplifying the required hardware these applications can be realised with more compact, integrated, systems such as those proposed in this thesis.

In summary, I strongly contend that widespread adoption of terahertz technologies depends upon advances in hardware and software such that these systems can be economically viable. Aligning with this goal, I propose a variety of measures to advance integrated terahertz systems built upon all-dielectric waveguides.

9.2 Outlook

9.2.1 Terahertz Integrated Circuits

In the years prior, terahertz integrated circuits have developed substantially as fabrication techniques have improved and new waveguides have emerged. At present there is now a wide-array of passive components available, including all the most foundational elements; routing elements, filters, multiplexers, and antennas. Simultaneously, the first tunable elements have been proposed, including switches and phase-shifters, though there is still significant engineering to be done to optimise these tunable devices. Alongside development of components, the hybrid integration of active components has also seen significant growth with many of the most important elements, sources, detectors, and mixers already demonstrated. This is to say, that much of the most foundational work has been performed, and the next step is to build monolithic integrated systems. I am optimistic that the barriers to this next step are more social and material than physical—to realise these systems, expertise and resources across design, fabrication, and characterisation need to be brought together alongside significant investment. To aid in this effort I believe it is necessary to standardise these technologies across the global research community through open collaboration. Mirroring developments in photonic integrated circuits, system level design needs to be simplified through the aid of software tools, such that someone designing a communication system is liberated from the burden of understanding the inner-workings of a power divider. Though traditionally, these engineering intensive pursuits have not been the primary focus of academic research teams, I believe they are critical to bridging the remaining gap between technology and application for terahertz systems.

9.2.2 Techniques Towards Applications

Following on from the previous section, there is still an obvious gap between the performance of practical systems and some laboratory demonstrations. This is most easily observed in imaging, where beautiful, high-resolution, terahertz images acquired over the course of days with cryogenic or high-power pump laser systems have been available in the literature for almost two decades. At the same time, rapidly acquired imaging systems are still yet to achieve such success. Similarly, in the realm of communications, champion data rates in the laboratory are being routinely reported through the use of new, more powerful hardware, without addressing the more fundamental issues, namely beam-forming, device and source efficiency, which have long been bottlenecks in terahertz systems. These issues require addressing at the foundational level, only through the development of hardware or the simplification of systems can these barriers be overcome. It is my opinion that, though there are still major innovations to be made, there are still unrealised gains in terahertz applications by focusing on the engineering of practical systems with existing modalities.

9.3 Concluding remarks

This thesis proposes a range of components and techniques for the realisation of terahertz systems. This broad approach is representative of the state of terahertz research, where specialised consideration of the hardware and analysis techniques is necessary to overcome the fundamental physical barriers posed by terahertz waves. I foresee that these contributions can be integrated into future, practical terahertz systems employing efficient, cost-effective components, that are suitable for societal adoption.

Bibliography

- [1] H.-J. Song and T. Nagatsuma, “Present and future of terahertz communications,” *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 256–263, 2011.
- [2] H. Hirashita, P. M. Koch, S. Matsushita, S. Takakuwa, M. Nakamura, K. Asada, H. B. Liu, Y. Urata, M.-J. Wang, W.-H. Wang, S. Takahashi, Y.-W. Tang, H.-H. Chang, K. Huang, O. Morata, M. Otsuka, K.-Y. Lin, A.-L. Tsai, Y.-T. Lin, S. Srinivasan, P. Martin-Cocher, H.-Y. Pu, F. Kemper, N. Patel, P. Grimes, Y.-D. Huang, C.-C. Han, Y.-R. Huang, H. Nishioka, L. C.-C. Lin, Q. Zhang, E. Keto, R. Burgos, M.-T. Chen, M. Inoue, and P. T. P. Ho, “First-generation science cases for ground-based terahertz telescopes,” *Publications of the Astronomical Society of Japan*, vol. 68, no. 1, R1, Dec. 2015.
- [3] T. Nakagawa, “Observations of the universe in the terahertz range: From akari to spica,” *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 6, pp. 1133–1139, 2015.
- [4] P. H. Siegel, “THz instruments for space,” *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 11, pp. 2957–2965, 2007.
- [5] C. Kulesa, “Terahertz spectroscopy for astronomy: From comets to cosmology,” *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 232–240, 2011.
- [6] C. Sirtori, “Bridge for the terahertz gap,” *Nature*, vol. 417, no. 6885, pp. 132–133, 2002.
- [7] R. Kleiner, “Filling the terahertz gap,” *Science*, vol. 318, no. 5854, pp. 1254–1255, 2007.
- [8] J. Chamberlain, “Where optics meets electronics: Recent progress in decreasing the terahertz gap,” *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, vol. 362, no. 1815, pp. 199–213, 2004.
- [9] M. C. Beard, G. M. Turner, and C. A. Schmuttenmaer, *Terahertz spectroscopy*, 2002.
- [10] T. Nagatsuma, G. Ducournau, and C. C. Renaud, “Advances in terahertz communications accelerated by photonics,” *Nature Photonics*, vol. 10, no. 6, pp. 371–379, 2016.
- [11] C. Castro, R. Elschner, T. Merkle, C. Schubert, and R. Freund, “Long-range high-speed THz-wireless transmission in the 300 GHz band,” in *2020 Third International Workshop on Mobile Terahertz Systems (IWMTS)*, IEEE, 2020.
- [12] B. Puttnam, M van den Hout, G Di Sciullo, R. Luis, G Rademacher, J Sakaguchi, C Antonelli, C Okonkwo, and H Furukawa, “22.9 Pb/s data-rate by extreme space-wavelength multiplexing,” in *49th European Conference on Optical Communications (ECOC 2023)*, IET, vol. 2023, 2023, pp. 1678–1681.
- [13] A. Ferrari, A. Napoli, J. K. Fischer, N. Costa, A. D’Amico, J. Pedro, W. Forysiak, E. Pincemin, A. Lord, A. Stavdas, *et al.*, “Assessment on the achievable throughput of multi-band ITU-T G. 652. D fiber transmission systems,” *Journal of Lightwave Technology*, vol. 38, no. 16, pp. 4279–4291, 2020.
- [14] T. Koonen, F. Gomez-Agis, F. Huijskens, K. A. Mekonnen, Z. Cao, and E. Tangdionga, “High-capacity optical wireless communication using two-dimensional IR beam steering,” *Journal of Lightwave Technology*, vol. 36, no. 19, pp. 4486–4493, 2018.

- [15] W. G. Alheadary, K.-H. Park, N. Alfaraj, Y. Guo, E. Stegenburgs, T. K. Ng, B. S. Ooi, and M.-S. Alouini, "Free-space optical channel characterization and experimental validation in a coastal environment," *Optics Express*, vol. 26, no. 6, pp. 6614–6628, 2018.
- [16] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 2231–2258, 2014.
- [17] IEEE, "IEEE standard for wireless multimedia networks," *IEEE Std 802.15.3-2023 (Revision of IEEE Std 802.15.3-2016)*, pp. 1–684, 2024.
- [18] K. Sengupta, T. Nagatsuma, and D. M. Mittleman, "Terahertz integrated electronic and hybrid electronic–photonic systems," *Nature Electronics*, vol. 1, no. 12, pp. 622–635, 2018.
- [19] B. M. Heffernan, Y. Kawamoto, K. Maekawa, J. Greenberg, R. Amin, T. Hori, T. Tanigawa, T. Nagatsuma, and A. Rolland, "60 gbps real-time wireless communications at 300 GHz carrier using a kerr microcomb-based source," *APL Photonics*, vol. 8, no. 6, 2023.
- [20] G. Ducournau, P. Szriftgiser, Y. Kawamoto, W. Gao, A. S. Mohammed, M. Zegaoui, M. Zaknoune, and T. Nagatsuma, "Photonics-enabled 1.04-tbit/s aggregated data-rate in the 600-GHz-band," in *2023 Asia-Pacific Microwave Conference (APMC)*, IEEE, 2023, pp. 327–329.
- [21] P. Sen, J. V. Siles, N. Thawdar, and J. M. Jornet, "Multi-kilometre and multi-gigabit-per-second sub-terahertz communications for wireless backhaul applications," *Nature Electronics*, vol. 6, no. 2, pp. 164–175, 2023.
- [22] F. Ellrich, M. Bauer, N. Schreiner, A. Keil, T. Pfeiffer, J. Klier, S. Weber, J. Jonuscheit, F. Friederich, and D. Molter, "Terahertz quality inspection for automotive and aviation industries," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 41, pp. 470–489, 2020.
- [23] K. B. Cooper, R. J. Dengler, N. Llombart, B. Thomas, G. Chattopadhyay, and P. H. Siegel, "THz imaging radar for standoff personnel screening," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 169–182, 2011.
- [24] E. Castro-Camus, M. Koch, and D. M. Mittleman, "Recent advances in terahertz imaging: 1999 to 2021," *Applied Physics B*, vol. 128, no. 1, p. 12, 2022.
- [25] H. Guerboukha, K. Nallappan, and M. Skorobogatiy, "Toward real-time terahertz imaging," *Advanced Optical Photonics*, vol. 10, no. 4, pp. 843–938, 2018.
- [26] Y. H. Tao, A. J. Fitzgerald, and V. P. Wallace, "Non-contact, non-destructive testing in various industrial sectors with terahertz technology," *Sensors*, vol. 20, no. 3, p. 712, 2020.
- [27] D. F. Plusquellic, K. Siegrist, E. J. Heilweil, and O. Esenturk, "Applications of terahertz spectroscopy in biosystems," *ChemPhysChem*, vol. 8, no. 17, pp. 2412–2431, 2007.
- [28] A. G. Markelz and D. M. Mittleman, "Perspective on terahertz applications in bioscience and biotechnology," *ACS Photonics*, vol. 9, no. 4, pp. 1117–1126, 2022.
- [29] O. B. Osman, Z. B. Harris, J. W. Zhou, M. E. Khani, A. J. Singer, and M. H. Arbab, "In vivo assessment and monitoring of burn wounds using a handheld terahertz hyperspectral scanner," *Advanced Photonics Research*, vol. 3, no. 5, p. 2100095, 2022.
- [30] X. E. R. Barker, G. Costa, R. I. Stantchev, A. I. Hernandez-Serrano, G. Nurumbetov, D. M. Haddleton, and E. Pickwell-MacPherson, "Monitoring the terahertz response of skin beneath transdermal drug delivery patches using sparse deconvolution," *IEEE Transactions on Terahertz Science and Technology*, 2023.
- [31] Y. Hu, M. Baggio, S. O. Dabironezare, A. Tamminen, B. Toy, J. Ala-Laurinaho, E. R. Brown, N. Llombart, S. X. Deng, V. P. Wallace, *et al.*, "650 GHz imaging as alignment verification for millimeter wave corneal reflectometry," *IEEE Transactions on Terahertz Science and Technology*, vol. 12, no. 2, pp. 151–164, 2022.
- [32] H. Lindley-Hatcher, R. Stantchev, X. Chen, A. I. Hernandez-Serrano, J. Hardwicke, and E. Pickwell-MacPherson, "Real time THz imaging—opportunities and challenges for skin cancer detection," *Applied Physics Letters*, vol. 118, no. 23, p. 230501, 2021.

- [33] D. Stanze, B. Globisch, R. J. Dietz, H. Roehle, T. Göbel, and M. Schell, "Multilayer thickness determination using continuous wave THz spectroscopy," *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 6, pp. 696–701, 2014.
- [34] M. Bauer, R. Hussung, C. Matheis, A. Mashkin, S. Krane, F. Pohlmann, and F. Friederich, "Terahertz non-destructive testing of power generator bars with a dielectric waveguide antenna," *International Journal of Microwave and Wireless Technologies*, vol. 15, no. 6, pp. 1038–1047, 2023.
- [35] T. Kubiczek, T. Schultze, and J. C. Balzer, "Burning depth determination in wood with THz 3D imaging based on an inverse linear synthetic aperture," in *2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, IEEE, 2023.
- [36] S. Krimi, J. Klier, J. Jonuscheit, G. von Freymann, R. Urbansky, and R. Beigang, "Highly accurate thickness measurement of multi-layered automotive paints using terahertz technology," *Applied Physics Letters*, vol. 109, no. 2, p. 021 105, 2016.
- [37] M. Ibrahim, D. Headland, W. Withayachumnankul, and C. Wang, "Nondestructive testing of defects in polymer–matrix composite materials for marine applications using terahertz waves," *Journal of Nondestructive Evaluation*, vol. 40, no. 2, p. 37, 2021.
- [38] Z. B. Harris, A. Virk, M. E. Khani, and M. H. Arbab, "Terahertz time-domain spectral imaging using telecentric beam steering and an f- θ scanning lens: Distortion compensation and determination of resolution limits," *Optics Express*, vol. 28, no. 18, pp. 26 612–26 622, 2020.
- [39] D. Mittleman, M Gupta, R. Neelamani, R. Baraniuk, J. Rudd, and M Koch, "Recent advances in terahertz imaging," *Applied Physics B*, vol. 68, pp. 1085–1094, 1999.
- [40] E. S. Lee, M. Kim, K. Moon, I.-M. Lee, D. W. Park, J.-H. Shin, H.-S. Kim, D.-H. Choi, K. S. Choi, D. H. Lee, *et al.*, "High-speed and cost-effective reflective terahertz imaging system using a novel 2D beam scanner," *Journal of Lightwave Technology*, vol. 38, no. 16, pp. 4237–4243, 2020.
- [41] B. Chung, D. Headland, and W. Withayachumnankul, "Terahertz imaging with 3D-printed risley-prism and telecentric objective," *IEEE Transactions on Terahertz Science and Technology*, 2024.
- [42] B. Chung, H. Lees, D. Headland, and W. Withayachumnankul, "Broadband and efficient terahertz beam scanning using a 3D-printed risley prism," in *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, 2022.
- [43] Z. B. Harris, S. Katletz, M. E. Khani, A. Virk, and M. H. Arbab, "Design and characterization of telecentric f- θ scanning lenses for broadband terahertz frequency systems," *AIP Advances*, vol. 10, no. 12, 2020.
- [44] D. Molter, K.-S. Ellenberger, J. Klier, S. Duran, J. Jonuscheit, G. von Freymann, N. Vieweg, and A. Deninger, "Kilohertz pixel-rate multilayer terahertz imaging of subwavelength coatings," *Applied Sciences*, vol. 12, no. 10, p. 4964, 2022.
- [45] A. Batra, J. Barowski, D. Damyanov, M. Wiemeler, I. Rolfes, T. Schultze, J. C. Balzer, D. Göhringer, and T. Kaiser, "Short-range SAR imaging from GHz to THz waves," *IEEE Journal of Microwaves*, vol. 1, no. 2, pp. 574–585, 2021.
- [46] D. Damyanov, T. Kubiczek, K. Kolpatzeck, A. Czylik, T. Schultze, and J. C. Balzer, "3D THz-TDS SAR imaging by an inverse synthetic cylindrical aperture," *IEEE Access*, vol. 11, pp. 9680–9690, 2023.
- [47] L. Yi, Y. Li, and T. Nagatsuma, "Photonic radar for 3D imaging: From millimeter to terahertz waves," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 29, no. 5: Terahertz Photonics, 2023.
- [48] A. Kannegulla, Z. Jiang, S. Rahman, M. Shams, P Fay, H. Xing, L.-J. Cheng, and L Liu, "Coded-aperture imaging using photo-induced reconfigurable aperture arrays for mapping terahertz beams," *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 3, pp. 321–327, 2014.

