

Enabling Polarisation and Frequency Control in Silicon-based Terahertz Integration

by

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Abstract

HIGH speed terahertz communications and sensing systems increasingly require compact and integrated solutions for polarization control and spectral filtering to support polarization multiplexing, dense frequency channelisation, and robust signal transmission. These functions are essential for improving spectral efficiency, suppressing interference, and maintaining signal integrity. However, in many existing terahertz implementations, polarization manipulation and filtering rely on bulky free space optics or discrete metallic waveguide components, resulting in large system footprint, alignment sensitivity, and limited scalability. This thesis is motivated by the need to realise fully integrated terahertz components for polarization control and filtering on a single platform that is low loss, mechanically robust, and compatible with scalable fabrication.

To address this challenge, this thesis develops a series of integrated terahertz components based on an all-silicon substrateless waveguide platform that combines effective medium and photonic crystal concepts. The proposed platform employs high-resistivity silicon waveguides surrounded by subwavelength perforations that form an effective medium cladding. This structure enables broadband low-loss guidance. Four key components are designed, fabricated, and characterised. First, all silicon polarization filters are realised using anisotropic effective medium waveguides and polarization-dependent Bragg grating dispersion, achieving broadband low-loss transmission for the in-plane polarization and strong rejection of the out-of-plane polarization. Second, an all-silicon bandpass filter is developed by combining a one-dimensional Bragg grating core with two-dimensional photonic crystal claddings, forming a pass-band with high out-of-band isolation that can be positioned across all IEEE 802.15.3d channels. During the fabrication and testing of these polarization and bandpass filters, it is observed that conventional long linear tapers required for interfacing integrated waveguides with metallic hollow waveguides are mechanically fragile and prone to damage, which limits practical integration. This observation motivates the development of compact all-silicon tapers that enable efficient mode conversion over a sub-wavelength scale while significantly improving mechanical robustness. These compact tapers are subsequently employed in the hybrid silicon-metal tunable bandpass filter, where the separation of the metallic slits modifies the field confinement of the

in-plane polarization, thereby shifting the high-pass cutoff frequency. These tunable bandpass filters demonstrate reliable performance and enable practical integration of tunable filtering functionality on the same platform.

In addition to device-level development, terahertz wireless communications experiments are performed to validate the system-level performance of the proposed components under real data transmission conditions. A photomixing-based communications system is used to evaluate insertion loss, filtering behaviour, and mode conversion in terms of bit error rate. The results confirm that the integrated silicon devices maintain stable transmission, improve channel isolation, and preserve data integrity. Overall, this thesis demonstrates a coherent and fabrication-ready set of integrated terahertz components for polarization control, filtering, mode conversion, and tunability, providing practical building blocks for compact and scalable terahertz communications front ends.

Originality 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 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.

Linxi Chen

May 22, 2026

Signed

Date

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Chapter 1

Introduction

THE terahertz spectrum lies between the microwave and infrared frequency regimes. This spectral region offers strong potential for applications in communications, sensing, imaging, and spectroscopy. Recent advances in terahertz integrated systems have highlighted the essential role of tunable terahertz components in enabling flexible and high performance system functionality. This chapter provides background knowledge on terahertz technologies and integrated platforms. Existing terahertz waveguides, including dielectric and substrateless waveguide structures, are reviewed together with resonant cavities and frequency selective components. Current approaches to tunable terahertz structures are also discussed to outline their operating principles and limitations. The chapter concludes with an overview of the thesis scope and main contributions.

1.1 Terahertz Technology and Applications

Extending from 0.1 to 10 THz, the terahertz frequency range occupies the spectra between microwave and infrared frequencies. Due to its wide bandwidth and short wavelength, it enables high data-rate wireless communications and fine scanning resolution (Sengupta et al., 2018; Tonouchi, 2007; Song and Nagatsuma, 2011). Historically, this frequency range has not been widely investigated because of the lack of efficient terahertz sources and detectors and low-loss transmission lines. Among these reasons, the scarcity of high-efficiency and stable terahertz sources has been the main challenge. Recent developments in ultrafast optoelectronics, semiconductor devices, and integrated photonics have significantly reduced this limitation. Reliable terahertz sources, such as photoconductive emitters, high-speed photodiodes, and quantum-cascade lasers (Siegel, 2002; Nagatsuma, 2011; Preu, 2025), are now available. Detectors based on Schottky diodes (Maestrini et al., 2010), resonant tunnelling diodes (RTD) (Izumi et al., 2017), Fermi-level managed barrier diodes (FMBD) (Ito and Ishibashi, 2016), and field-effect transistors (FET) (Knap et al., 2009) also provide high detection sensitivity. At the same time, advanced passive components enable precise manipulation of terahertz waves for a wide range of applications.

Although the terahertz spectrum is defined as a single continuous band, devices are hardly able to support the operation over the entire wide frequency range. Consequently, research and system development commonly focus on narrower, well-defined sub-bands, such as W-band, D-band, and J-band, which are defined in the microwave spectrum. These frequency ranges overlap with the WR rectangular waveguide bands, which are widely used in practical implementations and measurement systems. For component design, we are mainly concentrating on the WR-3.4 band (220–330 GHz), which overlaps with the IEEE 802.15.3d standard for high-data-rate wireless links of 252–322 GHz (Standards Committee, 2017; Petrov et al., 2020).

The selection of this band is based on the propagation characteristics of terahertz frequencies. While the terahertz spectrum offers the capacity for high-speed communications, the achievable communications performance is strongly limited by terahertz wave attenuation, including atmospheric absorption, free-space path loss, scattering from water droplets, and material losses (Schneider et al., 2012; Nagatsuma et al., 2016; Withayachumnankul et al., 2018). Atmospheric attenuation is frequency-dependent, thus forms specific transmission windows where absorption is relatively low, such as 200–300 GHz (Schneider et al., 2012), as shown in Fig. 1.1(a). As shown in Fig. 1.1(b),

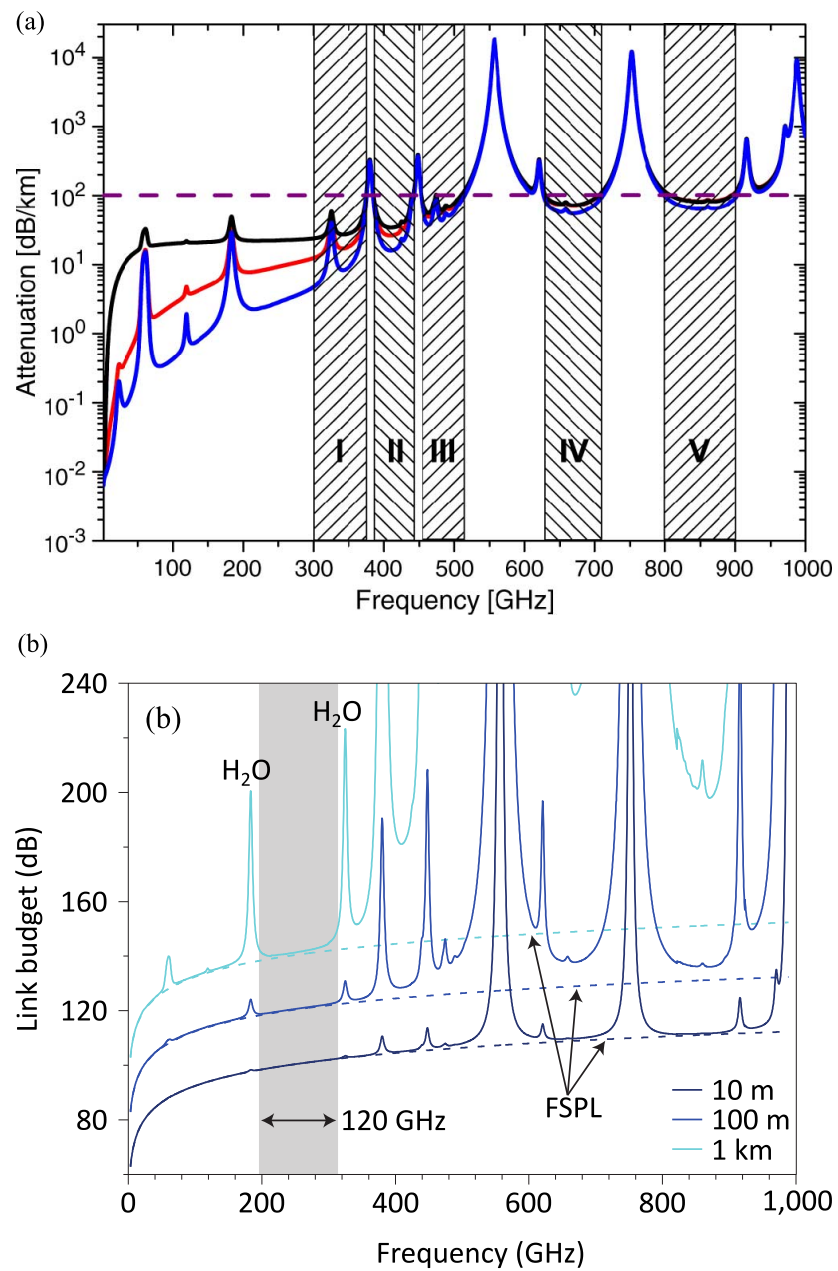


Figure 1.1. Impact of atmospheric attenuation and free-space path loss on terahertz waves. (a) Atmospheric attenuation as a function of frequency. Adopted from (Schneider et al., 2012). (b) Link budget at terahertz frequencies. Adopted from (Nagatsuma et al., 2016).

even within these windows, free-space path loss increases rapidly with frequency, thus becoming the dominant limitation for link distance unless compensated through high-gain antennas and low-loss components. Therefore, the WR-3.4 band offers an attractive trade-off between fractional bandwidth and achievable propagation loss, and also overlaps with the established IEEE next-generation communications standards. This WR-3.4 band has also become attractive because of its suitability for various applications (Petrov et al., 2020; Akyildiz et al., 2014; You et al., 2025a; Lees et al., 2023). Owing to the wide fractional bandwidth of the WR-3.4 band compared to microwave-wave bands, terahertz communications in that band can theoretically realise high data rates reaching hundreds of Gbit/s to several Tbit/s, exceeding the achievable data rate limitations of microwave-wave communications (Nagatsuma et al., 2016; Koenig et al., 2013), as shown in Fig. 1.2(a–b). The short wavelengths of the WR-3.4 band also enable highly directive beams and compact high-gain antennas, increasing the spectral utilisation efficiency, enhancing security, and reducing interference in line-of-sight links. Figure 1.2(b) also illustrates the maximum achievable link distances of 100 m with the data rates above 100 Gb/s. These advantages have contributed to the WR-3.4 band as a promising solution for future 6G and beyond communications (Petrov et al., 2020; Akyildiz et al., 2014).

Further to illustrate these communications capabilities, Figure 1.3 shows conventional terahertz communications system setups based on both electronic and photonic approaches, which have been widely reviewed and compared in (Nagatsuma et al., 2016; Akyildiz et al., 2014). For the transmitter side of the electronics-based communications setup, the terahertz frequency carrier is generated by up-converting a single-frequency microwave signal. This high-frequency signal is then amplified and mixed with the data band. The modulated signal is transmitted through waveguides or antennas, as shown in Fig. 1.3. The same setup can be applied to the receiver side. After receiving the modulated signal and mixing with the high-frequency signal for demodulation, the data band can be received. The setup is developed from well-developed radio-frequency communications systems into the terahertz range and has been widely used in many experimental and practical transceivers for short- to medium-range wireless communications. Instead of upconverting, the photonic-based communications setup generates the terahertz signal via optical heterodyning by photomixing two wavelength-tunable near-infrared lasers. The optical signal is downconverted to the sub-terahertz frequency and modulated with a baseband data signal. Then, the baseband data signal can be detected by the Schottky barrier diode (SBD) on the receiver side, as shown

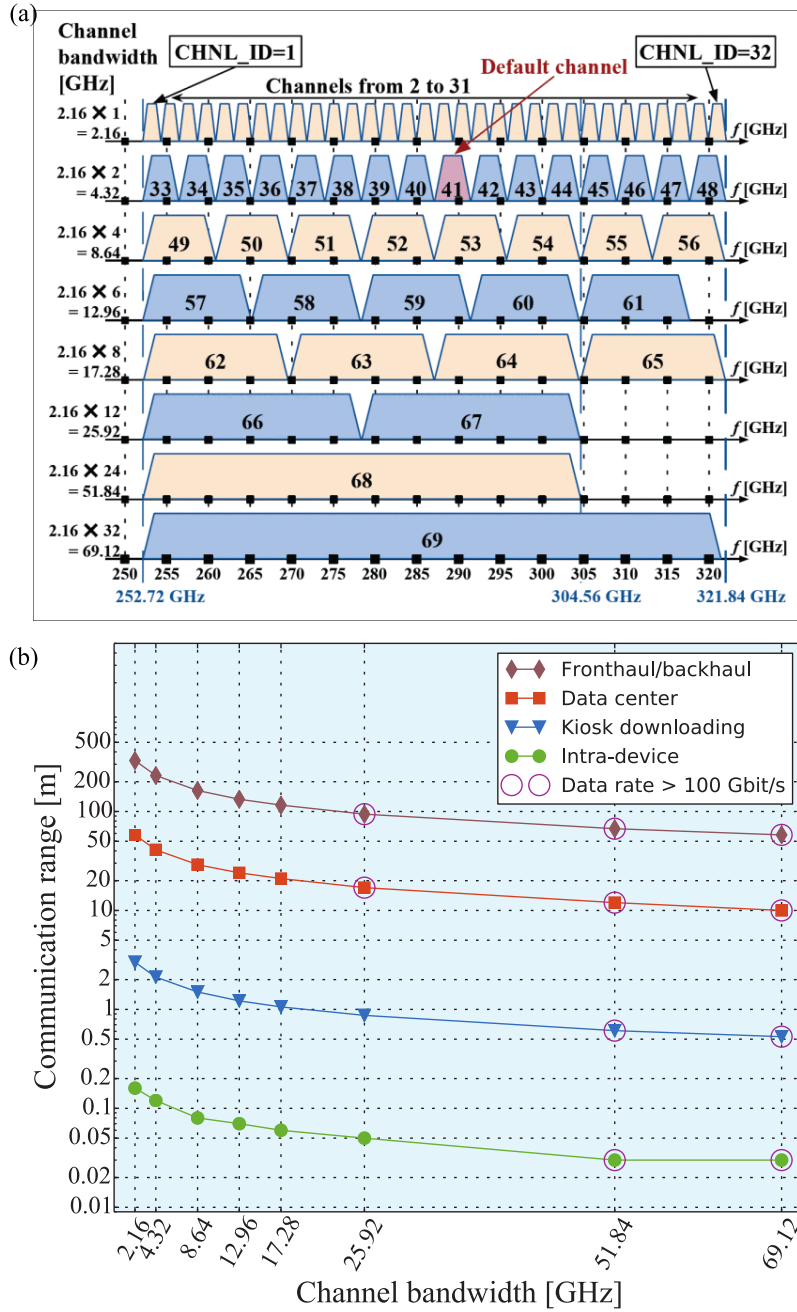


Figure 1.2. (a) IEEE 802.15.3d channel plan. (b) Range and rate values achievable in target IEEE 802.15.3d use cases. Adopted from (Petrov et al., 2020).

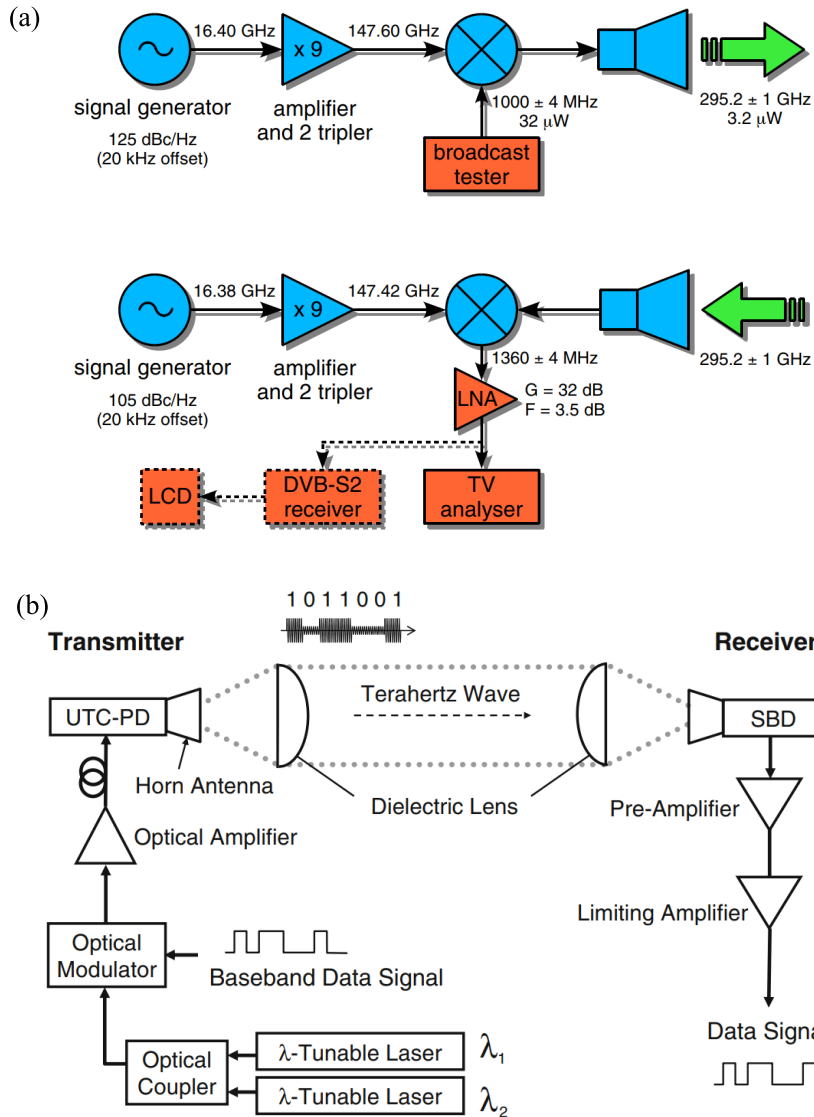


Figure 1.3. State-of-the-art terahertz communications setups. (a) Block diagram of the electronics-based terahertz communications system. (b) Block diagram of the photonics-based terahertz communications system. Adopted from (Kleine-Ostmann and Nagatsuma, 2011).

in Fig. 1.3(b). Owing to their highly flexible carrier frequency generation and ultra-wideband operation, photonics-based systems have supported experimental demonstrations of high-data-rate wireless communications.

Figure 1.4(a) shows the prospective application scenario for terahertz wireless communications. To meet communications requirements from short-range ultra-high-data-rate to longer-range high-data-rate, the setup employed a photonic-based transmitter and an electronic-based receiver. The predicted communications data rate can reach

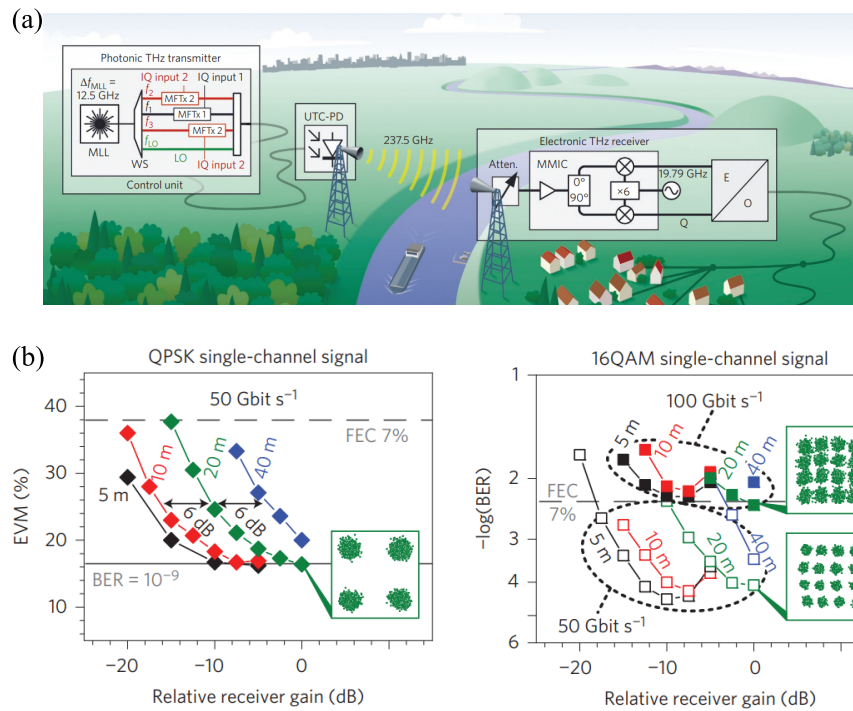


Figure 1.4. State-of-the-art terahertz communications demonstrations. (a) Prospective application scenario for terahertz wireless communications links. (b) Predicted communications capacity. Adopted from (Koenig et al., 2013).

up to 100 Gb/s with the carrier frequency of 237.5 GHz (Koenig et al., 2013), as shown in Fig. 1.4(b).

In addition to communications, terahertz sensing and imaging have also made significant progress. As many materials have been discovered with characteristic absorption features in the terahertz range, enabling the material property investigation using terahertz time-domain spectroscopy (THz-TDS) (Balakrishnan et al., 2009; Ferguson and Zhang, 2002). The short wavelength of terahertz frequencies also provides highly accurate chemical detection and characterisation ability (Tonouchi, 2007; Ferguson and Zhang, 2002; Lees et al., 2023), as shown in Fig. 1.5(a). Furthermore, it provides high spatial resolution below 1 mm and hence supports precise imaging of structural details without posing risks from ionising radiation as with X-rays. Terahertz radiation can also penetrate common packaging materials such as plastics, paper, and fabrics, and thus enhances hidden object detection and tracking tasks (Federici et al., 2005; Shen et al., 2005; Kowalski, 2019; You et al., 2025a,b), as shown in Fig. 1.5(b).

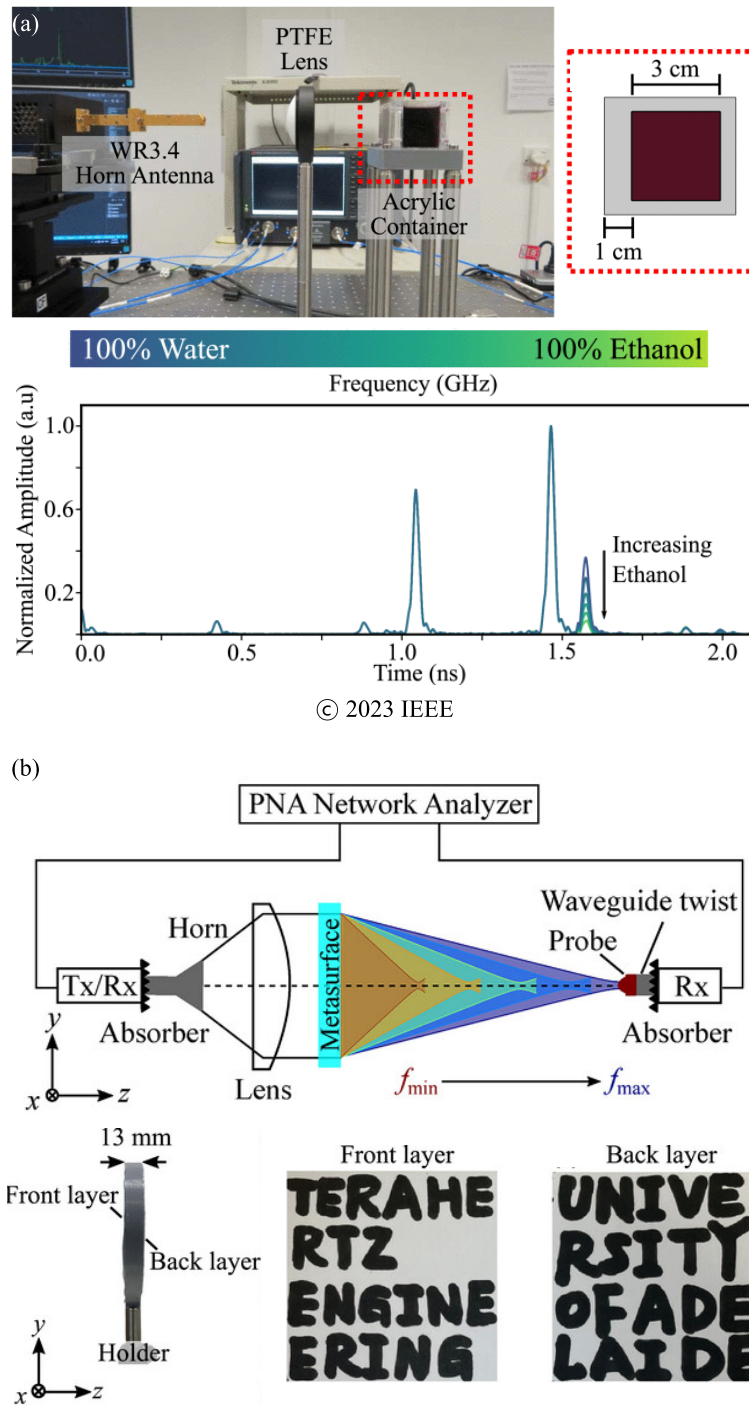


Figure 1.5. State-of-the-art terahertz spectroscopy and imaging demonstrations. (a) Terahertz in-container liquid characterisation, adopted from (Lees et al., 2023). (b) 3D terahertz confocal imaging, adopted from (You et al., 2025a).

Despite this increase in prospective applications, a fundamental issue faced by terahertz technology: efficient terahertz wave distribution and control, requiring a dedicated platform with a unique capacity to maintain signal integrity. The characteristics of a fast communications system utilise components with desirable properties of reduced propagation loss, low dispersion, and weak polarisation-induced effects. Similarly, a terahertz imaging and sensing system also requires platforms with a reliable source that generates a steady, tightly confined terahertz beam and a precise spectral filter. In summary, developing a reliable terahertz platform is essential towards the real-world application of terahertz technology (Schneider et al., 2012; Withayachumnankul et al., 2018).

1.2 Terahertz Waveguides and Devices

1.2.1 Existing Waveguides and Integrated Platforms

A range of integrated platforms has been developed for terahertz waveguiding, routing, and on chip device integration. Among these platforms, metallic waveguides, planar transmission lines, and photonic inspired waveguides are the most mature approaches. Each offers different strengths in mode confinement, propagation loss, fabrication method, and compatibility with electronic or photonic processes.

Metallic hollow waveguides are one of the most commonly used waveguiding technologies at terahertz frequencies. They originate from microwave designs and are scaled down to submillimetre dimensions. These waveguides are usually fabricated by CNC machining high-conductivity metals such as copper. The inner walls are often coated with gold to reduce oxidation and ohmic loss. Strong mode confinement and low propagation loss can be achieved because most of the electromagnetic field propagates in air. Due to this low loss, many terahertz components have been implemented using hollow waveguides. Examples include bandpass filters (Ding et al., 2017; Yang et al., 2017), orthomode transducers (Gomez-Torrent et al., 2018), and frequency conversion modules (Crowe et al., 2005). CNC-machined hollow waveguides also provide a practical packaging solution for terahertz devices. As shown in Fig. 1.6, individual components can be mounted in separate waveguide blocks and connected using standard flanges. This allows flexible testing at the component level and simplifies packaging compared with fully integrated systems (Jiang et al., 2016; Kawamoto et al., 2021; Feng et al., 2021). However, when operating at terahertz frequencies, the skin depth

1.2.1 Existing Waveguides and Integrated Platforms

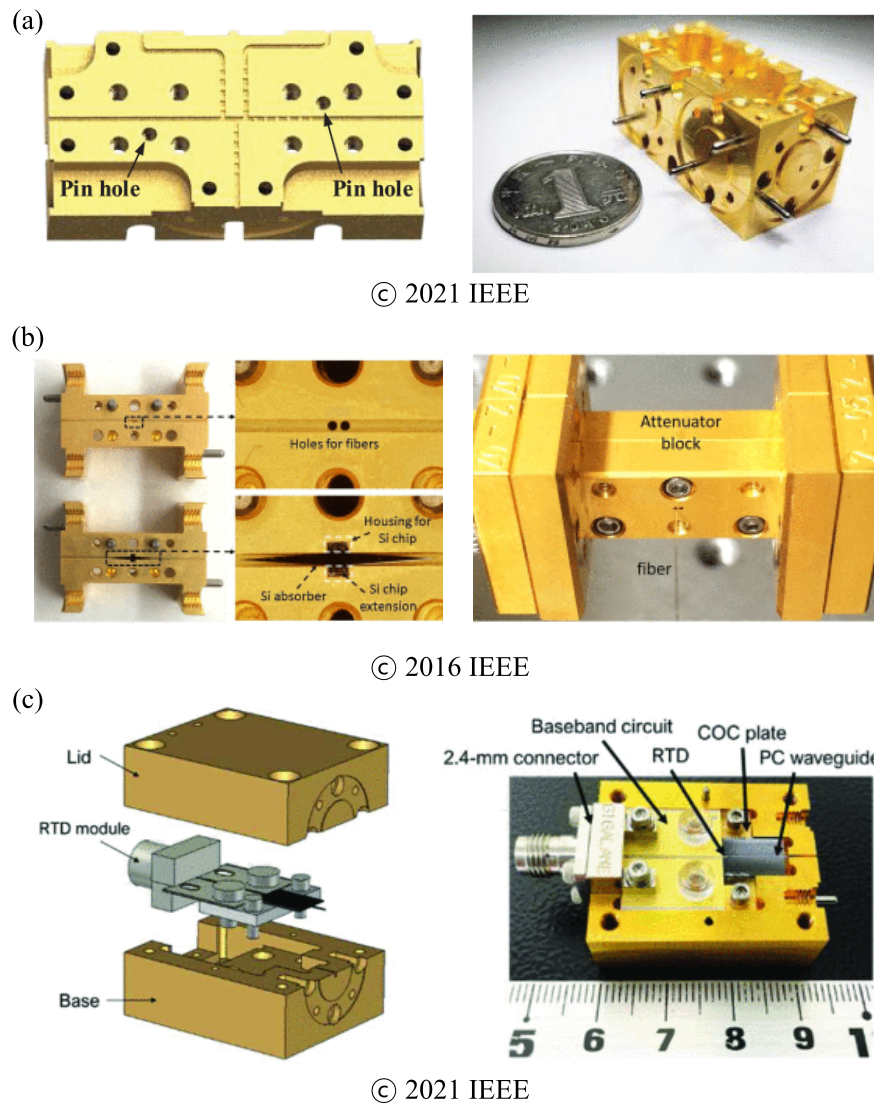


Figure 1.6. Rectangular terahertz waveguide components. (a) Fabricated manifold-coupled waveguide multiplexer, adopted from (Feng et al., 2021). (b) Assembled optically controlled waveguide attenuator, adopted from (Jiang et al., 2016). (c) Integrated resonant tunnelling diode with rectangular waveguide I/O using photonic crystal interface, adopted from (Kawamoto et al., 2021).

in metals becomes very small. Electrical currents are confined to a thin surface layer, which increases conductor loss. Surface roughness and machining tolerances further raise insertion loss, especially at higher frequencies. For these reasons, metallic hollow waveguides are suitable for laboratory characterisation but are not well suited to compact or chip-scale terahertz integration.

