Review Article

Terahertz Metamaterials for Free-Space and on-Chip Applications: From Active Metadevices to Topological Photonic Crystals

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Terahertz (THz) waves have exhibited promising applications in imaging, sensing, and communications, especially for the next-generation wireless communications due to the large bandwidth and abundant spectral resources. Modulators and waveguides to manipulate THz waves are becoming key components to develop the relevant technologies where metamaterials have exhibited extraordinary performance to control free-space and on-chip propagation, respectively. In this review, we will give a brief overview of the current progress in active metadevices and topological photonic crystals, for applications of terahertz free-space modulators and on-chip waveguides. In the first part, the most recent research progress of active terahertz metadevices will be discussed by combining metamaterials with various active media. In the second part, fundamentals of photonic topological insulations will be introduced where the topological photonic crystals are an emerging research area that would boost the development of on-chip terahertz communications. It is envisioned that the combination of them would find great potential in more advanced terahertz applications, such as reconfigurable topological waveguides and topologically-protected metadevices.

1. Introduction

Laser technology has reformed the information technology from traditional electronics to optical networks with broadband and higher data rate. One of the key components in all-optical communication systems is the efficient modulators which have made great progress in the visible and infrared. However, efficient, multifunctional, and fast-response modulators in the terahertz (THz) band are still severely lacking, which limits the development of terahertz applications such as nondestructive inspection, imaging, and next-generation wireless communications [1]. The general THz applications could be classified into three parts: communications, imaging, and sensing, all of which will strongly rely on efficient modulators for free-space or on-chip applications, especially in communications that would further require high-speed modulators and low-loss waveguides.

Natural materials usually have limited interactions with terahertz waves and would require large material thickness or high drive voltage to obtain a significant modulation depth. Metamaterials are thus introduced with the extraordinary enhancement of local fields so that the light-matter interactions will be boosted. The combination of active media and metamaterials would further enrich the performance of metamaterials which have exhibited a plethora of applications in control of wave properties including amplitude, phase, frequency, polarization, wavefront, and focal length, with smaller device footprint, thinner active media thickness, lower drive voltage, and/or larger modulation depth. On the other hand, on-chip terahertz applications with low loss are another mission to be completed to address the issues of signal transmission for communications with larger bandwidth and higher signal to noise ratio (lower bit error rate, BER). Active metamaterials have exhibited extraordinary capability to manipulate free-space electromagnetic waves while the emerging field of photonic topological insulators (PTIs) provides an excellent platform for robust and low-loss waveguides. Although the two categories address problems of wave propagation in free space and on chip, respectively; the underlying physics would guide each other. For example, the development of active metadevices would help the design of reconfigurable topological on-chip routers, and the robust features of photonic topological insulators would be employed to improve the performance.
of metadevices. Currently, the terahertz applications of PTIs are still under development, and we prepare this review article to combine the two categories which we think are very important for future terahertz applications.

In this review article, we will focus on the two parts: active hybrid metadevices and topological photonic crystals (TPCs), which could find solutions to address the bottlenecks in terahertz communications for efficient modalers and low-loss waveguides, respectively. The first part will introduce several basic configurations of hybrid metadevices by integrating with liquid crystals, phase change materials (PCMs), graphene, micro-electromechanical systems (MEMS), and semiconductors, and summarize the most recent progress of the different combinations. The second part will give a brief overview on fundamentals of PTIs which are one of the most state-of-the-art approaches to develop robust waveguides and summarize the progress of PTIs in TPCs. TPCs have seen a rapid development in infrared and microwaves, but are still an emerging research area in terahertz regime that would need further development.