- [49] D. Shrekenhamer, C. M. Watts, and W. J. Padilla, "Terahertz single pixel imaging with an optically controlled dynamic spatial light modulator," *Optics Express*, vol. 21, no. 10, pp. 12 507–12 518, 2013.
- [50] H. Matsumoto, I. Watanabe, A. Kasamatsu, and Y. Monnai, "Integrated terahertz radar based on leaky-wave coherence tomography," *Nature Electronics*, vol. 3, no. 2, pp. 122–129, 2020.
- [51] K. Murano, I. Watanabe, A. Kasamatsu, S. Suzuki, M. Asada, W. Withayachumnankul, T. Tanaka, and Y. Monnai, "Low-profile terahertz radar based on broadband leaky-wave beam steering," *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 1, pp. 60–69, 2017.
- [52] F. Blanchard, J. E. Nkeck, D. Matte, R. Nechache, and D. G. Cooke, "A low-cost terahertz camera," *Applied Sciences*, vol. 9, no. 12, p. 2531, 2019.
- [53] H. Sherry, J. Grzyb, Y. Zhao, R. A. Hadi, A. Cathelin, A. Kaiser, and U. Pfeiffer, "A 1kpixel cmos camera chip for 25fps real-time terahertz imaging applications," in *2012 IEEE International Solid-State Circuits Conference*, 2012, pp. 252–254.
- [54] J. Zdanevičius, M. Bauer, S. Boppel, V. Palenskis, A. Lisauskas, V. Krozer, and H. G. Roskos, "Camera for high-speed THz imaging," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 36, pp. 986–997, 2015.
- [55] D. Dufour, L. Marchese, M. Terroux, H. Oulachgar, F. Génèreux, M. Doucet, L. Mercier, B. Tremblay, C. Alain, P. Beaupré, *et al.*, "Review of terahertz technology development at INO," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 36, pp. 922–946, 2015.
- [56] R. Al Hadi, H. Sherry, J. Grzyb, Y. Zhao, W. Forster, H. M. Keller, A. Cathelin, A. Kaiser, and U. R. Pfeiffer, "A 1 k-pixel video camera for 0.7–1.1 terahertz imaging applications in 65-nm cmos," *IEEE Journal of Solid-State Circuits*, vol. 47, no. 12, pp. 2999–3012, 2012.
- [57] J.-B. Perraud, A. Chopard, J.-P. Guillet, P. Gellie, A. Vuillot, and P. Mounaix, "A versatile illumination system for real-time terahertz imaging," *Sensors*, vol. 20, no. 14, 2020.
- [58] N. Nemoto, N. Kanda, R. Imai, K. Konishi, M. Miyoshi, S. Kurashina, T. Sasaki, N. Oda, and M. Kuwata-Gonokami, "High-sensitivity and broadband, real-time terahertz camera incorporating a micro-bolometer array with resonant cavity structure," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 2, pp. 175–182, 2016.
- [59] R. Al Hadi, H. Sherry, J. Grzyb, Y. Zhao, W. Forster, H. M. Keller, A. Cathelin, A. Kaiser, and U. R. Pfeiffer, "A 1 k-pixel video camera for 0.7-1.1 terahertz imaging applications in 65-nm CMOS," *IEEE Journal of Solid-State Circuits*, vol. 47, no. 12, pp. 2999–3012, 2012.
- [60] E. Hack and P. Zolliker, "Terahertz holography for imaging amplitude and phase objects," *Optics Express*, vol. 22, no. 13, pp. 16 079–16 086, 2014.
- [61] T. Umezawa, A. Kanno, K. Kashima, A. Matsumoto, K. Akahane, N. Yamamoto, and T. Kawanishi, "Bias-free operational UTC-PD above 110 GHz and its application to high baud rate fixed-fiber communication and W-band photonic wireless communication," *Journal of Lightwave Technology*, vol. 34, no. 13, pp. 3138–3147, 2016.
- [62] Y. Koyama, Y. Kitazawa, K. Yukimasa, T. Uchida, T. Yoshioka, K. Fujimoto, T. Sato, J. Iba, K. Sakurai, and T. Ichikawa, "A high-power terahertz source over 10 mw at 0.45 THz using an active antenna array with integrated patch antennas and resonant-tunneling diodes," *IEEE Transactions on Terahertz Science and Technology*, vol. 12, no. 5, pp. 510–519, 2022.
- [63] T. Vogel, S. Mansourzadeh, U. Nandi, J. Norman, S. Preu, and C. J. Saraceno, "Performance of photoconductive receivers at 1030 nm excited by high average power THz pulses," *IEEE Transactions on Terahertz Science and Technology*, vol. 14, no. 2, pp. 139–151, 2024.
- [64] R. B. Kohlhaas, S. Breuer, L. Liebermeister, S. Nellen, M. Deumer, M. Schell, M. P. Semtsiv, W. T. Masselink, and B. Globisch, "637 μ W emitted terahertz power from photoconductive antennas based on rhodium doped InGaAs," *Applied Physics Letters*, vol. 117, no. 13, p. 131 105, Sep. 2020.

- [65] S Nellen, T Ishibashi, A Deninger, R. Kohlhaas, L Liebermeister, M Schell, and B Globisch, "Experimental comparison of UTC-and PIN-photodiodes for continuous-wave terahertz generation," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 41, pp. 343–354, 2020.
- [66] Y. Wang, T. Vogel, M. Khalili, S. Mansourzadeh, K. Hasse, S. Suntsov, D. Kip, and C. J. Saraceno, "High-power intracavity single-cycle THz pulse generation using thin lithium niobate," *Optica*, vol. 10, no. 12, pp. 1719–1722, 2023.
- [67] D. Maes, S. Lemey, G. Roelkens, M. Zaknoute, V. Avramovic, E. Okada, P. Szriftgiser, E. Peytavit, G. Ducournau, and B. Kuyken, "High-speed uni-traveling-carrier photodiodes on silicon nitride," *APL Photonics*, vol. 8, no. 1, p. 016104, Jan. 2023.
- [68] E. Abacioğlu, M. Grzeslo, T. Neerfeld, A. S. Mohammed, J. L. F. Estévez, G. Ducournau, and A. Stöhr, "500 GHz operational bandwidth MUTC-photodiodes with milliwatt terahertz output power levels," in *49th European Conference on Optical Communications (ECOC 2023)*, vol. 2023, 2023, pp. 1410–1413.
- [69] C. Millon, S. Houver, and C. J. Saraceno, "400 kHz repetition rate THz-TDS with 24 mW of average power driven by a compact industrial Yb-laser," *Optics Express*, vol. 31, no. 5, pp. 7922–7932, 2023.
- [70] P. Zhou, J. Chen, P. Yan, Z. Chen, D. Hou, and W. Hong, "A 280-325 GHz frequency multiplier chain with 2.5 dBm peak output power," in *2019 IEEE Custom Integrated Circuits Conference (CICC)*, 2019, pp. 1–4.
- [71] E. Öjefors, B. Heinemann, and U. R. Pfeiffer, "Active 220- and 325-GHz frequency multiplier chains in an sige hbt technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 5, pp. 1311–1318, 2011.
- [72] M. Asada and S. Suzuki, "Terahertz emitter using resonant-tunneling diode and applications," *Sensors*, vol. 21, no. 4, 2021.
- [73] S. Kitagawa, S. Suzuki, and M. Asada, "Wide frequency-tunable resonant tunnelling diode terahertz oscillators using varactor diodes," *Electronics Letters*, vol. 52, no. 6, pp. 479–481, 2016.
- [74] K. Ishigaki, M. Shiraishi, S. Suzuki, M. Asada, N. Nishiyama, and S. Arai, "Direct intensity modulation and wireless data transmission characteristics of terahertz-oscillating resonant tunnelling diodes," *Electronics Letters*, vol. 48, no. 10, pp. 582–583, 2012.
- [75] Y. Nishida, N. Nishigami, S. Diebold, J. Kim, M. Fujita, and T. Nagatsuma, "Terahertz coherent receiver using a single resonant tunnelling diode," *Scientific Reports*, vol. 9, no. 1, p. 18125, 2019.
- [76] M. Asada and S. Suzuki, "Room-temperature oscillation of resonant tunneling diodes close to 2 THz and their functions for various applications," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 37, pp. 1185–1198, 2016.
- [77] T. Nagatsuma, M. Fujita, A. Kaku, D. Tsuji, S. Nakai, K. Tsuruda, and T. Mukai, "Terahertz wireless communications using resonant tunneling diodes as transmitters and receivers," in *Third International Conference on Telecommunications and Remote Sensing*, vol. 1, 2014, pp. 41–46.
- [78] A. Dobroiu, R. Wakasugi, Y. Shirakawa, S. Suzuki, and M. Asada, "Absolute and precise terahertz-wave radar based on an amplitude-modulated resonant-tunneling-diode oscillator," in *Photonics*, Multidisciplinary Digital Publishing Institute, vol. 5, 2018, p. 52.
- [79] A. I. Harris, "Coherent and incoherent detection," in *ESA, From Ground-Based to Space-Borne Sub-mm Astronomy p 165-169 (SEE N91-21986 13-89)*, vol. 29, 1990.
- [80] S. Kim, J. Yun, D. Yoon, M. Kim, J.-S. Rieh, M. Urteaga, and S. Jeon, "300 GHz integrated heterodyne receiver and transmitter with on-chip fundamental local oscillator and mixers," *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 1, pp. 92–101, 2014.