Planar transmission lines, such as coplanar waveguides (CPWs) (Eblabla et al., 2016; Rivera-Lavado et al., 2022; Cao et al., 2014), microstrip lines (Murano et al., 2016; Lu et al., 2020; Haddad et al., 2023), and substrate-integrated waveguides (SIWs) (Wang

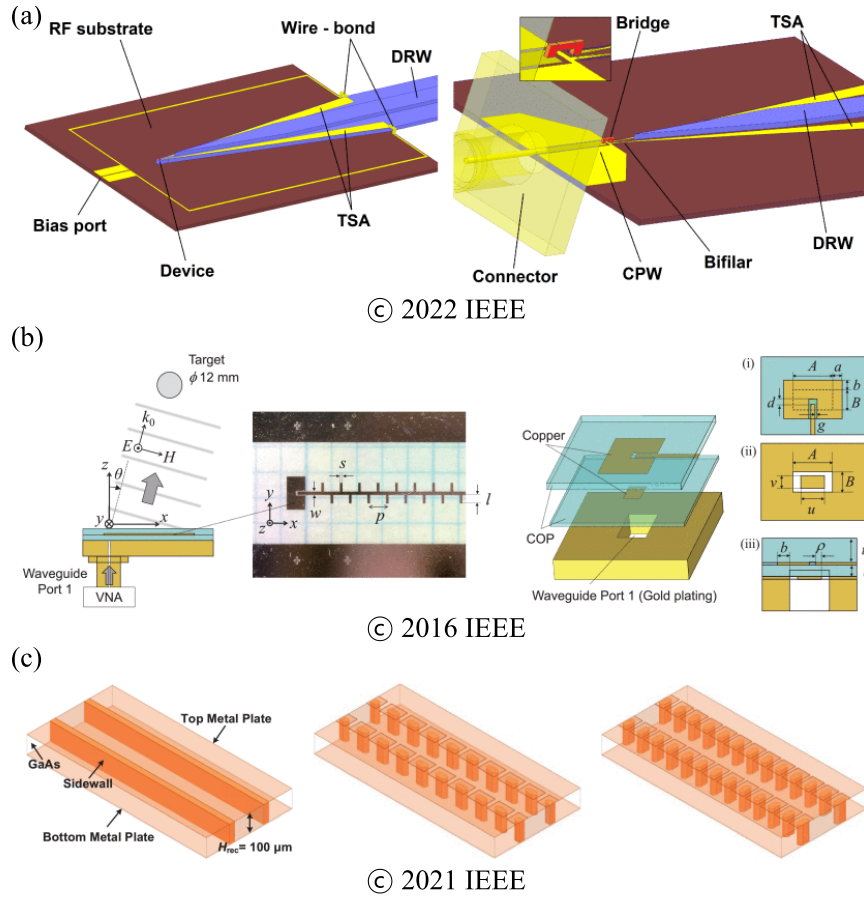


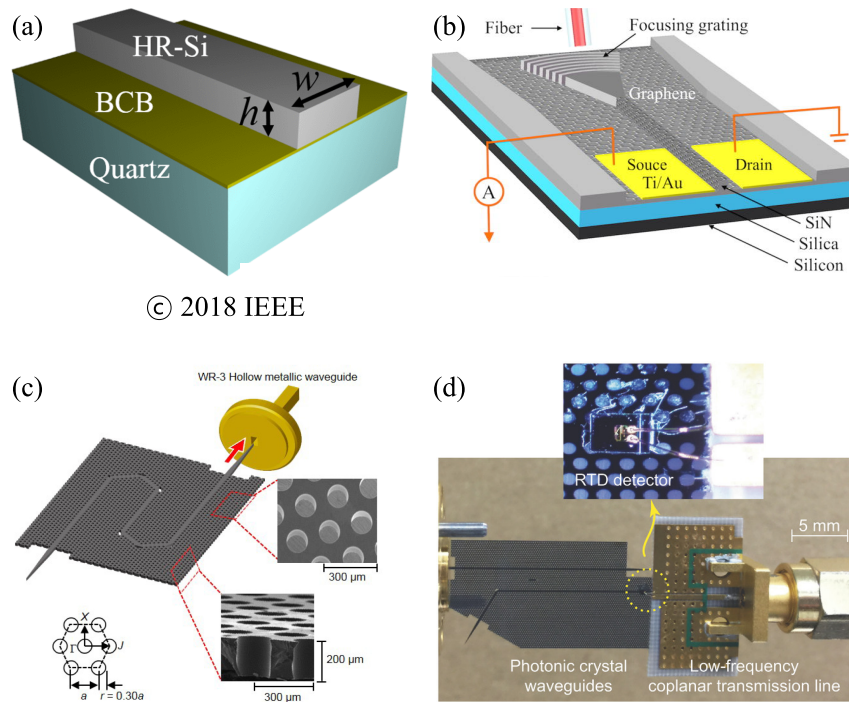
Figure 1.7. Planar transmission-line terahertz waveguides. (a) Coplanar waveguide with assembling setup figure, adopted from (Rivera-Lavado et al., 2022). (b) Microstrip leaky-wave antenna with experimental setup figure, adopted from (Murano et al., 2016). (c) Substrate-integrated waveguides, adopted from (Chiu and Li, 2021).

et al., 2020; Chiu and Li, 2021), have played an important role in the development of millimetre wave and sub terahertz circuits. They are compatible with standard lithographic processes and allow multiple components to be integrated on a single substrate. This makes them suitable for monolithic integration with active components such as diodes and transistors. As shown in Fig. 1.7(a), CPWs are attractive for on-wafer measurements because they require only a single metallisation layer and allow direct probe access. They have been used to realise compact terahertz detectors (Knap et al., 2009), mixers (Renaud et al., 2017), resonators (Eblabla et al., 2016), and transmission lines (Rivera-Lavado et al., 2022; Havlíček et al., 2025). These devices have been demonstrated on high-resistivity silicon, quartz, and polymer substrates. As shown in Fig. 1.7(b), microstrip lines provide a simple planar geometry and offer strong field confinement inside the dielectric layer. This enables the development of sub-terahertz

antennas (Murano et al., 2016; Haddad et al., 2023) and transitions (Tian et al., 2023) that can be fabricated together with active devices. Substrate integrated waveguides extend planar transmission line concepts by using rows of metallised vias to form a quasi-hollow channel. This structure provides better field confinement and lower radiation loss than CPWs or microstrip lines (Wang et al., 2020; Xu and Wu, 2005), as shown in Fig. 1.7(c). SIW structures have been used to implement terahertz filters (Chiu and Li, 2021; Wang et al., 2020) and leaky wave antennas (Liu et al., 2011) using printed circuit board or wafer-level fabrication. Overall, the ease of fabrication, planar form, and support for monolithic integration make these microwave-inspired guiding structures attractive for compact terahertz circuit design.

However, all these integrated platforms show degraded performance at higher terahertz frequencies. This is mainly caused by increased ohmic loss due to the reduced skin depth in metallic conductors. In coplanar waveguides, this appears as strong conductor loss associated with the short terahertz wavelength. It is also accompanied by substrate leakage caused by significant field penetration into the dielectric (Zhang et al., 2005; Rivera-Lavado et al., 2022; Cabello-Sánchez et al., 2018). Microstrip lines provide stronger field confinement. However, their performance becomes increasingly limited by dielectric absorption and higher metal loss as frequency increases (Haddad et al., 2023). Substrate integrated waveguides offer improved confinement, but their use of metallised vias makes them sensitive to fabrication tolerances. In addition, the dielectric substrates commonly used in SIWs introduce noticeable absorption loss (Wu et al., 2003). As a result, although CPW, microstrip, and SIW platforms are widely used and offer good planar compatibility at millimetre wave and lower sub terahertz frequencies below about 200 GHz, their intrinsic loss mechanisms and fabrication sensitivity increasingly limit their extension toward compact and low loss integrated systems at higher terahertz frequencies.

A large class of terahertz guiding structures has been adapted from photonic technologies originally developed for infrared and optical integrated circuits. These photonics inspired platforms include silicon on insulator waveguides (Amarloo et al., 2018; Amarloo and Safavi-Naeini, 2021; Sharma et al., 2020; Wang et al., 2015) and all dielectric photonic crystal waveguides (Yu et al., 2019b; Headland et al., 2020a; Withayachumnankul et al., 2018), as shown in Fig. 1.8. Their main advantage is the use of mature semiconductor fabrication techniques such as high-resolution lithography, deep etching, and CMOS-compatible processing. This enables compact and densely



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Figure 1.8. Photonics-inspired terahertz waveguides. (a) Terahertz silicon-on-insulator waveguide, adopted from (Amarloo et al., 2018). (b) Graphene-on-Si₃N₄ waveguide photodetector, adopted from (Wang et al., 2015). (c) Photonic crystal waveguide, adopted from (Tsuruda et al., 2015). (d) Integration of RTD with photonic crystal waveguide, adopted from (Withayachumnankul et al., 2018).

integrated devices to be fabricated on a single chip. As shown in Fig. 1.8(a–b), silicon on insulator waveguides benefit from the high refractive index contrast between silicon and silicon dioxide. This allows tight bends (Amarloo et al., 2018), compact splitters (Amarloo and Safavi-Naeini, 2021), interferometers (Wang et al., 2015), and resonators (Amarloo and Safavi-Naeini, 2021). At lower terahertz frequencies, this platform has also supported on-chip delay lines, compact filters (Maram et al., 2019), and hybrid electronic photonic circuits (Sharma et al., 2020). All-dielectric photonic crystal waveguides provide another powerful platform. They form bandgaps using periodic air hole lattices, which enables strong dispersion control. This approach supports sharp bends (Tsuruda et al., 2015), triplexers (Withayachumnankul et al., 2018), filters (Webber et al., 2021), and waveguide-mounted resonators with engineered high quality factors (Otter et al., 2014), as shown in Fig. 1.8(c). Several studies have also demonstrated terahertz photonic chips in which quantum cascade lasers or photoconductive antennas are integrated with photonic crystal circuits. These results highlight the potential for highly functional monolithic systems (Zhang et al., 2007; Iida et al.,

2003; Yu et al., 2019b), as shown in Fig. 1.8(d). Despite these advantages, photonics-inspired platforms face important challenges when scaled to the terahertz band. Silicon on insulator waveguides suffer from loss introduced by the oxide layer, which becomes significant at sub-terahertz frequencies. In addition, the fractional bandwidth of many photonics-inspired components is narrow, typically around 3 to 5 percent. This makes them difficult to use in wideband sub-terahertz systems. Photonic crystal waveguides avoid metal and substrate losses, but their designs are constrained by the need to maintain a photonic bandgap. Substrate-supported photonic crystal slabs can also support unwanted substrate modes. This often requires thick substrates, which increases structural complexity and fabrication difficulty. As a result, although substrate-supported photonics-inspired platforms offer strong design capability and have enabled many advanced terahertz devices, they are not ideal as a low-loss, broadband, and mechanically robust foundation for large-scale terahertz integrated systems.

In summary, metallic hollow waveguides, planar transmission line platforms, and photonics-inspired dielectric waveguides have all contributed to the development of terahertz components and systems. Hollow waveguides provide low-loss propagation and convenient packaging for laboratory testing, but they do not scale well to compact or chip-level integration. Planar transmission-line platforms support monolithic integration and benefit from mature fabrication processes, but their performance is limited by ohmic and dielectric losses as operation moves toward higher sub-terahertz and terahertz frequencies. Photonics-inspired platforms make use of advanced semiconductor processing and offer strong field control, but they are constrained by material loss, narrow fractional bandwidth, and fabrication complexity. These limitations indicate the need for a more balanced terahertz integration platform. Such a platform should support low-loss propagation and broadband operation. It should also provide mechanical stability, compact device size, and full compatibility with silicon microfabrication.

1.2.2 Effective-medium Waveguide Platform

High-resistivity silicon presents an attractive approach to achieving a balanced terahertz integration platform. Due to the very low dielectric loss tangent, typically 3×10^{-5} for float-zone material (Dai et al., 2004), the silicon material supports the propagation of waves without the loss of efficiency due to absorption loss. Silicon

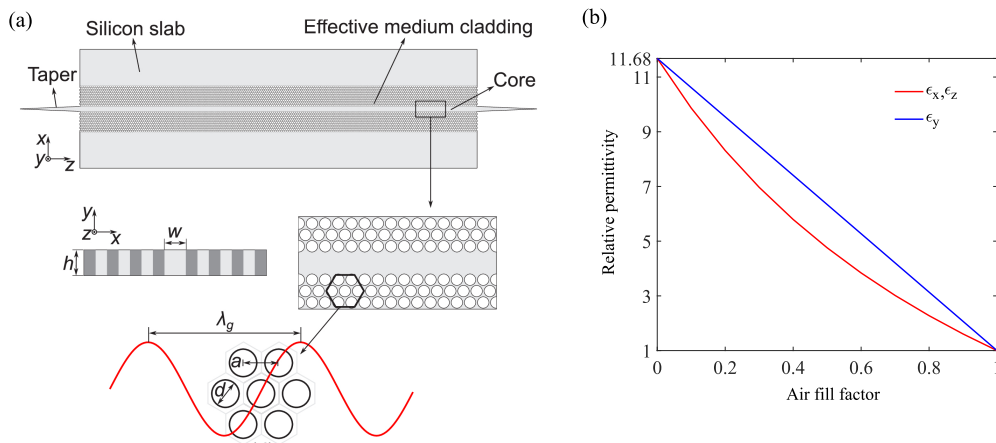


Figure 1.9. Effective-medium waveguide. (a) Waveguide structure, adopted from (Gao et al., 2021). (b) Effective relative permittivity as a function of the air fill factor.

is also a very low dispersive material in the terahertz regime, thus preserving the permittivity value of approximately 11.68 even at room temperature. Moreover, owing to the mechanical strength, stability at higher temperatures, and full processability using state-of-the-art micro-fabrication techniques, the properties render the high-resistivity silicon material the choice to establish terahertz waveguides and components (Tsuruda et al., 2015; Koala et al., 2022; Malekabadi et al., 2013). Indeed, there arises a need to realise platforms using mainly silicon to realise low-loss, broadband, and integrable terahertz platforms without the aid of lossy media, metallised claddings, or mechanically fragile suspended structures.

Effective medium waveguide has emerged as one of the most promising all-dielectric guiding platforms for integrated terahertz technology (Gao et al., 2021, 2020). Their development brings together ideas from photonic crystals, anisotropic material engineering, and subwavelength structural design in order to overcome the limitations associated with metallic, dielectric slab, and substrate integrated waveguides. As terahertz communications continues to advance beyond laboratory demonstrations and toward practical high capacity systems, there is a growing need for compact, low loss, broadband, and fabrication compatible guiding structures. Effective medium waveguides address many of these requirements simultaneously and therefore provide a unified platform upon which a diverse set of terahertz devices can be built.

As shown in Fig. 1.9 (a), the foundation of the effective medium waveguide concept lies in the ability to control the averaged electromagnetic response of a dielectric by introducing subwavelength geometric features. When a high-resistivity silicon slab is

patterned with periodic deep-subwavelength air holes, the structure behaves as a homogenised composite described by an effective permittivity (Cheben et al., 2018; Choy, 2015). With the effective medium cladding, the wave can be confined into the waveguide core by total internal reflection and thus realise the low-loss transmission. Different from a photonic crystal, the waveguide supports wide-band transmission with more design flexibility. For this thesis, the TE mode (in-plane polarisation) is defined with its electric field parallel to the xz -plane, while the TM mode (out-of-plane polarisation) is orthogonal to the xz -plane, as shown in Fig. 1.9 (a). The effective medium acts as an anisotropic material with the relative permittivity tensor $(\epsilon_x, \epsilon_y, \epsilon_z)$ calculated by

$$\epsilon_x = \epsilon_{\text{si}} \frac{(\epsilon_{\text{si}} + \epsilon_{\text{air}}) + (\epsilon_{\text{air}} - \epsilon_{\text{si}})\zeta}{(\epsilon_{\text{si}} + \epsilon_{\text{air}}) - (\epsilon_{\text{air}} - \epsilon_{\text{si}})\zeta}, \quad (1.1a)$$

$$\epsilon_y = \epsilon_{\text{si}} + (\epsilon_{\text{air}} - \epsilon_{\text{si}})\zeta, \quad (1.1b)$$

$$\epsilon_z = \epsilon_x, \quad (1.1c)$$

where the fill factor is

$$\zeta = \frac{\pi d^2}{4a^2}. \quad (1.2)$$

Here, $\epsilon_{\text{si}} = 11.68$ and $\epsilon_{\text{air}} = 1$ are the relative permittivities of silicon and air, respectively. The dimensions a and d are the hole diameter and lattice period. A variety of tensor values $\epsilon_{x,y,z}$ between $\epsilon_{\text{air}} = 1$ and $\epsilon_{\text{si}} = 11.68$ are available with different fill factors ζ . As shown in Fig. 1.9 (b), for symmetric hole lattices, the presence of air holes produces an anisotropic material, where the in-plane components of the permittivity tensors differ from the out-of-plane component due to the difference between the cladding materials. Additional in-plane anisotropies can then be introduced through the patterning of these holes in a non-symmetrical arrangement, which would permit control over the effective refractive index along separate axes (Gao et al., 2024). Such control over anisotropy would be possible without relying on metallic inclusions or layered designs, both of which would impart strong losses at terahertz frequencies. Since the structure is entirely dielectric and self-supporting, there is less absorption loss in effective medium waveguides in comparison to metal-coated or metal-confined structures, as this waveguide does not use materials that cause propagation loss (Gao et al., 2020). The cutoff issue in rectangular hollow waveguides is also not experienced in effective medium waveguides, enabling a wide operation bandwidth. In addition, the use of high-resistivity silicon ensures low free-carrier absorption and compatibility with standard deep reactive ion etching, which makes large-scale device fabrication

feasible. Together, these principles allow effective medium waveguides to function as a highly controllable platform that supports tailored modal behaviour at terahertz frequencies.

A broad range of components based on the effective medium waveguide concept has now been demonstrated, underscoring both the versatility and maturity of this platform (Gao et al., 2020; Dechwechprasit et al., 2023; Gao et al., 2024; Liang et al., 2021; Lees et al., 2021), as shown in Fig. 1.10. In essence, straight waveguides with minimal loss and controlled single-mode operation have been achieved through a tailored local lattice of holes to tightly confine the fundamental mode in the unpatterned core. Bends with a radius of a few wavelengths have been shown with minimal loss, leveraging the flexibility to topologically shape the effective permittivity to mitigate scattering loss during directional coupling (Gao et al., 2020; Lees et al., 2021). Beyond routing components, a high degree of index flexibility offers many options for more sophisticated functions. Effective-medium multi-beam antennas and multiplexers have been fabricated based on a tailored lattice parameter or symmetry to divert and selectively combine the propagating modes (Dechwechprasit et al., 2023; Gao et al., 2024). By introducing a gradual index topography, further examples of planar horn antennas have been fabricated based on a tailored index topography to facilitate efficient impedance matching and aperture-beam shaping (Liang et al., 2021). Here, it is shown that the advantage of an effective index-waveguiding approach is to leverage geometric modality to engineer complex modal and dispersion properties independently and without adding multiple layers of materials that are lossy in terahertz frequency operation. These properties collectively advance effective index-waveguides as a versatile and potent toolbox component for compact terahertz integrated systems.

Though the effective medium platform has facilitated a remarkable array of routing, multiplexing, and radiation devices, a number of key device types necessary for a functional terahertz system have been relatively unexplored. Specifically, future communications and sensing system architectures are highly dependent on precise polarisation control and high-performance spectral filtering, which require a level of modal guidance and index control well beyond the capabilities of index-engineered waveguides. Conventional polarisation rotators, splitters, and tunable devices have band-limited performance, high insertion loss, or require bulky configurations that do not scale well for high-density integration. Similarly, conventional terahertz bandpass filters and waveguide couplers are frustrated by the presence of metal loss, resonant operation

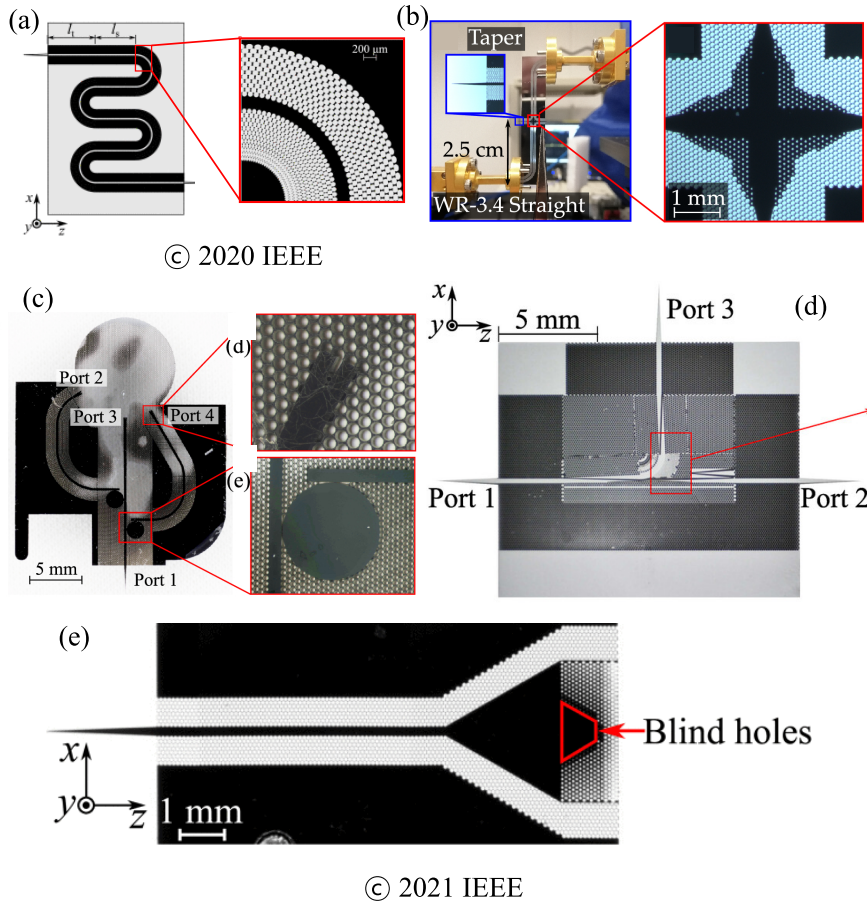


Figure 1.10. Existing passive components based on substrateless dielectric waveguide platform. (a) Bend waveguide, adopted from (Gao et al., 2020). (b) Waveguide crossing, adopted from (Lees et al., 2021). (c) Terahertz multi-beam antenna, adopted from (Dechwechprasit et al., 2023). (d) Polarisation multiplexer, adopted from (Gao et al., 2024). (e) Planar horn antenna, adopted from (Liang et al., 2021).

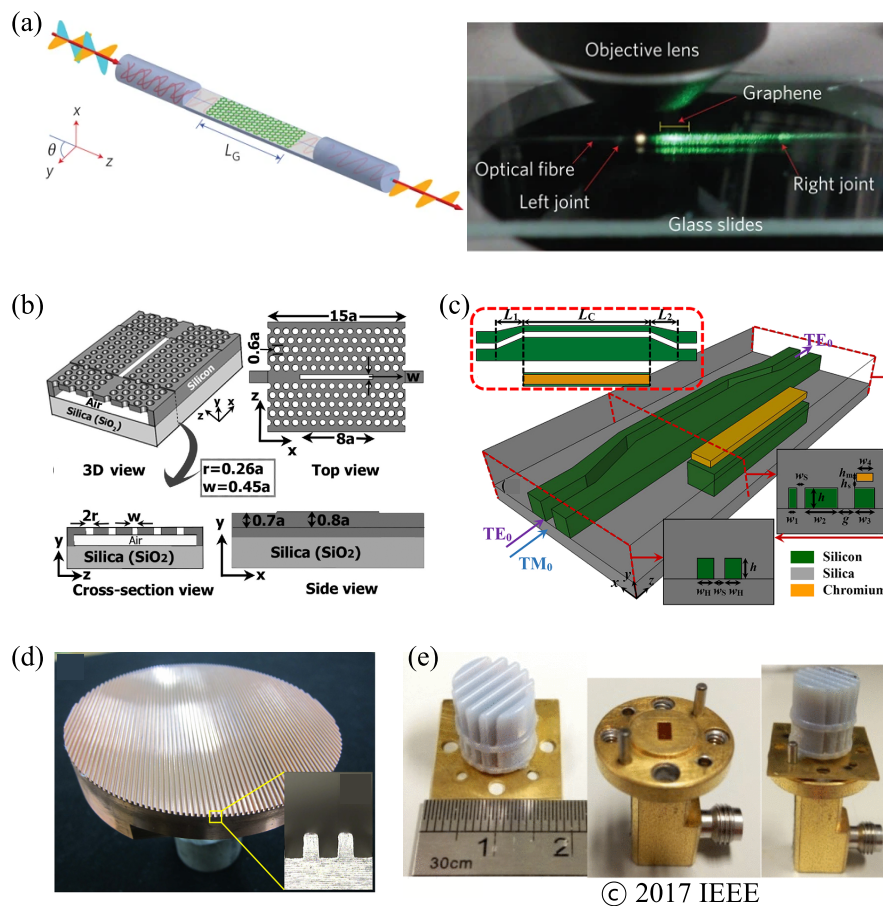
within very limited bandwidths, and complexity of fabrication that do not scale well for the development of highly integrated platforms. These are summarised to introduce the research challenges addressed in this thesis in the following sections.

1.3 Terahertz Polarisation Control and Filtering

1.3.1 Terahertz Polarisation Control

Polarisation filtering is essential in terahertz communication systems as any crosstalk between the data streams degrades the bit error ratio. In optical heterodyning transmitters, the amplitude of the terahertz wave modulates with the pump polarisation;

thus, changes in polarisation affect the signal directly (Nagatsuma et al., 2016; Koenig et al., 2013). Additionally, the signal experiences distortions during transmission along waveguides, through antennas, or through free space due to reflections or alignment errors. Polarisation distortion is essential to eliminate through a polarisation filter since it ensures the purity of the signal. Thus, the role of the polarisation filter is to provide pure signals by eliminating distortions during transmission. The review below will concentrate on integrated terahertz systems. Free-space systems, although well-developed, will not be considered in the analysis, as the concepts are different.



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Figure 1.11. State-of-the-art polarisers. (a) In-line broadband graphene photonic polariser with the measurement setup figure, adopted from (Bao et al., 2011). (b) TE-pass terahertz polarisation filter based on a slotted photonic crystal waveguide, adopted from (Prakash et al., 2018). (c) TE-pass slot waveguide terahertz polariser using an asymmetrical directional coupler, adopted from (Ni and Xiao, 2018). (d) Microwave polariser with a rounded shape at the edge of the periodic groove surface, adopted from (Li et al., 2015). (e) 3-D-printed cylinder microwave polariser, adopted from (Wang and Wong, 2017).

In photonics, a wide variety of integrated and fibre-based polarisers have been developed to provide high extinction with compact footprints (Bao et al., 2011; Xia et al., 2014). As shown in Fig. 1.11(a), a notable example is the broadband graphene fibre polariser, where a graphene-coated interaction region provides strong anisotropic absorption for polarisation discrimination (Bao et al., 2011). More recently, ultrathin conductive-film-based devices have taken advantage of advanced two-dimensional materials and novel fabrication techniques to further enhance polarisation performance (Xia et al., 2014). These designs demonstrate that extremely thin conductive sheets or films can achieve very high extinction ratios and broad bandwidth, and remain compatible with fibre or integrated platforms. However, these graphene and two-dimensional material-based designs require high quality large area material growth and precise transfer or stacking processes. Such fabrication steps are technically demanding, sensitive to defects and non-uniformity, and remain difficult to scale reliably for integrated terahertz applications.

Within silicon photonics technology, several TE-pass and TM-pass implementations have also been demonstrated (Prakash et al., 2018; Yang and Xiao, 2021; Ni and Xiao, 2018), as shown in Fig. 1.11(b–c). One approach uses a slotted photonic crystal waveguide in which the lattice is engineered to confine the TE mode while the TM mode is deliberately coupled to a lossy pathway and suppressed (Prakash et al., 2018). Another design uses an asymmetric slot waveguide directional coupler where the TM mode selectively couples into a lossy plasmonic branch, while the TE mode remains guided (Yang and Xiao, 2021). Innovations include the triple-guide coupler monolithically integrating with sub-wavelength grating segments to improve polarisation selectivity (Ni and Xiao, 2018). These components provide high extinction ratios with compact footprints, although they retain silicon-on-insulator configurations only within the near-infrared spectrum. Among these photonic components, there is control of modal birefringence and confinement using slots, photonic crystal lattices, and sub-wavelength grating structures, and then implementing a polarisation-selective loss mechanism.

At millimetre wave and terahertz frequencies, polarisation filtering has mainly relied on free-space implementations or metallic waveguide elements (Wang and Wong, 2017; Yamada et al., 2009; Li et al., 2015; Al-Alem et al., 2023), as shown in Fig. 1.11(d–e). Although similar designs are available at millimetre wave frequency bands, these are mostly free-space designs that typically consist of metal components, which are prone

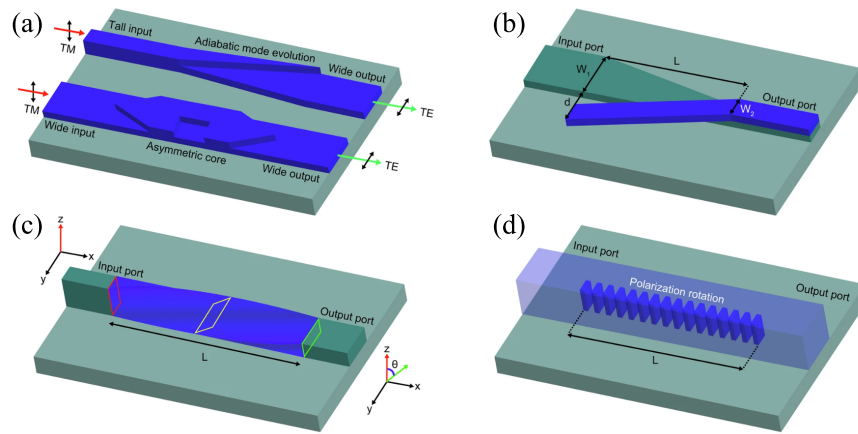


Figure 1.12. State-of-the-art on-chip photonic polarisation rotators, adopted from (Shahwar et al., 2024). (a) Generic schematics for mode-evolution (upper part) and mode coupling-based rotators (bottom part). (b) Mode-evolution-based polarisation coupling. (c) Twisted waveguide based on adiabatic mode conversion. (d) Polarisation rotators based on sub-wavelength gratings.

to increased material loss at terahertz frequency bands. Other designs based on dielectric materials are also mostly for free-space applications. In essence, the existing photonic and millimetre-wave solutions that have been effective at their current scales and frequencies are not readily applicable to the terahertz substrateless silicon technology. Photonic devices depend on oxide support layers, thin cores, and sometimes hybrid plasmonic channels (Bao et al., 2011; Xia et al., 2014; Prakash et al., 2018; Yang and Xiao, 2021; Ni and Xiao, 2018), which cannot be preserved in an all-silicon, wafer-based terahertz structure. Millimetre-wave wire grid and metallic groove-based polariser require metal surfaces, apertures, and alignment (Wang and Wong, 2017; Yamada et al., 2009; Li et al., 2015; Al-Alem et al., 2023), all of which introduce conductor loss, scattering, and external alignment tolerances that become more severe as the frequency increases into the terahertz band.