2. Active Metadevices

Arbitrary manipulation of electromagnetic (EM) waves has always been the most important mission in light-matter interactions; however, conventional materials have a limited range of permittivity and permeability due to the fixed types of lattice and constituent atoms. Metamaterials are artificially designed materials with subwavelength meta-atoms arranged in any lattice configuration so that EM waves could be molded by designing the desired values of permittivity and permeability [2, 3]. Many extraordinary observation and applications have emerged with the help of metamaterials, such as negative refraction [4], optical illusion [5], sub-diffraction imaging [6], and invisibility cloaking [7]. However, there still exit some technological challenges that pose barriers toward applications such as bulky sizes, high losses and complicated meta-atoms.

Metasurfaces provide an excellent solution as two-dimensional (2D) counterparts which have the capability to manipulate the amplitude, phase, polarization, and frequency of EM waves effectively [8, 9]. Soon after the first demonstrate of optical metasurfaces, metalenses were reported for diffraction-limited imaging as one of the representative breakthroughs in this area, together with metaholograms [10, 11]. On the other hand, the efficiency of metasurface devices (metadevices) could be improved by replacing metallic meta-atoms with all-dielectric ones employing the Mie scattering theory [12–14].

In addition to the abundant engineering freedom of metasurfaces in spatial domain, recent research hot spots focus on adding one more degree of freedom – temporal domain, by integrating with active/reconfigurable materials [15–17]. Such a type of hybrid metasurfaces add “wings” to the passive ones, and could “fly” higher in more demanding applications. Recently, there are lots of interesting progress in hybrid metasurfaces for active applications, especially in the terahertz band. In this section we focus on the progress of active metadevices for terahertz applications in terms of different active media/techniques integrated with metasurfaces. We hope that such a concise review could serve as a useful guide for newcomers to quickly follow up the current development of the field.

2.1. Active Metadevices Based on Liquid Crystals. Liquid crystals (LCs) are capable to manipulate electromagnetic waves in a broad spectral range from ultraviolet to microwave, and possess large optical anisotropy that could be actuated by various stimuli such as optical, thermal, electric, or magnetic fields. LCs comprise a collection of elongated molecules and are commonly divided into nematic, smectic, and cholesteric phases where the nematic phase is extensively applied whose molecule orientation tends to be ordered but spatial positions are totally random. The optical properties of nematic phase liquid crystals are determined by the orientation of molecules defining the ordinary and extraordinary axes. For the incident light with electric field along the z axis as shown in Figure 1(a), the effective permittivity tensor of LCs is approximately given by [22, 23]:

\[
\varepsilon_{LC} = \begin{bmatrix}
\varepsilon_o + \Delta \varepsilon \sin^2 \theta & \Delta \varepsilon \cos \theta \sin \theta \\
\Delta \varepsilon \cos \theta \sin \theta & \varepsilon_o + \Delta \varepsilon \cos^2 \theta
\end{bmatrix},
\]

where \(\varepsilon_o = n_o^2\), \(\varepsilon_e = n_e^2\) and \(\Delta \varepsilon = \varepsilon_e - \varepsilon_o\).

LCs have been widely applied in terahertz regime for modulators; however, the wavelength-scale thickness of LC layer renders the devices with bulky sizes, higher bias voltages, and lower switch speeds. Solutions were soon proposed by integrating with metamaterials to reduce the effective thickness of LCs for THz applications, such as phase modulators, polarization converters, tunable waveplates, and spatial light modulators [18–20, 24, 25]. The first prototype was demonstrated by Padilla’s group via combining LC with a metal-insulator-metal (MIM) type metamaterial in 2013 [26]. The thickness of LC layer was reduced to the scale of MIM cavity (tens microns) with a greatly improved performance due to the enhancement of electric field by the MIM cavity. High modulation depth (30%) and large frequency shift (4.6%) were achieved with a low driving voltage (4 V). The modulation depth was further improved to 75% by optimizing the MIM design and the device could function as a THz spatial light modulator [27]. Most recently, advanced manipulation of polarization of light was realized by LC-metasurfaces with enhanced asymmetric transmission [18]. Asymmetric transmission of circularly polarized light is well-known in planar asymmetric metamaterials; however, spin-locked optical chirality is not accessible with the conservation of mirror symmetry. By integrating with LCs, both spin-locked and spin-flipped chirality were observed attributed to the anisotropy of LCs that breaks the mirror symmetry of metamaterials (Figure 1(b)). The LC layer also enables the capability to dynamically manipulate the asymmetric transmission of terahertz radiation with external bias.