- [81] J. Grant, I. Escorcia-Carranza, C. Li, I. J. H. McCrindle, J. Gough, and D. R. S. Cumming, "A monolithic resonant terahertz sensor element comprising a metamaterial absorber and microbolometer," *Laser & Photonics Reviews*, vol. 7, no. 6, pp. 1043–1048,
- [82] F. Simoens, T. Durand, J. Meilhan, P. Gellie, W. Mainault, C. Sirtori, S. Barbieri, H. Beere, and D. Ritchie, "Terahertz imaging with a quantum cascade laser and amorphous-silicon microbolometer array," in *Millimetre Wave and Terahertz Sensors and Technology II*, K. A. Krapels and N. A. Salmon, Eds., International Society for Optics and Photonics, vol. 7485, SPIE, 2009, p. 74850M.
- [83] N. Oda, H. Yoneyama, T. Sasaki, M. Sano, S. Kurashina, I. Hosako, N. Sekine, T. Sudoh, and T. Irie, "Detection of terahertz radiation from quantum cascade laser using vanadium oxide microbolometer focal plane arrays," in *Infrared Technology and Applications XXXIV*, B. F. Andresen, G. F. Fulop, and P. R. Norton, Eds., International Society for Optics and Photonics, vol. 6940, SPIE, 2008, 69402Y.
- [84] Y. Zhang, S. Hosono, N. Nagai, S.-H. Song, and K. Hirakawa, "Fast and sensitive bolometric terahertz detection at room temperature through thermomechanical transduction," *Journal of Applied Physics*, vol. 125, no. 15, p. 151 602, Mar. 2019.
- [85] S. Cherednichenko, A. Hammar, S. Bevilacqua, V. Drakinskiy, J. Stake, and A. Kalabukhov, "A room temperature bolometer for terahertz coherent and incoherent detection," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 2, pp. 395–402, 2011.
- [86] D. Büchel, P. Pütz, K. Jacobs, M. Schultz, U. U. Graf, C. Risacher, H. Richter, O. Ricken, H.-W. Hübers, R. Güsten, C. E. Honingh, and J. Stutzki, "4.7-THz superconducting hot electron bolometer waveguide mixer," *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 2, pp. 207–214, 2015.
- [87] L. Liu, H. Xu, R. R. Percy, D. L. Herald, A. W. Lichtenberger, J. L. Hesler, and R. M. Weikle, "Development of integrated terahertz broadband detectors utilizing superconducting hot-electron bolometers," *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, pp. 282–286, 2009.
- [88] F. Rodriguez-Morales, K. S. Yngvesson, E. Gerecht, N. Wadefalk, J. Nicholson, D. Gu, X. Zhao, T. Goyette, and J. Waldman, "A terahertz focal plane array using HEB superconducting mixers and MMIC if amplifiers," *IEEE microwave and wireless components letters*, vol. 15, no. 4, pp. 199–201, 2005.
- [89] U. R. Pfeiffer, C. Mishra, R. M. Rassel, S. Pinkett, and S. K. Reynolds, "Schottky barrier diode circuits in silicon for future millimeter-wave and terahertz applications," *IEEE Transactions on Microwave Theory and techniques*, vol. 56, no. 2, pp. 364–371, 2008.
- [90] H. Ito and T. Ishibashi, "Fermi-level managed barrier diode for broadband and low-noise terahertz-wave detection," *Electronics Letters*, vol. 51, no. 18, pp. 1440–1442, 2015.
- [91] Y. Takida, S. Suzuki, M. Asada, and H. Minamide, "Sensitivity measurement of resonant-tunneling-diode terahertz detectors," in *2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2019.
- [92] J. L. Hesler and T. W. Crowe, "Responsivity and noise measurements of zero-bias schottky diode detectors," *2007 Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz Electronics*, pp. 89–92, 2007.
- [93] H.-J. Song, J.-Y. Kim, K. Ajito, M. Yaita, and N. Kukutsu, "Fully integrated ASK receiver MMIC for terahertz communications at 300 GHz," *IEEE Transactions on Terahertz Science and Technology*, vol. 3, no. 4, pp. 445–452, 2013.
- [94] T. Harter, C. Füllner, J. N. Kemal, S. Ummethala, J. L. Steinmann, M. Brosi, J. L. Hesler, E. Bründermann, A.-S. Müller, W. Freude, *et al.*, "Generalized Kramers–Kronig receiver for coherent terahertz communications," *Nature Photonics*, vol. 14, no. 10, pp. 601–606, 2020.
- [95] J. Zmuidzinis, "The role of coherent detection," *New Concepts for Far-Infrared and Submillimeter Space Astronomy*, 2004.

- [96] S.-G. Park, M. Melloch, and A. Weiner, “Comparison of terahertz waveforms measured by electro-optic and photoconductive sampling,” *Applied Physics Letters*, vol. 73, no. 22, pp. 3184–3186, 1998.
- [97] A. Nahata, A. S. Weling, and T. F. Heinz, “A wideband coherent terahertz spectroscopy system using optical rectification and electro-optic sampling,” *Applied Physics Letters*, vol. 69, no. 16, pp. 2321–2323, 1996.
- [98] D. Grischkowsky, S. Keiding, M. Van Exter, and C. Fattinger, “Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors,” *Journal of the Optical Society of America B*, vol. 7, no. 10, pp. 2006–2015, 1990.
- [99] M. Beck, T. Plötzing, K. Maussang, J. Palomo, R. Colombelli, I. Sagnes, J. Mangeney, J. Tignon, S. Dhillon, G. Klatt, *et al.*, “High-speed THz spectroscopic imaging at ten kilohertz pixel rate with amplitude and phase contrast,” *Optics Express*, vol. 27, no. 8, pp. 10 866–10 872, 2019.
- [100] K. Kolpatzeck, X. Liu, K.-H. Tybussek, L. Häring, M. Zander, W. Rehbein, M. Moehrle, A. Czylik, and J. C. Balzer, “System-theoretical modeling of terahertz time-domain spectroscopy with ultra-high repetition rate mode-locked lasers,” *Optics Express*, vol. 28, no. 11, pp. 16 935–16 950, 2020.
- [101] T. W. Crowe, J. L. Hesler, S. A. Retzliff, and D. S. Kurtz, “Higher power terahertz sources based on diode multipliers,” in *2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2017.
- [102] E. Bryerton, S. Retzliff, and J. Hesler, “High-power submillimeter wave solid-state sources,” in *2019 12th Global Symposium on Millimeter Waves (GSMM)*, 2019, pp. 29–31.
- [103] D. Koller, E. W. Bryerton, and J. L. Hesler, “WM380 (675–700 GHz) bandpass filters in milled, split-block construction,” *IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 6, pp. 630–637, 2018.
- [104] I. Dan, G. Ducournau, S. Hisatake, P. Szriftgiser, R.-P. Braun, and I. Kallfass, “A terahertz wireless communication link using a superheterodyne approach,” *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 1, pp. 32–43, 2019.
- [105] J. Hesler and T. Crowe, “Schottky heterodyne receivers with full waveguide bandwidth,” *NASA Tech Briefs*, 2011.
- [106] C.-M. Liu, L.-P. Carignan, and K. Wu, “Substrate-integrated nonradiative dielectric (SINRD) waveguide for THz integrated circuits and systems,” *IEEE Transactions on Terahertz Science and Technology*, vol. 13, no. 5, pp. 454–463, 2023.
- [107] N. Zerounian, W. Aouimeur, A.-S. Grimault-Jacquín, G. Ducournau, C. Gaquière, and F. Aniel, “Coplanar waveguides on BCB measured up to 760 GHz,” *Journal of Electromagnetic Waves and Applications*, vol. 35, no. 15, pp. 2051–2061, 2021.
- [108] E. Mavrona, J. Graf, E. Hack, and P. Zolliker, “Optimized 3D printing of THz waveguides with cyclic olefin copolymer,” *Optical Materials Express*, vol. 11, no. 8, pp. 2495–2504, 2021.
- [109] S. Makhlof, B. Khani, J. Lackmann, S. Dülme, and A. Stöhr, “Metallic 3D printed rectangular waveguides (WR3) for rapid prototyping of THz packages,” in *2018 First International Workshop on Mobile Terahertz Systems (IWMTS)*, 2018.
- [110] S. Li, Z. Dai, Z. Wang, P. Qi, Q. Su, X. Gao, C. Gong, and W. Liu, “A 0.1 THz low-loss 3D printed hollow waveguide,” *Optik*, vol. 176, pp. 611–616, 2019.
- [111] B. Zhang and H. Zirath, “Metallic 3-D printed rectangular waveguides for millimeter-wave applications,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 6, no. 5, pp. 796–804, 2016.
- [112] K. Soeda, K. Naganuma, K. Konishi, H. Tamaru, N. Mio, H. Ito, and J. Yumoto, “3D-printed waveguide for 220 GHz - 325 GHz band,” in *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, 2022.

- [113] X. Wen, Y. Yu, G. Shi, Z. Wang, Q. S. Cheng, Y. Li, A. Zhang, and C. Guo, "WR-3.4 band waveguide and bandpass filters using copper additive manufacturing," *IEEE Transactions on Microwave Theory and Techniques*, vol. 71, no. 3, pp. 1190–1200, 2023.
- [114] T. Reck, C. Jung-Kubiak, J. V. Siles, C. Lee, R. Lin, G. Chattopadhyay, I. Mehdi, and K. Cooper, "A silicon micromachined eight-pixel transceiver array for submillimeter-wave radar," *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 2, pp. 197–206, 2015.
- [115] P. J. Bruneau, H. D. Janzen, and J. S. Ward, "Machining of terahertz split-block waveguides with micrometer precision," in *2008 33rd International Conference on Infrared, Millimeter and Terahertz Waves*, 2008.
- [116] T. J. Reck, C. Jung-Kubiak, J. Gill, and G. Chattopadhyay, "Measurement of silicon micromachined waveguide components at 500-750 GHz," *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 1, pp. 33–38, 2014.
- [117] B. Beuerle, J. Champion, U. Shah, and J. Oberhammer, "A very low loss 220-325 GHz silicon micromachined waveguide technology," *IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 2, pp. 248–250, 2018.
- [118] C. Jung-Kubiak, T. J. Reck, J. V. Siles, R. Lin, C. Lee, J. Gill, K. Cooper, I. Mehdi, and G. Chattopadhyay, "A multistep DRIE process for complex terahertz waveguide components," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 5, pp. 690–695, 2016.
- [119] S. Makhlof, S. Dülme, M. Grzeslo, J. L. F. Estévez, V. Rymanov, J. Lackmann, and A. Stöhr, "Monolithically integrated THz photodiodes with CPW-to-WR3 e-plane transitions for photodiodes packages with WR3-outputs," *Journal of Lightwave Technology*, vol. 39, no. 24, pp. 7804–7812, 2021.
- [120] M. Anderberg, P. Sobis, V. Drakinskiy, J. Schlee, S. Dejanovic, A. Emrich, and J. Stake, "A 183-GHz Schottky diode receiver with 4 dB noise figure," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*, 2019, pp. 172–175.
- [121] L. Wang, Y. Zhang, and H. Wei, "A self-biased 210-260 GHz frequency tripler based on planar schottky diodes," in *2022 IEEE MTT-S International Wireless Symposium (IWS)*, vol. 1, 2022.
- [122] D. A. Montofré, R. Molina, A. Khudchenko, R. Hesper, A. M. Baryshev, N. Reyes, and F. P. Mena, "High-performance smooth-walled horn antennas for THz frequency range: Design and evaluation," *IEEE Transactions on Terahertz Science and Technology*, vol. 9, no. 6, pp. 587–597, 2019.
- [123] J. Carter, H. Lees, Q. Wang, S. J. Chen, S. Atakaramians, and W. Withayachumnakul, "Terahertz properties of common microwave dielectric materials," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 44, no. 11, pp. 873–884, 2023.
- [124] J. Cabello-Sanchez, H. Rodilla, V. Drakinskiy, and J. Stake, "Transmission loss in coplanar waveguide and planar Goubau line between 0.75 THz and 1.1 THz," in *2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, IEEE, 2018.
- [125] A. Rivera-Lavado, M. Ali, D. Gallego-Cabo, L.-E. García-Muñoz, D. V. Lioubtchenko, and G. Carpintero, "Contactless RF probe interconnect technology enabling broadband testing to the terahertz range," *IEEE Transactions on Terahertz Science and Technology*, vol. 13, no. 1, pp. 34–43, 2023.
- [126] L. Cao, A.-S. Grimault-Jacquín, N. Zerounian, and F. Aniel, "Design and vna-measurement of coplanar waveguide (CPW) on benzocyclobutene (BCB) at THz frequencies," *Infrared Physics & Technology*, vol. 63, pp. 157–164, 2014.
- [127] P. Lu, T. Haddad, B. Sievert, B. Khani, S. Makhlof, S. Dülme, J. F. Estévez, A. Rennings, D. Erni, U. Pfeiffer, *et al.*, "InP-based THz beam steering leaky-wave antenna," *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 2, pp. 218–230, 2020.
- [128] F. Fesharaki, T. Djerafi, M. Chaker, and K. Wu, "Low-loss and low-dispersion transmission line over DC-to-THz spectrum," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 4, pp. 611–618, 2016.