Besides the polarisation filter, the use of polarisation rotators becomes necessary since most guided-wave components tend to naturally support polarisation selectivity, and the polarisation of external sources often lacks adequate control. Without a transformation component on the chip, polarisation mismatch translates to higher insertion losses. A polarisation rotator on the integrated component ensures easy transformation to the required guided-wave mode.

Within silicon photonics, a wide range of integrated polarisation rotators have been demonstrated (Shahwar et al., 2024; Chen et al., 2011; Kwon and Werner, 2008; Fukuda et al., 2008; Wang and Dai, 2008; Zhang et al., 2009; Hou et al., 2019b), as shown in Fig. 1.12. Early designs use asymmetric waveguides to couple quasi-TE and quasi-TM modes. This coupling enables polarisation rotation through mode hybridisation (Wang and Dai, 2008; Zhang et al., 2009), as shown in Fig. 1.12(b). Later work introduced adiabatic mode evolution. In this approach, the waveguide geometry changes gradually so that one polarisation state is converted into the other with reduced scattering loss and improved bandwidth (Chen et al., 2011; Kwon and Werner, 2008), as shown in Fig. 1.12(c). More recent designs use subwavelength grating structures or multi-core waveguides. These structures improve control of birefringence and further increase the operating bandwidth (Fukuda et al., 2008; Hou et al., 2019b), as shown in Fig. 1.12(d). Although these theoretical principles provide a strong basis for polarisation rotator design, the corresponding photonic structures are not directly suitable for terahertz components. Many rely on thin silicon layers, oxide substrates, or metal-assisted processes, which lead to high loss at terahertz frequencies. Besides, the narrow fractional bandwidth limits their application in the WR-3.4 band. As a result, these established concepts need to be reinterpreted for terahertz operation. This requires new implementations in planar silicon waveguide platforms that can achieve low loss, good stability, and compatibility with integrated terahertz systems.

For these reasons, existing polarisation control technologies cannot be directly translated to a terahertz substrateless effective medium waveguide platform. There is a clear need for architectures that use only patterned high-resistivity silicon to achieve polarisation selectivity and rotation, thereby combining the compactness and integration strengths of photonic devices with the broadband, low-loss performance required at terahertz frequencies.

1.3.2 Terahertz Filtering

Bandpass filters are an essential part of modern high-frequency systems due to channel selection, suppression of interference, and realisation of sideband isolation. For heterodyne communications the terahertz range, a local oscillator band and an intermediate frequency signal are mixed to generate two sidebands around a carrier wave. This sideband signal, without bandpass filter selectivity, causes channel interference due to aliasing effects. For future links, tunable bandpass filters are further required to

reconfigure the occupied band without physically changing hardware. The literature on millimetre-wave and optical filters provides many powerful solutions in their own contexts, but they rely on resonant cavities, metallic surfaces, or multilayers that are fundamentally incompatible with the self supporting silicon effective medium waveguide platform (Gohari et al., 2023; Hu et al., 2012; Zhao et al., 2022; Zhuang et al., 2015; Wang et al., 2020).

Several technologies have been explored to achieve bandpass behaviour at millimetre-wave and optical frequencies. Silicon micromachined hollow waveguide filters are a well-established approach that extends conventional metal waveguide technology into the sub-terahertz range (Gohari et al., 2023; Hu et al., 2012; Zhao et al., 2022; Zhuang et al., 2015; Wang et al., 2020). As shown in Fig. 1.13(a), these filters use chains of resonant cavities whose coupled modes define the filter poles. Cross-coupling between

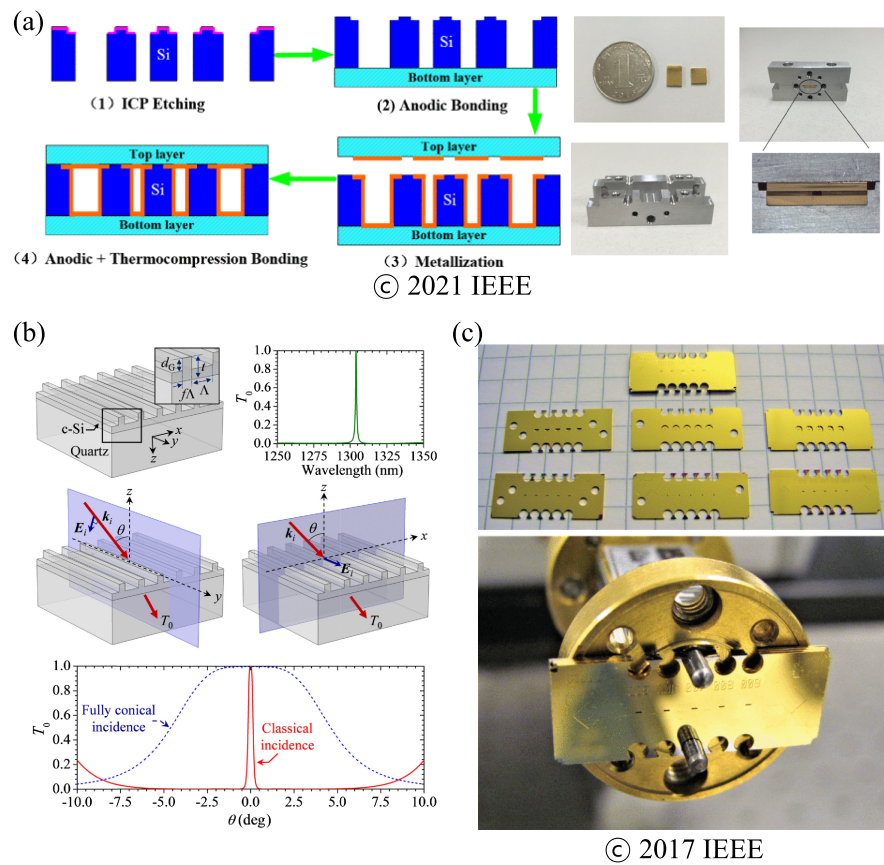


Figure 1.13. State-of-the-art bandpass filters. (a) Silicon micromachined elliptic cavity waveguide filter with the passband from 383.9 to 416.1 GHz, adopted from (Zhuang et al., 2015). (b) Divergence-tolerant resonant bandpass filter working at the resonant frequency of 229 THz, adopted from (Ko et al., 2016). (c) Narrowband dual-mode cavity filters with the passband from 267.5 to 272.5 GHz, adopted from (Glubokov et al., 2019).

non-adjacent cavities is deliberately introduced to create transmission zeros, which sharpens the transition between the passband and stopbands. The unloaded quality factor is mainly determined by the surface resistance of the metal-coated silicon walls. Elliptic or ridge cavity cells are formed by deep reactive ion etching in silicon and then metallised, providing compact filters with good control of the passband (Zhuang et al., 2015). Experimental studies have shown that small deviations in cavity geometry or alignment can shift the resonant frequency and reduce the quality factor (Zhuang et al., 2015; Glubokov et al., 2019). These filters offer accurate spectral control and compatibility with hollow waveguide hardware, but their performance at terahertz frequencies is limited. Ohmic loss in the metal increases with frequency, and fabrication tolerances become more critical as the dimensions shrink. A related approach extends SIW concepts toward the terahertz range. A compact SIW bandpass filter using via fences and metallised surfaces has been demonstrated (Wang et al., 2020). In these designs, the via fences form a quasi-hollow waveguide, while coupling elements define the passband response. Although cavity-based SIW filters can provide strong passband discrimination, they still rely on metal boundaries and multilayer fabrication. At high terahertz frequencies, conductor roughness becomes a dominant loss mechanism, and the embedded dielectric in SIW introduces additional propagation loss.

Beyond metal-defined waveguide cavities, a broad class of photonics-inspired planar and multilayer resonance filters has been developed. These filters rely on guided mode interference, Bragg scattering, and defect state localisation for spectral shaping (Ferraro et al., 2019; Niraula et al., 2015; Glubokov et al., 2017; Ko et al., 2016; Li, 2010), as shown in Fig. 1.13(b). In these structures, phase-matched coupling between an incident wave and a guided mode supported by a periodic high-index grating produces a narrow-band resonance. This resonance can show a flat transmission band and sharp spectral edges. Photonic crystal slab designs use bandgap confinement and introduce a defect to form a passband inside a forbidden frequency range. Guided mode resonance filters based on periodic dielectric gratings placed above reflective layers have demonstrated strong spectral shaping and flat passbands (Ferraro et al., 2019). Other approaches show that thick multilayer stacks can be replaced by a carefully engineered optical interface (Niraula et al., 2015). Multi-membrane resonator stacks, including circular cavity designs operating around 270 GHz, use mode splitting to create transmission zeros and improve selectivity (Glubokov et al., 2017, 2019), as shown in Fig. 1.13(c). Additional studies show that phase compensation can improve tolerance to beam divergence (Ko et al., 2016). Photonic crystal variants with patterned defect regions also

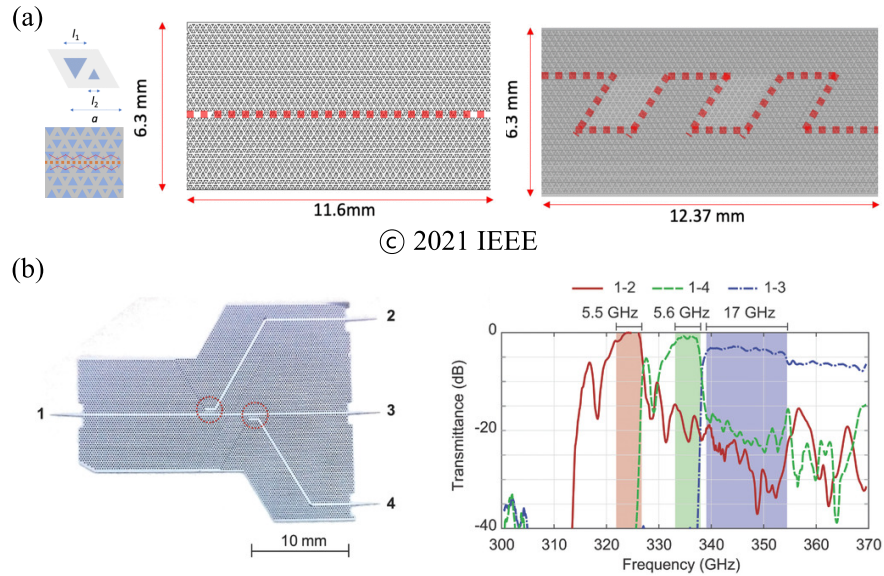


Figure 1.14. State-of-the-art bandpass filters based on photonic crystal. (a) Topological valley photonic crystal Waveguide with the passband from 320 to 348 GHz, adopted from (Webber et al., 2021). (b) Photonic-crystal triplexer with passbands of 314 – 327 GHz and 327 – 336 GHz, adopted from (Yata et al., 2016).

produce narrow passbands by suppressing lateral leakage through Bragg scattering (Li, 2010). This family of filters offers good spectral control and compact device size. However, their performance is often sensitive to polarisation and incidence angle. Many designs also require precise alignment of multiple layers or bonded reflective stacks. These requirements make integration into guided-wave terahertz transceiver platforms difficult. In many cases, high-precision packaging are needed.

Photonic crystal waveguides form a related but different class that mainly focuses on controlling dispersion and scattering in line defect channels (Yang et al., 2020; Withayachumnankul et al., 2018; Webber et al., 2021; Yu et al., 2019c; Li et al., 2022), as shown in Fig. 1.14(a–b). The basic theory is slow light and band-edge engineering. By tuning the lattice parameters, the dispersion of the guided mode can be flattened. This reduces the group velocity and allows control of group velocity dispersion. As a result, low loss and relatively low dispersion can be achieved over a limited frequency band. The guided mode is confined by the two-dimensional photonic bandgap. Its scattering behaviour is very sensitive to the local lattice geometry. Using this approach, photonic crystal waveguides have been demonstrated for terahertz communications with reduced back-scattering and better tolerance to sharp bends (Webber et al., 2021). Other

designs achieve both low loss and low dispersion through careful dispersion engineering (Yu et al., 2019c). However, when these structures are used for bandpass filtering by operating near the band edge or by adding local defects, the group delay often varies strongly. The usable bandwidth is also limited. This can make equalisation difficult in high symbol rate terahertz links.

In parallel with efforts focused on fixed-frequency filters, significant attention has been devoted to tunable terahertz bandpass filters. A wide range of tunable bandpass filters has been reported at microwave, millimetre-wave, and terahertz frequencies. These filters can be classified by their tuning mechanisms, which mainly include mechanical actuation and active material modulation. In both cases, tunability is achieved by modifying the resonant condition of the filter, resulting in a shift of the passband centre frequency.

Mechanical tuning-based filters are governed by classical resonant cavity and coupled resonator filter theory (Johnson, 2020; Wang et al., 2019; Lv et al., 2022; Gavdush et al., 2020; Mohammadi et al., 2024). In this framework, the centre frequency is determined by the physical dimensions of the resonant elements. Parameters such as cavity length, gap size, and periodic spacing define the electrical length of the structure. When these dimensions change, the phase accumulation condition also changes, leading to a shift in the resonant frequency (Johnson, 2020). At terahertz frequencies, mechanical tuning is realised by physically deforming or repositioning parts of the structure. Typical examples include waveguide bandpass filters using bimorph microactuators to adjust cavity dimensions (Wang et al., 2019) and gradient metal hole arrays with adjustable spacing (Gavdush et al., 2020). These methods provide predictable and continuous frequency tuning. However, they rely on moving parts and accurate mechanical control, which increases structural complexity and reduces long-term reliability. As a result, mechanical tuning is difficult to implement in compact terahertz integrated systems.

Active tuning in photonic platforms is based on perturbation theory for guided wave propagation. In a waveguide or resonator, the resonant frequency depends on the propagation constant of the guided mode. This propagation constant is determined by the effective refractive index of the structure. When the refractive index changes, the propagation constant also changes, which shifts the resonant frequency (Emami et al., 2017; Zhang et al., 2019; Antonio-Lopez et al., 2010; Tripathi et al., 2010). One common approach is carrier-induced refractive index modulation. In this method, carrier injection or depletion is used to modify the effective index of the guided mode,

which enables tunable bandpass behaviour in integrated waveguides and resonators (Antonio-Lopez et al., 2010). Another widely used approach is thermal tuning. Here, the refractive index is adjusted through the thermo-optic effect, and the resonance frequency is controlled using integrated heaters (Tripathi et al., 2010). A related method uses effective index modulation in multimode interference structures. In this case, a change in refractive index alters the interference condition and shifts the passband centre frequency (Zhang et al., 2019). These active tuning methods are well established at optical and near-infrared frequencies and do not require mechanical motion. However, at terahertz frequencies, the achievable refractive index change is small, which

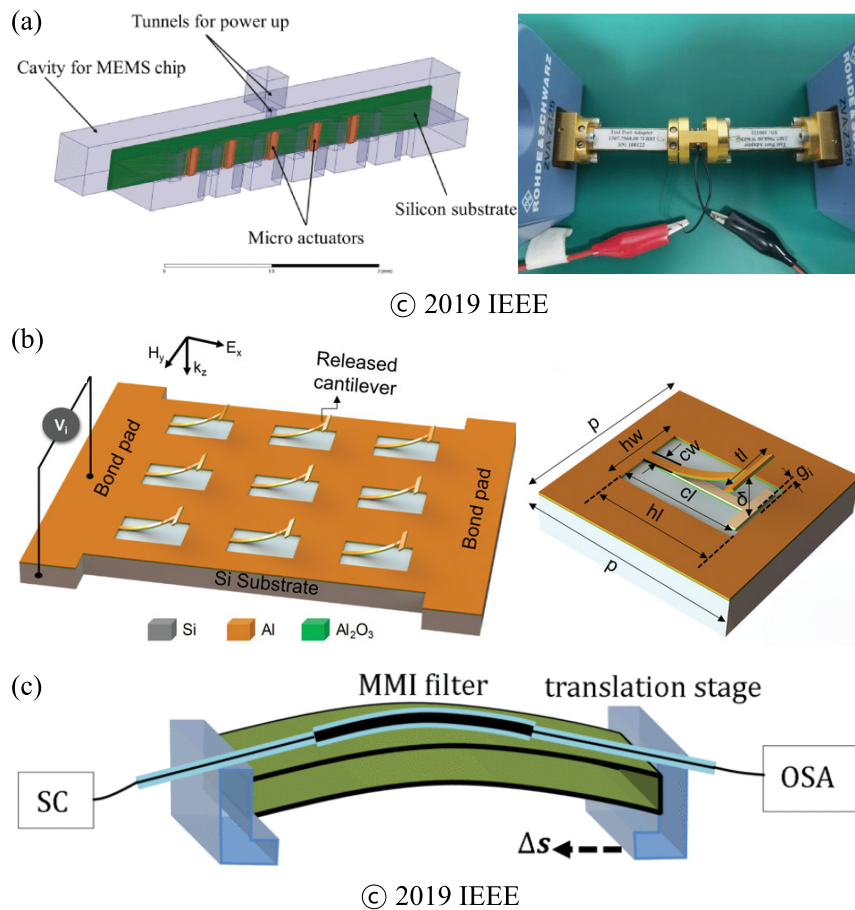


Figure 1.15. State-of-the-art tunable bandpass filters. (a) Tunable waveguide bandpass filter based on bimorph microactuators with the tunable passband from 4.8 to 7.8 GHz, adopted from (Wang et al., 2019). (b) Electromechanically tunable frequency-agile metamaterial bandpass filter with the tunable passband from 296 to 614 GHz, adopted from (Pitchappa et al., 2022). (c) Tunable multimode interference bandpass filter with the tunable passband from 150 to 157 GHz, adopted from (Zhang et al., 2019).

limits the tuning range. In addition, these designs often rely on thin silicon layers, oxide substrates, or metallic heaters, which introduce extra loss and thermal instability when applied to terahertz waveguides.

In summary, mechanical tuning relies on geometric control of resonant cavities, while active tuning relies on perturbation-induced changes in effective refractive index. Mechanical tuning offers a wide and predictable tuning range and follows well-established resonant cavity theory. Active tuning avoids mechanical motion and allows compact implementations with continuous electrical or thermal control. However, the achievable tuning range is limited at terahertz frequencies, and additional loss and thermal instability arise from thin silicon layers, oxide substrates, or metallic heaters.

For future terahertz communications and sensing systems, there is a strong demand for bandpass filters that provide low loss, broad relative bandwidth, and simple structures. Ideally, these filters should be realised using all-dielectric or mainly dielectric technologies to reduce ohmic loss. At the same time, they should offer precise spectral control and be compatible with high-resistivity silicon used in integrated terahertz circuits. Meeting these requirements requires new design strategies. These strategies should utilise effective medium concepts, tailored dispersion, and careful geometric design to achieve the required filtering and coupling behaviour without relying on complex multilayer stacks or highly resonant metallic elements.

While polarisation control and filtering define the spectral and vector properties of terahertz signals in integrated waveguides, these functions must operate within a complete front-end system. In practical terahertz platforms, this requires efficient interconnection between on-chip dielectric waveguides and standard hollow metallic waveguides used for signal routing, packaging, and measurement. The ability to transfer terahertz signals reliably between these different guiding structures is therefore essential for system integration. This motivates the discussion of mode conversion in the following section.

1.3.3 Mode Convertor

Robust coupling between an all-silicon effective medium waveguide and a hollow metallic waveguide is essential for terahertz front-end integration. This is especially important in the 220 to 330 GHz WR 3.4 band, where on-chip guided signals must connect reliably to standard waveguide ports. As shown in Fig. 1.16(a), conventional long

linear tapers gradually expand the dielectric mode to match the waveguide aperture. However, their millimetre scale length makes them mechanically fragile. They are prone to damage during sample separation, fixture tightening, or repeated handling.

To overcome fragility associated with long linear geometry, compact mode-coupling interfaces have been explored (Kumar et al., 2023; Ngo et al., 2024; Headland et al., 2025b; Sethi et al., 2017; Fu et al., 2014; Almeida et al., 2003). A quarter-wave dielectric slot section has been shown to achieve mode and impedance transformation without longitudinal expansion by forming a discrete matching layer between silicon and hollow waveguide (Kumar et al., 2023). Although much shorter than linear transitions, this structure remains sensitive to slot height, slot continuity, and silicon–metal alignment; degraded slot verticality or etch bias leads directly to mismatch. A taper-free slot coupling design eliminates linear expansion entirely by reshaping lateral confinement before coupling into the metallic guide (Ngo et al., 2024), as shown in Fig. 1.16(b), but the low coupling efficiency at lower frequencies is still a challenge due to the mode and impedance mismatch.

Broadband point-source coupling for silicon terahertz guides further removes length-based transformation and relies instead on confined radiation launching into the free space (Headland et al., 2025b). While this enables operation covering WR-3.4, it is not suitable for coupling between the silicon waveguide and the hollow waveguide. In

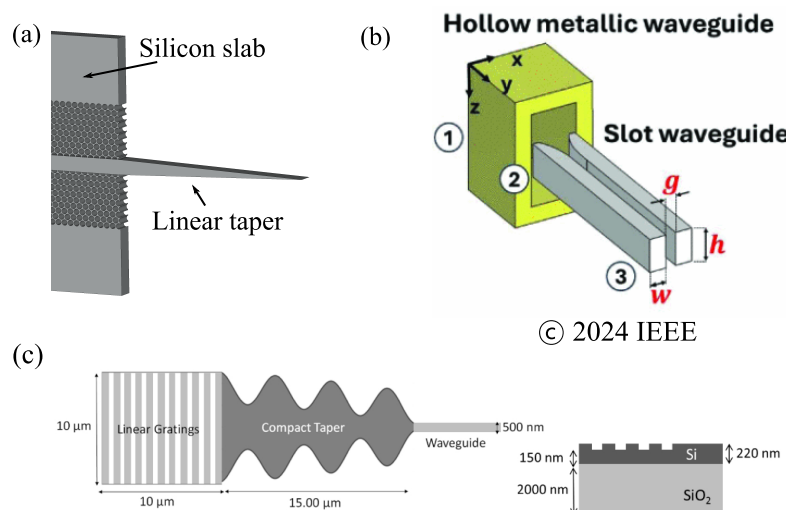


Figure 1.16. State-of-the-art tapers. (a) Linear taper. (b) Slot waveguide with taperless interfaces, adopted from (Ngo et al., 2024). (c) Ultra-compact waveguide taper, adopted from (Sethi et al., 2017).

parallel, compact linear tapers derived from silicon photonics minimise footprint by adjusting curvature and rate of width change (Sethi et al., 2017; Fu et al., 2014), as shown in Fig. 1.16(c); however, shortening the taper beyond a certain point increases susceptibility to higher-order mode excitation and frequency-dependent mismatch. Nanotaper variants compress the field into a deeply subwavelength cross-section to achieve direct profile matching (Almeida et al., 2003). However, the fractional bandwidth is not enough for the sub-terahertz range.

Across these compact coupling concepts, the key limitation is not the absence of transformation methods but rather the extreme tolerance dependence required to sustain broadband, low-reflection behaviour at 220–330 GHz. Quarter-wave slot alignment, taperless lateral confinement accuracy, point-source radiation control, and ultra-short linear taper smoothness all impose tight dimensional requirements that translate into yielding loss, or back-reflection-dominated bandwidth narrowing. These constraints underline the need for coupling strategies capable of short-length mode conversion without narrowing tolerance windows, radiation leakage, or alignment-induced mismatch when interfaced with hollow metallic standards.

1.4 Thesis Outline and Contributions

This thesis presents a systematic development of compact, low loss, and integrable terahertz filters tailored for emerging on chip communications and sensing platforms. As the terahertz spectrum continues to enable high-capacity wireless links, ultrafast signal distribution, and spectroscopic functionality, the realisation of a scalable integrated architecture remains a central technological objective. Although substantial progress has been made in source and detector engineering, the passive interconnect layer, including polarisation handling, spectral selection, and mode interface, lacks a unified silicon-based solution that can achieve low-loss performance together with reliable wafer-scale fabrication. This work addresses this gap by developing a set of integrated components, including broadband polarisation-discrimination devices, high-selectivity filters, and efficient mode converters, all based on an all-silicon effective-medium platform, which is further extended with hybrid metal coupling interfaces to enable reconfigurable channel allocation.

This thesis is organised into six chapters. Chapter 1 provides an introduction to terahertz science and technology, the motivation for component development based on

compact integrated waveguide platforms, and the existing challenges. Chapter 6 provides a comprehensive conclusion and an outlook for future research directions. Chapters 2 to 5 contain the original research contributions, which are outlined as follows:

The main body of the thesis begins with Chapter 2, which focuses on broadband all-silicon polarisation filters. By introducing a longitudinal slot into the effective medium waveguide core, we achieve broadband polarisation selectivity while suppressing cross-coupling between orthogonal field components. This chapter introduces the operating principles of anisotropic index engineering and provides full-wave simulations and experimental verification. The designs are verified experimentally, demonstrating low insertion loss, high polarisation purity, and wide operational bandwidth, confirming suitability for multichannel terahertz communications systems that require strict polarisation purity and minimal link budget degradation. The content of this chapter has been presented at conference (Chen et al., 2023) and published in (Chen et al., 2025b).

- **L. Chen**, W. Gao, C. Fumeaux and W. Withayachumnankul, Compact broadband terahertz filter based on effective medium, *2023 5th Australian Microwave Symposium (AMS)*, Melbourne, Australia, 2023, pp. 1-2.
Awarded the Australian Microwave Symposium Best Student Paper.
- **L. Chen**, W. Gao, C. Fumeaux and W. Withayachumnankul, (2024) Terahertz integrated polarisation filter based on slotted Bragg grating, in *IEEE Transactions on Terahertz Science and Technology*, vol. 15, no. 3, pp. 473-480.

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

Chapter 3 introduces a series of bandpass filters developed on the substrateless silicon platform. High selectivity filtering is achieved by combining cascaded one-dimensional and two-dimensional photonic crystal structures with effective-medium cladding. This approach enables accurate control of the passband centre frequency and bandwidth, while maintaining good tolerance to fabrication variations. Filter designs are presented for four terahertz communications channels. Two channels are fabricated and experimentally characterised. The measured results show low insertion loss together with strong out-of-band suppression. Communications experiments further demonstrate the spectral reshaping capability of the proposed filters. These include effective

suppression of out-of-band noise and improved channel isolation, while maintaining error-free data transmission. These results demonstrate that the proposed platform provides a scalable and high-performance filtering solution for future multi-band terahertz systems. The content of this chapter has been presented at a conference (Chen et al., 2024) and has also been published (Chen et al., 2025a).

- **L. Chen**, W. Gao, M. Abdullah, J. Hesler, C. Fumeaux and W. Withayachumnankul, (2025) All-dielectric bandpass filters for IEEE 802.15.3d terahertz communications, in *IEEE Transactions on Terahertz Science and Technology (Early Access)*.
- **L. Chen**, W. Gao, J. Hesler, C. Fumeaux and W. Withayachumnankul, Dielectric bandpass filter for terahertz communications, *2024 IEEE Asia-Pacific Microwave Conference (APMC)*, Bali, Indonesia, 2024, pp. 546-548.
- **L. Chen**, W. Gao, J. Hesler, C. Fumeaux and W. Withayachumnankul, All-dielectric bandpass filters for terahertz communications, *2026 Australasian Symposium on Antennas (ASA)* Adelaide, Australia, 2026.

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

Chapter 4 presents the development of compact silicon tapers for efficient mode matching between the dielectric waveguide and hollow waveguide. The chapter introduces two compact all-silicon tapers that utilise the combined operation of dielectric rod antenna coupling and slot guided confinement. The designs achieve a longitudinal footprint of only half a guided wavelength for operation between 220 and 330 GHz, while sustaining an average low coupling loss across the full band. Compared with conventional linear tapers, the presented structures significantly reduce device length and enhance mechanical robustness and alignment tolerance. Terahertz communications experiments confirm that the tapers preserve signal integrity under high data rate modulation, demonstrating reliable transmission performance without introducing noticeable distortion or dispersion. These compact tapers thereby enable efficient conversion between guiding platforms and support system-level integration of filters, multiplexers, and polarisation control units. The content of this chapter has been published (Chen et al., 2026).

- **L. Chen**, W. Gao, C. Fumeaux and W. Withayachumnankul, (2026) Ultra-compact waveguide couplers for all-silicon terahertz platform, *Advanced Photonics Research*

Invited for a special issue on On-chip Terahertz Photonic Manipulation for Future Communications.

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

Chapter 5 extends the passive platform by introducing a tunable bandpass filter that integrates silicon and metal. The design integrates dielectric one-dimensional photonic crystal guidance with a parallel plate metallic waveguide to achieve compact, low-loss, and reconfigurable spectral control. The photonic crystal region forms a broad high-frequency stopband, while the metallic section sets the low-frequency cutoff through adjustment of the plate separation. By combining these two mechanisms, the filter demonstrates a very sharp transition between the passband and stopband together with a high rejection level over a wide spectral range. The metallic gap can be varied to tune not only the centre frequency but also the bandwidth. The hybrid architecture demonstrates frequency reconfigurability under applied control conditions and opens a pathway for adaptive channel management in future integrated terahertz systems.

Chapter 2

Terahertz Integrated Polarisation Filter

ALL-silicon substrateless integrated systems are suitable to wide-ranging terahertz applications due to their low-loss characteristics. A broadband, high-extinction level polarisation filter is in demand for these on-chip systems to select the desired polarisation when monomode operation of the dielectric host waveguide is required. Existing photonic designs for polarisation filtering cannot cope with a large fractional bandwidth in the terahertz range. To increase the bandwidth and rejection level of the filter, a longitudinal slot is introduced into the host waveguide. Experimental validation shows a high average polarisation extinction ratio of 23.5 dB between the TM and TE polarizations and an insertion loss of around 1.5 dB for the TM polarisation over a -15 -dB stopband of 87 GHz covering the whole IEEE communications band between 252 and 325 GHz. The proposed filter will be an essential component for terahertz communications to maintain the polarisation purity in substrateless dielectric waveguides.

2.1 Introduction

Integrated polarisation filtering has been extensively explored in photonic platforms, with various structural mechanisms demonstrated to achieve polarisation selectivity. While these approaches establish the feasibility of on chip polarisation control, their direct applicability to terahertz integrated systems remains limited due to fundamental constraints in bandwidth, loss, and platform compatibility, as discussed in Chapter 1.

In particular, many existing polarisation filtering concepts rely on substrate assisted birefringence enhancement, resonance driven dispersion, or metallic confinement, which either restrict the achievable bandwidth or introduce significant loss at terahertz frequencies (Ni and Xiao, 2019; Prakash et al., 2018; Kim et al., 2016; Cheng et al., 2023; Li et al., 2018; Wang et al., 2012). These limitations become critical for broadband terahertz communication frontends, where low insertion loss, wide operational bandwidth, and monolithic integration are simultaneously required. This motivates the investigation of a polarisation filter specifically tailored for all silicon substrateless terahertz integrated platforms, which can preserve polarisation purity while maintaining high efficiency and broadband performance.