Regarding active control of wavefront that is essential for antenna and Lidar applications, programmable LC-
Metasurfaces were reported by Wu et al. [19]. In this work, two states with a phase difference of $\pi$ was found by carefully modulating the bias voltage while sustaining the constant transmission intensity. By encoding the two states of unit cells as 0 and 1 with a logical sequence, the programmable metasurface was demonstrated to actively deflect THz wave with a maximum angle of $32^\circ$ (Figure 1(c)).

MIM-type metamaterials were employed in this work which could only operate in the reflection mode and require a large modulation voltage (40 V) due to the thick insulator layer. For transmission type devices, bilayer LC-metasurfaces were recently reported [20] as illustrated in Figure 1(d). In this configuration, the metallic wires play the role of a metasurface to enhance local field as well as spatially addressable electrodes. With a spatial gradient voltage applied on the LC layer, wavefront deflection was observed with an angle of $4.5^\circ$ at 0.8 THz where the local phase shift of $55^\circ$ was obtained at a low voltage (20 V). This

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**Figure 1:** Active metadevices integrated with LCs. (a) Schematic illustration showing the angle $\theta$ of an LC molecule for permittivity tensor calculation. (b) Spin-locked and spin-flipped chirality realized by planar metasurfaces integrated with LCs [18]. (c) Programmable LC-based metasurface [19]. (d) LC integrated two-layer metasurface working in transmission mode [20]. (e) Larger phase shift reported in a shorter wavelength [21].
work proposed an interesting approach for transmission-type active metadevices; however, the phase modulation range was less than $2\pi$ that poses limitation in metasurface applications. Mie resonances could be applied for a larger phase modulation range as shown in Figure 1(e) [21], where a phase shift of $2\pi$ was achieved at a wavelength of 660 nm via a bias voltage of 12 V with an overall high transmission efficiency of 36%.

For LCs in the THz waves, one of major concerns for LC-based metadevices is the so-called “boundary-effect” [28, 29], which will lead to an uneven distribution of refractive index of LCs so that the effective refractive index is often less than the theoretical value. Another concern that should be addressed is the modulation speed that is limited by the intrinsic response time of LCs, especially for thicker LC layers. Through an appropriate combination with metamaterials, the LC-based metadevices would be very promising for terahertz spatial light modulators.

2.2. Active Metadevices Integrated with Phase Change Materials. Phase change materials (PCMs) could change between crystalline state and amorphous state (Figure 2(a)) by external stimuli such as heat, optical excitation, and bias voltage, leading to a conductivity change of three to four orders of magnitude [30, 35–38]. The combination of PCMs and metamaterials have shown a plethora of interesting physical phenomena and device applications in the terahertz regime. Volatile vanadium dioxide (VO$_2$) is a typical type of PCMs where the phase change process of VO$_2$ is accompanied with a very interesting effect of temperature hysteresis, i.e., the phase change threshold shifts in heating and refrigerating processes (342 K and 330 K, respectively). This hysteresis phenomenon was employed for temperature memory devices [35]. In addition, the phase change process could occur in the vicinity of local high field in metamaterials (as high as 4 MV·cm$^{-1}$) and a nonlinear response was induced by a standard THz pulse [39].