- [129] T.-Y. Chiu and C.-H. Li, "Low-loss low-cost substrate-integrated waveguide and filter in GaAs IPD technology for terahertz applications," *IEEE Access*, vol. 9, pp. 86 346–86 357, 2021.
- [130] C.-M. Liu, L.-P. Carignan, S. Xiao, Y. He, and K. Wu, "Substrate-integrated hybrid metallo-dielectric waveguide architecture for millimeter-wave and terahertz applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 71, no. 9, pp. 3958–3967, 2023.
- [131] A. Krivovitca, U. Shah, O. Glubokov, and J. Oberhammer, "Micromachined silicon-core substrate-integrated waveguides at 220–330 GHz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 12, pp. 5123–5131, 2020.
- [132] J. Cabello-Sanchez, V. Drakinskiy, J. Stake, and H. Rodilla, "Terahertz planar Goubau line components on thin suspended silicon substrate," in *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, IEEE, 2022.
- [133] M. Zehar, G. Moreno, A. Chahadih, I. Turer, A. Ghaddar, and T. Akalin, "Low loss terahertz planar Goubau line on high resistivity silicon substrate," in *2013 13th Mediterranean Microwave Symposium (MMS)*, 2013.
- [134] B. Thomas, J. Gill, A. Maestrini, C. Lee, R. Lin, S. Sin, A. Peralta, and I. Mehdi, "An integrated 520-600 GHz sub-harmonic mixer and tripler combination based on GaAs MMIC membrane planar schottky diodes," in *35th International Conference on Infrared, Millimeter, and Terahertz Waves*, 2010.
- [135] I. Belio-Apaolaza, J. Seddon, D. Moro-Melgar, H. P. Indiran, C. Graham, K. Balakier, O. Cojocari, and C. C. Renaud, "Photonically-driven Schottky diode based 0.3 THz heterodyne receiver," *Optics Express*, vol. 30, no. 24, pp. 43 223–43 236, 2022.
- [136] Y.-C. Liu, Y. Li, L.-A. Yang, Y. Lu, X. Ma, J.-P. Ao, and Y. Hao, "Terahertz monolithic integrated cavity filter based on cyclic etched SiC via-holes," *IEEE Transactions on Electron Devices*, vol. 68, no. 1, pp. 311–317, 2021.
- [137] H.-J. Song, J.-Y. Kim, K. Ajito, N. Kukutsu, and M. Yaita, "50-Gb/s direct conversion QPSK modulator and demodulator MMICs for terahertz communications at 300 GHz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 3, pp. 600–609, 2014.
- [138] R. Lai, X. B. Mei, W. R. Deal, W. Yoshida, Y. M. Kim, P. H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, and A. Fung, "Sub 50 nm InP HEMT device with Fmax greater than 1 THz," in *2007 IEEE International Electron Devices Meeting*, 2007, pp. 609–611.
- [139] V. Radisic, K. M.K. H. Leong, X. Mei, S. Sarkozy, W. Yoshida, and W. R. Deal, "Power amplification at 0.65 THz using InP HEMTs," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 3, pp. 724–729, 2012.
- [140] S. Yang, W. Yu, X. Yang, X. Lv, H. Zirath, and Z. S. He, "A terahertz-wave double-band transition from substrate integrated waveguide to rectangular waveguide for InP MMIC," in *2018 IEEE International Conference on Integrated Circuits, Technologies and Applications (ICTA)*, 2018, pp. 140–141.
- [141] K. Mueller, C. Preuss, R. Kress, E. Mutlu, and N. Weimann, "Rectangular waveguide to coplanar waveguide transition for 110 to 170 GHz," in *2024 15th German Microwave Conference (GeMiC)*, 2024, pp. 296–299.
- [142] P. K. Tien, "Integrated optics and new wave phenomena in optical waveguides," *Reviews of Modern Physics*, vol. 49, pp. 361–420, 2 1977.
- [143] K. C. Kao and G. A. Hockham, "Dielectric-fibre surface waveguides for optical frequencies," in *Proceedings of the Institution of Electrical Engineers, IET*, vol. 113, 1966, pp. 1151–1158.
- [144] S. Y. Siew, B. Li, F. Gao, H. Y. Zheng, W. Zhang, P. Guo, S. W. Xie, A. Song, B. Dong, L. W. Luo, *et al.*, "Review of silicon photonics technology and platform development," *Journal of Lightwave Technology*, vol. 39, no. 13, pp. 4374–4389, 2021.

- [145] T. Sharma, J. Wang, B. K. Kaushik, Z. Cheng, R. Kumar, Z. Wei, and X. Li, "Review of recent progress on silicon nitride-based photonic integrated circuits," *IEEE Access*, vol. 8, pp. 195 436–195 446, 2020.
- [146] S. Arafin and L. A. Coldren, "Advanced InP photonic integrated circuits for communication and sensing," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 1, art. no. 6100612, 2017.
- [147] M. Naftaly and R. Miles, "Terahertz time-domain spectroscopy of silicate glasses and the relationship to material properties," *Journal of Applied Physics*, vol. 102, no. 4, 2007.
- [148] N. Chudpooti, N. Duangrit, A. D. Burnett, J. R. Freeman, T. B. Gill, C. Phongcharoenpanich, U. Imberg, D. Torrungrueng, P. Akkaraekthalin, I. D. Robertson, *et al.*, "Wideband dielectric properties of silicon and glass substrates for terahertz integrated circuits and microsystems," *Materials Research Express*, vol. 8, no. 5, p. 056 201, 2021.
- [149] R. T. Ako, A. Upadhyay, W. Withayachumnankul, M. Bhaskaran, and S. Sriram, "Dielectrics for terahertz metasurfaces: Material selection and fabrication techniques," *Advanced Optical Materials*, vol. 8, no. 3, p. 1 900 750, 2020.
- [150] H. Xin and M. Liang, "3-D-Printed microwave and THz devices using polymer jetting techniques," *Proceedings of the IEEE*, vol. 105, no. 4, pp. 737–755, 2017.
- [151] C. H. Brodie, I. Spotts, H. Reguigui, C. A. Leclerc, M. E. Mitchell, J. F. Holzman, and C. M. Collier, "Comprehensive study of 3D printing materials over the terahertz regime: Absorption coefficient and refractive index characterizations," *Optical Materials Express*, vol. 12, no. 9, pp. 3379–3402, 2022.
- [152] T. Whittaker, S. Zhang, A. Powell, C. J. Stevens, J. Y. C. Vardaxoglou, and W. Whittow, "3D printing materials and techniques for antennas and metamaterials: A survey of the latest advances," *IEEE Antennas and Propagation Magazine*, vol. 65, no. 3, pp. 10–20, 2023.
- [153] E. Castro-Camus, M. Koch, and A. I. Hernandez-Serrano, "Additive manufacture of photonic components for the terahertz band," *Journal of Applied Physics*, vol. 127, no. 21, p. 210 901, Jun. 2020.
- [154] A. L. S. Cruz, C. M. B. Cordeiro, and M. A. R. Franco, "3D printed hollow-core terahertz fibers," *Fibers*, vol. 6, no. 3, 2018.
- [155] S. Atakaramians, S. A. V., H. Ebendorff-Heidepriem, M. Nagel, B. M. Fischer, D. Abbott, and T. M. Monro, "THz porous fibers: Design, fabrication and experimental characterization," *Optics Express*, vol. 17, no. 16, pp. 14 053–14 062, 2009.
- [156] B. Chen, W. Wei, J. Shao, B. Xu, H. Zhu, G. Xu, and C. Wu, "Spatially, spectrally single-mode and mechanically flexible 3D-printed terahertz transmission waveguides," *IEEE Photonics Journal*, vol. 14, no. 1, pp. 1–7, 2022.
- [157] A. Kaur, J. C. Myers, M. I. M. Ghazali, J. Byford, and P. Chahal, "Affordable terahertz components using 3D printing," in *2015 IEEE 65th Electronic Components and Technology Conference (ECTC)*, 2015, pp. 2071–2076.
- [158] M. Weidenbach, D. Jahn, A. Rehn, S. F. Busch, F. Beltrán-Mejía, J. C. Balzer, and M. Koch, "3D printed dielectric rectangular waveguides, splitters and couplers for 120 GHz," *Optics Express*, vol. 24, no. 25, pp. 28 968–28 976, 2016.
- [159] D. Jahn, M. Weidenbach, J. Lehr, L. Becker, F. Beltrán-Mejía, S. F. Busch, J. C. Balzer, and M. Koch, "3D printed terahertz focusing grating couplers," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 38, pp. 708–716, 2017.
- [160] J. Dai, J. Zhang, W. Zhang, and D. Grischkowsky, "Terahertz time-domain spectroscopy characterization of the far-infrared absorption and index of refraction of high-resistivity, float-zone silicon," *Journal of the Optical Society America B*, vol. 21, no. 7, pp. 1379–1386, 2004.
- [161] J. Ornik, M. Sakaki, M. Koch, J. C. Balzer, and N. Benson, "3D printed Al₂O₃ for terahertz technology," *IEEE Access*, vol. 9, pp. 5986–5993, 2021.

- [162] K. Berdel, J. Rivas, P. Bolivar, P. de Maagt, and H. Kurz, "Temperature dependence of the permittivity and loss tangent of high-permittivity materials at terahertz frequencies," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 4, pp. 1266–1271, 2005.
- [163] N. Matsumoto, T. Hosokura, K. Kageyama, H. Takagi, Y. Sakabe, and M. Hangyo, "Analysis of dielectric response of TiO_2 in terahertz frequency region by general harmonic oscillator model," *Japanese Journal of Applied Physics*, vol. 47, no. 9S, p. 7725, 2008.
- [164] D. Headland, M. Fujita, G. Carpintero, T. Nagatsuma, and W. Withayachumnankul, "Terahertz integration platforms using substrateless all-silicon microstructures," *APL Photonics*, vol. 8, no. 9, art. no. 091101, 2023.
- [165] H. Amarloo and S. Safavi-Naeini, "Terahertz line defect waveguide based on silicon-on-glass technology," *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 4, pp. 433–439, 2017.
- [166] H. Amarloo, N. Ranjkesh, and S. Safavi-Naeini, "Terahertz silicon-BCB-quartz dielectric waveguide: An efficient platform for compact THz systems," *IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 2, pp. 201–208, 2018.
- [167] K. Tsuruda, M. Fujita, and T. Nagatsuma, "Extremely low-loss terahertz waveguide based on silicon photonic-crystal slab," *Optics Express*, vol. 23, no. 25, pp. 31 977–31 990, 2015.
- [168] W. Gao, W. S. L. Lee, X. Yu, M. Fujita, T. Nagatsuma, C. Fumeaux, and W. Withayachumnankul, "Characteristics of effective-medium-clad dielectric waveguides," *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 1, pp. 28–41, 2021.
- [169] H. Lees, D. Headland, and W. Withayachumnankul, "Terahertz extreme skin-depth waveguides," *IEEE Transactions on Terahertz Science and Technology*, vol. 14, no. 5, pp. 758–767, 2024.
- [170] H. Lees, D. Headland, S. Murakami, M. Fujita, and W. Withayachumnankul, "Terahertz radar with all-dielectric leaky-wave antenna," *APL Photonics*, vol. 9, no. 3, p. 036 107, Mar. 2024.
- [171] H. Lees, C. Hayes, and W. Withayachumnankul, "Terahertz coherence tomography for in-container liquid characterization," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 29, no. 5: Terahertz Photonics, art. no. 8600408, 2023.
- [172] O. L. Krivanek and J. H. Mazur, "The structure of ultrathin oxide on silicon," *Applied Physics Letters*, vol. 37, no. 4, pp. 392–394, 1980.
- [173] A. Sproul and M. Green, "Intrinsic carrier concentration and minority-carrier mobility of silicon from 77 to 300 K," *Journal of Applied Physics*, vol. 73, no. 3, pp. 1214–1225, 1993.
- [174] J. Vedde, T. Clausen, and L. Jensen, "Float-zone silicon for high volume production of solar cells," in *3rd World Conference on Photovoltaic Energy Conversion, 2003. Proceedings of, IEEE*, vol. 1, 2003, pp. 943–946.
- [175] R. Koala, R. Maru, K. Iyoda, L. Yi, M. Fujita, and T. Nagatsuma, "Ultra-low-loss and broadband all-silicon dielectric waveguides for WR-1 band (0.75–1.1 THz) modules," in *Photonics*, vol. 9, 2022, p. 515.
- [176] S. Shekhar, W. Bogaerts, L. Chrostowski, J. E. Bowers, M. Hochberg, R. Soref, and B. J. Shastri, "Roadmapping the next generation of silicon photonics," *Nature Communications*, vol. 15, no. 1, p. 751, 2024.
- [177] B. E. Deal and A. Grove, "General relationship for the thermal oxidation of silicon," *Journal of Applied Physics*, vol. 36, no. 12, pp. 3770–3778, 1965.
- [178] R. Adar, M. Serbin, and V. Mizrahi, "Less than 1 dB per meter propagation loss of silica waveguides measured using a ring resonator," *Journal of Lightwave Technology*, vol. 12, no. 8, pp. 1369–1372, 1994.
- [179] N. Ranjkesh, M. Basha, A. Taeb, A. Zandieh, S. Gigoyan, and S. Safavi-Naeini, "Silicon-on-glass dielectric waveguide—part I: For millimeter-wave integrated circuits," *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 2, pp. 268–279, 2015.