Recently, a Bragg grating implemented with an effective-medium has been proposed as an alternative promising way for filter design on the substrateless, all-silicon integrated platform (Gao et al., 2021). Specifically, the modal indices of Bragg gratings can be controlled by selecting waveguide dimensions and effective medium claddings so as to minimize the transmission loss caused by radiation and weak wave confinement at the frequency band edges. The absence of substrate resulted in significant efficiency improvement in the terahertz range. However, the spectral coverage of the stop band remained relatively narrow, while the birefringence of the filter was not specifically investigated.

In this chapter, we present a broadband terahertz polarisation filter implemented by cascading multiple Bragg gratings with various periods, created based on the effective-medium-clad waveguide platform. To further enhance bandwidth and polarisation extinction ratio while minimizing insertion loss and required footprint, effective-medium slots are introduced along the grating core. In effect, the filter can cover the fractional -15 -dB stop bandwidth of 25% over the whole communications band between 252 and 325 GHz. The proposed design is experimentally validated. In Section 2.2.1, we review the theory of Bragg grating and effective-medium, as well as their combination that forms the basis of the proposed filter. In Section 2.2.2, we discuss the effect of the

longitudinal slot and how it increases the rejection level over a broad bandwidth. The realisation of the filter is presented in Section 2.3, followed by the conclusion given in Section 2.4.

2.2 Design Principles

The general principle of the polarisation filter is to introduce anisotropy in the propagation of the two modes. This will allow to suppress one mode by subjecting it to the Bragg condition in a periodic step-impedance structure, while keeping the other mode nearly unaffected. The following two sections explain how this can be achieved in the effective-medium waveguide platform. All modal index analyses are based on port-mode simulations in CST Microwave Studio 2023.

2.2.1 Effective-medium-clad Bragg Grating

Bragg gratings implemented with effective medium cladding have been proposed to increase the design flexibility (Gao et al., 2021). As shown in Fig. 2.1, the periodically repeated silicon segments with different widths, and thus with different modal indices (n_l and n_h) are cladded by an effective medium, which is realised using subwavelength perforation of the silicon slab. For this design, the TE mode (in-plane polarisation) is defined with its electric field parallel to the xz -plane, while the TM mode (out-of-plane polarisation) is orthogonal to the xz -plane. The effective-medium acts as an anisotropic material with the relative permittivity tensor $(\varepsilon_x, \varepsilon_y, \varepsilon_z)$ calculated by

$$\varepsilon_x = \varepsilon_{\text{si}} \frac{(\varepsilon_{\text{si}} + \varepsilon_{\text{air}}) + (\varepsilon_{\text{air}} - \varepsilon_{\text{si}})\zeta}{(\varepsilon_{\text{si}} + \varepsilon_{\text{air}}) - (\varepsilon_{\text{air}} - \varepsilon_{\text{si}})\zeta}, \quad (2.1a)$$

$$\varepsilon_y = \varepsilon_{\text{si}} + (\varepsilon_{\text{air}} - \varepsilon_{\text{si}})\zeta, \quad (2.1b)$$

$$\varepsilon_z = \varepsilon_x, \quad (2.1c)$$

where the fill factor is

$$\zeta = \frac{\pi d^2}{4a^2}. \quad (2.2)$$

Here, $\varepsilon_{\text{si}} = 11.68$ and $\varepsilon_{\text{air}} = 1$ are the relative permittivities of silicon and air, respectively. The dimensions a and d are the hole diameter and lattice period. A variety of tensor values $\varepsilon_{x,y,z}$ between $\varepsilon_{\text{air}} = 1$ and $\varepsilon_{\text{si}} = 11.68$ are available with different fill factors ζ .

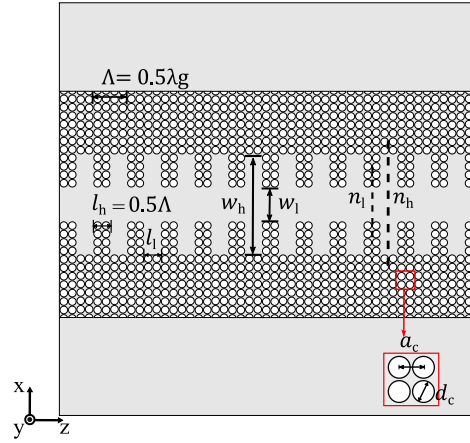


Figure 2.1. Uniform effective-medium-clad Bragg grating from the top view. The grating is realised on a 250- μm thick silicon wafer with a relative permittivity $\epsilon_{\text{si}} = 11.68$, different sections with different silicon widths, lead to a modal index modulation of n_h , n_l . The dimensions are $w_h = 630 \mu\text{m}$, $w_l = 250 \mu\text{m}$ and $\Lambda = 228 \mu\text{m}$. An air–silicon effective medium cladding with a fill factor $\zeta_c = 0.63$ is realised by perforating the silicon slab with holes with diameter $d_c = 51 \mu\text{m}$ and periodicity $a_c = 57 \mu\text{m}$.

The main aim of the TE polarisation filter design is to achieve a high polarisation extinction ratio within the terahertz wireless communications band using the grating structure. To this end, three key parameters must be considered: the TE modal index difference, $\Delta n_{\text{TE}} = n_h - n_l$, the difference in average modal indices between TE and TM, $\Delta n_{\text{avg}} = n_{\text{avg(TE)}} - n_{\text{avg(TM)}}$ (Cheben et al., 2018), and the number of grating periods, N_g . The TE modal index difference correlates with the TE rejection level and bandwidth of the stopband. The difference in modal indices between the TE and TM modes affects TM transmission performance, and the rejection level for TE mode increases with the number of grating periods, N_g . It is notable that the TE modal index difference and the average modal index difference between the TE and TM modes are increased by the anisotropy of the cladding medium.

By comparing the required fractional bandwidth 25% for the polarisation filter with the filter fractional bandwidth of 5.8% presented in (Gao et al., 2021), it is apparent that the bandwidth of the stopband for the TE polarisation needs to be increased. There are two approaches that can be applied to achieve a wide bandwidth, namely increasing the waveguide width difference $\Delta w = w_h - w_l$ to increase the TE modal index difference, or alternatively, increasing the cladding's fill factor ζ_c . Increasing the modal index difference requires decreasing the width of the narrow grating segment, i.e., the segment with low-index n_l . However, the average TE modal index $n_{\text{avg(TE)}}$ is more sensitive to

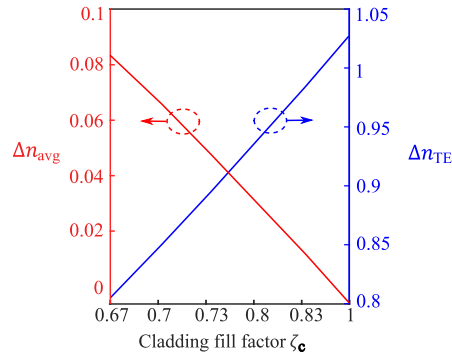


Figure 2.2. Modal index characteristics. The TE modal index difference Δn_{TE} and the difference in modal indices between TE and TM Δn_{avg} of a uniform un-slotted Bragg grating as shown in Fig. 2.1, as a function of the cladding fill factor.

the grating width variation than the cladding fill factor. A narrower grating will decrease the average TE modal index $n_{avg(TE)}$ and therefore increase the grating period Λ , which may cause undesired leaky-wave radiation for the TM mode at high frequency. Therefore, the second approach is selected, namely increasing the cladding fill factor ζ_c . As shown in Fig. 2.2, for a given silicon grating configuration, the TE modal difference Δn_{TE} increases with the increased cladding fill factor ζ_c . However, a high fill factor, i.e. a larger size of holes, will degrade the mechanical strength. According to the grating principle (Cheben et al., 2018), the selected grating period Λ should be equal to the TE guided half-wavelength, i.e., $\Lambda = \lambda / (2n_{avg(TE)})$, while remaining much smaller than the TM guided half-wavelength. To achieve that, the equivalent birefringence should be increased for the larger difference between TE and TM modal indices. However, the average modal index difference, i.e., $\Delta n_{avg} = n_{avg(TE)} - n_{avg(TM)}$ decreases with an increase in fill factor as shown in Fig. 2.2. Therefore, the TE modal index difference can be increased at the expense of the birefringence and sample mechanical strength.

2.2.2 Effective-medium Slot

To overcome the constraints of achieving a wide TE stopband while maintaining low-loss TM transmission, an additional design feature is introduced in the form of a central slot in the effective-medium-clad Bragg gratings. As shown in Fig. 2.3, this slotted grating is realised by perforating the grating core, with hole diameter d_s and subwavelength period of a_s .

To investigate the slot effect, we set the slotted grating dimensions as shown in Fig. 2.3, while varying the slot fill factor ζ_s from 0 to 1, assuming the slot fill factor ζ_s has the

2.2.2 Effective-medium Slot

same definition as in Eq. 2.2. As shown in Fig. 2.4(a), for the TE mode with increasing slot fill factor ζ_s , the modal index difference Δn_{TE} increases. This indicates a wide stopband and a larger grating period for the TE mode. Increasing the slot fill factor also results in an increased difference in average modal indices, $\Delta n_{\text{avg}} = n_{\text{avg(TE)}} - n_{\text{avg(TM)}}$, in turn enhances birefringence and consequently improves TM mode transmission. The same method is applied to investigate the impact of slot width, which equals the hole size. As shown in Fig. 2.4(b), for the TE mode, the grating has a higher modal index difference Δn_{TE} with larger slot width w_s . As can be deduced from in Fig. 2.4(a)–(b), given the same silicon corrugation, a wider TE stopband can be achieved using a higher slot fill factor ζ_s , i.e., a larger hole diameter d_s , or a larger slot width w_s . However, as shown in Fig. 2.4(b), the average modal index difference Δn_{avg} decreases with

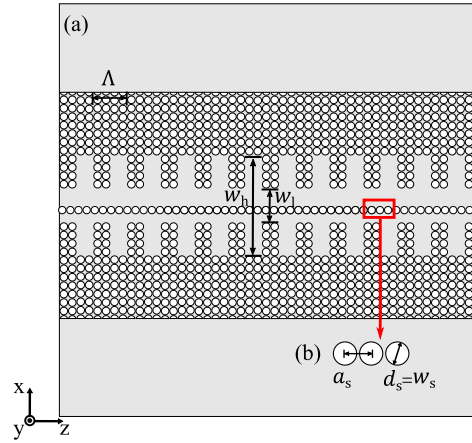


Figure 2.3. Uniform slotted effective-medium-clad Bragg grating. (a) Air–silicon effective medium cladding and slot with the same fill factor $\zeta_s = \zeta_c = 0.63$. $w_h = 630 \mu\text{m}$, $w_l = 250 \mu\text{m}$. (b) Slot realised by perforating the silicon slab with $a_s = 56 \mu\text{m}$ and $d_s = 50 \mu\text{m}$.

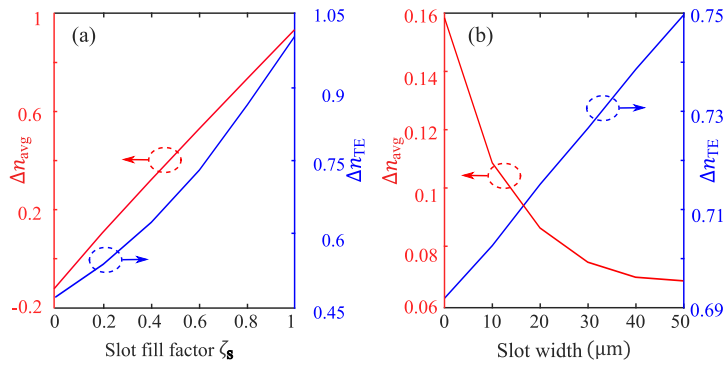


Figure 2.4. Characteristics of Modal index. Modal index characteristics Δn_{TE} and Δn_{avg} of a uniform slotted Bragg grating as a function of (a) slot fill factor and (b) slot width.

increasing slot width w_s . In other words, increasing the slot width will also decrease the equivalent birefringence.

A circular hole within a square lattice limits the maximum fill factor range to 0.78. Moreover, due to fabrication constraints, the minimum distance between two adjacent holes should be larger than $6\text{ }\mu\text{m}$. Considering these limitations, we use the same fill factor for both the cladding and slot, $\zeta_s = \zeta_c$, setting the factor at an achievable level and focusing solely on optimizing the slot width w_s .

To validate our findings regarding slot inclusion, we have designed a slotted effective-medium Bragg grating filter as shown in Fig. 2.5, to compare with the original grating

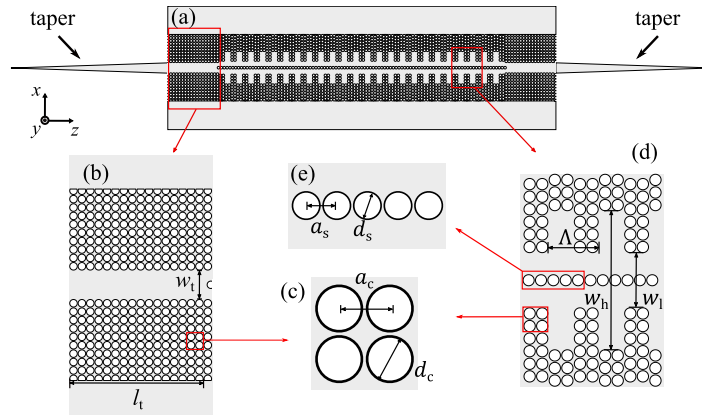


Figure 2.5. Slotted effective-medium Bragg grating filter. (a) Top view. (b) Nominal waveguide. (c) Square lattice of the effective medium cladding. (d) Slotted Bragg grating. (e) Effective-medium slot realised as a line of holes. The geometric parameters of the design are $w_t = 200\text{ }\mu\text{m}$, $l_t = 1000\text{ }\mu\text{m}$, $a_c = 57\text{ }\mu\text{m}$, $d_c = 51\text{ }\mu\text{m}$, $w_h = 630\text{ }\mu\text{m}$, $w_l = 250\text{ }\mu\text{m}$, $\Lambda = 228\text{ }\mu\text{m}$, $a_s = 56\text{ }\mu\text{m}$, $d_s = 50\text{ }\mu\text{m}$.

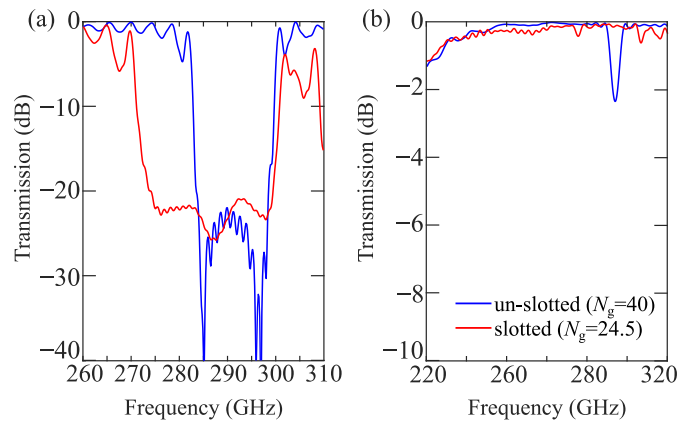


Figure 2.6. Simulated transmission results of the un-slotted and slotted filters with the same Bragg frequency. (a) For the TE mode, and (b) for the TM mode.

2.3 Filter Design

Table 2.1. Dimensions of each cascaded section

	Stopband (GHz)	Cladding							Slot		
		w_h (μm)	w_l (μm)	Λ (μm)	N_g	ζ_c	a_c (μm)	d_c (μm)	ζ_s	a_s (μm)	d_s (w_s) (μm)
Section 1	245–263	200	580	240	20	0.66	60	55	0	0	0
Section 2	260–290	220	610	240	10	0.6	60	52	0.6	46	40
Section 3	268–297	250	630	228	15	0.63	57	51	0.63	56	50
Section 4	295–330	230	550	212	10.5	0.663	53	48.7	0.663	54.4	50

filter in Fig. 2.1. Full-wave simulations of both structures were performed using the time-domain solver in CST Microwave Studio 2023, with an accuracy setting of -40 dB. A loss tangent of 3×10^{-5} and a relative permittivity of 11.68 are adopted for the silicon material. As shown in Fig. 2.6, a wider -15 -dB stop bandwidth for the TE mode wave are achieved with the slot. However, the results also show a strong transition ripple at the edge of the passbands, which are caused by the modal index mismatch between the solid waveguide core and the slot (Macleod, 2007). To mitigate this, apodisation (Wang, 2013, PhD dissertation) needs to be applied for the polarisation filter design, which will be illustrated in Section 2.3. The slotted filter can use a smaller number of grating periods compared to a corresponding un-slotted filter while still achieving a similar rejection level. As the reflection level for both modes increase with a growing number of grating periods, using a smaller number of grating periods weakens the reflection effect, thereby enhancing TM mode transmission, as shown in Fig. 2.6(b).

2.3 Filter Design

This section introduces cascaded filter design with apodisation to further expand the stopband to match the requirements in terahertz communications.

2.3.1 Filter Sectioning

To cover the terahertz wireless communications band, from 252 to 325 GHz (Standards Committee, 2017), we use cascaded Bragg gratings with different filter frequency ranges. Multi-sections of gratings are connected in the Bragg frequency order from low to high, where the grating period gradually decreases across different sections. To avoid radiation for the TM mode at high frequencies caused by the leaky-wave effect, the equivalent birefringence needs to be increased by increasing the difference in

average modal indices Δn_{avg} , and the grating period of each section needs to be decreased to the subwavelength range of TM mode within the whole communications band. According to the investigations in Section 2.2.2, a higher difference in average modal indices Δn_{avg} can be achieved with higher slot fill factor ζ_s and narrower slot width w_s . However, the fabrication process limits the minimum slot width to 20 μm . Besides, a higher slot fill factor will decrease the average modal index n_{eff} of the TE mode. Thus the grating period has to be increased. Accordingly, we use the un-slotted grating filter for the section with the lowest Bragg grating frequency and modify the structure dimensions to gradually increase the average modal index n_{eff} for each section. For the un-slotted grating, the average modal index n_{eff} of the TE mode is larger compared with the slotted grating, thus a smaller grating period is naturally achieved. Also, we properly select the grating number N_g of each section for better TM mode transmission and a compact footprint based on the discussions in Section 2.2.2.

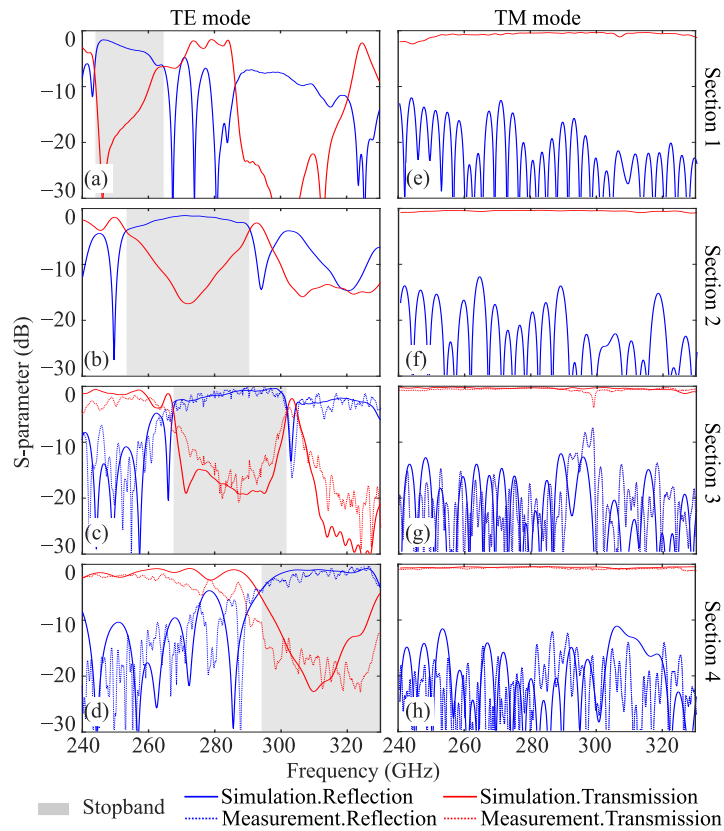


Figure 2.7. Transmission and reflection profiles for different filter sections. (a-d) TE and (e-h) TM modes. (a), (e) Section 1. (b), (f) Section 2. (c), (g) Section 3. (d), (h) Section 4.

2.3.1 Filter Sectioning

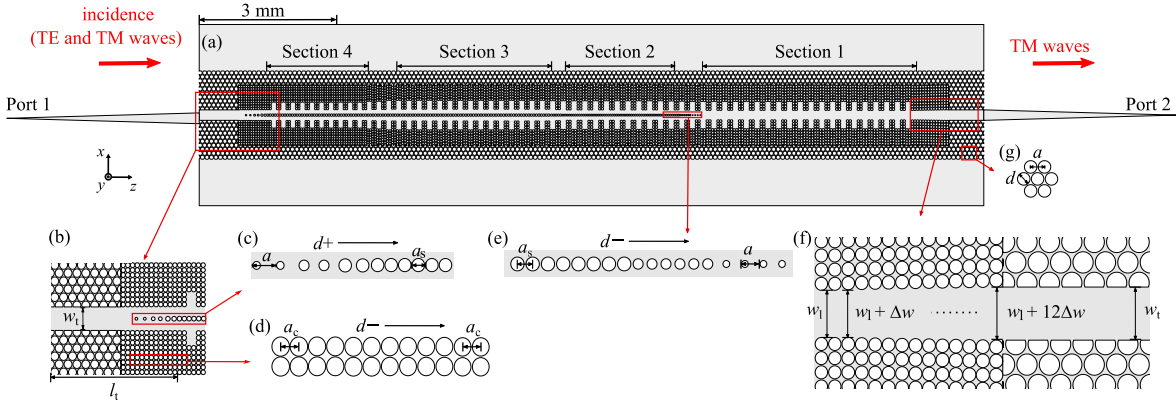


Figure 2.8. Broadband polarisation filter. (a) Top view. (b) Transition waveguide with the transition length $l_t = 1500 \mu\text{m}$. (c) Slot apodisation, with increased hole diameter from $30 \mu\text{m}$ to $50 \mu\text{m}$ and decreased hole period from $a = 95 \mu\text{m}$ to $a_s = 54.4 \mu\text{m}$. (d) Transition waveguide cladding part, with the constant lattice period $a_c = 53 \mu\text{m}$ and decreased hole period from $51 \mu\text{m}$ to $48.7 \mu\text{m}$. (e) Slot transition part between Section 1 and Section 2, with decreased hole diameter from 40 to $20 \mu\text{m}$ and increased hole period from $a_s = 46 \mu\text{m}$ to $a = 56 \mu\text{m}$. (f) Transition waveguide core apodisation part, with $w_t = 200 \mu\text{m}$, $\Delta w = 1 \mu\text{m}$, and $w_t = 225 \mu\text{m}$. (g) Standard waveguide cladding with $a = 100 \mu\text{m}$, $d = 90 \mu\text{m}$.

In the specific design presented in the following, we use four gating sections with the dimensions of each section shown in Table 2.1. As the rejection level increases owing to the overlapping spectral responses, a smaller grating number N_g is permissible for Sections 2–4 to attain a high TE rejection level and high TM transmission. Using un-slotted and slotted filter structure as shown in Figs. 2.1 and 2.5, the simulated S -parameters results for each section decrease in the order of Bragg frequency as shown in Fig. 2.7(a)–(d). It is observed that the emergence of the second stopband at high frequencies for the TE mode is attributed to leaky waves due to the large TE modal index difference, $\Delta n_{\text{TE}} = n_h - n_l$. This implies that in the cascaded polarisation filter, the filter response is contingent upon the direction of the wave incident. As shown in Fig. 2.8(a), when the wave is incident from the low-frequency section, i.e., Section 1, the TE mode within 290–320 GHz will be radiated by Section 1 and cannot be filtered by Sections 3 and 4. Conversely, if the wave is incident from the high-frequency section side, i.e., Section 4, the TE mode wave can be filtered out through reflection in descending frequency order, thereby minimizing radiation.

As shown in Fig. 2.9(a), a single filter section is fabricated by the deep reactive ion etching (DRIE) process using a 250- μm -thick high-resistivity silicon wafer with a relative

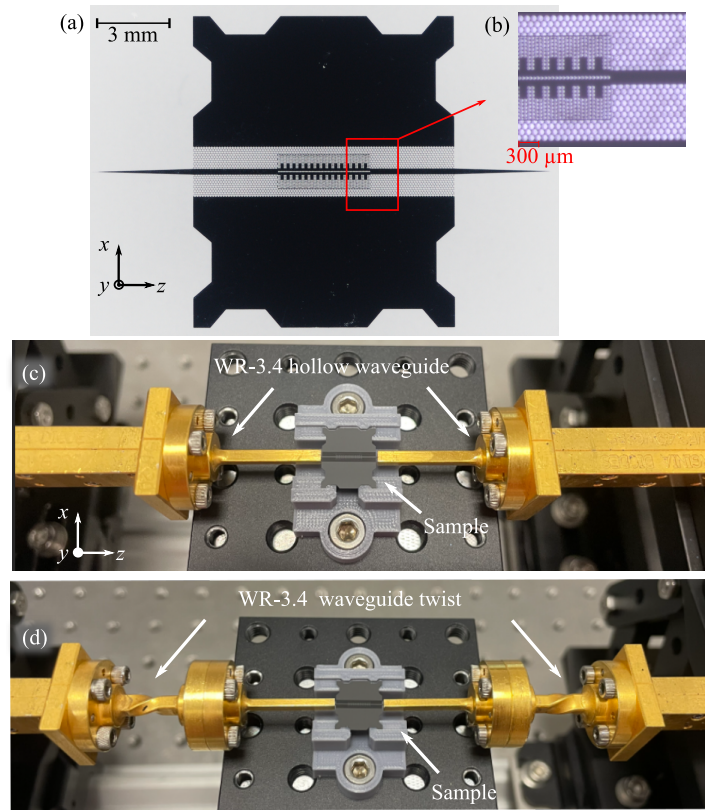


Figure 2.9. Fabricated slotted effective-medium Bragg grating filter and measurement setup. (a) Fabricated sample containing only Section 3. (b) Microscope image depicting a slotted Bragg grating and a transition waveguide. (c) TM mode measurement setup. The tapered structures are inserted into the WR-3.4 hollow waveguides for excitation, while the sample is secured by a 3D-printed polylactic acid (PLA) holder. The WR-3.4 waveguide excites the polarisation in the y -direction for the filter sample. Measurements are performed using a Keysight vector network analyzer equipped with VDI WR-3.4 extension modules covering 220–330 GHz. (d) TE mode measurement setup by adding the WR-3.4 waveguide twists to rotate the polarisation to the x -direction.

permittivity of 11.68 and an estimated loss tangent of 3×10^{-5} . Each of the 4 sections is made to occupy the same overall device footprint of $10.0 \text{ mm} \times 11.9 \text{ mm}$ by modifying the length of transition waveguides as shown in Fig. 2.5(b). To experimentally verify the design, the measurement is conducted with a Keysight vector network analyzer (VNA) with VDI WR-3.4 extension modules spanning from 220 to 330 GHz with 1001 points. An IF bandwidth of 100 kHz was used. The measurement results of two WR-3.4 hollow waveguides connected back-to-back have been used as a reference for calibration. As shown in Fig. 2.9(c)–(d). The measured and simulated results for Section 3 are in good agreement as shown in Fig. 2.7(c) and (g). However, for the TE mode of Section 4 as shown in Fig. 2.7(d), the stopband frequency red-shifts by 5 GHz, and the

2.3.2 Realisation of Cascaded Filter

Table 2.2. Comparison on the state of the art polarisation filters

Ref.	Structure	Wavelength	Pol.	ER (dB)	Length (λ_0)	BW	Loss (dB)	Substrate
(Ni and Xiao, 2019)	Slot waveguide	1.55 μm	TE	36	39.13	13 percent	0.42	SiO ₂
(Prakash and Sen, 2020)	Photonic crystal	1.55 μm	TM	45	3.22	7.7 percent	0.6	SiO ₂
(Mohammed et al., 2022)	Cascaded coupler	1.57 μm	TE	33	166.56	6 percent	0.52	SiO ₂
(Yu et al., 2019a)	Hybrid grating	1.55 μm	TM	20	14.84	9 percent	2.5	SiO ₂
This work	Cascaded Bragg grating	1039 μm	TM	23.5	16.74	25 percent	1.5	Nil

bandwidth is broadened by 10 GHz. This is mainly because of fabrication inaccuracies, as small holes tend to be over-etched.

2.3.2 Realisation of Cascaded Filter

Referring to the discussion in Section 2.3.1, each section has different average modal indices Δn_{eff} . So, it is necessary to introduce a transition section between every two sections, thereby improving impedance matching in the cascaded polarisation filter. These transitions are tailored to realise a gradual change of the grating width as well as of the fill factors of the cladding and slot, ζ_c , ζ_s . In addition, two straight waveguide sections are applied on both sides of the cascaded polarisation filter for mode matching to the hollow feeding waveguides.

Figure 2.8 shows the final structure of the broadband polarisation filter. For design validation, the polarisation filter sample with the dimensions of 17.4 mm $\times$ 11.9 mm is fabricated as shown in Fig. 2.10(a), with detailed views of the 4 sections in Fig. 2.10(b)–(e).

As shown in the simulation results in Fig. 2.11(a), for the TE mode suppression, the design shows 87 GHz of -15 dB stop-bandwidth, with an average filter rejection level of -25 dB and a roll-off rate calculated from -3 to -15 dB of 4.33 dB/GHz. Moreover, the transmission ripple of the TE passband is well mitigated by the transition parts. Due to the small grating number for each section, the average insertion loss for the

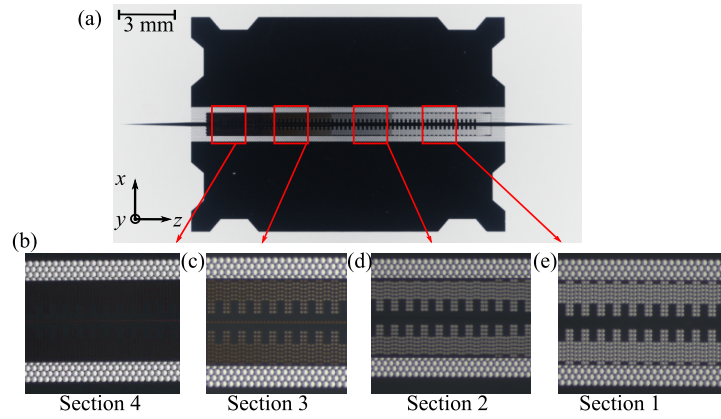


Figure 2.10. Fabricated polarisation filter. (a) Full-band polarisation filter sample. (b–e) Microscope images of different sections.