Recently, many notable works were reported by integrating metamaterials with PCMs for THz modulators. A larger phase shift is the key mission in metasurface applications that is commonly limited by the one-layer thin-film metasurfaces. The work proposed by Zhao et al. [30] reported a large phase modulation of 138° in the process of VO$_2$ phase change that is integrated with a split ring resonator as shown in Figure 2(b). The proposed metamaterial supports coupled LC and dipole resonances, and a dramatic phase shift of the coupled mode occurs due to the photoinduced phase transition of VO$_2$. The dynamic modulation scheme of VO$_2$ integrated metadevices was also studied by Zhang et al. [31] as shown in Figure 2(c) where they have thoroughly probed the modulation features induced by various stimuli including thermal, electrical and optical approaches. Besides phase and amplitude modulation of THz waves, VO$_2$-metasurfaces were shown to control wavefront dynamically. In 2019, dynamic meta-holography was reported via applying external heat to the VO$_2$ integrated metasurface and broadband holography was observed with the split ring resonators (Figure 2(d)) [32]. The phase transition of VO$_2$ was also applied to manipulate polarization states of THz radiation. Most recently, temperature controlled optical activity and negative refractive index of terahertz waves were demonstrated with a multilayer metamaterial [33] (Figure 2(e)). Chiral to achiral transition occurs when the VO$_2$ changes from an insulator to a metallic state by controlling the...
temperature of the metadevice, which leads to the change of circular birefringence from 70° to 0° and circular dichroism from 0.6 to 0.

Germanium telluride (GeTe) is another commonly adopted PCM in the terahertz regime with a nonvolatile feature whose electrical and optical properties can be changed at a nanosecond timescale by thermal, electrical, or optical stimuli [34]. The dynamic response of a hybrid metallic metadevice integrated with GeTe were demonstrated with a remarkable frequency shift from 0.58 THz to 0.73 THz. A 35 dB amplitude modulation was accompanied at 0.58 THz in the process of phase change from crystalline to amorphous state that occurs within 35 ns (Figure 2(f)). This work also shows the possibility to implement an all-dielectric GeTe metamaterial for reversible THz devices.

PCMs are under continuous development to expand the range of material formulations and improve switching time, which are promising tunable materials for THz applications. Meanwhile, the actuation of PCMs is simple and versatile via electricity, optics or heat. However, the phase transition temperature of GeTe-based PCM is rather high, and the transition of VO₂ is volatile. Furthermore, simultaneous realization of 2π phase modulation in both amorphous and crystalline states of PCM is very challenging, and the intermediate states of PCM cannot be effectively utilized. In short, PCMs are promising materials for applications of nonvolatile reconfigurable metadevices, but performance in terahertz band still requires to be improved for efficient applications.

2.3. Active Metadevices Integrated with Graphene. Since graphene was peeled from bulk graphite in 2004, the related research has seen an explosive growth due to its excellent mechanical, thermal, electrical, and optical properties, showing excellent performance in solar cells, LEDs, transistors, and ultrafast lasers [40–42]. Graphene has a unique linear dispersion, zero bandgap, excessive carrier transport properties, and its electrons behave as massless Dirac fermions with extremely high mobility at room temperature. Graphene also exhibits excellent optical property, which can be characterized by its photoconductivity. Under random phase approximation, the surface conductivity of graphene can be expressed by the Kubo equation [43–46]:

\[
\sigma_g = \sigma_{\text{intra}} + \sigma_{\text{inter}} = \frac{j \varepsilon^2 k_B T}{\omega + j/\tau} \ln \left[ \frac{2 \cosh \left( \frac{\mu_f}{2k_B T} \right)}{\cosh \left( \frac{\mu_f}{2k_B T} \right) + \cosh \left( \frac{\mu_f - \mu_e}{2k_B T} \right)} \right]
\]

\[
G(\xi) = \sinh \left( \frac{\xi}{k_B T} \right) / \left[ \cosh \left( \frac{E_F}{k_B T} \right) + \cosh \left( \frac{E_F + \mu_f}{2k_B T} \right) \right],
\]