- [180] N. Ranjkesh, H. Amarloo, S. Gigoyan, N. Ghafarian, M. A. Basha, and S. Safavi-Naeini, "1.1 THz U-Silicon-On-Glass (U-SOG) waveguide: A low-loss platform for THz high-density integrated circuits," *IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 6, pp. 702–709, 2018.
- [181] W. Ayres, P. Vartanian, and A. Helgesson, "Propagation in dielectric slab loaded rectangular waveguide," *IRE Transactions on Microwave Theory and Techniques*, vol. 6, no. 2, pp. 215–222, 1958.
- [182] K. Nanjyo, Y. Kawamoto, H. Kitagawa, D. Headland, M. Fujita, and K. Kitamura, "Deflection of electromagnetic waves by pseudogravity in distorted photonic crystals," *Physical Review A*, vol. 108, p. 033 522, 3 2023.
- [183] T. Sagisaka, R. Kaname, M. Kikuchi, N. Kukutsu, D. Headland, L. Yi, M. Fujita, and T. Nagatsuma, "Integrated terahertz optics with effective medium for 600-GHz-band imaging," in *2020 International Topical Meeting on Microwave Photonics (MWP)*, IEEE, 2020, pp. 62–65.
- [184] D. Headland, W. Withayachumnankul, M. Fujita, and T. Nagatsuma, "Terahertz slab-mode beam launchers using photonic crystal waveguides and integrated optics," in *14th Pacific Rim Conference on Lasers and Electro-Optics (CLEO PR 2020)*, Optica Publishing Group, 2020.
- [185] D. Headland, A. K. Klein, M. Fujita, and T. Nagatsuma, "Dielectric slot-coupled half-Maxwell fisheye lens as octave-bandwidth beam expander for terahertz-range applications," *APL Photonics*, vol. 6, no. 9, p. 096 104, Sep. 2021.
- [186] R. Kakimi, M. Fujita, M. Nagai, M. Ashida, and T. Nagatsuma, "Capture of a terahertz wave in a photonic-crystal slab," *Nature Photonics*, vol. 8, no. 8, pp. 657–663, 2014.
- [187] C. M. Yee and M. S. Sherwin, "High-Q terahertz microcavities in silicon photonic crystal slabs," *Applied Physics Letters*, vol. 94, no. 15, p. 154 104, 2009.
- [188] D. Headland, M. Fujita, and T. Nagatsuma, "Bragg-mirror suppression for enhanced bandwidth in terahertz photonic crystal waveguides," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 26, no. 2, art. no. 4900109, 2019.
- [189] W. Withayachumnankul, M. Fujita, and T. Nagatsuma, "Integrated silicon photonic crystals toward terahertz communications," *Advanced Optical Materials*, vol. 6, no. 16, p. 1800 401, 2018.
- [190] Y. Yang, Y. Yamagami, X. Yu, P. Pitchappa, J. Webber, B. Zhang, M. Fujita, T. Nagatsuma, and R. Singh, "Terahertz topological photonics for on-chip communication," *Nature Photonics*, vol. 14, no. 7, pp. 446–451, 2020.
- [191] A. Kumar, M. Gupta, P. Pitchappa, N. Wang, M. Fujita, and R. Singh, "Terahertz topological photonic integrated circuits for 6G and beyond: A Perspective," *Journal of Applied Physics*, vol. 132, no. 14, p. 140 901, Oct. 2022.
- [192] T. C. Choy, *Effective Medium Theory: Principles and Applications*. Oxford University Press, 2015, vol. 165.
- [193] W. Gao, X. Yu, M. Fujita, T. Nagatsuma, C. Fumeaux, and W. Withayachumnankul, "Effective-medium-cladded dielectric waveguides for terahertz waves," *Optics Express*, vol. 27, no. 26, pp. 38 721–38 734, 2019.
- [194] E. A. J. Marcatili, "Dielectric rectangular waveguide and directional coupler for integrated optics," *The Bell System Technical Journal*, vol. 48, no. 7, pp. 2071–2102, 1969.
- [195] S. M. Hanham, M. M. Ahmad, S. Lucyszyn, and N. Klein, "Led-switchable high-q packaged THz microbeam resonators," *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 2, pp. 199–208, 2017.
- [196] D. Headland, W. Withayachumnankul, X. Yu, M. Fujita, and T. Nagatsuma, "Unclad microphotonics for terahertz waveguides and systems," *Journal of Lightwave technology*, vol. 38, no. 24, pp. 6853–6862, 2020.

- [197] V. R. Almeida, Q. Xu, C. A. Barrios, and M. Lipson, "Guiding and confining light in void nanostructure," *Optics Letters*, vol. 29, no. 11, pp. 1209–1211, 2004.
- [198] Y. Zhao, J.-H. Buchholz, T. Greuter, X. Liu, G. V. Bögel, K. Seidl, and J. C. Balzer, "Sensitive and robust millimeter-wave/terahertz photonic crystal chip for biosensing applications," *IEEE Access*, vol. 10, pp. 92 237–92 248, 2022.
- [199] R. A. Soref, J. Schmidtchen, and K. Petermann, "Large single-mode rib waveguides in GeSi-Si and Si-on-SiO₂," *IEEE Journal of Quantum Electronics*, vol. 27, no. 8, pp. 1971–1974, 1991.
- [200] J. C. Myers, A. Kaur, J. A. Byford, and P. Chahal, "Investigation of modulation-capable silicon waveguides for efficient on-wafer terahertz interconnects," in *2015 IEEE 65th Electronic Components and Technology Conference (ECTC)*, 2015, pp. 1010–1016.
- [201] A. Kumar, M. Ali, D. Headland, and G. Carpintero, "Compact and robust silicon waveguide to hollow metallic waveguide coupling using a quarter-wave dielectric slot waveguide for mmW and THz waves," in *2023 International Topical Meeting on Microwave Photonics (MWP)*, IEEE, 2023.
- [202] H. Lees, W. Gao, and W. Withayachumnankul, "All-silicon, low-cross-talk terahertz waveguide crossing based on effective medium," *Optics Letters*, vol. 46, no. 21, pp. 5469–5472, 2021.
- [203] W. Bogaerts and S. K. Selvaraja, "Compact single-mode silicon hybrid rib/strip waveguide with adiabatic bends," *IEEE Photonics Journal*, vol. 3, no. 3, pp. 422–432, 2011.
- [204] D. Headland, X. Yu, M. Fujita, and T. Nagatsuma, "Near-field out-of-plane coupling between terahertz photonic crystal waveguides," *Optica*, vol. 6, no. 8, pp. 1002–1011, 2019.
- [205] W.-P. Huang, "Coupled-mode theory for optical waveguides: An overview," *Journal of the Optical Society of America B*, vol. 11, no. 3, pp. 963–983, 1994.
- [206] M. Gupta, A. Kumar, P. Pitchappa, Y. J. Tan, P. Szriftgiser, G. Ducournau, and R. Singh, "150 gbps THz chipscale topological photonic diplexer," *Advanced Materials*, vol. 36, no. 19, p. 2309497, 2024.
- [207] P. Dechwechprasit, C. Fumeaux, and W. Withayachumnankul, "Integrated resonant cavities on substrateless terahertz dielectric waveguide platform," in *2021 46th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, 2021.
- [208] P. Dechwechprasit, R. T. Ako, S. Sriram, C. Fumeaux, and W. Withayachumnankul, "Terahertz disk resonator on a substrateless dielectric waveguide platform," *Optics Letters*, vol. 48, no. 17, pp. 4685–4688, 2023.
- [209] S. M. Hanham, C. Watts, W. J. Otter, S. Lucyszyn, and N. Klein, "Dielectric measurements of nanoliter liquids with a photonic crystal resonator at terahertz frequencies," *Applied Physics Letters*, vol. 107, no. 3, p. 032903, Jul. 2015.
- [210] S. M. Hanham, J.-H. Buchholz, H. Fischer, U. Gollor, J. Lehmke, W. Wischmann, I. Ghosh, E. Lia, B. Walter, F. Bavedila, *et al.*, "Low dielectric filling factor millimeter-wave photonic crystal resonator micromachined from NTD high-resistivity silicon," *IEEE Transactions on Microwave Theory and Techniques*, 2024.
- [211] K. Honda, E. Garmire, and K. Wilson, "Characteristics of an integrated optics ring resonator fabricated in glass," *Journal of Lightwave Technology*, vol. 2, no. 5, pp. 714–719, 1984.
- [212] P. Dechwechprasit, H. Lees, D. Headland, C. Fumeaux, and W. Withayachumnankul, "1-to-N terahertz integrated switches enabling multi-beam antennas," *Optica*, vol. 10, no. 11, pp. 1551–1558, 2023.
- [213] A. Yariv, "Critical coupling and its control in optical waveguide-ring resonator systems," *IEEE Photonics Technology Letters*, vol. 14, no. 4, pp. 483–485, 2002.
- [214] Y. Rui, S. Zhou, X. Tu, X. Yan, B. Yan, C. Zhang, Z. Ye, H. Zhang, J. Xie, Q.-Y. Zhao, L.-B. Zhang, X.-Q. Jia, H. Wang, L. Kang, J. Chen, and P. Wu, "All-silicon low-loss THz temporal differentiator based on microring waveguide resonator platform," *Light: Advanced Manufacturing*, vol. 5, no. LAM2023090066, p. 1, 2024.

- [215] J. Xie, X. Zhu, X. Zang, Q. Cheng, L. Chen, and Y. Zhu, "Terahertz integrated device: high- Q silicon dielectric resonators," *Optics Materials Express*, vol. 8, no. 1, pp. 50–58, 2018.
- [216] Z. Wang, S. Yuan, G. Dong, R. Wang, L. Chen, X. Wu, and X. Zhang, "On-chip single-mode high- Q terahertz whispering gallery mode resonator," *Optics Letters*, vol. 44, no. 11, pp. 2835–2838, 2019.
- [217] W. Bogaerts, P. De Heyn, T. Van Vaerenbergh, K. De Vos, S. Kumar Selvaraja, T. Claes, P. Dumon, P. Bienstman, D. Van Thourhout, and R. Baets, "Silicon microring resonators," *Laser & Photonics Reviews*, vol. 6, no. 1, pp. 47–73, 2012.
- [218] Y. Kawamoto, T. Yoshioka, N. Shibata, D. Headland, M. Fujita, R. Koma, R. Igarashi, K. Hara, J.-I. Kani, and T. Nagatsuma, "300-GHz-band diplexer for frequency-division multiplexed wireless communication," *IEICE Transactions on Electronics*, vol. 106, no. 11, pp. 722–726, 2023.
- [219] W. Gao, W. S. Lee, C. Fumeaux, and W. Withayachumnankul, "Effective-medium-clad Bragg grating filters," *APL Photonics*, vol. 6, no. 7, 2021.
- [220] V. Petrov, T. Kurner, and I. Hosako, "IEEE 802.15. 3d: First standardization efforts for sub-terahertz band communications toward 6G," *IEEE Communications Magazine*, vol. 58, no. 11, pp. 28–33, 2020.
- [221] D. Headland, W. Withayachumnankul, M. Fujita, and T. Nagatsuma, "Gratingless integrated tunneling multiplexer for terahertz waves," *Optica*, vol. 8, no. 5, pp. 621–629, 2021.
- [222] D. Headland, W. Withayachumnankul, M. Fujita, T. Nagatsuma, P. Szriftgiser, and G. Ducournau, "200 Gbit/s terahertz tunneling demultiplexer in 300 GHz band," in *2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2023.
- [223] L. Chen, W. Gao, C. Fumeaux, and W. Withayachumnankul, "Compact broadband terahertz filter based on effective medium," in *2023 5th Australian Microwave Symposium (AMS)*, 2023.
- [224] J. He, D. Liu, B. Pan, Y. Huang, M. Zhu, M. Zhang, and D. Dai, "High-performance lithium-niobate-on-insulator optical filter based on multimode waveguide gratings," *Optics Express*, vol. 30, no. 19, pp. 34 140–34 148, 2022.
- [225] W. Gao, C. Fumeaux, and W. Withayachumnankul, "Terahertz integrated polarization beam splitter based on effective-medium waveguide," in *2021 IEEE Asia-Pacific Microwave Conference (APMC)*, IEEE, 2021, pp. 100–102.
- [226] W. Gao, W. Withayachumnankul, M. Fujita, and T. Nagatsuma, "Terahertz integrated polarization rotator based on effective-medium-clad waveguide," in *2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2023.
- [227] W. Deng, L. Chen, S. Yuan, Y. Wang, R. Wang, Z. Wang, Y. Yu, X. Wu, and X. Zhang, "Silicon-based integrated terahertz polarization beam splitters," *J. Lightwave Technol.*, vol. 40, no. 1, pp. 170–178, 2022.
- [228] W. Deng, L. Chen, H. Zhang, S. Wang, Z. Lu, S. Liu, Z. Yang, Z. Wang, S. Yuan, Y. Wang, R. Wang, Y. Yu, X. Wu, X. Yu, and X. Zhang, "On-chip polarization- and frequency-division demultiplexing for multidimensional terahertz communication," *Laser & Photonics Reviews*, vol. 16, no. 10, p. 2 200 136, 2022.
- [229] W. Gao, M. Fujita, S. Murakami, T. Nagatsuma, C. Fumeaux, and W. Withayachumnankul, "Ultra-wideband terahertz integrated polarization multiplexer," *Laser & Photonics Reviews*, art. no. 2400270 (In press),
- [230] L. Jia, T.-Y. Liow, J. Song, X. Luo, N. Duan, S. C. Koh, Q. Fang, M. Yu, and G. Lo, "Compact optical polarization rotators based on an asymmetric silicon waveguide," *IEEE Photonics Technology Letters*, vol. 25, no. 22, pp. 2229–2232, 2013.
- [231] W. Withayachumnankul, R. Yamada, M. Fujita, and T. Nagatsuma, "All-dielectric rod antenna array for terahertz communications," *APL Photonics*, vol. 3, no. 5, Apr. 2018, 051707.