TM mode of the connected structure is 1.5 dB, as shown in Fig. 2.11(b). The resulting average extinction ratio reaches 23.5 dB within the communications band, as shown in Fig. 2.11(c). It is worth noting that blind holes are present within the claddings of Sections 3 and 4 and the slots of Sections 2, 3, and 4 in the fabricated sample. As visible in Fig. 2.11, while the center frequency and bandwidth of the stopband for the TE mode remain unaffected, the measured reflection level of the TM mode is higher than predicted in simulations at frequencies above 280 GHz. This is due to the blind holes that increase the TM average modal index and match the Bragg grating period of the frequency from 285 to 315 GHz, thus increasing the reflection of TM mode. This effect has been confirmed through simulation. Using CST Studio 2023, we replicate the fabricated sample with blind holes, as illustrated in Fig. 2.12(c). The simulated results closely matched the measured data, as shown in Fig. 2.13(b). In comparison with the designed structure shown in Fig. 2.12(a), the fabricated sample exhibits stronger reflection as shown in Fig. 2.12(b). The blind area also increases the TE average modal index, which decreases the guided wavelength, i.e., $\lambda/n_{\text{avg(TE)}}$, and leads to radiation in the higher frequency range of 307 to 330 GHz, as shown in Fig. 2.13(a). This effect has been confirmed through simulation. Overall, this design realises the polarisation filtering function for TE waves within the whole wireless communications band. Table 2.2 compares the state-of-the-art polarisation filters. While the photonic crystal in (Prakash and Sen, 2020) demonstrates a high extinction ratio and compact footprint, its bandwidth is limited. By integrating approaches from (Ni and Xiao, 2019; Mohammed et al., 2022; Yu et al., 2019a), our design achieves the widest bandwidth, along with a compact footprint and high extinction ratio.

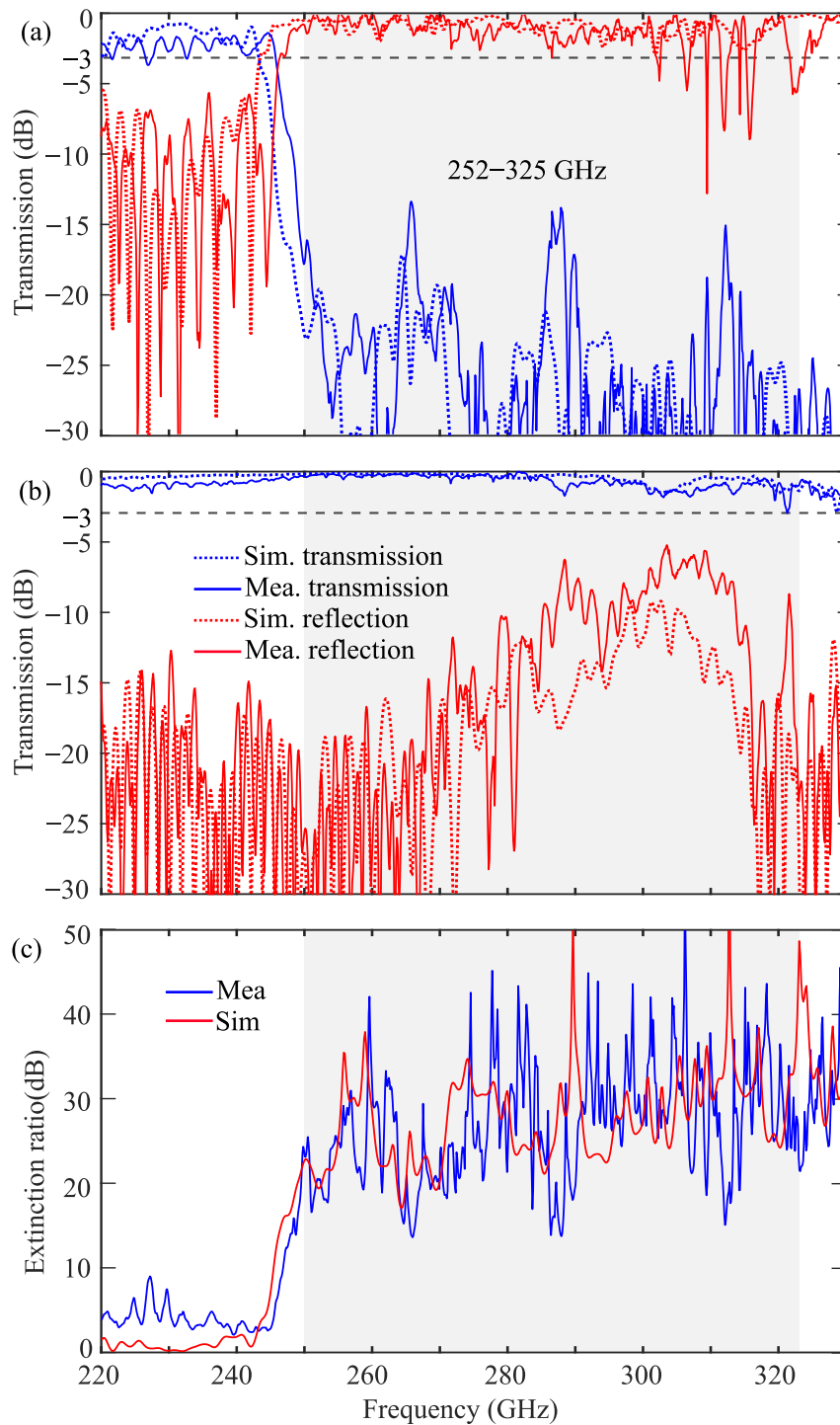


Figure 2.11. Performance parameters for the polarisation filter. Simulated and measured S-parameter results for (a) the TE mode and (b) the TM mode. (c) Polarisation extinction ratio between the TM and TE mode.

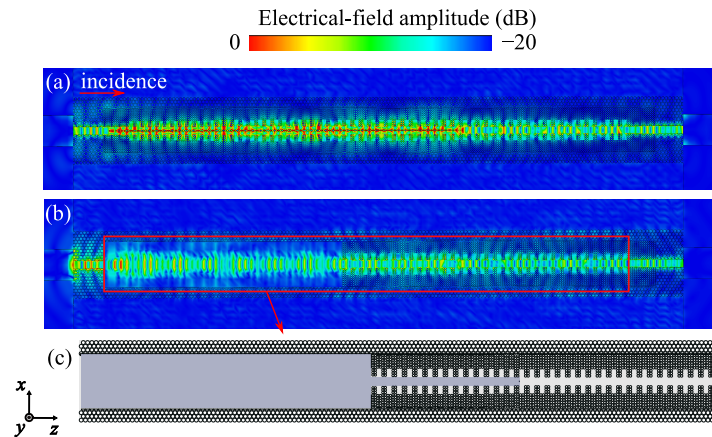


Figure 2.12. Simulated E -field amplitude distributions at 306 GHz. (a) For the designed structure, and (b) for the fabricated sample structure. (c) Schematic for the complete polarisation filters. Highlighted are the blind areas including the claddings of Sections 3 and 4 and the slots of Sections 2, 3, and 4 with a remaining silicon thickness of 10 μm .

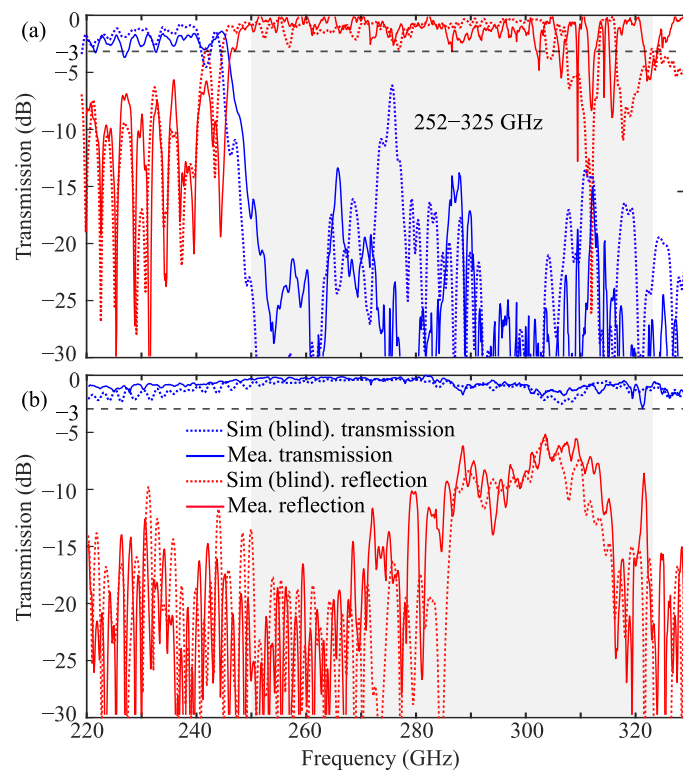


Figure 2.13. Simulated and measured S -parameter results. (a) For the TE, and (b) for the TM modes for the designed structure and the fabricated sample structure with blind holes.

2.4 Conclusion

In this chapter, we have proposed a slotted effective-medium Bragg grating filter to enhance design flexibility for polarisation filtering, with the aim of covering the entire terahertz communications band from 252–325 GHz. The modal index analysis shows that the slotted filter can achieve a broader TE stopband and higher rejection levels compared to the un-slotted filter. By cascading un-slotted and slotted grating sections, an all-silicon slotted Bragg grating filter based on effective-medium waveguide has been realised. For the TE mode waves, the average filter rejection level is -25 dB. For the TM mode, the low-loss transmission with an average insertion loss of 1.5 dB has been achieved.

This design can be applied to polarisation-sensitive systems to maintain polarisation purity by effectively filtering out the TE mode. The ability to selectively transmit only the TM mode enhances the performance of communications systems, where signal integrity is crucial. Moreover, the proposed polarisation filter can be integrated with multiplexers (Gao et al., 2024) and demultiplexers, with the potential of significantly improving channel capacity and transmission data rates in polarisation-division multiplexing systems. By reducing crosstalk between channels, it ensures that multiple signals can be transmitted simultaneously with minimal interference, thus enhancing overall performance.

Chapter 3

All-Dielectric Bandpass Filters

AS the demand for high-speed terahertz communications grows, bandpass filters become essential for managing the spectrum. However, the development of efficient planar bandpass filters for terahertz frequencies remains limited. This study introduces a new class of terahertz bandpass filters on an all-silicon, substrate-less platform. The design employs cascaded 2D and 1D photonic crystal structures with effective-medium claddings. The proposed approach allows for precise control of the center frequency and bandwidth, providing the flexibility to filter designs that can potentially cover all 69 channels in the IEEE 802.15.3d standard between 252 GHz and 325 GHz. In this work, we demonstrate filter designs for four different channels, with two representative prototypes fabricated and characterized. Experimental results show low insertion loss better than 1.5 dB, high out-of-band rejection beyond 25 dB, flat group delay of 0.25 ns within the 3-dB passband, and low group delay dispersion around 0.01 ns². Communications experiments confirm the ability of the filter to reshape the terahertz spectrum, suppress out-of-band noise by 17 dB, and improve channel isolation while preserving data integrity. This method provides a promising solution for scalable, high-performance filtering in future terahertz communications systems.

3.1 Introduction

Owing to the increased communications capacity requirements, sub-terahertz bands have attracted considerable attention. In particular, the terahertz frequency band from 252–325 GHz defined by IEEE 802.15.3d is anticipated to enable line-of-sight communications with data rates exceeding 100 Gb/s over transmission distances up to a few hundred meters, supporting future sixth-generation wireless systems. To achieve low-loss and broadband terahertz communications, all-dielectric substrateless integrated waveguide platforms based on photonic crystals and effective-medium theory have been proposed. Within these platforms, the demand for on-chip bandpass filters is emerging, as they are essential for enhancing signal-to-noise ratio while covering wide communication bands with high performance and design flexibility.

Leveraging both microwave and photonic technologies, terahertz bandpass filters have been extensively investigated (Chiu and Li, 2021; Dehghanian et al., 2023; Glubokov et al., 2017, 2019; Jguirim et al., 2019; Miek et al., 2020; Yang et al., 2017; Yun et al., 2019; Wang et al., 2020; Wen et al., 2022; Li et al., 2025; Webber et al., 2021; Gohari et al., 2023; Niraula et al., 2015; Song et al., 2014; Yuan et al., 2020). However, tradeoffs remain among insertion loss, bandwidth, compactness, fabrication complexity, and cost. Metallic bandpass filters inspired by microwave designs can provide high rejection levels and sharp roll-off, but fabrication complexity and metal-induced loss become increasingly severe at higher frequencies (Jguirim et al., 2019; Yang et al., 2017; Glubokov et al., 2017; Wen et al., 2022; Li et al., 2025; Glubokov et al., 2019; Miek et al., 2020; Wang et al., 2020; Gohari et al., 2023). Alternatively, dielectric photonic approaches such as Bragg gratings and photonic crystals offer lower loss and simplified fabrication, yet typically suffer from large longitudinal footprints or limited passband flexibility (Yun et al., 2019; Dehghanian et al., 2023; Niraula et al., 2015; Song et al., 2014; Yuan et al., 2020; Chrostowski and Hochberg, 2015). These limitations motivate the development of compact, broadband, and low-loss bandpass filters that are fully compatible with all-silicon substrateless terahertz integrated platforms.

In this chapter, we propose a series of terahertz bandpass filters based on a substrateless all-silicon integrated waveguide platform (Gao et al., 2019), utilizing a combination of one-dimensional (1D) and two-dimensional (2D) photonic crystals. Preliminary analyses and simulations were conducted to verify the concept (Chen et al., 2023). Building on this foundation, the present work provides a comprehensive investigation of the proposed filters, and establishes a systematic design method. Specifically,

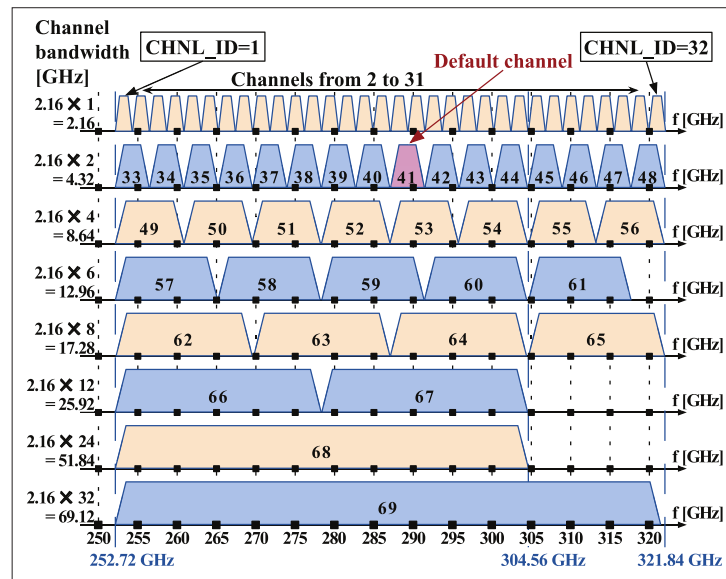


Figure 3.1. IEEE 802.15.3d channel spectrum plan (Petrov et al., 2020).

1D photonic crystals implemented on the waveguide core function as low-pass filters, while cascaded 2D photonic crystal claddings act as high-pass filters. The resulting bandpass filters are fully integrated on the effective-medium-clad waveguide platform, enhancing filtering efficiency and integration compatibility. The proposed design strategy offers high flexibility and scalability, enabling coverage of all 69 bands defined by the IEEE 802.15.3d standard (Petrov et al., 2020; Standards Committee, 2017), as shown in Fig. 3.1, while achieving low insertion loss, high out-of-band rejection, compact footprint, and low fabrication complexity. Furthermore, we conduct terahertz on-chip communications experiments to demonstrate the filter’s ability to enhance signal-to-noise ratio by suppressing out-of-band noise and improving spectral efficiency. Section 3.2 presents the filter design, while Section 3.3 describes the fabrication, characterization, and communications experiments, followed by the conclusion.

3.2 Design Methodology

The bandpass filter design is divided into two sections: a high-pass filter implemented with a cascaded 2D photonic crystal and a low-pass filter realized with an apodized 1D photonic crystal, with detailed discussions provided below.

3.2.1 High-pass Filter

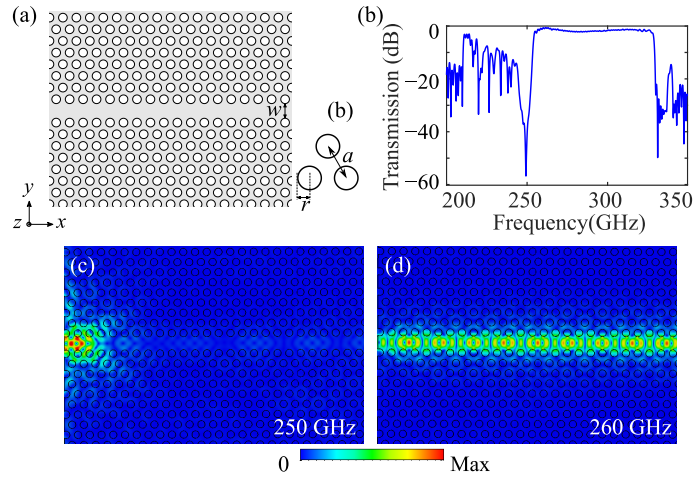


Figure 3.2. Design of terahertz photonic crystal waveguide. (a) Basic structure with waveguide width $w = 327 \mu\text{m}$, hole period $a = 300 \mu\text{m}$ and hole radius $r = 96 \mu\text{m}$. (b) Corresponding simulated transmission results. (c) Simulated instantaneous electrical-field distribution at 250 GHz and (d) 260 GHz. The passband arises from the photonic bandgap.

3.2.1 High-pass Filter

Photonic crystals are typically implemented by introducing periodic hole arrays on a silicon slab, with a period approximately equal to half the guided wavelength. This structure leads to a photonic bandgap in which wave propagation is completely suppressed. By simply removing a row of holes, a defect is created through which waves can propagate, while being confined by the surrounding photonic bandgap claddings, thus forming a waveguide, as shown in Fig. 3.2(a). The bandwidth of the waveguide is determined by the radius-period ratio, r/a , while the center frequency can be adjusted by altering the period, a . As shown in Fig. 3.2(b), the structure not only ensures low-loss transmission within the passband but also exhibits a steep roll-off rate between the stopband and the passband. The narrow stopband with a high rejection level, known as a mini-stopband, is caused by mode coupling (Olivier et al., 2001; Smith et al., 2000). Leveraging this characteristic, photonic crystal waveguides can function as high-pass filters, as shown in the field distribution in Figs. 3.2(c)–(d). However, due to the frequency dependence of the bandgap structure, the high rejection level is confined to a very narrow frequency range, as outside the band gap region, waves leak into the 2D photonic crystal slab and exhibit high scattering and radiation losses.

To cover a wide stopband at lower frequencies, we propose a cascaded 2D photonic crystal filter, as shown in Fig. 3.3(a). The cladding consists of five sections with increasing hole periods and diameters while maintaining the same radius-period ratio

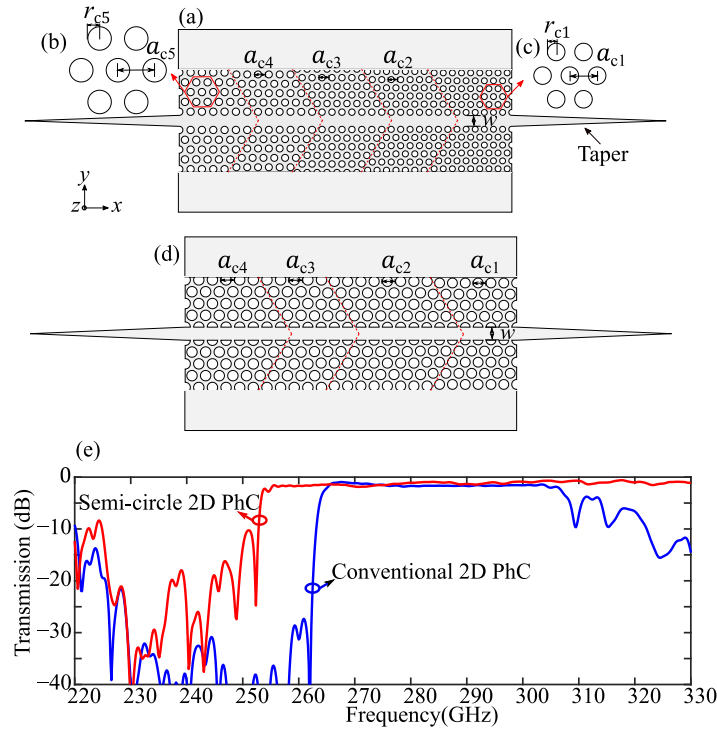


Figure 3.3. Schematic of the proposed cascaded 2D photonic crystal waveguide. (a) Top view. Magnified view of the photonic crystal hexagonal lattice with (b) the maximum period a_{c5} , and (c) the minimum period a_{c1} . (d) Schematic of the proposed semi-circle cascaded 2D photonic crystal waveguide. (e) Simulated results of two cascaded 2D photonic crystal waveguides (a) and (d).

as 0.32. The waveguide core width remains constant by adjusting the cladding sections. In this way, the center frequency of the passband for each section decreases, causing the mini-stop band to shift to a lower frequency. Collectively, the mini-stop bands of all sections merge, resulting in a wide stopband at low frequencies, as shown in Fig. 3.3(e). Figures 3.4 (a)–(f), demonstrate the distinct stopbands established in local sections.

However, because the high rejection bands periodically appear at both sides of the bandgap, as a result of the coupling of modes with the same symmetry Shahid et al. (2013), the mini-stop bands at higher frequencies also shift to lower frequencies. This shift falls within the collective passband, thereby reducing the bandwidth of the combined structure. This feature can be used to create channels with narrow passbands, effectively increasing the rejection level at high frequencies. However, for channels with wide passbands, such as Channel 69 from 252.72 GHz to 321.84 GHz, the passband bandwidth of each section needs to be expanded. To address this issue, as illustrated

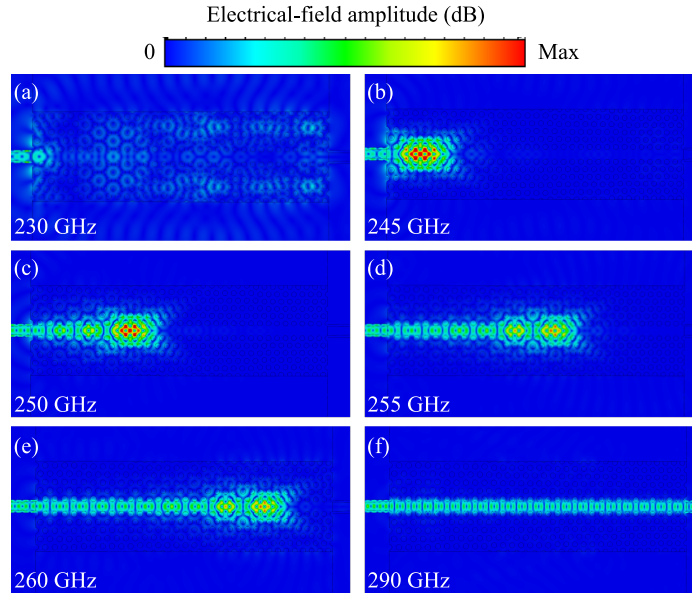


Figure 3.4. Simulated instantaneous electrical-field distribution for the cascaded 2D photonic crystal waveguide in Fig. 3.3(a) at: (a) 230 GHz, (b) 245 GHz, (c) 250 GHz, (d) 255 GHz, (e) 260 GHz, and (g) 290 GHz.

in Headland et al. (2019), the bandwidth of a photonic crystal waveguide can be increased by suppressing the Bragg effect and by increasing the radius-period ratio, r/a . We replace the holes adjacent to the waveguide core with semi-circles and increased the waveguide width, while using a larger radius-period ratio of 0.38, as shown in Fig. 3.3(b). As illustrated in Fig. 3.3(e), the semi-circle structure exhibits a wide, low-loss passband encompassing the passband of Channel 69, ranging from 252.72 GHz to 321.84 GHz.

3.2.2 Low-pass Filter

To realize the low-pass filter, a 1D photonic crystal formed by a hole array is integrated into the core of the dielectric waveguide, as shown in Fig. 3.5(a), achieving a sharp roll-off rate. This structure can be seamlessly combined with the 2D photonic crystal filter, enabling a compact footprint while maintaining high performance. By properly selecting the hole radius and period of the 1D photonic crystal, a wide stopband with a high rejection level can be created at high frequencies. The working principle of the 1D photonic crystal is akin to that of a Bragg grating. However, it provides significantly higher rejection within a similar length due to the strong index contrast between silicon and air. This property enables a more compact footprint and structural simplicity.

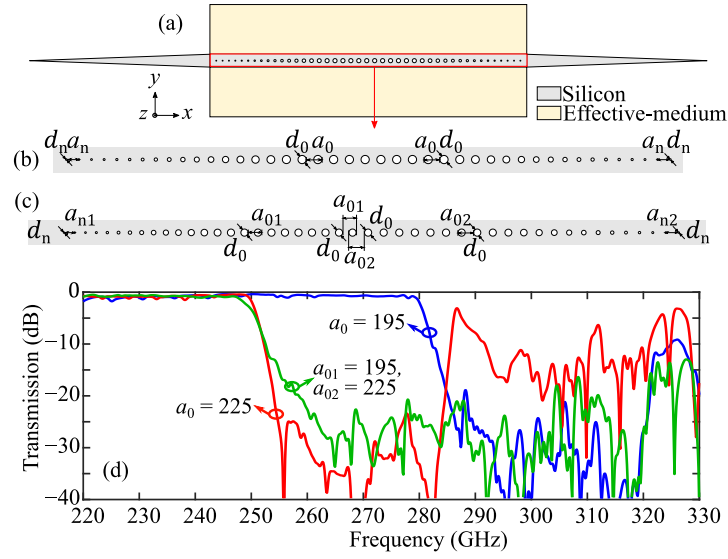


Figure 3.5. Schematic of the proposed apodized 1D photonic crystal waveguide. (a) Top view. (b) Symmetric apodization along the x -axis, with hole diameter and lattice constant varying from a_0 , d_0 to a_n , d_n to broaden the stopband at high frequencies. (c) 1D photonic crystal with two apodized periods a_{01} and a_{02} connected. (d) Simulated results of apodized 1D photonic crystal waveguides (b) with different periods a_0 (blue and red curves), and with two connected apodized periods, a_{01} and a_{02} (green curve).

However, such a strong index contrast at the input of the filter can also cause ripples in the spectral response, degrading the passband performance (Wang, 2013, PhD dissertation). To maintain a smooth response of the passband, apodization controlled by a window function can be applied to taper the filter input and output regions. In this design, the Blackman window function applies to both hole diameter and period apodization to minimize the ripple (Lai, 2003). As shown in the Figs. 3.5(b)–(c), each apodized hole period and diameter can be calculated by:

$$\Delta x_n = (x_0 - x_N) \left(k_0 - k_1 \cos \left(\frac{2\pi n}{N} \right) + k_2 \cos \left(\frac{4\pi n}{N} \right) \right), \quad (3.1)$$

$$x_n = x_0 - \Delta x_n, \quad (3.2)$$

$$\left[k_0 = \frac{1-\alpha}{2}, k_1 = 0.5, k_2 = \frac{\alpha}{2} \right], \quad (3.3)$$

where α , selected as 0.1, is the apodization factor applied to both parameters; N is the total number of apodized holes; x_n is the n^{th} apodized hole diameter or period. Uniform holes are inserted into the middle region for a high rejection level.

3.2.3 Bandpass Filter

However, the full structure combining the 2D photonic crystal cladding and 1D photonic crystal core requires a long simulation time. To accelerate the simulation, we simulate the structure in Fig. 3.5(a) with the cladding replaced with an artificial anisotropic homogenised material, in order to confirm the operation of this 1D photonic crystal as a low-pass filter. Based on the Maxwell–Garnett approximations (Choy, 2015; Subashiev and Luryi, 2006), a slab formed by a periodic lattice can be treated as a homogeneous material when the periodicity is deeply sub-wavelength; thus wave diffraction and scattering are negligible. This is commonly referred to as an “effective medium”. The relative permittivity tensor ($\epsilon_x, \epsilon_y, \epsilon_z$) can be calculated using Formula 2.1 and 2.2.

Therefore, a constant fill factor ζ equal to the fill factor of the 2D photonic crystal in Section 3.2.1 will be applied to the tensor calculations, allowing the cladding to be replaced by a single anisotropic material, as shown in Fig. 3.5(a).

It should be noted that the substituting effective homogeneous material does not exhibit bandgap or mode coupling properties. Thus, the high rejection level caused by the 2D photonic crystal will not appear in the transmission results. By applying the effective-medium method for the cladding, the stopband range of the 1D photonic crystal core can be determined more efficiently and in isolation of 2D photonic crystal effects. In this design, the maximum and minimum hole diameters of the 1D photonic crystal are set to 103 μm and 20 μm , respectively, taking the fabrication tolerances into account. The stopband at high frequency can be designed by modifying the hole period of the 1D photonic crystal, as shown in Fig. 3.5(d). However, for low-frequency channels such as channels 34, 49, and 57, the stopband of the 1D photonic crystal, as shown in Fig. 3.5(d), cannot cover the entire wideband. To address this, we used a cascaded structure that employs two different periods of 1D photonic crystal, as illustrated in Fig. 3.5(c), to cover a wide high-frequency stopband while maintaining a high roll-off rate and low transmission loss in the passband.

3.2.3 Bandpass Filter

As the stopbands at low and high frequencies are covered by the 2D photonic crystal cladding and 1D photonic crystal core, a bandpass filter can be realized by integrating these two structures, as shown in Fig. 3.6. It is noteworthy that at lower passband frequencies, the evanescent field of the 1D photonic crystal can penetrate into the 2D photonic crystal cladding, resulting in wave interference and a degraded transmission

Table 3.1. Dimensions of each channel design

	3-dB passband (GHz) IEEE 802.15.3d	Type	w (μm)	a_{c1}	a_{c2}	a_{c3}	a_{c4}	a_{c5}	r/a	a_{01}	a_{n1}	a_{02}	a_{n2}
CH34	257.04–261.36	whole (Fig.3.3b)	380	298	298	308	318	328	0.32	213	183	185	155
CH52	278.64–287.28	whole (Fig.3.3b)	325	262	271	286	311	330	0.32	195	165	195	165
CH45	304.56–308.88	whole (Fig.3.3b)	330	228	234	248	289	323	0.32	178	158	178	158
CH69	252.72–321.84	semi (Fig.3.3d)	380	373	373	373	413	413	0.38	169	129	169	129

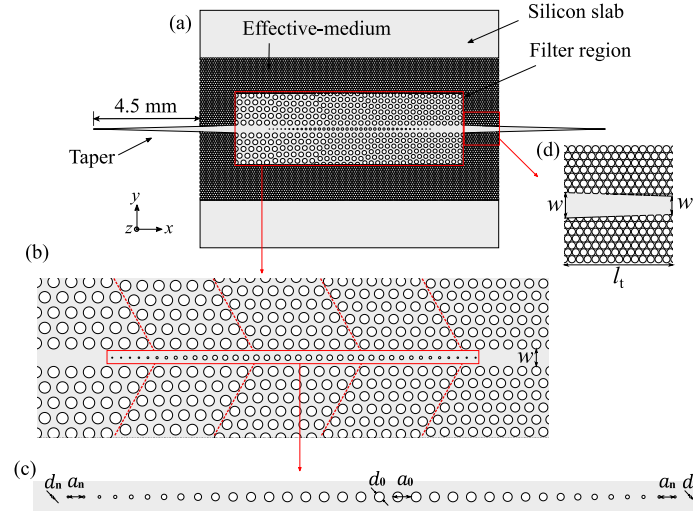


Figure 3.6. Schematic of the proposed bandpass filter. (a) Top view. (b) Bandpass filter region. (c) Magnified view of the 1D photonic crystal with the symmetric apodized holes. (d) Transition waveguide with the transition length l_t , and apodized width from w to w_t .

level. To ensure better wave confinement and to prevent interference between the 1D photonic crystal core and the 2D photonic crystal cladding, the waveguide core width is increased by 13–30%.