Here, \( \hbar \) is the reduced Planck’s constant, \( e \) is the charge of an electron, \( k_B \) is the Boltzmann’s constant, \( \omega \) is the angular frequency, \( \mu_f \) is chemical potential, \( E_F \) is Fermi level, and \( T \) is temperature. In the visible and mid-infrared regions, the conductivity of graphene is governed by interband transitions (Figure 3(a)) [47], while in the far-infrared and THz regime, the conductivity of graphene is dominated by intraband transitions. In the THz regime, the contribution of interband transitions for conductivity is negligible. Thus, the conductivity of graphene can be approximated in the form of Drude-like model [48]:

\[
\sigma_g(\omega) = \frac{iE_F e^2}{\pi \hbar^2 (\omega + i\tau^{-1})}. \quad \text{(3)}
\]

The electrical conductivity is proportional to Fermi level and thus can be effectively modulated by tuning the Fermi level.

The first demonstration of graphene-based metadevices for terahertz applications was reported in 2011 where a tunable surface plasmon polariton (SPP) resonance was realized by patterning the graphene film [53]. The periodic pattern of graphene shifted the plasmonic frequency to the terahertz regime, which was modulated by external bias. Soon after this pioneering work, a more effective terahertz modulator was proposed [54] by integrating graphene with multilayer metamaterials. This combination provokes strong localized interactions between terahertz fields and graphene, resulting in a 47% amplitude modulation at the resonant frequency and 32.2° phase modulation. However, the range of phase change is poor due to the thin film of monolayer graphene, which severely limits their applications in dynamic wavefront manipulation. In 2015, Miao et al. adopted a new mechanism to achieve a wide range of phase modulation based on a MIM configuration as illustrated in Figure 3(b) [49]. The large range of phase change originates from coupled mode theory [55], and switching of operation between underdamped and overdamped regimes leads to a large shift of phase that could be achieved by tuning voltage applied on the thin-film graphene layer. Meanwhile, similar mechanism of coupled mode theory was applied in the work as illustrated in Figure 3(c) [50], and 2π phase modulation can be obtained by changing the resonance modes from underdamped to overdamped regimes at 1.1 THz by controlling the gate voltage. Effective polarization control was realized by integrating graphene layer with metamaterials. By tuning the gate voltage (0–1.8 V), the transmission amplitude of right-handed circular polarization (RCP) could be modulated by 99% at 1.1 THz with the left-handed circular polarization (LCP) component unchanged. The asymmetry modulation of RCP and LCP leads to a large contrast of circular dichroism (CD) of 45 dB at 1.1 THz.

In addition to the sole stimulus of electrical actuation on graphene, electro-optical hybrid modulation was recently explored to operate as an optical diode [51]. As shown in Figure 3(d), a typical Fano resonance was excited with the asymmetric resonators whose resonant features were modulated by the graphene film. An interesting asymmetric modulation of the mode occurs at a fixed optical pump intensity of 0.7 W cm⁻² by merely tuning the bias voltage. The modulation depth at -5 V is 5 times larger than that of +5 V. This observation is partially due to defects of graphene film, and majorly contributed by the injection of photocarriers into
graphene from silicon substrate due to the optical pump which results in the shift of Fermi level of graphene, suggesting that low-power continuous optical stimulus can also efficiently modulate graphene. Most recently, a reverse modulation of terahertz transmission was demonstrated [52] utilizing a highly-doped graphene/nanoslot antenna (G/NA) by optical pump. Strong absorption of terahertz radiation was realized which results in a complete blocking of the incident terahertz waves without pump (Figure 3(e)). When the G/NA device was illuminated by the optical pump, transmission window was open due to the photo-induced transparency of graphene, which leads to a distinctive modulation from absorption to transparency. This process occurred in an ultrafast time scale of 1.83 ps with a large modulation depth (80%). The strong confinement of localized electric fields by the nanoslot contributes to the large modulation depth, and the accompanied optical phonon emission leads to the rapid relaxation of photocarriers due to the fast hot-carrier cooling process.