- [232] D. Headland, W. Withayachumnankul, R. Yamada, M. Fujita, and T. Nagatsuma, "Terahertz multi-beam antenna using photonic crystal waveguide and Luneburg lens," *APL Photonics*, vol. 3, no. 12, Dec. 2018, 126105.
- [233] D. Headland, X. Yu, M. Nagai, M. Fujita, and T. Nagatsuma, "Packaged dish antenna for wireless terahertz photonic crystal waveguide devices," in *2020 International Symposium on Antennas and Propagation (ISAP)*, 2021, pp. 15–16.
- [234] D. Headland, A. Kumar, H. Lees, W. Withayachumnankul, and G. Carpintero, "Matched dielectric slot waveguide as an all-dielectric terahertz magnetic dipole," *Optics Letters*, vol. 49, no. 5, pp. 1361–1364, 2024.
- [235] H. M. Santos, E. D. Lima, P. Pinho, L. M. Pessoa, D. Moro-Melgar, and H. M. Salgado, "Scalable high-gaussicity split-block diagonal horn antenna for integration with sub-THz devices," in *2019 16th European Radar Conference (EuRAD)*, 2019, pp. 353–356.
- [236] D. Filipovic, S. Gearhart, and G. Rebeiz, "Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses," *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, no. 10, pp. 1738–1749, 1993.
- [237] R. Koala, D. Headland, M. Fujita, and T. Nagatsuma, "Dish-antenna-integrated resonant tunneling diode module for terahertz wireless applications," *Proceedings of the XXXIVth URSI General Assembly*, 2021.
- [238] A. Kumar, D. C. Gallego, D. Headland, M. Ali, N. Xenidis, D. Lioubtchenko, and G. Carpintero, "Contactless cost-effective polarizer for mm-wave dielectric rod waveguide," in *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, 2022.
- [239] J. Barowski, L. Schmitt, K. Kother, and M. Hoffmann, "Design, simulation, and characterization of MEMS-based slot waveguides," *IEEE Transactions on Microwave Theory and Techniques*, vol. 71, no. 9, pp. 3819–3828, 2023.
- [240] A. Kumar, D. C. Gallego, M. Ali, A. Rivera-Lavado, D. Headland, and G. Carpintero, "Broadband 770° phase shifter for mm-waves using controllable delocalization of modal fields in a dielectric rod waveguide," in *2023 IEEE/MTT-S International Microwave Symposium - IMS 2023*, 2023, pp. 732–735.
- [241] U. Shah, E. Decrossas, C. Jung-Kubiak, T. Reck, G. Chattopadhyay, I. Mehdi, and J. Oberhammer, "Submillimeter-wave 3.3-bit RF MEMS phase shifter integrated in micromachined waveguide," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 5, pp. 706–715, 2016.
- [242] S. Rahiminejad, M. Alonso-delPino, T. J. Reck, A. Peralta, R. Lin, C. Jung-Kubiak, and G. Chattopadhyay, "A low-loss silicon MEMS phase shifter operating in the 550-GHz band," *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 5, pp. 477–485, 2021.
- [243] U. Shah, T. Reck, H. Frid, C. Jung-Kubiak, G. Chattopadhyay, I. Mehdi, and J. Oberhammer, "A 500-750 GHz RF MEMS waveguide switch," *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 3, pp. 326–334, 2017.
- [244] Y. Wang, J. Hu, and Y. Luo, "A terahertz tunable waveguide bandpass filter based on bimorph microactuators," *IEEE Microwave and Wireless Components Letters*, vol. 29, no. 2, pp. 110–112, 2019.
- [245] L. Schmitt, J. Barowski, and M. Hoffmann, "THz phase shifter based on MEMS-actuated slot waveguides," in *2022 Fifth International Workshop on Mobile Terahertz Systems (IWMTS)*, 2022, pp. 1–4.
- [246] X. Zhao, U. Shah, O. Glubokov, and J. Oberhammer, "Micromachined subterahertz waveguide-integrated phase shifter utilizing supermode propagation," *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 7, pp. 3219–3227, 2021.

- [247] C Siegel, V Ziegler, C Von Wächter, B Schönlinner, U Prectel, and H Schumacher, “Switching speed analysis of low complexity RF-MEMS switches,” in *Proceedings of German Microwave Conference (GeMiC)*, 2006, pp. 28–30.
- [248] A. Verger, A. Pothier, C. Guines, P. Blondy, O. Vendier, and F. Courtade, “Nanogap MEMS micro-relay with 70 ns switching speed,” in *2012 IEEE 25th International Conference on Micro Electro Mechanical Systems (MEMS)*, 2012, pp. 717–720.
- [249] Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, “Micrometre-scale silicon electro-optic modulator,” *Nature*, vol. 435, no. 7040, pp. 325–327, 2005.
- [250] L. Alloatti, D. Korn, R. Palmer, D. Hillerkuss, J. Li, A. Barklund, R. Dinu, J. Wieland, M. Fournier, J. Fedeli, *et al.*, “42.7 gbit/s electro-optic modulator in silicon technology,” *Optics Express*, vol. 19, no. 12, pp. 11 841–11 851, 2011.
- [251] D. W. Vogt, A. H. Jones, and R. Leonhardt, “Thermal tuning of silicon terahertz whispering-gallery mode resonators,” *Applied Physics Letters*, vol. 113, no. 1, p. 011 101, Jul. 2018.
- [252] S. Seliverstov, S. Svyatodukh, and G. Goltsman, “Thermal phase shift in THz silicon effective-medium waveguide,” *Applied Physics Letters*, vol. 123, no. 9, p. 092 202, Sep. 2023.
- [253] N. C. Harris, Y. Ma, J. Mower, T. Baehr-Jones, D. Englund, M. Hochberg, and C. Galland, “Efficient, compact and low loss thermo-optic phase shifter in silicon,” *Optics Express*, vol. 22, no. 9, pp. 10 487–10 493, 2014.
- [254] S. Seliverstov, A. Kozhukhovskiy, S. Svyatodukh, and G. Goltsman, “Terahertz phased array antenna based on integrated taper emitters,” *Applied Physics Letters*, vol. 124, no. 12, p. 121 106, Mar. 2024.
- [255] A. Kumar, M. Gupta, P. Pitchappa, N. Wang, P. Szriftgiser, G. Ducournau, and R. Singh, “Phototunable chip-scale topological photonics: 160 gbps waveguide and demultiplexer for THz 6G communication,” *Nature Communications*, vol. 13, no. 1, p. 5404, 2022.
- [256] M. Van Exter and D. Grischkowsky, “Carrier dynamics of electrons and holes in moderately doped silicon,” *Physical Review B*, vol. 41, no. 17, p. 12 140, 1990.
- [257] K. Willis, S. Hagness, and I. Knezevic, “A generalized drude model for doped silicon at terahertz frequencies derived from microscopic transport simulation,” *Applied Physics Letters*, vol. 102, no. 12, 2013.
- [258] T.-I. Jeon and D. Grischkowsky, “Nature of conduction in doped silicon,” *Physical Review Letters*, vol. 78, pp. 1106–1109, 6 1997.
- [259] A. Kannegulla, M. I. B. Shams, L. Liu, and L.-J. Cheng, “Photo-induced spatial modulation of THz waves: Opportunities and limitations,” *Optics Express*, vol. 23, no. 25, pp. 32 098–32 112, 2015.
- [260] L. Fekete, J. Hlinka, F. Kadlec, P. Kužel, and P. Mounaix, “Active optical control of the terahertz reflectivity of high-resistivity semiconductors,” *Optics Letters*, vol. 30, no. 15, pp. 1992–1994, 2005.
- [261] I. Hooper, N. Grant, L. Barr, S. Horne, J. D. Murphy, and E. Hendry, “High efficiency photomodulators for millimeter wave and THz radiation,” *Scientific Reports*, vol. 9, no. 1, p. 18 304, 2019.
- [262] Y. Deng, Y. Shi, P. Li, P. Fay, L.-J. Cheng, and L. Liu, “A cost-effective approach for achieving subwavelength THz imaging using photoinduced coded-apertures on mesa-array structures,” *IEEE Transactions on Terahertz Science and Technology*, vol. 12, no. 6, pp. 658–666, 2022.
- [263] K. Sasao and Y. Monnai, “Variable terahertz attenuator integrated on nonradiative guide using photoinduced carriers,” *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 3, pp. 256–259, 2020.

- [264] M. J. W. Rodwell, J. Rode, H. W. Chiang, P. Choudhary, T. Reed, E. Bloch, S. Danesgar, H.-C. Park, A. C. Gossard, B. J. Thibeault, W. Mitchell, M. Urteaga, Z. Griffith, J. Hacker, M. Seo, and B. Brar, "THz indium phosphide bipolar transistor technology," in *2012 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*, 2012, pp. 1–4.
- [265] K. Ahi, "Review of GaN-based devices for terahertz operation," *Optical Engineering*, vol. 56, no. 9, p. 090 901, 2017.
- [266] S. Iwamatsu, M. Ali, J. L. Fernandez-Estevez, M. Grzeslo, I. Mohammad, S. Makhlof, G. Carpintero, and A. Stöhr, "Integrated ultra-broadband THz photodiode with silicon rod waveguide interface," in *2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, IEEE, 2023.
- [267] X. Yu, T. Ohira, J.-Y. Kim, M. Fujita, and T. Nagatsuma, "Waveguide-input resonant tunnelling diode mixer for THz communications," *Electronics Letters*, vol. 56, no. 7, pp. 342–344, 2020.
- [268] T. Umezawa, A. Kanno, K. Akahane, A. Matsumoto, N. Yamamoto, and T. Kawanishi, "Study of high power generation in UTC-PD at 110-210 GHz," in *Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XI*, SPIE, vol. 10531, 2018, pp. 132–138.
- [269] S. Nellen, S. Lauck, E. Peytavit, P. Szriftgiser, M. Schell, G. Ducournau, and B. Globisch, "Coherent wireless link at 300 GHz with 160 Gbit/s enabled by a photonic transmitter," *Journal of Lightwave Technology*, vol. 40, no. 13, pp. 4178–4185, 2022.
- [270] S. Kitagawa, M. Mizuno, S. Saito, K. Ogino, S. Suzuki, and M. Asada, "Frequency-tunable resonant-tunneling-diode terahertz oscillators applied to absorbance measurement," *Japanese Journal of Applied Physics*, vol. 56, no. 5, p. 058 002, 2017.
- [271] S. Kitagawa, S. Suzuki, and M. Asada, "Wide frequency-tunable resonant tunnelling diode terahertz oscillators using varactor diodes," *Electronics Letters*, vol. 52, no. 6, pp. 479–481, 2016.
- [272] D. J. Headland, Y. Nishida, X. Yu, M. Fujita, and T. Nagatsuma, "Terahertz oscillator chips backside-coupled to unclad microphotronics," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 29, no. 3, art. no. 8500111, 2023.
- [273] X. Yu, D. Headland, Y. Nishida, R. A.S. D. Koala, J. Kim, M. Fujita, and T. Nagatsuma, "Hybrid integration between resonant tunneling diodes and unclad microphotonic diplexer for dual-channel coherent terahertz receiver," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 28, no. 3, art. no. 8500210, 2022.
- [274] Y. Kawamoto, K. Kawaguchi, M. Tanaka, Y. Nishida, M. Fujita, and T. Nagatsuma, "Integration of terahertz resonant tunneling diode with broadband dielectric waveguide using corrugated mode converter," in *2023 Asia-Pacific Microwave Conference (APMC)*, 2023, pp. 655–657.
- [275] N. H. Ngo, Y. Inose, Y. Kawamoto, Y. Nishida, M. Fujita, and T. Nagatsuma, "WR-2.2-band (330-500 GHz) packaged resonant tunneling diode receiver module for terahertz communications," in *2023 Asia-Pacific Microwave Conference (APMC)*, 2023, pp. 399–401.
- [276] Y. Takida, S. Suzuki, M. Asada, and H. Minamide, "Sensitive terahertz-wave detector responses originated by negative differential conductance of resonant-tunneling-diode oscillator," *Applied Physics Letters*, vol. 117, no. 2, 2020.
- [277] A. E. Torres-García, J. M. Pérez-Escudero, J. Teniente, R. Gonzalo, and I. Ederra, "Silicon integrated subharmonic mixer on a photonic-crystal platform," *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 1, pp. 79–89, 2021.
- [278] D. Headland, M. Ali, D. C. Gallego, and G. Carpintero, "Broadband liquid sensing of sealed microfluidic channel using mm-wave dielectric rod waveguide," in *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, 2022.
- [279] Y. Zhao, K. Vora, X. Liu, G. v. Bögel, K. Seidl, and J. C. Balzer, "Photonic crystal resonator in the millimeter/terahertz range as a thin film sensor for future biosensor applications," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 43, no. 5, pp. 426–444, 2022.