For integration with other components in the effective-medium platform, the standard design of an effective medium (Gao et al., 2019) is added to both sides of the bandpass filter, as shown in Fig. 3.6(d). Additionally, the effective medium is incorporated as the secondary cladding to enhance wave confinement, enabling a more compact footprint compared to configurations using only photonic crystal claddings. The length

3.2.3 Bandpass Filter

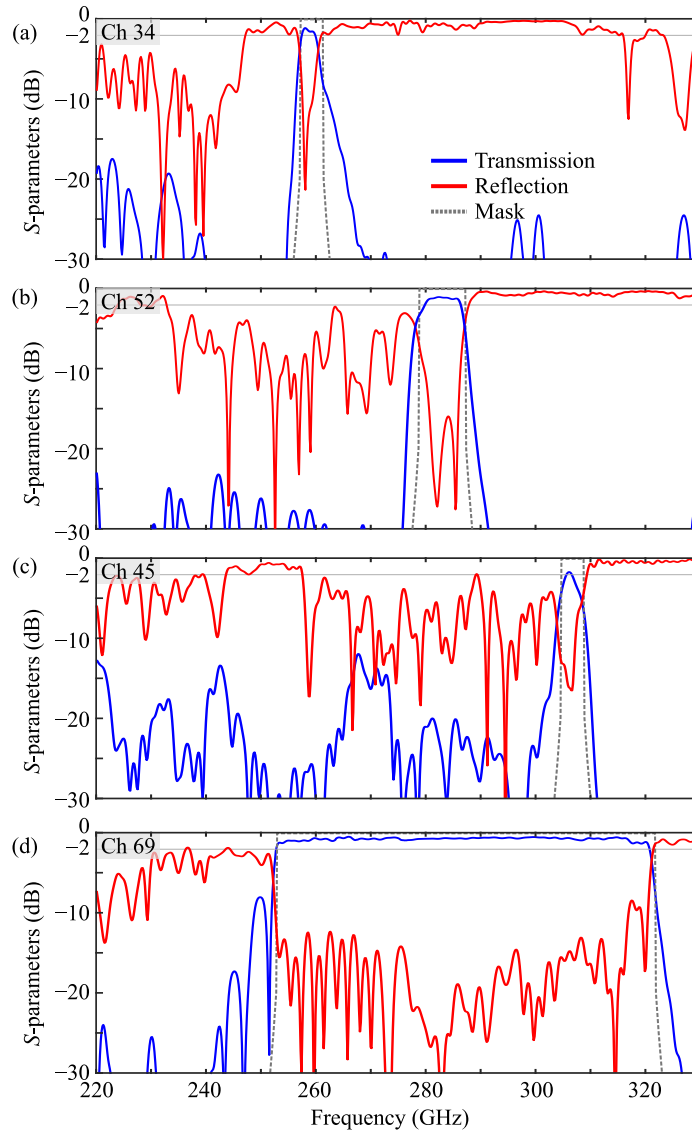


Figure 3.7. Simulated results of four bandpass filters for (a) Channel 34, (b) Channel 52, (c) Channel 45, and (d) Channel 69 compared with the spectral masks from IEEE 802.15.3d – 2017 (Standards Committee, 2017).

of the standard waveguide l_t is adjusted to ensure that the footprint of all bandpass filters across different channels remains identical at $15.4 \text{ mm} \times 6 \text{ mm}$. This footprint is much more compact than conventional metallic hollow waveguide-based filter designs (Jguirim et al., 2019; Miek et al., 2020), while maintaining equivalent performance across the IEEE 802.15.3d-defined bands.

As first illustrative example shown in Fig. 3.7(c), an integrated bandpass filter is realized for Channel 45 (Petrov et al., 2020), covering the frequency range from 304.56 GHz to 308.88 GHz, using the structure depicted in Fig. 3.6 with dimensions provided

Table 3.2. Comparison on the state-of-the-art integrated bandpass filters operated at nearby frequencies

Ref.	Filtering structure	f_0 (GHz)	FBW (%)	Max. IL (dB)	Out-of-band rejection (dB)	Material	Fab. method	Topology
(Li et al., 2025)	Dual-mode resonators	133.4	17.9	1.5	20	Copper	PCB	On-chip
(Wen et al., 2022)	High-order resonators	280	2.86	1.8	60	Copper	3D printing	Metallic waveguide
(Yuan et al., 2020)	Bragg grating	300	6.7	3.5	15	Zeonex	3D printing	Metallic waveguide
(Webber et al., 2021)	Photonic crystal	336.44	8.8	2	>10	Silicon	DRIE	On-chip
Channel 52	Photonic crystal	284	3.5	1.6	25	Silicon	DRIE	On-chip
Channel 69*	Photonic crystal	287.28	24	0.8	25	Silicon	DRIE	On-chip

*Simulation results

in Table 3.1. Since Channel 45 (as shown in Fig. 3.1) has a high stopband start frequency (304.56 GHz) among all 69 channels, it serves as a useful case to evaluate the upper bandwidth limitation of the 2D photonic crystal cladding stopband. On the other hand, Channel 52, covering 278.64 GHz to 287.28 GHz, can be realized by increasing all five hole periods of the cladding and increasing the maximum hole period and the difference between the maximum and minimum hole periods of the 1D photonic crystal. As a result, the upper and lower cutoffs are shifted to lower frequencies. This allows the realization of Channel 52, with a lower center frequency and a wider 3-dB passband of 8.64 GHz, as shown in Fig. 3.7(b).

For channels with a wide passband, such as Channel 69, which ranges from 252.7 GHz to 321.84 GHz, the cladding structure needs to be modified to minimize the Bragg grating effects across the wide passband. This is achieved by applying a semi-circular arrangement with holes adjacent to the core and increasing the hole radius compared to channels 45 and 52 as discussed in Section 3.2.1. Using the cladding structure shown in Fig. 3.3(d) and the dimensions provided in Table 3.1, Channel 69 is covered as shown in Fig. 3.7(d).

For low-frequency channels such as channels 34, 49, and 57, we used the cascaded structure of the 1D photonic crystal, as shown in Fig. 3.5(c), to cover a wide high-frequency stopband, along with the 2D cladding structure shown in Fig. 3.3(a). As shown in Fig. 3.7(a), for Channel 34, ranging from 257.04 GHz to 261.36 GHz, the wide stopband at high frequency is covered with a high rejection level.

In summary, there are three bandpass filter structures that can be used to realize all 69 channels based on the passband center frequency and bandwidth.

- For channels with a low center frequency (253.8–271.8 GHz) and a narrow passband (2.16–12.96 GHz), the conventional 2D photonic crystal cladding, as shown in Fig. 3.3(a), combined with a cascaded 1D photonic crystal featuring two different hole periods, as shown in Fig. 3.5(c), can be used.
- For Channel 69, the semi-circular 2D cladding, as shown in Fig. 3.3(e), along with the conventional 1D photonic crystal, provides the widest passband of 69.12 GHz.
- For the remaining channels, the filters can be realized by applying the conventional 2D cladding, as shown in Fig. 3.3(a), and 1D photonic crystal structures, as shown in Fig. 3.5(b).

3.3 Fabrication and Measurement

This section illustrates the design validation of terahertz bandpass filters through measurement and communications testing, demonstrating their effectiveness for high-speed signal transmission.

3.3.1 Realized Bandpass Filters

To experimentally validate the proposed design, filters for channels 34 and 52 are fabricated by the deep reactive ion etching (DRIE) process using a 250- μm -thick high-resistivity silicon wafer with a relative permittivity of 11.68 and an estimated loss tangent of 3×10^{-5} . Samples are shown in Figs. 3.8(a)–(b). The measurement is conducted with a Keysight vector network analyzer (VNA) with VDI WR-3.4 extension modules spanning from 220 to 330 GHz with 1001 points, as shown in Fig. 3.8(c). An IF bandwidth of 100 kHz is used. Measurement results of two WR-3.4 hollow waveguides connected back-to-back are used as a reference for calibration.

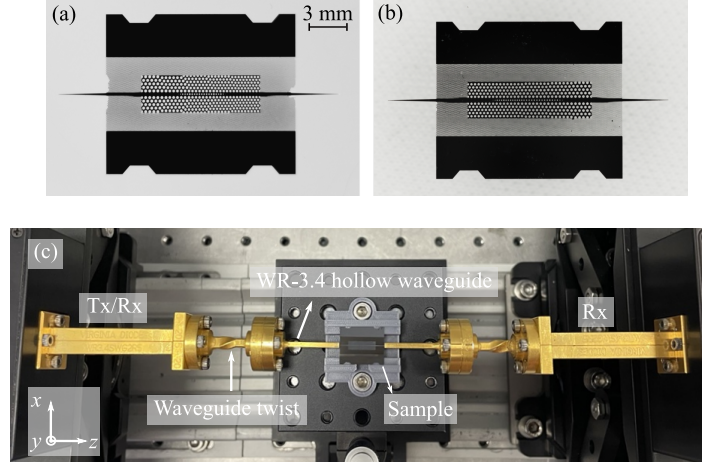


Figure 3.8. Fabricated bandpass filter and measurement setup. Fabricated sample of (a) Channel 52 and (b) Channel 34. (c) Measurement setup for S -parameters. The tapered structures are inserted into the WR-3.4 hollow waveguides for excitation, while the sample is secured by a 3D-printed polylactic acid (PLA) holder, which is positioned to avoid interference with wave propagation. The WR-3.4 waveguides and twists are added to excites the polarization in the x -direction for the filter sample. Measurements are performed using a Keysight vector network analyzer equipped with VDI WR-3.4 extension modules covering 220–330 GHz.

As shown in Figs. 3.9(a)–(d), the measured results for fabricated channels 34 and 52 closely match the simulated data. The observed center frequency right-shift in the measurement results is caused by minor discrepancies in hole dimensions between the designed and fabricated structures. Compared with the transmission masks that defined in the IEEE standard, our designs show high roll-off rate, high average rejection level of 25 dB, with low insertion loss below 1.5 dB. The loss is mainly responsible by the cascaded 2D photonic crystal claddings, where discontinuities enhance stopband rejection but introduce additional insertion loss. This loss can be mitigated through apodization of the claddings; however, the apodization would also increase the overall device footprint. To investigate the dispersion characteristics of the proposed filters, we calculate the group delay, τ_g , and group delay dispersion, GDD, for the two filter designs by:

$$\tau_g = -\frac{d\phi(\omega)}{d\omega}, \quad (3.4)$$

$$\text{GDD} = \frac{d\tau_g}{d\omega} = -\frac{d^2\phi(\omega)}{d\omega^2}, \quad (3.5)$$

where $\phi(\omega)$ is the transmission phase response, and ω is the angular frequency.

3.3.1 Realized Bandpass Filters

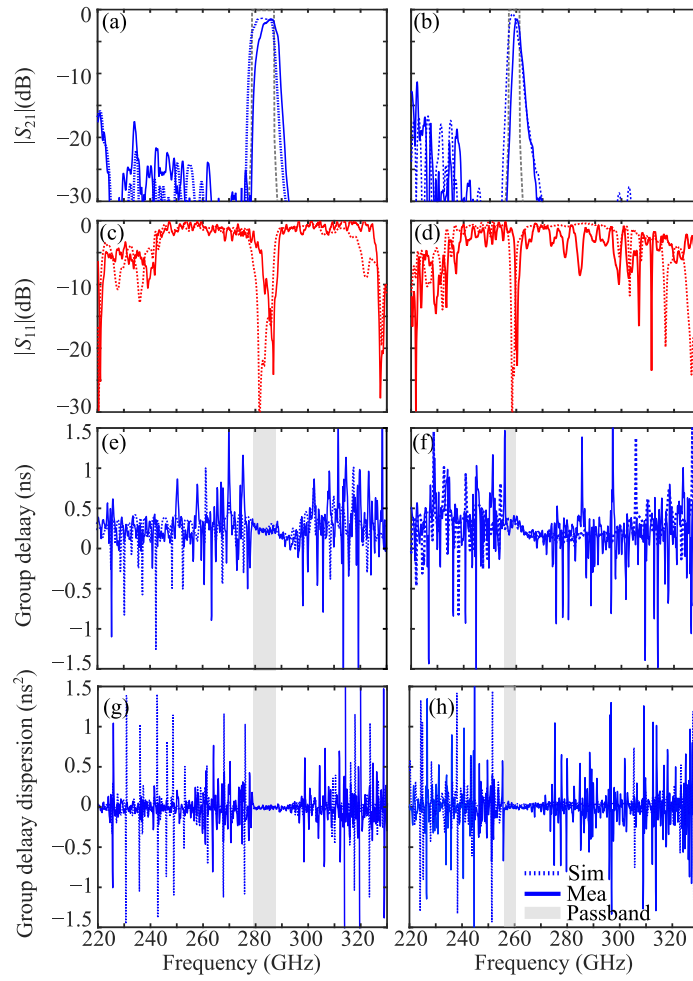


Figure 3.9. Simulated and measured S -parameters, group delay, and group delay dispersions of bandpass filter samples: (a), (c), (e) and (g) for channel 52; (b), (d), (f) and (h) for Channel 34.

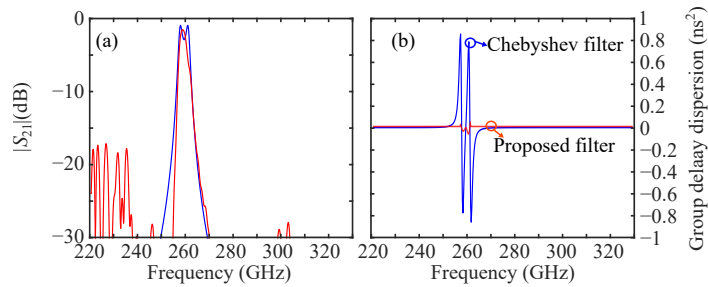


Figure 3.10. Simulated transmission response comparison. (a) Simulated S_{21} comparison between the proposed filter and a second-order Chebyshev filter with a similar passband response. (b) Group delay dispersion comparison between the proposed filter and the second order Chebyshev filter.

The group delays and group delay dispersions in both simulation and measurement are extracted from the unwrapped phase, after de-embedding the phase contributions introduced by the hollow waveguides. As shown in Figs. 3.9(e)–(h), the measurements agree well with the simulations. The measured group delay within the 3-dB passbands for both channels is flat at 0.25 ns. As shown in Figs. 3.10(a)–(b), compared to narrow-band second-order Chebyshev bandpass filters, which exhibit oscillatory group delay dispersion due to passband poles, our filter achieves a flat group delay dispersion within the 3-dB passbands for Channel 52, with approximately 0.01 ns^2 . This low dispersion corresponds to a pulse broadening factor of about 1.08 for a 4-GHz Gaussian input, meaning the output pulse duration increases by only 8%.

As shown in Table II, our design achieves competitive insertion loss. This low insertion loss can be attributed to the low material loss and high fabrication accuracy of the single-layer silicon structure. Moreover, the design can be readily scaled to other frequencies and adapted to fit a specified bandwidth by adjusting the structural parameters while maintaining comparable performance, owing to the accuracy of the fabrication process. The simulation results for Channel 69 demonstrate that a wider FBW corresponds to a lower insertion loss in our design. Consequently, the proposed filter exhibits performance comparable to the wideband filter design in (Li et al., 2025). In addition to scalability, DRIE fabrication mechanism allows for parallel processing of multiple samples. This approach offers significant advantages in both unit cost and time efficiency compared to metallic-based filter designs.

3.3.2 Communications Demonstration

To validate the design's performance in terahertz communications, a comprehensive characterization experiment is conducted. As shown in Fig. 3.11(a–b), on the transmitter side, the signal with the desired terahertz spectrum is generated by mixing the up-converted local oscillator (LO) signal with the intermediate frequency (IF) signal within the VDI upconverting mixer. However, frequency mixing inherently generates both the upper and lower sidebands around the LO frequency, resulting in a double-sideband spectrum as shown in Fig. 3.11(c). For parallel channelized communications systems, single sideband operation is important for channel isolation and enhanced spectrum efficiency. To achieve this, we insert our bandpass filters to suppress the lower sideband. Since the mixer cannot perform IQ modulation, we use the arbitrary waveform generator (AWG) to perform IF vector modulation using a subcarrier at an

3.3.2 Communications Demonstration

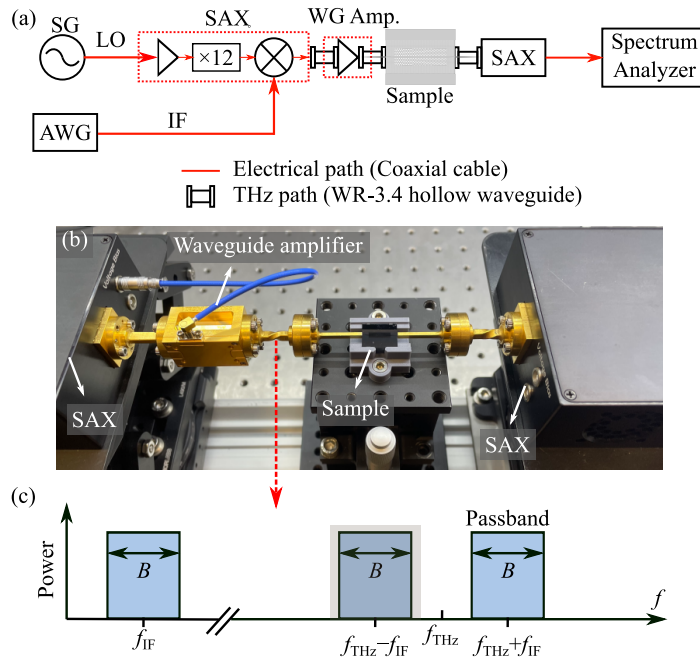


Figure 3.11. Experiment setup to demonstrate sideband suppression. (a) Block diagram of the setup. (b) Photo of the measurement setup. (c) Spectral diagram of up-conversion. AWG: arbitrary waveform generator. IF: intermediate frequency. SG: signal generator. LO: local oscillator. SAX: signal generator extension module. WG Amp: waveguide amplifier. The LO signal frequencies are set to 21.2 GHz for Channel 34 and 23.1 GHz for Channel 52. The carrier frequency from the AWG is set to 5 GHz with the symbol rate of 4 Gbaud for Channel 34, and 6 GHz with the symbol rate of 8 Gbaud for Channel 52.

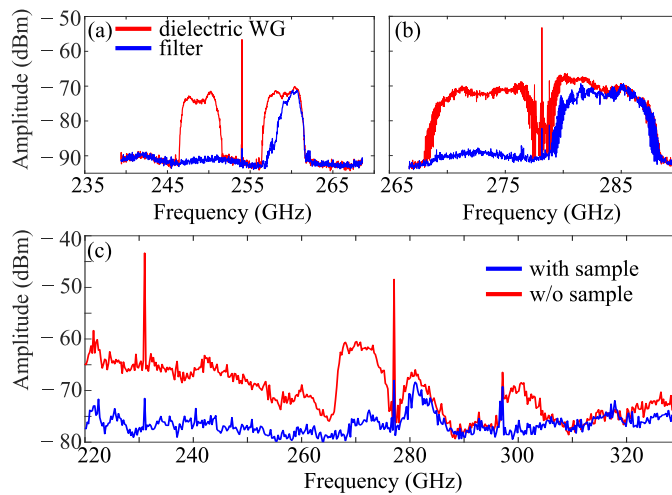


Figure 3.12. Terahertz communications spectra with and without the filter. (a) Channel 34 compared with the standard waveguide (b) Channel 52 compared with the standard waveguide and (c) Channel 52 with waveguide amplifier.

IF frequency. In this experiment, the IF signal is generated by AWG employing quadrature phase shift keying (QPSK) modulation, with a center frequency f_{IF} and bandwidth B . The LO and IF signals are set to ensure that the upper sideband of the up-converted spectrum falls within the passband of the designed bandpass filters, with the center frequency $12 \times f_{\text{LO}} + f_{\text{IF}}$ matches the center frequency of the passband. Based on the VNA measurement results, the LO frequencies are set to 21.2 GHz for Channel 34 and 23.1 GHz for Channel 52, while the IF signals are set to 5 GHz with a symbol rate of 4 Gbaud for Channel 34, and 6 GHz with a symbol rate of 8 Gbaud for Channel 52. With a roll-off factor of 0.35, the resulting upper sideband is located at 259.4 ± 2.7 GHz for Channel 34, and 283.2 ± 5.4 GHz for Channel 52. On the receiver side, a SAX is connected to the spectrum analyzer to observe the filtered terahertz spectrum. By comparing the results with a dielectric waveguide (Gao et al., 2019), our filters can achieve single sideband operation with a sharp transition between the passband and stopband, as shown in Figs. 3.12(a)–(b).

In communications systems, amplifiers are commonly used to increase output power, but they amplify signals across the entire operating frequency range, resulting in the amplification of not only the desired spectrum but also out-of-band noise. Additionally, spectrum regrowth, primarily caused by amplifier nonlinearities, is often observed in high-frequency systems. Employing sharp bandpass filters can effectively suppress out-of-band signals resulting from this phenomenon. To validate our design, we added the VDI WR4.3AMP, which has 24 dB gain from 170–260 GHz, after the mixer on the transmitter side and compared the filtered result with that obtained without the bandpass filter. As shown in Fig. 3.12(c), the out-of-band noise is suppressed by 17 dB, while maintaining low-loss transmission for the upper sideband.

Furthermore, to illustrate the real-world terahertz communications capability, the bit-error-rate (BER) is calculated with the setup shown in Fig. 3.13. On the transmitter side, the terahertz signal is generated via optical heterodyning by photomixing two tunable near-infrared lasers. The baseband IF signal is produced by the pattern generator of the BER tester Agilent J-BERT N4903B modulated by on-off keying, with a data rate adjustable from 0.6 to 7.0 Gbit/s. Then the IF signal is modulated onto coupled optical signals in a Mach-Zehnder modulator (MZM). The optical signal is then downconverted to the sub-terahertz frequency via a uni-traveling-carrier photodiode (UTC-PD). The carrier frequencies are set to 260 GHz for Channel 34 and 285 GHz

3.3.2 Communications Demonstration

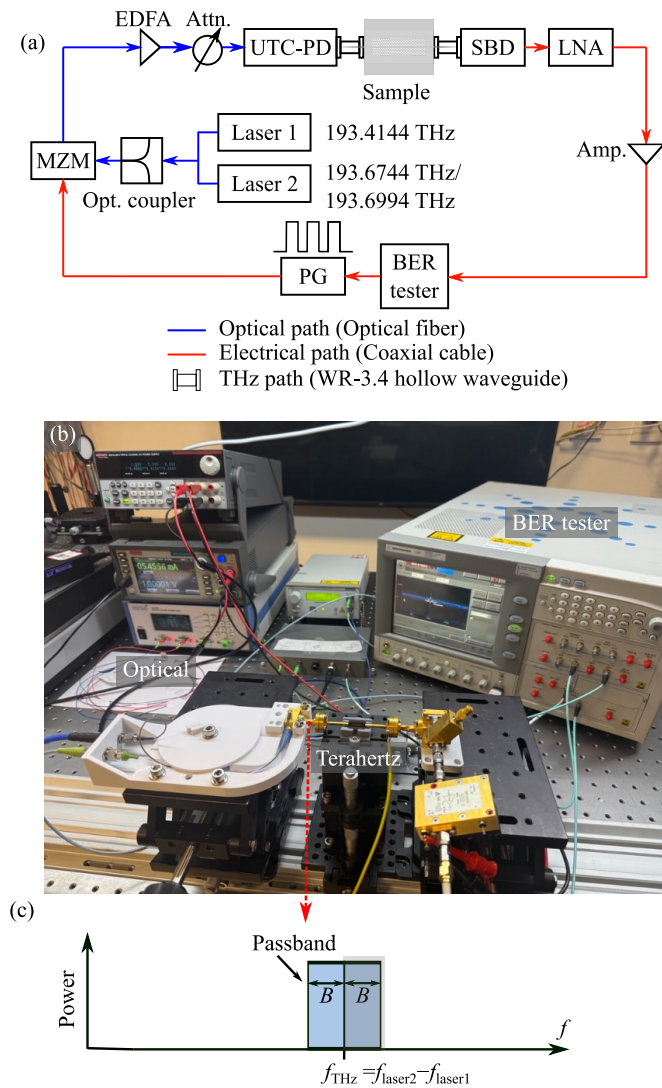


Figure 3.13. Bit error rate test setup. (a) Bit error rate test schematic. (b) Photo of the test setup. (c) Spectral diagram of down-conversion. MZM: Mach-Zehnder modulator, EDFA: Erbium-doped fiber amplifier, Attn.: attenuator, UTC-PD: Uni-travelling carrier photodiode, SBD: Schottky barrier diode, LNA: Low-noise amplifier, PG: pattern generator, BER tester: bit-error-rate tester.

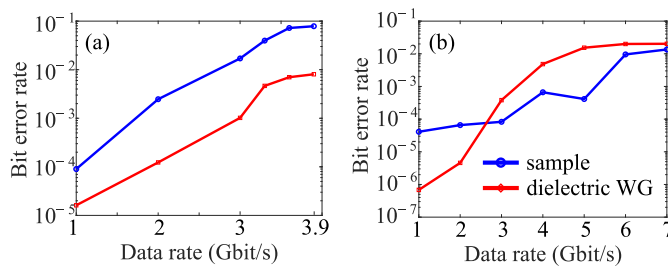


Figure 3.14. Bit error rate measurement results. Bit error rate versus data rate at the carrier frequency of (a) 260 GHz using sample Channel 34, and (b) 285 GHz using sample Channel 52. The carrier frequencies correspond to the start frequencies of the measured passbands.

for Channel 52, corresponding to the higher cutoff frequencies of the measured passbands as shown in Fig. 3.9. As a result, the lower sideband of the generated signal falls within the passband of the samples, while the higher sideband is filtered out, as shown in Fig. 3.13(c). On the receiver side, a Schottky barrier diode (SBD) is used to detect and retrieve the modulated terahertz signal. The recovered data signal is subsequently amplified by a low-noise amplifier (LNA) and fed back to the BER tester, Agilent J-BERT N4903B.

Pseudorandom binary sequence data with a data length of $2^{23} - 1$ is employed in the BER test. As shown in Fig. 4.9, the BER of sample Channel 34 is degraded compared to the dielectric waveguide, due to a slightly higher insertion loss than dielectric waveguide and its narrower passband observed in the fabricated sample measurement results, as shown in Fig. 3.9(c). This narrower bandwidth with a sharper transition and higher rejection level at the band edges reduces the signal-to-noise ratio with increased data rate and thus high BER. In contrast, sample Channel 52, with its wider passband, demonstrates higher data rate communications capability and lower BER. Its high out-of-band rejection also results in better BER performance than the standard waveguide. These results demonstrate that the proposed filters can effectively enhance high-speed communications performance by suppressing out-of-band noise and improving the signal-to-noise ratio that is an essential requirement for future 6G systems.

3.4 Conclusion

We have presented a design method for all-silicon, substrate-less terahertz bandpass filters based on cascaded 2D and 1D photonic crystal structures combined with effective-medium cladding. The method allows precise tuning of the center frequency and bandwidth through three structural parameters, enabling the design of filters for all 69 channels across 252–325 GHz defined in the IEEE 802.15.3d standard. Four representative channels have been investigated, two of which have been fabricated, showing good agreement between simulation and measurement. The results demonstrate low insertion loss below 1.5 dB, high out-of-band rejection averaging 25 dB, flat group delay within the 3-dB passband of 0.25 ns, and low group delay dispersion around 0.01 ns^2 . Communications testing further confirms the effectiveness of the filters by demonstrating single-sideband terahertz spectrum shaping with -17 dB out-of-band noise suppression, enabling improved channel isolation and preservation of transmitted data quality. These results validate the proposed method as a practical solution for

3.4 Conclusion

implementing low-loss, high-rejection bandpass filters in future high-speed terahertz communications systems.

Chapter 4

Ultra-Compact Waveguide Couplers

EFFICIENT mode coupling between dielectric and metallic hollow waveguides is critical in the development of integrated terahertz systems based on all-silicon platforms. Conventional dielectric linear tapers, while commonly used, require long and thin structures, typically $3\lambda_0$ to achieve a low coupling loss, resulting in increased device footprint and a high risk of mechanical breakage during fabrication and alignment. In this work, we present two compact all-silicon couplers, each leveraging the combined principles of dielectric rod antennas and slot waveguides. The proposed designs feature compact footprints of only $0.5\lambda_0$ in length for operation across 220–330 GHz and demonstrate an average coupling loss of -1.25 dB across this band. Compared to conventional linear tapers, the proposed design reduces footprint, improves mechanical robustness and ease of alignment. Experimental validation through terahertz communications measurements demonstrates bit error rates (BER) below 10^{-11} for out-of-plane polarisation and below 10^{-7} for in-plane polarisation at 275 GHz with a 7 Gbit/s data rate, and stable performance at a BER of 10^{-4} under high signal-to-noise conditions. The proposed couplers facilitate efficient mode conversion between different waveguides, making them valuable components for system-level integration in future terahertz communications frontends.

4.1 Introduction

Efficient mode coupling between dielectric waveguides and metallic hollow waveguides is essential for integrated waveguide components and experimental characterization. The conventional linear taper, illustrated in Fig. 4.1, is widely used to achieve this transition through gradual impedance and mode evolution. For operation in the sub-millimeter-wave regime, such tapers typically require millimeter-scale lengths and narrow widths, which impose stringent alignment tolerances.

During the fabrication and measurement of our previous designs, we found that these long and slender linear tapers are mechanically fragile and prone to breakage, particularly during handling and alignment with metallic waveguides. This practical limitation significantly reduces fabrication yield and complicates experimental measurements, motivating the need for a more compact and mechanically robust taper design that can maintain low coupling loss while improving ease of use.

Various coupling strategies have been proposed in both microwave and photonic domains. Microwave-inspired dielectric tapers achieve broadband coupling through impedance matching, while photonic approaches such as grating- and slot-based couplers offer compact footprints (Pousi et al., 2006; Hou et al., 2019a; Generalov et al., 2014; Van Laere et al., 2007; Halir et al., 2010; Smith et al., 2014; Headland et al., 2024; Krasnokutska et al., 2019). However, many existing designs are optimized for free-space or fiber coupling and are not directly suited for robust, broadband coupling to hollow waveguides. These considerations motivate the development of a compact taper specifically designed to improve mechanical robustness without compromising coupling performance.

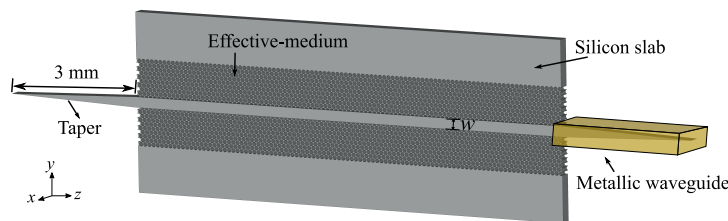


Figure 4.1. Effective-medium waveguide with linear tapers. The taper length is 3 mm and the waveguide core is 225 μm for operation in the 220–330 GHz frequency range. These tapers are inserted into metallic waveguides during characterization to facilitate efficient coupling.