We believe that graphene-based metadevices will play an important role in many fields, especially in terahertz applications, due to the unique properties such as unique linear dispersion, zero bandgap, exceptional carrier transport, etc. The recent interesting observation of band engineering with Moiré lattice would further push the development of multilayer graphene stacked at a magic angle [48, 56] that would benefit applications in terahertz band.

2.4. Active Metadevices Based on Micro-Electromechanical Systems. Micro-electromechanical systems (MEMS) are the basic component of the most advanced integrated system. In the past 20 years, MEMS technology has been widely applied in real life from radio frequency to microwaves, which has the advantages of low loss, low power, low cost, and high sensitivity. MEMS has been used for switches [57], phase shifters [58], tunable filters [59], modulators, and tunable antennas [59]. With a flexible electrical drive reconfigurability, MEMS provides a powerful platform to manipulate electromagnetic waves and enables adaptive and multifunctional responses. With the development of advanced fabrication techniques, applications of MEMS in the terahertz band have exhibited great potential in manipulating properties of light by combining it with metamaterials. One of the typical examples is the dynamic modulation of polarization states which are one of the most basic properties of electromagnetic waves, and extensive attention has been paid to manipulating polarization properties [60–62]. The representative work [63] combined the comb-drive actuators with metamaterials to achieve dynamic switching of anisotropy with a Maltese cross-shaped microstructure array. One arm of the cross-shaped microstructures can be driven by electrostatic force in horizontal direction leading to the switch of unit cells from the cross structure with a \( C_4 \) symmetry to an anisotropic T-shaped structure. The actuators applied in this work are scalable and could be extended to shorter wavelength.
Another commonly adopted MEMS technique is the bimorph cantilevers, which are composed of two materials with different Young’s modulus. The typical material combination of bimorph cantilevers is aluminum and aluminum oxide that can be handled by CMOS compatible processes. When the micromachining is completed, silicon oxide, as the sacrificial layer, is removed by hydrofluoric acid vapor, and the cantilevers will be released exhibiting natural deformation due to residual stress. The cantilever deformation can be controlled through electrostatic actuation, thereby completing the dynamic switching procedure. For the simplest metallic wire cantilevers, the maximum air gap (g) is obtained by estimating the curvature radius (r) of the wire:

$$\frac{1}{r} = \frac{6n(1 + n)(m\sigma_{Al} - \sigma_{d})}{t_{Al}E_{Al}[K + 3mn(1 + n^2)]},$$  \hspace{1cm} (4)$$

Here, $K = 1 + 4mn + 6mn^2 + 4mn^3 + mn^4$, $m = E_{Al}/E_{d}$, $n = t_{Al}/t_{d}$, and $t_{Al}$ and $t_{d}$ are the thickness of aluminum and aluminum oxide; $E_{Al}$ and $E_{d}$ are the Young’s modulus of the two materials; $\sigma_{Al}$ and $\sigma_{d}$ are the residual stresses of the two materials. The residual stress and Young’s modulus of materials at room temperature are determined by material properties and fabrication process, which can be approximately regarded as constants. Therefore, the radius of curvature obtained from equation 4 is adjusted by changing $t_{Al}$ and $t_{d}$. Once the radius of curvature is determined, g can be calculated by the equation $g = r(1 - \cos (l/r))$. Such a metallic cantilever supports basic dipole resonance, whose frequency is modulated by changing the effective length and air gap of the cantilever and thus adjusting the equivalent capacitance ($C_{eff}$) and equivalent inductance ($L_{eff}$).