- [280] S. Iwamatsu, D. Headland, I. Mohammad, M. Fujita, and A. Stöhr, “THz near-field imaging sensor using integrated substrateless silicon interferometer,” in *2024 15th German Microwave Conference (GeMiC)*, 2024, pp. 221–224.
- [281] S. Jia, L. Zhang, S. Wang, W. Li, M. Qiao, Z. Lu, N. M. Idrees, X. Pang, H. Hu, X. Zhang, L. K. Oxenløwe, and X. Yu, “2 x 300 Gbit/s line rate PS-64QAM-OFDM THz photonic-wireless transmission,” *Journal of Lightwave Technology*, vol. 38, no. 17, pp. 4715–4721, 2020.
- [282] J. Dittmer, J. Tebart, C. Füllner, C. Koos, A. Stöhr, and S. Randel, “200 Gbit/s wireless THz transmission over 52m using optoelectronic signal generation,” in *2023 53rd European Microwave Conference (EuMC)*, 2023, pp. 134–137.
- [283] D. Headland, W. Withayachumnankul, M. Fujita, and T. Nagatsuma, “Gratingless integrated tunneling multiplexer for terahertz waves,” *Optica*, vol. 8, no. 5, pp. 621–629, 2021.
- [284] C.-Y. Liu, H.-E. Ding, S.-H. Wu, and T.-L. Wu, “Significant crosstalk reduction in high-density hollow dielectric waveguides by photonic crystal fence,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 2, pp. 1316–1326, 2021.
- [285] H. Zafar, B. Paredes, I. Taha, J. E. Villegas, M. Rasras, and M. F. Pereira, “Compact and broadband adiabatically bent superlattice-waveguides with negligible insertion loss and ultra-low crosstalk,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 29, no. 6, art. no. 4400109, 2023.
- [286] M. Mrejen, H. Suchowski, T. Hatakeyama, C. Wu, L. Feng, K. O’Brien, Y. Wang, and X. Zhang, “Adiabatic elimination-based coupling control in densely packed subwavelength waveguides,” *Nature Communications*, vol. 6, no. 1, art. no. 7565, 2015.
- [287] S. Jahani and Z. Jacob, “Transparent subdiffraction optics: Nanoscale light confinement without metal,” *Optica*, vol. 1, no. 2, pp. 96–100, 2014.
- [288] S. Jahani, S. Kim, J. Atkinson, J. C. Wirth, F. Kalhor, A. A. Noman, W. D. Newman, P. Shekhar, K. Han, V. Van, R. G. DeCorby, L. Chrostowski, M. Qi, and Z. Jacob, “Controlling evanescent waves using silicon photonic all-dielectric metamaterials for dense integration,” *Nature Communications*, vol. 9, no. 1, art. no. 1893, 2018.
- [289] M. F. Kabir, M. B. Mia, I. Ahmed, N. Jaidye, S. Z. Ahmed, and S. Kim, “Anisotropic leaky-like perturbation with subwavelength gratings enables zero crosstalk,” *Light: Science & Applications*, vol. 12, no. 1, art. no. 135, 2023.
- [290] S. Z. Ahmed, I. Ahmed, M. B. Mia, N. Jaidye, and S. Kim, “Ultra-high extinction ratio polarization beam splitter with extreme skin-depth waveguide,” *Optics Letters*, vol. 46, no. 9, p. 2164, 2021.
- [291] M. B. Mia, S. Z. Ahmed, N. Jaidye, I. Ahmed, and S. Kim, “Mode-evolution-based ultra-broadband polarization beam splitter using adiabatically tapered extreme skin-depth waveguide,” *Optics Letters*, vol. 46, no. 18, pp. 4490–4493, 2021.
- [292] I. Ahmed, S. Z. Ahmed, N. Jaidye, M. B. Mia, A. Bernussi, and S. Kim, “High-density integrated delay line using extreme skin-depth subwavelength grating waveguides,” *Optics Letters*, vol. 48, no. 7, pp. 1662–1665, 2023.
- [293] A. Jäckel, D. Ulm, T. Kleine-Ostmann, E. Castro-Camus, M. Koch, and J. Ornik, “Achromatic quarter-waveplate for the terahertz frequency range made by 3D printing,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 43, no. 7, pp. 573–581, 2022.
- [294] D. Hale, “The physical properties of composite materials,” *Journal of materials science*, vol. 11, pp. 2105–2141, 1976.
- [295] S. M. Rytov, “Electromagnetic properties of a finely stratified medium,” *3*, vol. 2, 1956, pp. 466–475.

- [296] S. Iwamatsu, M. Ali, J. L. Fernández-Estévez, J. Tebart, A. Kumar, S. Makhoulouf, G. Carpintero, and A. Stöhr, “Ultra-wideband multi-octave planar interconnect for multi-band THz communications,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 44, no. 7-8, pp. 532–550, 2023.
- [297] Y. Rui, S. Zhou, X. Tu, X. Yan, B. Yan, C. Zhang, Z. Ye, H. Zhang, J. Xie, Q.-Y. Zhao, *et al.*, “All-silicon low-loss THz temporal differentiator based on microring waveguide resonator platform,”
- [298] M. Mittendorff, S. Li, and T. E. Murphy, “Graphene-based waveguide-integrated terahertz modulator,” *ACS Photonics*, vol. 4, no. 2, pp. 316–321, 2017.
- [299] H. Huang, K. Liu, B. Qi, and V. J. Sorger, “Re-analysis of single-mode conditions for silicon rib waveguides at 1550 nm wavelength,” *Journal of Lightwave Technology*, vol. 34, no. 16, pp. 3811–3817, 2016.
- [300] P. Müllner and R. Hainberger, “Single-mode criterion for rib waveguides with small cross sections,” in *Physics and Simulation of Optoelectronic Devices XIV*, SPIE, vol. 6115, 2006, pp. 436–443.
- [301] K. Tsuruda, M. Fujita, and T. Nagatsuma, “Extremely low-loss terahertz waveguide based on silicon photonic-crystal slab,” *Optics Express*, vol. 23, no. 25, pp. 31 977–31 990, 2015.
- [302] D. Dai and S. He, “Analysis of characteristics of bent rib waveguides,” *Journal of the Optical Society of America A*, vol. 21, no. 1, pp. 113–121, 2004.
- [303] A. Brimont, X. Hu, S. Cuffe, P. R. Romeo, G. Saint Girons, A. Griol, A. Zanzi, P. Sanchis, and R. Orobtcouk, “Low-loss and compact silicon rib waveguide bends,” *IEEE Photonics Technology Letters*, vol. 28, no. 3, pp. 299–302, 2015.
- [304] *Lithoz GmbH*, <https://lithoz.com/en/3d-printer/overview/>, Accessed: 2024-05-27.
- [305] *Lithoz 360*, <https://lithoz.com/en/materials/lithalox-360/>, Accessed: 2024-05-27.
- [306] A. C. Turner, C. Manolatou, B. S. Schmidt, M. Lipson, M. A. Foster, J. E. Sharping, and A. L. Gaeta, “Tailored anomalous group-velocity dispersion in silicon channel waveguides,” *Optics express*, vol. 14, no. 10, pp. 4357–4362, 2006.
- [307] C. V. Poulton, A. Yaacobi, D. B. Cole, M. J. Byrd, M. Raval, D. Vermeulen, and M. R. Watts, “Coherent solid-state LIDAR with silicon photonic optical phased arrays,” *Optics Letters*, vol. 42, no. 20, pp. 4091–4094, 2017.
- [308] F. Morichetti, A. Annoni, M. Sorel, and A. Melloni, “High-sensitivity in-band OSNR monitoring system integrated on a silicon photonics chip,” *IEEE Photonics Technology Letters*, vol. 25, no. 19, pp. 1939–1942, 2013.
- [309] S. Schneider, M. Lauermann, P.-I. Dietrich, C. Weimann, W. Freude, and C. Koos, “Optical coherence tomography system mass-producible on a silicon photonic chip,” *Optics Express*, vol. 24, no. 2, pp. 1573–1586, 2016.
- [310] S. Zhao, W. Liu, J. Chen, Z. Ding, and Y. Shi, “Broadband arbitrary ratio power splitters based on directional couplers with subwavelength structure,” *IEEE Photonics Technology Letters*, vol. 33, no. 10, pp. 479–482, 2021.
- [311] Z. Sheng, Z. Wang, C. Qiu, L. Li, A. Pang, A. Wu, X. Wang, S. Zou, and F. Gan, “A compact and low-loss MMI coupler fabricated with CMOS technology,” *IEEE Photonics Journal*, vol. 4, no. 6, pp. 2272–2277, 2012.
- [312] D. Levy, K. H. Park, R. Scarmozzino, R. Osgood, C. Dries, P. Studenkov, and S. Forrest, “Fabrication of ultracompact 3-dB 2 x 2 MMI power splitters,” *IEEE Photonics Technology Letters*, vol. 11, no. 8, pp. 1009–1011, 1999.
- [313] D. J. Thomson, Y. Hu, G. T. Reed, and J.-M. Fedeli, “Low loss MMI couplers for high performance MZI modulators,” *IEEE Photonics Technology Letters*, vol. 22, no. 20, pp. 1485–1487, 2010.

- [314] Q. Deng, L. Liu, X. Li, and Z. Zhou, "Arbitrary-ratio 1-2 power splitter based on asymmetric multimode interference," *Optics Letters*, vol. 39, no. 19, pp. 5590–5593, 2014.
- [315] A. Zanzi, A. Brimont, A. Griol, P. Sanchis, and J. Marti, "Compact and low-loss asymmetrical multimode interference splitter for power monitoring applications," *Optics Letters*, vol. 41, no. 2, pp. 227–229, 2016.
- [316] Z. Li, X. Huang, Y. Liu, Y. Kuang, H. Guan, L. Tian, Z. Li, and W. Han, "Ultra-compact low-loss variable-ratio 1-2 power splitter with ultra-low phase deviation based on asymmetric ladder-shaped multimode interference coupler," *Optics Express*, vol. 28, no. 23, pp. 34 137–34 146, 2020.
- [317] K. Xu, L. Liu, X. Wen, W. Sun, N. Zhang, N. Yi, S. Sun, S. Xiao, and Q. Song, "Integrated photonic power divider with arbitrary power ratios," *Optics Letters*, vol. 42, no. 4, pp. 855–858, 2017.
- [318] Archimedes, *On Spirals*. 225 BCE.
- [319] A. Ebrahimi, W. Withayachumnankul, S. Al-Sarawi, and D. Abbott, "High-sensitivity metamaterial-inspired sensor for microfluidic dielectric characterization," *IEEE Sensors Journal*, vol. 14, no. 5, pp. 1345–1351, 2013.
- [320] D. W. Vogt and R. Leonhardt, "Ultra-high Q terahertz whispering-gallery modes in a silicon resonator," *APL Photonics*, vol. 3, no. 5, p. 051 702, Feb. 2018.
- [321] P. U. Jepsen, J. K. Jensen, and U. Møller, "Characterization of aqueous alcohol solutions in bottles with THz reflection spectroscopy," *Optics Express*, vol. 16, no. 13, pp. 9318–9331, 2008.
- [322] Y. Yomogida, Y. Sato, R. Nozaki, T. Mishina, and J. Nakahara, "Comparative dielectric study of monohydric alcohols with terahertz time-domain spectroscopy," *Journal of Molecular Structure*, vol. 981, no. 1-3, pp. 173–178, 2010.
- [323] K. Murano, S. Fukuma, S. Suzuki, M. Asada, W. Withayachumnankul, T. Tanaka, and Y. Monnai, "Design of terahertz leaky-wave antenna driven by resonant-tunneling diode," in *2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2017.
- [324] N. J. Karl, R. W. McKinney, Y. Monnai, R. Mendis, and D. M. Mittleman, "Frequency-division multiplexing in the terahertz range using a leaky-wave antenna," *Nature Photonics*, vol. 9, no. 11, pp. 717–720, 2015.
- [325] H. Guerboukha, R. Shrestha, J. Neronha, O. Ryan, M. Hornbuckle, Z. Fang, and D. M. Mittleman, "Efficient leaky-wave antennas at terahertz frequencies generating highly directional beams," *Applied Physics Letters*, vol. 117, no. 26, p. 261 103, 2020.
- [326] Q. L. Zhang, B. J. Chen, K. F. Chan, and C. H. Chan, "Terahertz circularly and linearly polarized leaky-wave antennas based on spin-orbit interaction of spoof surface plasmon polaritons," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 8, pp. 4347–4358, 2021.
- [327] M. Fujita and T. Nagatsuma, "Photonic crystal technology for terahertz system integration," in *Terahertz Physics, Devices, and Systems X: Advanced Applications in Industry and Defense*, M. F. Anwar, T. W. Crowe, and T. Manzur, Eds., International Society for Optics and Photonics, vol. 9856, SPIE, 2016, 98560P.
- [328] A. Suminokura, T. Ishigaki, M. Fujita, and T. Nagatsuma, "Grating coupler for terahertz-wave integrated circuits," in *Asia-Pacific Radio Science Conference (AP-RASC)*, vol. 9856, 2013, DJ2b–3.
- [329] H. Zhang, C. Liang, J. Song, C. Fu, X. Zang, L. Chen, and J. Xie, "Terahertz out-of-plane coupler based on compact spot-size converter," *Chinese Optics Letters*, vol. 20, no. 2, p. 021 301, 2022.
- [330] H. Guerboukha, M. Sakaki, R. Shrestha, J. Li, N. Benson, and D. M. Mittleman, "Photonic crystal THz leaky-wave antenna 3D-printed in alumina," in *2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2023.