To realise a high coupling efficiency within the wide bandwidth of 220–330 GHz, we combined a rod waveguide antenna and a slot waveguide to propose two compact silicon coupler designs that feature attractive properties of both approaches. This hybrid approach leverages the broadband impedance matching and mode-transition benefits of rod structures, along with the strong field confinement and compact footprint offered by slot waveguides.

4.2 Design Methodology

The slot structure typically consists of a narrow low-index region introduced between two high-index dielectric regions. Due to the strong index contrast at the dielectric interfaces, the electromagnetic field can be strongly confined within the slot region. As a result, the slot structure has been widely used in waveguide design (Smith et al., 2014), and has also been demonstrated as a magnetic dipole radiator in all-dielectric terahertz systems (Headland et al., 2024). This magnetic dipole behavior enables efficient coupling to the transverse magnetic field, making it particularly well-suited for taper coupler design where compactness and strong field interaction are essential for broadband mode conversion. However, the significant index mismatch between the air slot and silicon slab increases reflection, necessitating apodisation of the slot width to improve impedance matching. Additionally, in magnetic dipole antenna configurations, the operating frequency is determined by the slot length, which imposes limitations on the achievable bandwidth. To enable efficient coupling across a wide frequency range, the slot radiator can be integrated with a rod waveguide antenna, combining the broadband capability of the rod with the strong confinement of the slot.

An apodised slot taper with the frontend being significantly narrower than the base can be realised, as shown in Figs. 4.2(a–c). The taper length is defined by the elliptical long radius r_z , while the taper width is determined by the elliptical short radius r_y and the separation distance g , as shown in Fig. 4.2(c). To maintain a compact footprint, we fix the longer radius r_z at 500 μm , and then optimize the separation g and the shorter radius r_y to achieve improved performance. However, due to practical fabrication constraints, the minimum realizable hole diameter is approximately 12 μm . As such, the narrow gap $g = 7.5 \mu\text{m}$ at the end of the tapered slot cannot reliably be produced. This narrow gap is prone to being over- or under-etched, and may distort the intended geometry and affect the final device performance. To mitigate these risks and achieve

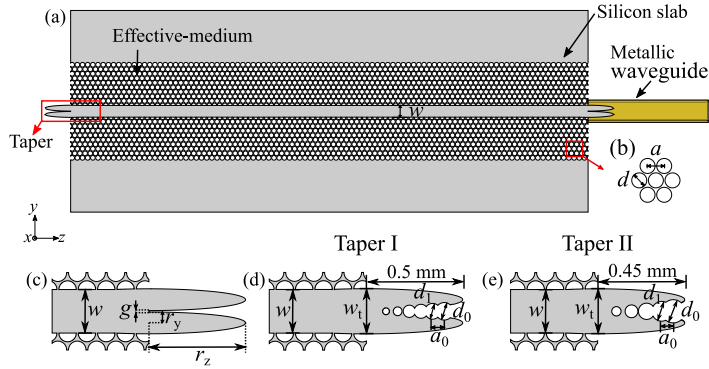


Figure 4.2. Proposed taper designs. (a) Top view of the waveguide with a core width w of $225\ \mu\text{m}$ and a silicon thickness of $250\ \mu\text{m}$. (b) Waveguide cladding with $a = 100\ \mu\text{m}$, $d = 90\ \mu\text{m}$. (c) Basic elliptical taper defined by radii r_z and r_y , with a separation $g = 7.5\ \mu\text{m}$ between the two elliptical sections. (d) Proposed taper design optimized for the in-plane polarisation, featuring a taper length $r_z = 0.5\ \text{mm}$, taper width $w_t = 232.5\ \mu\text{m}$, maximum air hole diameter $d_0 = 45\ \mu\text{m}$, apodised with a step size of $10\ \mu\text{m}$, and a hole period $a_0 = 60\ \mu\text{m}$. (e) Proposed taper design supporting both polarisations, with a taper length $r_z = 0.45\ \text{mm}$, taper width $w_t = 232.5\ \mu\text{m}$, maximum air hole diameter $d_0 = 60\ \mu\text{m}$, apodised with a step size of $18\ \mu\text{m}$, and a hole period $a_0 = 78\ \mu\text{m}$.

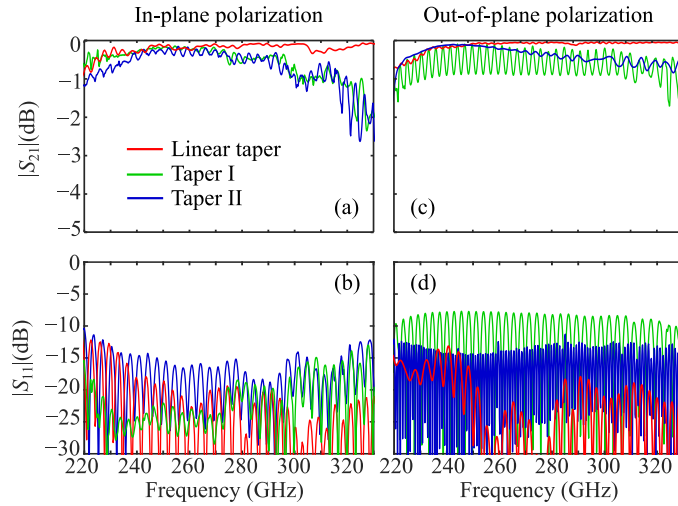


Figure 4.3. Simulation results of taper designs. (a–b) Simulated S -parameters of in-plane polarisation waves for the waveguide with a linear taper against Tapers I and II. (c–d) Simulated S -parameters of out-of-plane polarisation waves for the waveguide with a linear taper against Tapers I and II.

reliable fabrication, we replaced the apodised slot with apodised-diameter air holes, as illustrated in Fig. 4.2(d).

In this case, the use of apodised air holes with small diameter steps provides a gradual variation in the air slot width, which leads to smooth mode evolution for the in-plane polarised field. The full-wave simulations conducted in CST Studio are shown in Figs. 4.3(a–d). Compared to the long linear taper, the compact Taper I achieves similarly low-loss transmission for the in-plane polarisation, though a minor degradation occurs at higher frequencies due to the taper length not fully matching the guided wavelength. However, for the out-of-plane polarisation, Taper I results in high reflection, as shown in Figs. 4.3(c–d). Compared to the long linear taper, which provides a continuous geometric narrowing and therefore a relatively smooth impedance matching for the out-of-plane polarisation, Taper I introduces discrete periodic loading from the hole array. The out-of-plane electric field overlaps strongly with the first row of holes and experiences a sharp change in the effective index at the entrance of the taper. This results in discontinuous mode conversion into leaky and higher-order mode, causing increased scattering loss and higher reflection levels, as shown in Figs. 4.3(c–d).

To maintain a compact footprint while improving the out-of-plane performance, the maximum hole diameter and the apodisation step are increased in the second design, as illustrated in Fig. 4.2(e). This adjustment creates sharper silicon tips and shortens the taper length, which reduces the number of index perturbations experienced by the out-of-plane electric field and minimizes the impedance mismatch at the taper entrance. As a result, Taper II provides a smoother evolution of the out-of-plane mode toward the metallic waveguide. As shown in Figs. 4.3(c–d), Taper II yields lower reflection and stable transmission for the out-of-plane polarisation, which is attributed to a stronger confinement of the field for this polarisation. For the in-plane polarisation, Taper II introduces local field distortion due to the sharper taper geometry and produces slightly higher reflection than the linear taper, as shown in Figs. 4.3(a–b). Nevertheless, it still demonstrates comparable insertion loss and reflection levels within 220 to 330 GHz. Overall, Taper I achieves efficient coupling for the in-plane mode, while Taper II provides improved coupling for both the in-plane and out-of-plane polarisations within 220 to 330 GHz.

4.3 Results

For validation, we fabricate the designs using deep reactive ion etching (DRIE) on 250- μm -thick high-resistivity silicon wafers. The wafers have a relative permittivity of 11.68 and an estimated loss tangent of 3×10^{-5} . The fabricated samples of different lengths are shown in Figs. 4.4(a–b). Measurements are performed using a Keysight vector network analyzer (VNA) paired with Virginia Diodes (VDI) WR-3.4 extension modules, enabling frequency sweeps from 220 to 330 GHz across 1001 points, as shown in Figs. 4.4(c–d). For calibration purposes, we used the transmission characteristics of two WR-3.4 hollow waveguides connected back to back as a reference.

The measurement results in Figs. 4.5(c–l) show a low insertion loss of below 3 dB and a low average reflection level of -12 dB from 220–330 GHz. The measured results exhibit

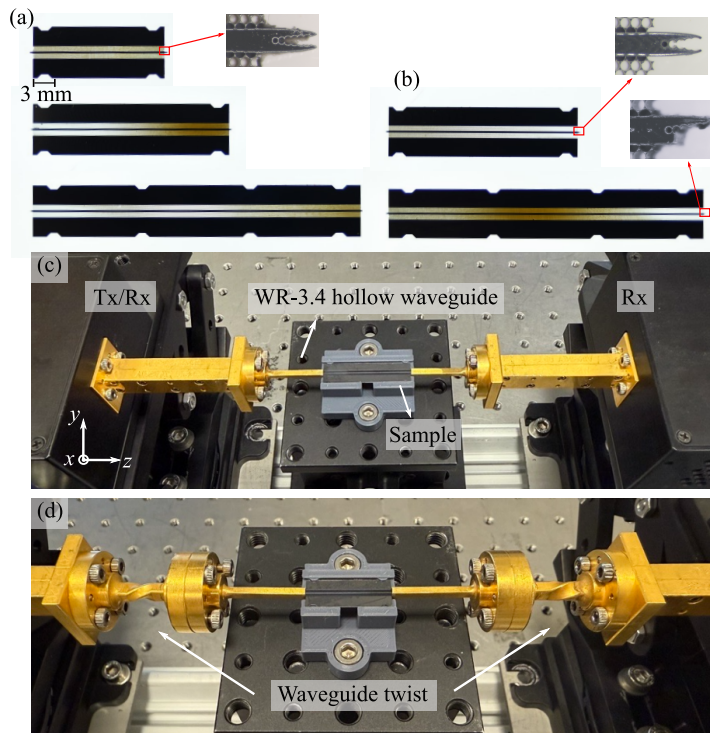


Figure 4.4. Fabricated samples and measurement setup. Fabricated samples of (a) Taper I with 2, 3, and 5 cm length and (b) Taper II with 3 and 5 cm length. (c) Measurement setup for the out-of-plane polarisation. The tapers are inserted into the WR-3.4 hollow waveguides for excitation, while the sample is secured by a 3D-printed polylactic acid (PLA) holder, which is positioned to avoid interference with wave propagation. Measurements are performed using a Keysight vector network analyzer equipped with VDI WR-3.4 extension modules covering 220–330 GHz. (d) In-plane polarisation measurement setup by adding the WR-3.4 waveguide twists to rotate the polarisation to the z-direction.

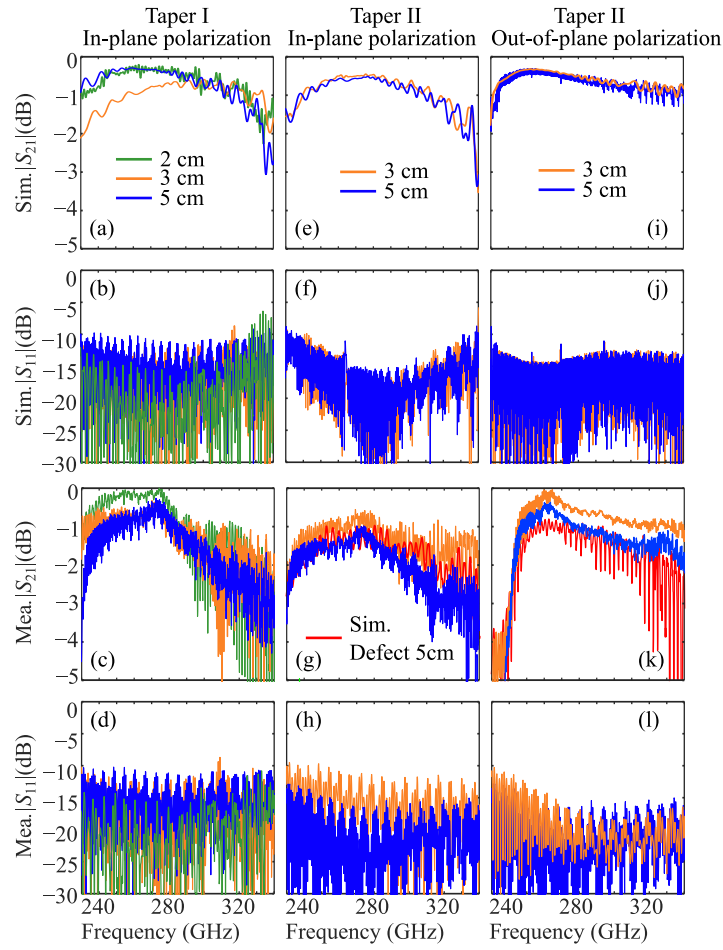


Figure 4.5. Simulated and measured S -parameters of waveguide samples: (a-d) In-plane-polarised responses of the Taper I design shown in Fig. 4.2 with different lengths. (e-h) In-plane-polarised responses of the Taper II design shown in Fig. 4.2(e) with different lengths. (i-l) Out-of-plane-polarised responses of the Taper II design shown in Fig. 4.2(e) with different lengths. (g) and (k) present the comparison between the measured and simulated defect 5 cm Taper II sample shown in Fig. 4(b).

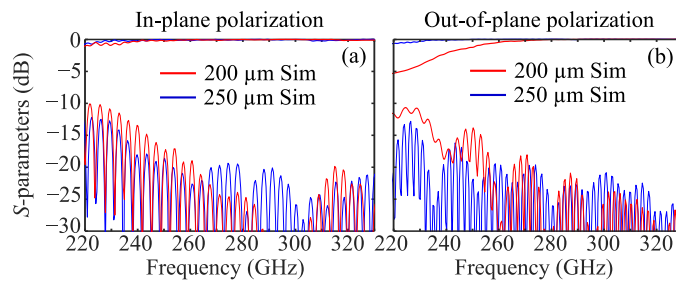


Figure 4.6. Simulated S -parameters for a 5cm waveguide with linear tapers of different thicknesses for (a) in-plane polarisation and (b) out-of-plane polarisation.

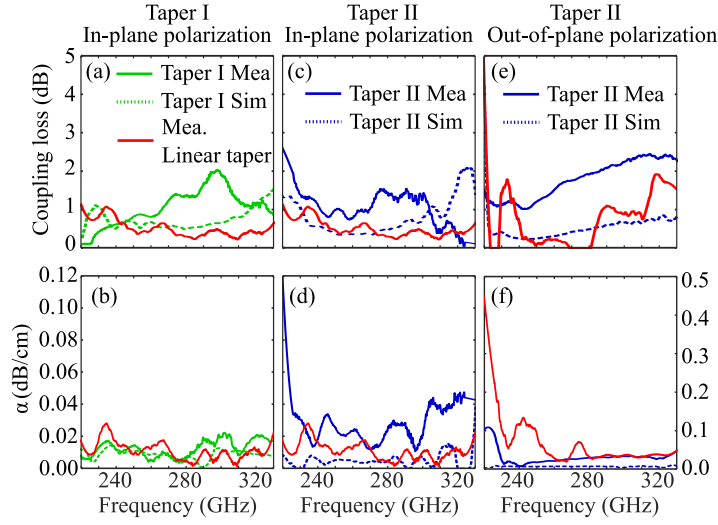


Figure 4.7. Simulated and measured coupling loss and attenuation coefficient for different polarisation states of the proposed designs, compared with the linear taper: (a–b) for Taper I; (c–f) for Taper II.

higher insertion loss compared to simulation, primarily due to over-etching of the taper air holes and front-end elliptical defect in some of the fabricated samples, as shown in Figs. 4.5(g–k). The defect structure reduces the confinement of the incident wave, resulting in higher insertion loss for both in-plane and out-of-plane polarisations. This effect is confirmed by simulation and illustrated in Figs. 4.5(g–k). By comparing the transmission responses of these samples of identical couplers but different lengths, we extract the coupling loss L_c using: $L_{\text{total}} = 2L_c + \alpha l$ [dB]. Here, L_{total} is the total transmission loss of the sample, l is the length of the waveguide excluding the tapers and α is the attenuation coefficient per centimeter. We also measure the conventional linear taper design as shown in Fig. 4.1 with waveguide lengths $l = 1, 2, 3$ and 5 cm lengths and calculated the coupling loss L_c and propagation loss α . These linear-taper waveguides follow the same design as in (Gao et al., 2020), which employs the identical effective-medium cladding structure used in our work and therefore provides a suitable reference for comparing coupling efficiency and transmission performance. Unfortunately, the waveguide with linear taper shown in (Gao et al., 2020) was fabricated with $200\text{ }\mu\text{m}$ -thick silicon wafer, and this thickness difference leads to degradation in the low-frequency region of $220\text{--}240$ GHz for the out-of-plane polarisation. From 275 GHz, however, the $200\text{ }\mu\text{m}$ -thick sample exhibits the same transmission and reflection levels as the $250\text{ }\mu\text{m}$ -thick structure (Gao et al., 2020), as confirmed by the simulations shown in Figs. 4.6(a–b). As shown in Fig. 4.7, the proposed taper designs

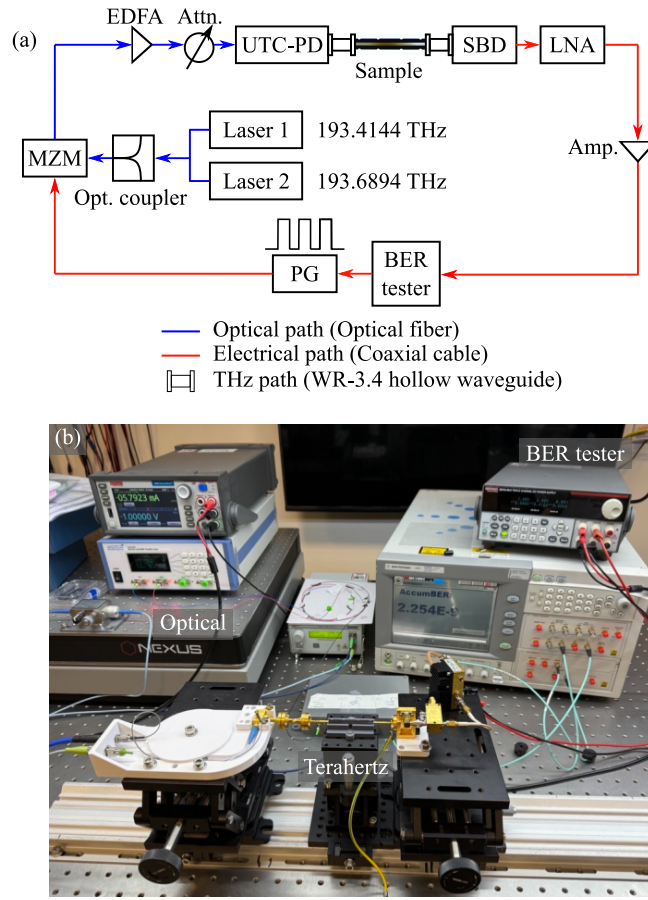


Figure 4.8. Bit error rate test setup. (a) Bit error rate test schematic. MZM: Mach-Zehnder modulator, EDFA: Erbium-doped fiber amplifier, Attn.: attenuator, UTC-PD: Uni-travelling carrier photodiode, SBD: Schottky barrier diode, LNA: Low-noise amplifier, PG: pattern generator, BER tester: bit-error-rate tester. (b) Photo of the test setup.

achieve coupling loss and attenuation coefficients comparable to the 3 mm linear taper, while providing a more compact footprint with a taper length of only 0.5 mm. The higher coupling loss and attenuation coefficient observed at high frequencies is attributed to the increased insertion loss of the defective 5 cm Taper II sample.

To validate the performance of the proposed design in terahertz communications systems, a comprehensive bit-error-rate (BER) characterization experiment is carried out using the setup shown in Figs. 4.8(a–b). On the transmitter side, a terahertz signal is generated via optical heterodyning by photomixing two tunable near-infrared lasers. The baseband modulating signal is provided by the pattern generator of a BER tester, Agilent J-BERT N4903B, with a data rate tunable between 0.6 and 7.0 Gbit/s. The modulated optical signal is then downconverted to the sub-terahertz range at the carrier

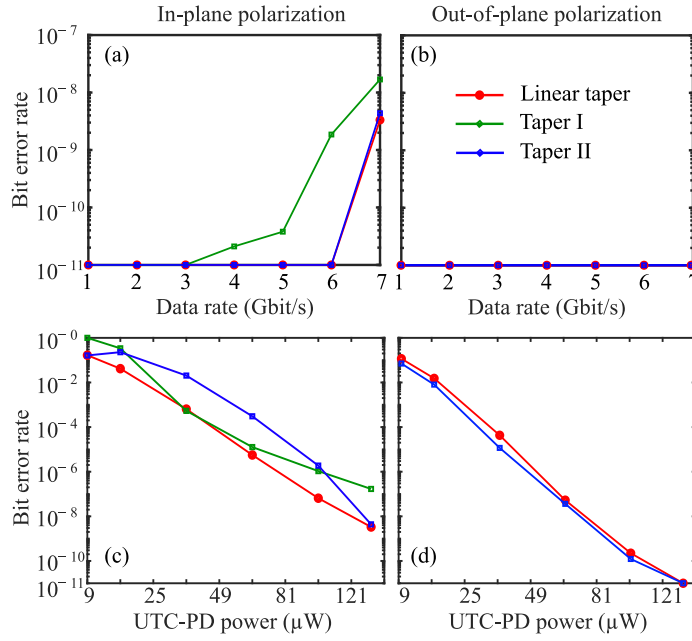


Figure 4.9. Measurement results of BER. (a–b) Bit error rate versus data rate at the carrier frequency of 275 GHz with the UTC-PD current of 5.8 mA. (c–d) Bit error rate versus UTC-PD current at the carrier frequency of 275 GHz with the data rate of 7 Gbit/s. Data points plotted at 10^{-11} correspond to actual BER values below 10^{-11} , shown at this level for clarity.

frequency of 275 GHz using a uni-traveling-carrier photodiode (UTC-PD). The Schottky barrier diode (SBD) is used to detect and demodulate the incoming terahertz signal on the receiver side. The recovered signal is amplified by a low-noise amplifier (LNA) and returned to the BER tester for analysis.

For this test, we use 3 different samples, including the linear taper design and the two proposed compact designs Tapers I and II shown in Figs. 4.2(d–e). All samples are 5 cm long to test the communications quality with the highest attenuation coefficient. A pseudorandom binary sequence (PRBS) with a length of $2^{23} - 1$ is used for all the BER testing. As shown in Figs. 4.9(a–b), with increasing data rate and a UTC-PD power of 134μ W, the proposed compact taper design Taper I achieves very low bit error rate (BER), remaining below 10^{-11} up to 3 Gbit/s, with a maximum BER of 1.68×10^{-7} observed at 7 Gbit/s for the in-plane polarised waves. Taper II maintains a BER below 10^{-11} until 6 Gbit/s, with a maximum of 4.37×10^{-9} at 7 Gbit/s.

Since the lowest detectable BER for the tester is 10^{-11} , the results indicate error-free transmission at 7 Gbit/s for the out-of-plane polarisation. Since the highest data rate is limited by the BERT, the proposed design demonstrates the potential to support

higher data rates. To assess the robustness of the transmission quality against noise and signal degradation, we further evaluate the BER under reduced UTC-PD current levels, effectively lowering the signal-to-noise ratio (SNR). As shown in Figs. 4.9(c–d), the BER remains below 10^{-4} when the UTC-PD power exceeds $4.24\text{ }\mu\text{W}$ for the in-plane polarisation and $3.36\text{ }\mu\text{W}$ for the out-of-plane polarisation. These results demonstrate the reliability and efficiency of our taper design in terahertz communications systems.

4.4 Conclusion

We have proposed and experimentally validated two compact all-silicon waveguide coupler designs based on the combination of rod waveguide antenna and slot waveguide concepts for two polarisations. With taper lengths of 450 and $500\text{ }\mu\text{m}$, the designs achieve a low average coupling loss of -1.25 dB across the wide $220\text{--}330\text{ GHz}$ terahertz band. Communications tests further confirm reliable transmission performance, achieving bit error rates below 10^{-11} at 275 GHz with the data rate of 7 Gbit/s for the out-of-plane polarisation and 10^{-7} for the in-plane polarisation, and maintaining low error rates under high signal-to-noise conditions. Beyond standalone coupling, the compact and robust design is adaptable to other all-silicon terahertz components, offering a practical solution for scalable and efficient integrated terahertz systems.

Chapter 5

Tunable Bandpass Filters with Hybrid Waveguide Integration

Tunable bandpass filters are essential for terahertz front-end systems requiring flexible channel allocation. However, compact and low-loss tunable bandpass filters remain challenging on integrated platforms. This work bridges that gap by presenting a high-performance, widely tunable terahertz bandpass filter based on a hybrid silicon–metal architecture. A fixed all-silicon waveguide with inserted 1D photonic crystals defines the high-frequency stopband, while mechanically adjustable metallic parallel plate waveguides introduce a tunable low-frequency cutoff. Multiple communications channels defined by IEEE 802.15.3d are realised by varying only the metal gap. Full-wave simulations demonstrate stable bandpass responses with low insertion loss of 1 dB and strong out-of-band rejection exceeding 40 dB. The results also show flat and low group delay dispersion around 0.002 ns^2 within the 3-dB passband. A compact and modular packaging scheme using CNC-machined metal plates, 3D-printed COC holders, and a differential-screw-based tuning mechanism provides micrometer-resolution control with precise alignment. This approach provides a practical solution for reconfigurable terahertz filtering, with implications for reconfigurable front-end architectures in future high-data-rate wireless systems.

5.1 Introduction

Owing to the wide range of terahertz applications, including high-capacity communications (Petrov et al., 2020), non-destructive sensing (You et al., 2025b), and high-resolution imaging (You et al., 2025a), the demand for compact and low-loss components capable of manipulating terahertz waves is continuously increasing. All-silicon substrateless waveguides have recently gained significant attention for terahertz integrated circuits. Various types of all-silicon self-supported waveguides have been proposed, including photonic crystal waveguides (Tsuruda et al., 2015), effective-medium waveguides (Gao et al., 2020; Headland et al., 2020b), and extreme skin-depth waveguides (Lees et al., 2024). Importantly, all four low-loss all-silicon waveguide types can be integrated within a unified platform, as they can realise interconnections between passive components. More recently, several frequency-selective structures have been explored on all-silicon substrateless waveguide platforms. Bragg grating filters implemented in effective-medium-clad silicon waveguides enable high-rejection stopbands through periodic refractive-index modulation (Gao et al., 2021). Frequency selection based on terahertz tunneling effects has also been demonstrated using controlled waveguide discontinuities. In this approach, specific frequency components are selectively coupled from a dielectric waveguide into an adjacent slab through optical tunneling. The coupled fields then propagate as leaky waves, enabling spatial separation and multiplexing of different frequency channels in a compact integrated structure (Headland et al., 2021). In addition, advanced all-silicon bandpass filters combining one- and two-dimensional photonic crystal structures with effective-medium claddings have achieved low insertion loss and high selectivity across multiple IEEE 802.15.3d channels (Chen et al., 2024).

Despite the progress in frequency-selective devices, tunable bandpass filters are still lacking for these all-silicon waveguide platforms. In terahertz communications systems, tunable bandpass filters are essential for dynamic spectral control. Tunable filters allow the passband to be adjusted to different channels without changing the hardware. This enables flexible allocation of spectrum and supports multi-channel operation. An ideal bandpass filter should exhibit low insertion loss, low in-band dispersion, high out-of-band rejection, and high roll-off rate between the passband and stopbands. These characteristics ensure effective band isolation, prevent wasted spectrum, and suppress out-of-band noise. Moreover, a tunable bandpass filter should not

only provide tunability of the passband but also maintain stable performance across all tuned states.

As discussed in Section 1.3.2, tunable bandpass filters have been widely explored in the microwave and optical domains using resonant structures, multilayer metasurfaces, or tunable materials (Shukoor and Dey, 2023; Phon et al., 2018; Wang et al., 2019; Lv et al., 2022; Gavdush et al., 2020; Pitchappa et al., 2022; Mohammadi et al., 2024; Chen et al., 2018; Khater et al., 2021; Ghahremani and Moradi, 2018). While these approaches offer effective frequency control, they have the limitation for fabrication complexity and scalability with self-supported silicon platforms.

Recent work has demonstrated contactless tuning of dielectric waveguides using nearby metallic structures to modify the electromagnetic boundary conditions (Headland et al., 2025a). By adjusting the separation between metallic elements placed close to an unclad silicon waveguide, the cutoff frequency of the in-plane polarised mode can be shifted to higher frequencies, effectively realising a tunable high-pass filtering response. Resonant notch filters have been realised with tunable resonance frequencies using this mechanism. The same mechanism can be extended to realise practical tunable bandpass filters. By combining this in-plane high-pass filtering mechanism with one-dimensional (1D) photonic crystals that form a wide stopband at high frequencies. The proposed design realises a tunable bandpass filter. This filter exhibits low transmission loss enabled by the dielectric waveguide, high out-of-band rejection provided by the metal plates, and tunability of both the passband bandwidth and centre frequency through adjustment of the metal-slot width.

5.2 Design Methodology

The proposed bandpass filter is formed by integrating a dielectric waveguide with two distinct structural elements: a metallic slot and a 1D photonic crystal, as shown in Fig. 5.1. The dielectric waveguide runs along the propagation direction and is externally confined by metallic boundaries placed on either sides the waveguide, forming a metal slot. In the central section of the waveguide, a periodic array of air holes is introduced to realise a 1D photonic crystal. The metallic slot and the 1D photonic crystals are combined with waveguide and operate together to shape the spectral response. The bandpass response is formed by combining the metal slot, which defines the low-frequency cutoff, with the 1D photonic crystal, which introduces an additional

5.2.1 Tunable High-pass Filter

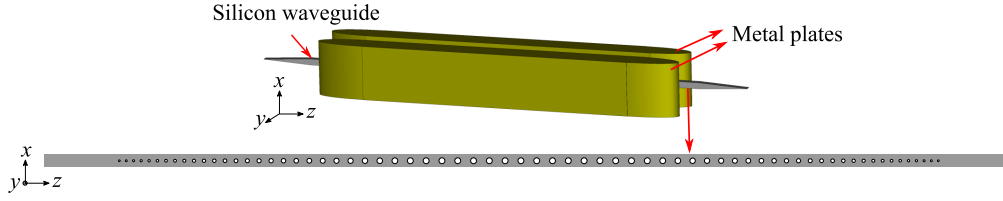


Figure 5.1. Schematic of the proposed tunable bandpass filter.

stopband at high frequencies. Because this high-frequency stopband coincides with the upper limit of the relevant frequency band, the photonic crystal effectively functions as a low pass filter. The tunability of the proposed filter is achieved by adjusting the width of the metal slot. A detailed discussion of the operating principles is presented below.