Based on the bimorph cantilevers, lots of interesting applications have been reported by combining them with metamaterials. One of the typical applications is to achieve intrinsic chirality with spatial deformation [64] as shown in Figure 4(a). The handedness of spiral was switched by inflating N₂ gas in the upper or lower chamber to generate pressure difference. The height of the spiral center can reach 60 μm at ±10 Pa pressure difference resulting in a significant optical activity of ±28°. By arranging the unit cells in a C₄ symmetric configuration, birefringence was eliminated. Although such a pneumatic drive configuration works well with a large deformation, it is difficult to be integrated into miniaturized systems. A very simple L-shaped bimorph cantilevers were then proposed that could also provide a large chirality with electrostatic force actuation so that it could be easily integrated into a miniaturized system [65]. The residual stress provides a gradient force that drives the L-shaped structure to form a three-dimensional half-spiral with intrinsic chirality. Two L-shaped structures with opposite chirality were placed in one supercell, and the two neighboring structures were electrically isolated as shown in Figure 4(b). A programmable chirality switch with four different chiral states (achiral, dextrorotary, levorotatory, and racemic) could be realized through a weak electrostatic drive (10 V). The optical chirality as outputs follows the exclusive or
(XOR) logic gate with the binary drive as input signals. Such a configuration also enables giant programmable polarization rotation which provides a large amplitude modulation by combining with a polarizer. Therefore, the L-shaped chiral device could be designed as an intensity-modulated terahertz spatial light modulator for applications in single-pixel imaging.

Some interesting physical phenomena would emerge in the modulation process by combining MEMS with metamaterials. In 2017, Cong et al. [66] reported a dynamic metamaterial that can be switched between the underdamped and overdamped regions by an electrostatic drive through carefully engineering the radiative loss and nonradiative loss of the resonant system. As a result, the actuation of cantilevers can not only shift the resonance frequency from 0.74 THz to 1.34 THz but also change the phase span of the mode from a full $2\pi$ range (OFF state) to $\pi$ range (ON state) as shown in Figure 4(c). Meanwhile, toroidal responses could also be probed with the spatial deformation of MEMS cantilevers by utilizing four split-ring resonators (SRRs, Figure 4(d)) arranged in one supercell [67]. In the planar configuration, toroidal responses (head-to-tail magnetic dipoles) were enhanced by the neighboring opposite orien\-\tated SRRs, but the enhancement of the toroidal component is limited in such a planar configuration. When the SRRs were deformed with an out-of-plane configuration at different temperatures, the out-of-plane toroidal component was enhanced by nearly 5 orders of magnitude as the bending angle reached 90°, which leads to an order of magnitude enhancement of the total toroidal intensity. In addition to electrostatic and thermal actuation of cantilevers, mechanical strain deforming of the geometry would enable the topological change of resonators in the metamaterial and thus lead to modulation of resonance frequency, chirality, and polarization selectivity. For example, the nanotrench of resonators could be closed by bending the flexible metamaterial (Figure 4(e)) [68], which results in a complete electromagnetic extinction from the visible to microwave. A similar strategy was applied to a structure with four-fold symmetry, and when inner bending was applied in the vertical direction, symmetry was reduced to 2-fold once the two horizontal arms of the structure were shorted.

Currently, it is readily to fabricate MEMS cantilevers with resolution in hundreds to tens microns with conventional techniques, which could be applied in many terahertz applications. However, it might not work well in shorter wavelength when the size of unit cells scales down to nanometers. In addition, reliability would be a severe problem when the samples comprise of thousands of unit cells where they will have a nonuniform distribution with defects such as unreleased cantilevers in certain areas. More efforts still need to be paid for developing stable MEMS-based meta-devices.