- [331] M. Steeg, N. Yonemoto, J. Tebart, and A. Stöhr, “Substrate-integrated waveguide PCB leaky-wave antenna design providing multiple steerable beams in the V-band,” *Electronics*, vol. 6, no. 4, 2017.
- [332] P. Lu, T. Haddad, J. Tebart, M. Steeg, B. Sievert, J. Lackmann, A. Rennings, and A. Stöhr, “Mobile THz communications using photonic assisted beam steering leaky-wave antennas,” *Optics Express*, vol. 29, no. 14, pp. 21 629–21 638, 2021.
- [333] P. Dechwechprasit, C. Fumeaux, and W. Withayachumnankul, “Integrated disk resonator on substrateless dielectric waveguide platform for terahertz switch applications,” in *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, IEEE, 2022.
- [334] J. Liang, W. Gao, H. Lees, and W. Withayachumnankul, “All-silicon terahertz planar horn antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 11, pp. 2181–2185, 2021.
- [335] D. Headland and W. Withayachumnankul, “Continuous leakage from slow-wave structure for integrated all-dielectric uniform leaky wave antenna,” in *2022 16th European Conference on Antennas and Propagation (EuCAP)*, 2022.
- [336] S. Kim, D. A. Westly, B. J. Roxworthy, Q. Li, A. Yulaev, K. Srinivasan, and V. A. Aksyuk, “Photonic waveguide to free-space gaussian beam extreme mode converter,” *Light: Science Applications*, vol. 7, no. 1, 2018.
- [337] D. Zheng, G.-B. Wu, D. Wang, K. F. Chan, K. Wu, and C. H. Chan, “Planar leaky-wave antenna featuring wideband fixed-beam radiation and tailorable directional angle for millimeter-wave applications,” *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 4, pp. 3238–3250, 2023.
- [338] D. R. Jackson, C. Caloz, and T. Itoh, “Leaky-wave antennas,” *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2194–2206, 2012.
- [339] D. Headland and W. Withayachumnankul, “Leaky-mode analysis of micro-structured dielectric waveguides toward integrated tunneling multiplexers with enhanced bandwidth,” in *2021 IEEE Asia-Pacific Microwave Conference (APMC)*, 2021, pp. 335–337.
- [340] J. Hu and C. R. Menyuk, “Understanding leaky modes: Slab waveguide revisited,” *Advances in Optics and Photonics*, vol. 1, no. 1, pp. 58–106, 2009.
- [341] S. J. Jang, Y. M. Song, C. I. Yeo, C. Y. Park, J. S. Yu, and Y. T. Lee, “Antireflective property of thin film a-Si solar cell structures with graded refractive index structure,” *Optics Express*, vol. 19, no. S2, A108–A117, 2011.
- [342] W. H. Southwell, “Gradient-index antireflection coatings,” *Optics Letters*, vol. 8, no. 11, pp. 584–586, 1983.
- [343] J. K. Kim, A. N. Noemaun, F. W. Mont, D. Meygaard, E. F. Schubert, D. J. Poxson, H. Kim, C. Sone, and Y. Park, “Elimination of total internal reflection in GaInN light-emitting diodes by graded-refractive-index micropillars,” *Applied Physics Letters*, vol. 93, no. 22, 2008, 221111.
- [344] B. E. Saleh and M. C. Teich, *Fundamentals of Photonics*. John Wiley & Sons, 2019.
- [345] S. F. Busch, M. Weidenbach, J. C. Balzer, and M. Koch, “THz optics 3D printed with topas,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 37, pp. 303–307, 2016.
- [346] A. Sengupta, A. Bandyopadhyay, B. Bowden, J. Harrington, and J. Federici, “Characterisation of olefin copolymers using terahertz spectroscopy,” *Electronics Letters*, vol. 42, no. 25, p. 1, 2006.
- [347] D. Zwyssig, E. Hack, P. Zolliker, and E. Mavrona, “3D printed microfluidic devices using topas filament for THz spectroscopic measurements,” *Optical Materials Express*, vol. 13, no. 4, pp. 1031–1040, 2023.

- [348] E. Mavrona, J. Graf, E. Hack, and P. Zolliker, “Optimized 3D printing of THz waveguides with cyclic olefin copolymer,” *Optical Materials Express*, vol. 11, no. 8, pp. 2495–2504, 2021.
- [349] W. Shao and Q. Chen, “Performance analysis of an all-dielectric planar Mikaelian lens antenna for 1-D beam-steering application,” *Optics Express*, vol. 29, no. 18, pp. 29 202–29 214, 2021.
- [350] R. Appleby and H. B. Wallace, “Standoff detection of weapons and contraband in the 100 GHz to 1 THz region,” *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 11, pp. 2944–2956, 2007.
- [351] R. Cheville and D. Grischkowsky, “Time domain terahertz impulse ranging studies,” *Applied Physics Letters*, vol. 67, no. 14, pp. 1960–1962, 1995.
- [352] K. Iwaszczuk, H. Heiselberg, and P. U. Jepsen, “Terahertz radar cross section measurements,” *Optics Express*, vol. 18, no. 25, pp. 26 399–26 408, 2010.
- [353] K. B. Cooper, R. J. Dengler, N. Llombart, T. Bryllert, G. Chattopadhyay, E. Schlecht, J. Gill, C. Lee, A. Skalare, I. Mehdi, *et al.*, “Penetrating 3-D imaging at 4-and 25-m range using a submillimeter-wave radar,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 12, pp. 2771–2778, 2008.
- [354] K. B. Cooper, R. J. Dengler, N. Llombart, B. Thomas, G. Chattopadhyay, and P. H. Siegel, “THz imaging radar for standoff personnel screening,” *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 169–182, 2011.
- [355] M. Hitzler, S. Saulig, L. Boehm, W. Mayer, W. Winkler, N. Uddin, and C. Waldschmidt, “Ultracompact 160-GHz FMCW radar MMIC with fully integrated offset synthesizer,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 5, pp. 1682–1691, 2017.
- [356] K. Cooper, R. Dengler, N. Llombart, T. Bryllert, G. Chattopadhyay, I. Mehdi, and P. Siegel, “An approach for sub-second imaging of concealed objects using terahertz (THz) radar,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 30, pp. 1297–1307, 2009.
- [357] K. Murata, K. Murano, I. Watanabe, A. Kasamatsu, T. Tanaka, and Y. Monnai, “See-through detection and 3D reconstruction using terahertz leaky-wave radar based on sparse signal processing,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 39, pp. 210–221, 2018.
- [358] Y. Ito and Y. Monnai, “Dynamic phase measurement for vibrometry based on leaky-wave terahertz radar,” in *2021 IEEE Asia-Pacific Microwave Conference (APMC)*, 2021, pp. 339–340.
- [359] Y. Álvarez, R. Cambor, C. Garcia, J. Laviada, C. Vázquez, S. Ver-Hoeye, G. Hotopan, M. Fernández, A. Hadarig, A. Arbolea, and F. Las-Heras, “Submillimeter-wave frequency scanning system for imaging applications,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 11, pp. 5689–5696, 2013.
- [360] Y. Ito and Y. Monnai, “Unambiguous detection of multiple objects using leaky-wave terahertz radar based on stepwise signal processing,” in *2020 45th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2020.
- [361] A. F. Fercher, W. Drexler, C. K. Hitzenberger, and T. Lasser, “Optical coherence tomography-principles and applications,” *Reports on progress in physics*, vol. 66, no. 2, p. 239, 2003.
- [362] L. Thrane, R. H. Jacobsen, P. U. Jepsen, and S. Keiding, “THz reflection spectroscopy of liquid water,” *Chemical Physics Letters*, vol. 240, no. 4, pp. 330–333, 1995.
- [363] P. U. Jepsen, U. Møller, and H. Merbold, “Investigation of aqueous alcohol and sugar solutions with reflection terahertz time-domain spectroscopy,” *Optics Express*, vol. 15, no. 22, pp. 14 717–14 737, 2007.
- [364] S. Busch, M. Weidenbach, M. Fey, F. Schäfer, T. Probst, and M. Koch, “Optical properties of 3D printable plastics in the THz regime and their application for 3D printed THz optics,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 35, pp. 993–997, 2014.
- [365] H.-B. Liu, H. Zhong, N. Karpowicz, Y. Chen, and X.-C. Zhang, “Terahertz spectroscopy and imaging for defense and security applications,” *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1514–1527, 2007.

- [366] P. Bawuah and J. A. Zeitler, “Advances in terahertz time-domain spectroscopy of pharmaceutical solids: A review,” *Trends in Analytical Chemistry*, vol. 139, p. 116 272, 2021.
- [367] W. S. Lee, A. Ferrante, W. Withayachumnankul, and J. A. Able, “Assessing frost damage in barley using terahertz imaging,” *Optics Express*, vol. 28, no. 21, pp. 30 644–30 655, 2020.
- [368] I. Cacciari and S. Siano, “Use of THz reflectometry for roughness estimations of archeological metal surfaces,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 38, no. 4, pp. 503–517, 2017.
- [369] S. Zhong, “Progress in terahertz nondestructive testing: A review,” *Frontiers of Mechanical Engineering*, vol. 14, no. 3, pp. 273–281, 2019.
- [370] D. Molter, K.-S. Ellenberger, J. Klier, S. Duran, J. Jonuscheit, G. von Freymann, N. Vieweg, and A. Deninger, “Kilohertz pixel-rate multilayer terahertz imaging of subwavelength coatings,” *Applied Sciences*, vol. 12, no. 10, 2022.
- [371] K. Su, Y.-C. Shen, and J. A. Zeitler, “Terahertz sensor for non-contact thickness and quality measurement of automobile paints of varying complexity,” *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 4, pp. 432–439, 2014.
- [372] A. D. Burnett, W. Fan, P. C. Upadhy, J. E. Cunningham, M. D. Hargreaves, T. Munshi, H. G. Edwards, E. H. Linfield, and A. G. Davies, “Broadband terahertz time-domain spectroscopy of drugs-of-abuse and the use of principal component analysis,” *Analyst*, vol. 134, no. 8, pp. 1658–1668, 2009.
- [373] S. Cherednichenko, A. Hammar, S. Bevilacqua, V. Drakinskiy, J. Stake, and A. Kalabukhov, “A room temperature bolometer for terahertz coherent and incoherent detection,” *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 2, pp. 395–402, 2011.
- [374] T. Nagatsuma, T. Kumashiro, Y. Fujimoto, K. Taniguchi, K. Ajito, N. Kukutsu, T. Furuta, A. Wakatsuki, and Y. Kado, “Millimeter-wave imaging using photonics-based noise source,” in *2009 34th International Conference on Infrared, Millimeter, and Terahertz Waves*, IEEE, 2009.
- [375] J. Wang, M. Naftaly, and E. Wasige, “An overview of terahertz imaging with resonant tunneling diodes,” *Applied Sciences*, vol. 12, no. 8, p. 3822, 2022.
- [376] R. Han, Y. Zhang, Y. Kim, D. Y. Kim, H. Shichijo, E. Afshari, *et al.*, “Active terahertz imaging using schottky diodes in CMOS: Array and 860-GHz pixel,” *IEEE Journal of Solid-State Circuits*, vol. 48, no. 10, pp. 2296–2308, 2013.
- [377] N. Oda, “Uncooled bolometer-type terahertz focal plane array and camera for real-time imaging,” *Comptes Rendus Physique*, vol. 11, no. 7-8, pp. 496–509, 2010.
- [378] J. Zdanevičius, S. Boppel, M. Bauer, A. Lisauskas, V. Palenskis, V. Krozer, and H. G. Roskos, “A stitched 24×24 field-effect transistor detector array and low-noise readout electronics for real-time imaging at 590 GHz,” in *2014 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, 2014.
- [379] S.-H. Shin and S. Lucyszyn, “Benchmarking a commercial (sub-)THz focal plane array against a custom-built millimeter-wave single-pixel camera,” *IEEE Access*, vol. 8, pp. 191 174–191 190, 2020.
- [380] P. Zolliker, M. Shalaby, E. Söllinger, E. Mavrona, and E. Hack, “Real-time high resolution THz imaging with a fiber-coupled photo conductive antenna and an uncooled microbolometer camera,” *Sensors*, vol. 21, no. 11, p. 3757, 2021.
- [381] F. Lexer, C. K. Hitzenberger, A. Fercher, and M. Kulhavy, “Wavelength-tuning interferometry of intraocular distances,” *Applied Optics*, vol. 36, no. 25, pp. 6548–6553, 1997.
- [382] S.-H. Yun, G. J. Tearney, J. F. de Boer, N. Iftimia, and B. E. Bouma, “High-speed optical frequency-domain imaging,” *Optics Express*, vol. 11, no. 22, pp. 2953–2963, 2003.
- [383] S. Schneider, M. Lauermann, C. Weimann, W. Freude, and C. Koos, “Silicon photonic optical coherence tomography system,” in *CLEO: Applications and Technology*, Optical Society of America, 2014, ATu2P–4.

- [384] S. Schneider, M. Lauermann, P.-I. Dietrich, C. Weimann, W. Freude, and C. Koos, “Optical coherence tomography system mass-producible on a silicon photonic chip,” *Optics Express*, vol. 24, no. 2, pp. 1573–1586, 2016.
- [385] T. Nagatsuma, H. Nishii, and T. Ikeo, “Terahertz imaging based on optical coherence tomography,” *Photonics Research*, vol. 2, no. 4, B64–B69, 2014.
- [386] H. Kitahara, M. Tani, and M. Hangyo, “Frequency-domain optical coherence tomography system in the terahertz region,” *Applied Physics B*, vol. 126, no. 1, pp. 1–6, 2020.
- [387] H. Momiyama, Y. Sasaki, I. Yoshimine, S. Nagano, T. Yuasa, and C. Otani, “Improvement of the depth resolution of swept-source THz-oct for non-destructive inspection,” *Optics Express*, vol. 28, no. 8, pp. 12 279–12 293, 2020.
- [388] Y. Tamenori, H. Tokunaga, L. Yi, and T. Nagatsuma, “Water content estimation in thermal insulation layer using millimeter-wave optical coherence tomography,” *IEICE Transactions on Electronics*, vol. 105, no. 1, pp. 1–8, 2022.
- [389] D. Stanze, B. Globisch, R. J. B. Dietz, H. Roehle, T. Göbel, and M. Schell, “Multilayer thickness determination using continuous wave THz spectroscopy,” *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 6, pp. 696–701, 2014.
- [390] W. Withayachumnankul and M. Naftaly, “Fundamentals of measurement in terahertz time-domain spectroscopy,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 35, no. 8, pp. 610–637, 2014.
- [391] D. Cozzolino, R. Damberg, L. Janik, W. Cynkar, and M. Gishen, “Analysis of grapes and wine by near infrared spectroscopy,” *Journal of Near Infrared Spectroscopy*, vol. 14, no. 5, pp. 279–289, 2006.
- [392] M. Urbano-Cuadrado, M. Luque de Castro, P. Pérez-Juan, J. García-Olmo, and M. Gómez-Nieto, “Near infrared reflectance spectroscopy and multivariate analysis in enology: Determination or screening of fifteen parameters in different types of wines,” *Analytica Chimica Acta*, vol. 527, no. 1, pp. 81–88, 2004.
- [393] E. Wilkes, “Comparison of common methods for measuring alcohol in wine,” *AWRI Technical Review*, no. 257, pp. 7–10, 2022.