5.2.1 Tunable High-pass Filter

The tunable high-pass filtering mechanism employed in this work is based on the external electromagnetic perturbation theory previously developed for terahertz silicon waveguides (Headland et al., 2025a). Metallic plates placed on both sides of the

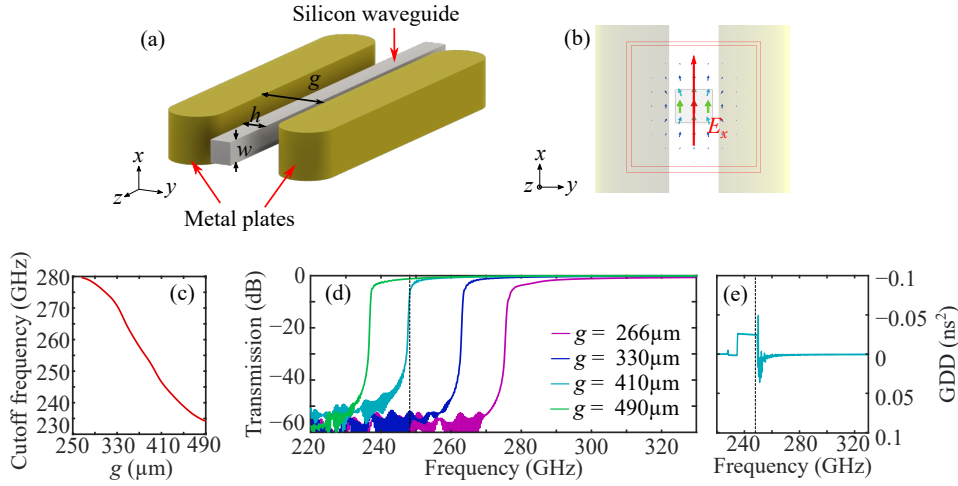


Figure 5.2. Schematic of the tunable high-pass filter. (a) Silicon waveguide with width $w = 225 \mu\text{m}$ and thickness $h = 250 \mu\text{m}$ positioned between two metallic plates. The separation between the plates is g . (b) E -field of the in-plane polarised mode. (c) Lower cutoff frequency of the in-plane polarised mode as a function of metal gap g . (d) Simulated transmission responses of the tunable high-pass filter for different metal gaps g . (e) Group delay dispersion for high-pass filter with metal-slot width $g = 410 \mu\text{m}$.

waveguide provide a parallel-plate-like transverse confinement (Sasao and Monnai, 2020), similar to a dielectric-loaded parallel-plate waveguide in its TE_1 mode, where electric-wall boundary conditions control the transverse field distribution and the cut-off behavior.

As the separation between the metallic boundaries is reduced, the effective modal index of the metal-loaded waveguide decreases (Tamir et al., 2013; Pozar, 2021). The resulting change in dispersion makes the cutoff frequency move to higher frequency as the metal separation decreases. By adjusting the separation between the metallic boundaries, the strength of the external perturbation can be continuously controlled, providing a practical tuning mechanism, as shown in Fig. 5.2(c). Based on this principle, an unclad dielectric silicon waveguide is adopted for its structural simplicity and low-loss characteristics in the terahertz band (Headland et al., 2020b). With a waveguide width w of 225 μm and thickness of 200 μm , the structure supports low-loss transmission over 150–400 GHz (Headland et al., 2020b). To improve the transition between the waveguide sections with and without metallic perturbation, the metallic plates are apodised with an elliptical profile, whose smooth arch geometry suppresses abrupt impedance discontinuities and reduces reflection, as shown in Fig. 5.2 (a–b). This approach is preferred over other polynomial profiles because the elliptical geometry naturally produces a smooth field expansion. In principle, this operation is similar to that of a horn antenna, where a gradual widening of the guiding structure is used to improve impedance matching at the interface. By varying the slot width g , the high-pass cutoff frequency can be tuned, as shown in Fig. 5.2(d). However, the minimum achievable slot width is limited by the silicon wafer thickness h of 250 μm used in this work, which constrains the highest cutoff frequency to approximately 280 GHz. The filter also shows a flat and low group delay dispersion for around 0.001 ns^2 within the 3-dB passband, as shown in Fig. 5.2(e).

5.2.2 Low-pass Structure Using 1D Photonic Crystal

In this design, as shown in Fig. 5.3(a), a 1D photonic crystal is employed with 26 uniform holes in the central region to provide strong high-frequency rejection, and linearly apodised holes on each side to smooth the spectral response with apodised hole number $N = 16$ on each side. Linear apodisation is applied to both the hole diameter and the period, with the diameter varying from $d_0 = 103 \mu\text{m}$ to a minimum d_n of 20 μm , and the difference between the maximum a_0 and minimum periods a_N set to 160 μm ,

5.2.2 Low-pass Structure Using 1D Photonic Crystal

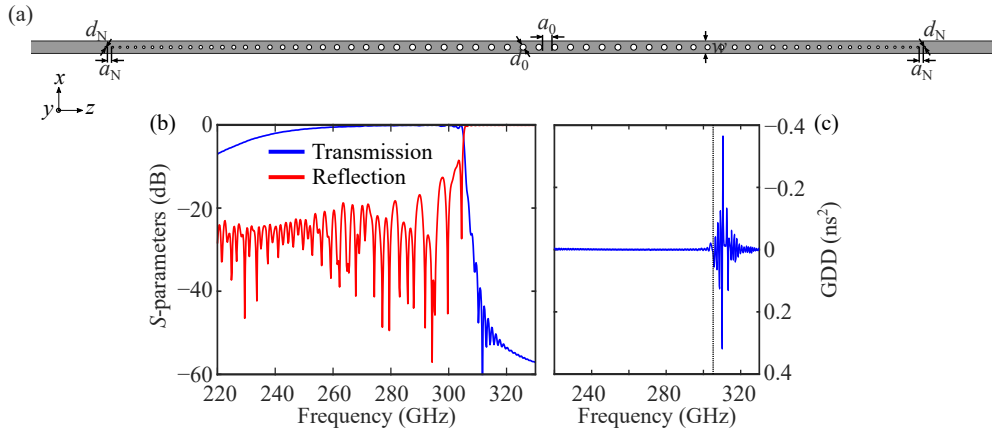


Figure 5.3. Schematic of the apodised 1D photonic crystal. (a) Symmetric apodisation along the x -axis, with hole diameter and lattice constant varying from a_0, d_0 to a_N, d_N . (b–c) Simulated S-parameter results and group delay dispersion of the apodised 1D photonic crystal waveguide with $a_0 = 230 \mu\text{m}$.

as shown in Fig. 5.3(a). With the hole diameters and the period variation range fixed at a normalised ratio of 0.1, the high-frequency cutoff of the filter is tuned by adjusting only the maximum period a_0 . Increasing a_0 shifts the stopband edge toward lower frequencies, thereby decreasing the cutoff frequency, as illustrated in Chapter 3 Fig.5. Figure 5.3(b) shows the simulated S-parameter response for $a_0 = 230 \mu\text{m}$, exhibiting a flat low-loss passband below the cutoff frequency, followed by a sharp roll-off and strong attenuation at higher frequencies. The reflection remains low in the passband and increases rapidly near the band edge. Besides, below the cutoff frequency of 305.23 GHz, the filter exhibits a flat and low group delay dispersion for around 0.006 ns^2 , as shown in Fig. 5.3(c). Low-frequency radiation is mainly attributed to the reduced field confinement of the dielectric waveguide. At low frequencies, the guided mode is less confined and exhibits a larger evanescent field, which increases its sensitivity to discontinuities and promotes coupling to radiation modes. This behaviour can be alleviated by improving modal confinement, for example by increasing the waveguide width or introducing dielectric claddings. In this design, for simplicity, this effect is acceptable since the low-loss transmission band starts from 252 GHz, corresponding to the lower edge of the targeted IEEE communications band (Standards Committee, 2017). Thus, the undesired radiation occurs beyond the band of interest.

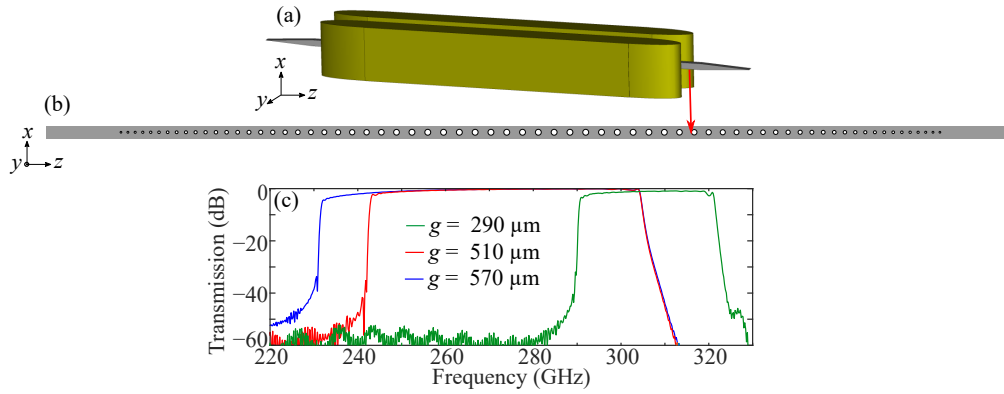


Figure 5.4. Schematic of the integrated tunable bandpass filter. (a–b) Filter structure with an apodised 1D photonic crystal waveguide positioned between two metallic plates. (c) Simulated transmission responses of the tunable bandpass filter for different metal gaps g .

5.2.3 Tunable Bandpass Filter Realisation and Optimisation

As shown in Figs. 5.4(a) to (c), inserting the apodised one dimensional photonic crystal waveguide into the metallic slot produces a stopband that is bounded at low frequency by the cutoff imposed by the metal boundaries. When the metal gap is reduced, the lower cutoff frequency increases due to stronger confinement between the plates, which enables bandwidth tuning of the filter. For relatively large gaps ($g \gtrsim 0.5\lambda_g$), the metallic boundaries act as a weak perturbation and mainly suppress low-frequency components, with little influence on modal dispersion (Snyder et al., 1983). As the gap becomes narrower ($g \lesssim 0.2\lambda_g$), the metal-induced confinement increases the TE_1 cutoff frequency and reduces the propagation constant β , corresponding to a longer guided wavelength. For a fixed Bragg period, the Bragg condition is therefore satisfied at a higher frequency, causing the photonic crystal stopband to shift upward together with the metal-defined lower cutoff. As a result, both the lower and higher cutoff frequencies move toward higher frequencies, and the entire passband shifts upward rather than only tuning the lower band edge, as observed when the slot width is reduced to $290\ \mu\text{m}$.

As shown in Fig. 5.5(e), in the low-frequency stopband, a low reflection level is observed and can be attributed to the elliptical shape of the metal plates. Although the fully apodised metallic slot effectively improves mode coupling, it also forms a Vivaldi antenna-like structure, which leads to increased radiation loss at low frequencies. To address this issue, a configuration using rectangular metal plates without apodisation

is first investigated, as shown in Fig. 5.5(c). While the low-frequency stopband reflection level is increased, the non-apodised structure degrades the transmission performance within the passband and introduces strong oscillations around the cutoff frequency due to the abrupt geometric transition, as shown in Fig. 5.5(f). To improve mode coupling while suppressing radiation, a short apodised section is introduced into the structure, as shown in Fig. 5.5(d). As shown in Fig. 5.5(g), this quasi-apodised configuration preserves low-loss transmission within the 3-dB passband while effectively increasing the reflection level in the low-frequency stopband compared with the fully elliptical metal-plate design.

5.3 Communications Channel Realisation

As shown in Fig. 5.6, the bandpass filter is implemented on a hybrid silicon–metal platform and incorporates a protective supporting frame together with a short section of effective-medium cladding to protect the unclad silicon waveguide and to enable integration with other substrateless components. Compact silicon tapers developed in Chapter 4 are included at both the input and output ports for fabrication robustness and efficient interconnection. To realise multiple communications channels using the same silicon waveguide, a parameter analysis is carried out, and the design dimensions are selected as explained in the following. The 1D photonic crystal period is set to $a_0 = 293 \mu\text{m}$, with the air-hole diameter of $d_0 = 103 \mu\text{m}$, and a silicon waveguide

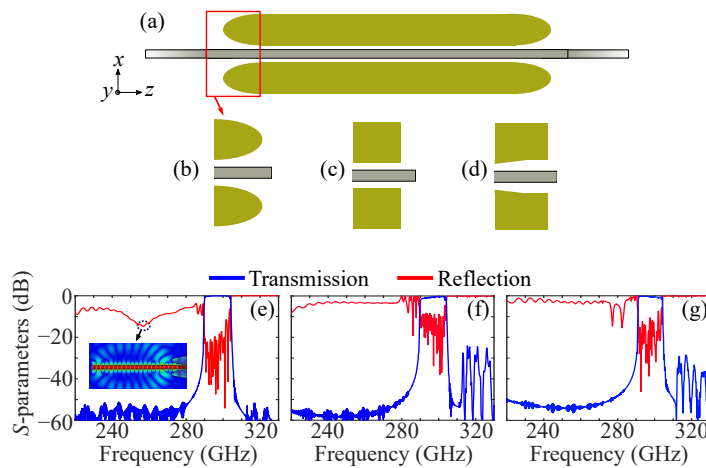


Figure 5.5. Proposed apodisation types. (a) Top view of the tunable bandpass filter. (b) Elliptically apodised slot. (c) Straight slot. (d) Quasi-apodised slot. (e–g) Simulated S -parameters of the proposed apodisation types.

width of $w = 225 \mu\text{m}$. These parameters are fixed for all simulated cases, and different communications channels are obtained by adjusting only the metal gap g . Specifically, the metal gap is set to $266 \mu\text{m}$, $348 \mu\text{m}$, and $436 \mu\text{m}$ to realise Channels 60, 63, and 66, respectively, while all other structural parameters remain unchanged. These 3 channels have been chosen as they have different center frequencies and bandwidths, as shown in Fig. 3.1.

As shown in Fig. 5.7, a clear and well-defined bandpass response is achieved for each channel configuration. Within the 3-dB passbands, the insertion loss remains low around 1 dB. The reflection is suppressed below -15 dB across the 3-dB passbands. Outside the passband, strong attenuation is observed on both the lower- and higher-frequency sides, with out-of-band rejection exceeding 40 dB. Although the passband center frequency shifts with the metal gap, the bandwidth and sharp transition remain comparable across all tuning states. Compared with the spectral mask defined in IEEE 802.15.3d (Standards Committee, 2017), the proposed filter exhibits a sharp transition between the passband and stopbands, lower rejection level of out-of-band, closely matches the mask requirements, and maintains consistent performance across all realised channels. The filters also show flat group-delay dispersion within the 3-dB

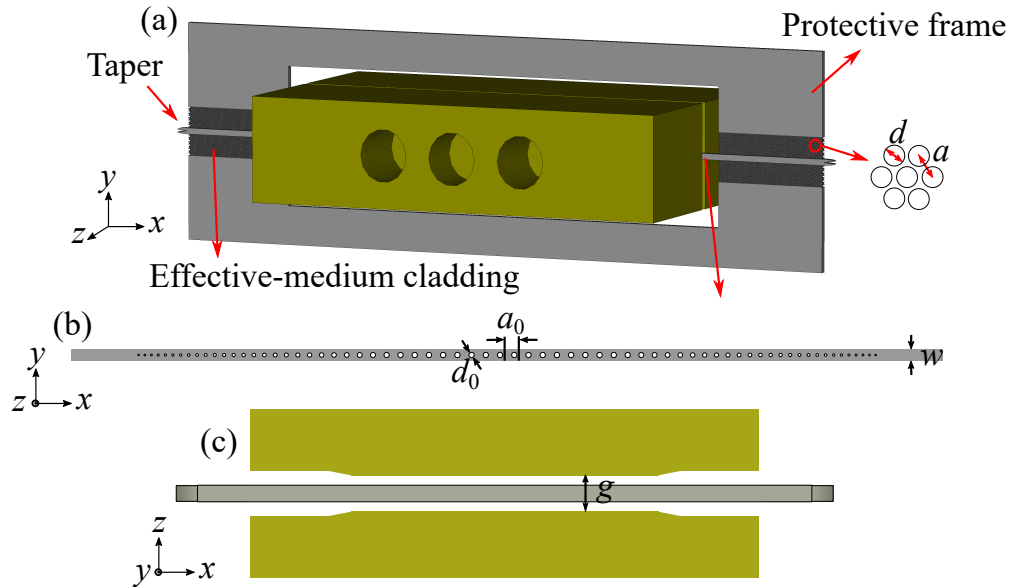


Figure 5.6. Proposed tunable bandpass filter. (a) Schematic of the filter incorporating a protective frame and compact tapers. An effective-medium cladding with hole diameter $d = 90 \mu\text{m}$ and period $a = 90 \mu\text{m}$ is added at the edges of the silicon waveguide. (b) Inserted 1D photonic crystal waveguide with hole diameter $d_0 = 103 \mu\text{m}$, period $a_0 = 293 \mu\text{m}$, and waveguide width $w = 225 \mu\text{m}$. (c) Top view of the filter showing two quasi-apodised metallic plates separated by a distance g .

5.3 Communications Channel Realisation

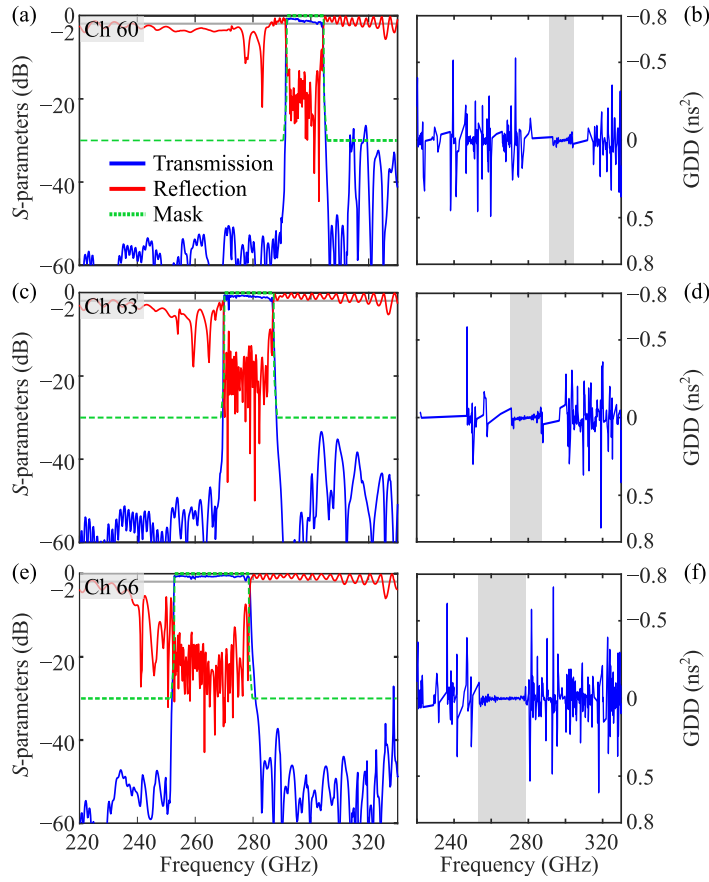


Figure 5.7. Simulated S -parameter results and group delay dispersion of three bandpass filters for (a–b) Channel 60 realised with $g = 266 \text{ } \mu\text{m}$, (c–d) Channel 63 realised with $g = 348 \text{ } \mu\text{m}$, and (e–f) Channel 66 realised with $g = 436 \text{ } \mu\text{m}$, compared with the spectral masks from IEEE 802.15.3d – 2017 (Standards Committee, 2017).

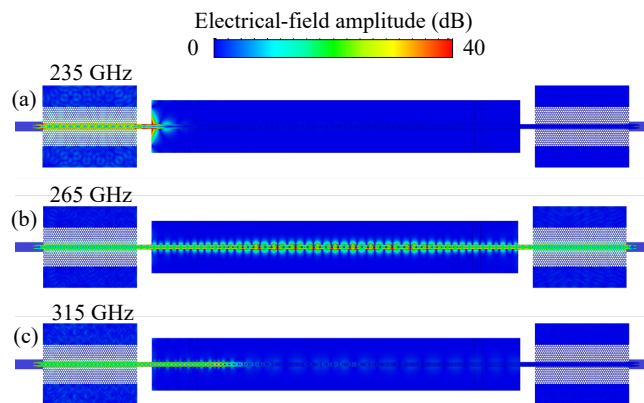


Figure 5.8. Simulated instantaneous electrical-field distribution for Channel 66 in Fig. 5.7(c) at: (a) 235 GHz, (b) 265 GHz, and (c) 315 GHz.

passbands of all three realised channels, with an average value of approximately 0.002 ns². This low dispersion corresponds to a pulse broadening factor of about 1.003 for a 4-GHz Gaussian input, indicating that the output pulse duration increases by only around 0.3%. Electric-field amplitude distributions of Channel 66 are examined. As shown in Fig. 5.8(a), at frequencies below the passband of 235 GHz, the field is largely confined to the input waveguide and decays rapidly upon entering the metallic slot-loaded filtering section. As shown in Fig. 5.8(b), at the passband frequency of 265 GHz, the field propagates smoothly through the entire device, including the tapers and the photonic crystal region, with strong confinement within the silicon waveguide. At frequencies above the passband of 315 GHz, the field again attenuates within the photonic crystal filtering section, resulting in the stopband, as shown in Fig. 5.8(c).

5.4 Package and Implementation

In this section, the design and implementation of a practical package for the tunable bandpass filter are presented. The assembly approach, mechanical tuning mechanism, and integration aspects are discussed to demonstrate the feasibility of controlled tunability.

5.4.1 Dielectric Sample Assembly

As shown in Figs. 5.9(a–b), the silicon slab region of the device is intentionally extended beyond the functional filtering section to facilitate mechanical handling and secure mounting. The chip is placed on a COC support stage fabricated using 3D printing. This stage provides precise vertical and lateral positioning of the unclad silicon waveguide while avoiding direct physical contact with the waveguide sidewalls. To ensure repeatable and accurate alignment, positioning dowels are incorporated into the dielectric stage, constraining the silicon chip location and preventing lateral shift or rotation during assembly. The chip is secured in place using plastic M2 screws, which provide sufficient clamping force while avoiding electrical contact and minimising the risk of mechanical damage to the silicon waveguide.

5.4.2 Tuning Stage Integration

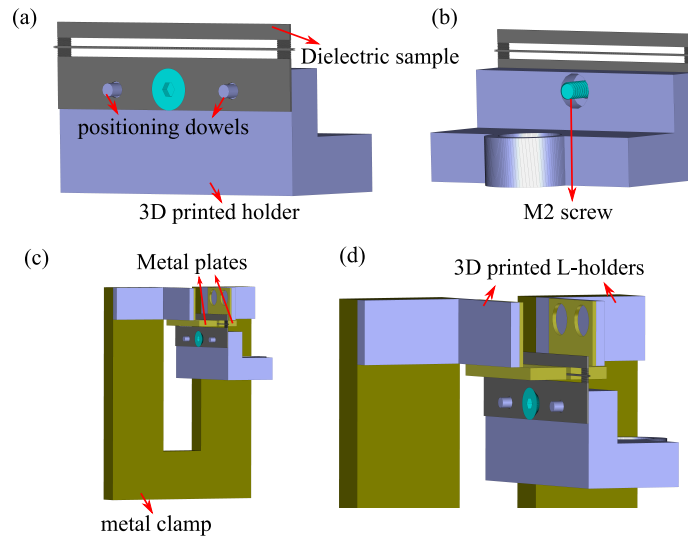


Figure 5.9. Schematic of the proposed package. (a–b) Assembly of the dielectric sample using 3D-printed COC holders with positioning dowels and plastic M2 screws. (c) Integration of the metal plates with the metal clamp and the dielectric sample. (d) Assembly of the CNC-machined metal plates using 3D-printed L-holders for mounting onto the metal clamp.

5.4.2 Tuning Stage Integration

Once the silicon chip is securely mounted, the metallic components forming the tunable boundaries are assembled around it. As shown in Figs. 5.9(c–d), the CNC-machined metal plates are mounted onto the 3D printed COC L-holders, which provide mechanical support and precise positioning of the metallic boundaries relative to the silicon waveguide. The 3D printed COC L-holders are also integrated with a Thorlabs differential screw, allowing controlled adjustment of the separation between the opposing metallic walls. By rotating the differential screw, the metal gap can be tuned with micrometer-level resolution while maintaining parallelism and planarity of the metallic boundaries. The COC L-holders are then mounted onto the metal clamp, completing the integration of the tuning stage.

The complete assembly is mounted on a stable base compatible with standard optical tables and terahertz measurement fixtures. This modular packaging approach allows the silicon chip or metallic components to be replaced or reconfigured without modification to the supporting structure, facilitating systematic tuning experiments and future design extensions.

5.5 Conclusion

A tunable terahertz bandpass filter based on a hybrid silicon–metal platform has been presented. Multiple communications channels are realised using a single silicon waveguide structure by adjusting only the metal-slot gap without structural redesign. Stable bandpass responses with low insertion loss and strong out-of-band rejection are confirmed by simulations. Compared with the spectral mask defined in IEEE 802.15.3d (Standards Committee, 2017), the proposed filter shows low in-band insertion loss, higher out-of-band rejection level and matched sharp transition between pass and stopbands. A practical and compact packaging scheme is developed, combining CNC-machined metal plates with 3D-printed COC holders and a differential-screw-based tuning mechanism. Although the design still does not allow independent tuning of the bandwidth and center frequency, this approach enables micrometer resolution tuning while maintaining alignment and mechanical stability, demonstrating a feasible route toward reconfigurable and integrable terahertz filtering solutions.

Chapter 6

Summary and Outlook

THIS chapter summaries the main outcomes of the thesis and outlines directions for future research. The work demonstrates that all-silicon effective-medium waveguide platform can realise low-loss, compact, and tunable terahertz integrated components, including polarisation filters, bandpass filters, and compact couplers. Future research directions are then discussed. These include inverse design methods for compact polarisation rotators and topology-based approaches for reflectionless bandpass filters. These directions aim to improve integration density, spectral control, and robustness. Overall, this chapter highlights pathways toward practical and high-performance terahertz integrated systems for communication and sensing applications.

6.1 Thesis Conclusion

This doctoral thesis focused on the development of integrated terahertz waveguide components based on the all-silicon platform, with an emphasis on low loss propagation, compact integration, and practical tunability. The work targets key functional building blocks required for terahertz communication systems, including polarisation filter, frequency selective filters, compact couplers, and tunable bandpass filters. The proposed devices are designed to be compatible with substrateless and effective medium waveguide platforms, enabling monolithic integration and scalable fabrication.

The first contribution of this thesis is the development of integrated terahertz polarisation filters using effective medium waveguide engineering. By combining Bragg grating structures with effective medium cladding and slot based perturbations, strong polarisation discrimination was achieved within a compact footprint. The proposed polarisation filters exhibit high extinction ratio, low insertion loss, and broadband operation. This work demonstrates that effective medium concepts provide an additional degree of freedom for tailoring modal dispersion and polarisation response in integrated terahertz waveguides.

The second contribution is the realisation of all dielectric terahertz bandpass filters based on cascaded high-pass and low-pass filtering mechanisms. High-pass behaviour was achieved through waveguide cutoff engineering, while low-pass filtering was implemented using one dimensional photonic crystal structures. By cascading these elements, compact bandpass filters with sharp spectral transitions were realized. The fabricated devices showed good agreement between simulation and measurement. Communication experiments further demonstrated the suitability of the proposed filters for high data rate terahertz wireless links.

The third contribution focuses on compact waveguide coupling. An ultra compact waveguide coupler was developed to enable efficient power transfer over a short interaction length. This coupling approach significantly reduced device size while maintaining good spectral performance. The compact coupler serves as an important building block for densely integrated terahertz circuits and was successfully incorporated into tunable bandpass filter designs.

The final contribution of this thesis is the development of tunable terahertz bandpass filters through metallic-dielectric waveguide integration. External metallic boundaries

were introduced to perturb the electromagnetic fields of dielectric waveguides without modifying the waveguide core. This approach enabled continuous tuning of cut-off frequencies and passband characteristics via mechanical adjustment. Direct modal analysis confirmed the tuning mechanism. Packaged devices have been designed for stable and repeatable tuning performance, highlighting the practicality of the proposed approach.

Overall, this thesis demonstrates that the all-silicon waveguide platform can support a wide range of high performance terahertz components, including polarisation filters, fixed and tunable bandpass filters, and compact couplers. These components can be monolithically integrated with other terahertz devices such as sources, detectors, antennas, and signal processing units. The integration of frequency selective and tunable components provides a pathway toward compact, flexible, and high performance terahertz frontends for future communication and sensing applications.

6.2 Outlook

The work presented in this thesis provides practical building blocks for future terahertz integrated systems. The proposed filters, couplers, and tuning methods are compatible with a common dielectric and all-silicon platform. This enables straightforward integration with other terahertz components. These results also highlight several opportunities to extend the functionality of terahertz integrated circuits. In particular, future systems will require higher integration density, better spectral control, and improved robustness. To address these needs, three research directions are identified: inverse designed polarisation rotators, and topology based bandpass filters.

Inverse design of terahertz polarisation rotator

Polarisation multiplexing is an effective way to increase data rate in terahertz communications. To support this technique, compact and broadband polarisation rotators with low loss are required. Existing designs often involve trade offs between bandwidth, size, and fabrication complexity. These limitations restrict their use in highly integrated systems.

Inverse design provides a systematic method to overcome these challenges. Instead of relying on fixed geometries, the structure is optimised directly toward a target polarisation response. This allows multiple design parameters to be adjusted at the same

time. Inverse design is well suited for terahertz structures, where performance can be sensitive to small geometric variations. By including fabrication constraints during optimisation, the resulting designs can remain robust and manufacturable.

The expected outcome of this approach is a compact polarisation rotator with broadband operation and high extinction ratio. Improved tolerance to fabrication errors is also anticipated. Such a device would support polarisation multiplexing and improve spectral efficiency in future terahertz communication systems.

Topology-optimised design for terahertz reflectionless bandpass filters

Reflectionless behaviour in the stopbands is highly desirable for terahertz integrated systems. In conventional bandpass filters, unwanted frequency components are often reflected back toward the source. At terahertz frequencies, these reflections can easily form standing waves and disturb the operation of nearby components. This degrades system stability and increases sensitivity to impedance mismatch, especially when filters are directly integrated with sources, detectors, or amplifiers.

In this thesis, the term topology-optimised design refers to topology optimisation techniques for electromagnetic structure design, rather than topological insulators or topological photonic materials. Topology-optimised design provides a flexible approach to achieving stopband reflectionless behaviour. Instead of relying on predefined filter sections, the structure is optimised directly to control both transmission and reflection responses. In this framework, the optimisation objective can enforce strong attenuation in the stopbands while simultaneously minimising reflection through engineered impedance matching and mode control, rather than through absorptive mechanisms. Unwanted spectral components are therefore suppressed without being reflected back into the system, reducing interaction between integrated components.

For terahertz applications, topology optimisation can be combined with dielectric waveguide platform and effective medium concept to ensure low-loss propagation and fabrication compatibility. The expected outcome is a class of compact bandpass filters that maintain good transmission in the passband while exhibiting low reflection in the stopbands over a wide frequency range. Such filters can improve system robustness and simplify integration for multiplexing, tunable filtering, and adaptive signal routing in terahertz integrated circuits.

Overall, these future directions aim to extend the functionality and robustness of terahertz integrated systems. By combining advanced design methods with low loss dielectric platforms, it is expected that more compact, stable, and versatile terahertz components can be realised. These developments will support the continued transition of terahertz technology from laboratory demonstrations toward practical communication and sensing applications.

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