2.5. Active Metadevices with Semiconductors. When light interacts with semiconductors with photon energy exceeding bandgap energy, electrons in the valence band will be excited to the conduction band, leaving holes in the valence band, thereby changing the conductivity. The photocarriers have a limited lifetime that is characterized by relaxation time. When the optical pump intensity is within a certain range, the concentration of free carriers is approximately proportional to the intensity, and conforms to the distribution of Drude model:

$$\sigma(\omega) = \varepsilon_0 \frac{\omega_p^2 \tau}{1 - i \omega \tau},$$

where the plasma frequency is expressed as $\omega_p^2 = ne^2/\varepsilon_m \varepsilon_0$, $\omega$ is the vacuum permittivity, $m$ is electronic quality, $n$ is carrier concentration, and $\tau$ is scattering time. As revealed by the model, the plasma frequency determines conductivity, and thus controls the intrinsic properties of semiconductors whose properties could be controlled by modulating the photocarrier concentration ($n$).

In the terahertz band, silicon (Si), germanium (Ge), and gallium arsenide (GaAs) are the most used semiconductors, and carrier concentration could be modulated via optical pumping or electric excitation. Integrating semiconductors with metamaterials would enable a powerful modulation capability for electromagnetic waves due to the multi-order enhancement of local field strength. The first demonstration was reported in 2006 by Padilla et al. [74] to achieve a low-threshold, high-contrast, all-optical terahertz modulator by tuning the conductivity of GaAs substrate of the metamaterial. An obvious modulation of transmission amplitude was observed from 15% to 50% with a pump fluence of 1 $\mu$J-cm$^{-2}$. In 2008, Chen et al. [75] proposed hybrid metamaterial resonators that were composed of metallic resonators and silicon islands. Compared to the direct modulation of the substrate, the hybrid metamaterials have larger freedom to design the unit cell and could be applied for a more complex modulation of electromagnetic waves including phase, polarization, and frequency. Based on the type of hybrid metamaterials, a plethora of promising applications have been reported, such as dynamic electromagnetically induced transparent [76, 77], three-dimensional intrinsic chiral switch [78], and polarization control [69, 79].

More attractive functionalities emerge by using the hybrid resonators to design metasurfaces. The example in Figure 5(a) shows an ultrafast terahertz polarizing beam splitter by arranging the hybrid resonators with a phase gradient so that the cross-polarized component was deflected and spatially deviated with the co-polarized component [69]. This all-optical modulation scheme enables a switching speed in the gigahertz scale which lays the foundation of polarization division multiplexing and demultiplexing for terahertz wireless communications. To further improve the modulation speed, low temperature grown GaAs was adopted as the active medium, and the resonance frequency of metamaterials was shifted by 280 GHz in a femtosecond scale at 2.08 THz (Figure 5(b)) [70]. A more complex configuration was proposed by integrating two types of photoactive semiconductors into metamaterials (Figure 5(c)). A polarization-dependent all-optical switch was realized which possesses two intrinsic switching times...
at orthogonal polarizations determined by the relaxation dynamics of the active media, i.e., silicon and germanium [71]. This scheme would be promising for multiplexing in signal processing of terahertz communications.

One of the obstacles in above mentioned hybrid metadevices is the inevitable ohmic loss from metallic resonators that limits operating efficiency. All-dielectric metamaterials based on Mie resonance could solve the problem without Ohmic loss channel. The overall size of dielectric resonators is larger than that of metallic counterparts, but richer resonance modes exist which could be exploited for a wider range of applications. Silicon is the most commonly used material for all-dielectric metamaterials in long wavelengths due to the relatively large refractive index, low absorption coefficient and mature processing technologies. In addition to the abundant functionalities enabled by dielectric metasurfaces, the strategy of all-optical modulation could be directly applied to the silicon resonators for dynamic responses. One typical example is shown in Figure 5(d) [72], where the silicon resonators were designed with frequency overlapped electric and magnetic dipoles for unidirectional radiation satisfying Kerker’s condition. On the other hand, from the aspect of coupled mode theory, the cavity was designed in the underdamped regime (under Kerker’s condition) that covers a $2\pi$ phase span around the resonant frequency in the passive state. An external pump will perturbate the balance between nonradiative and radiative losses of the cavity. Transition from underdamped to overdamped regime occurred by increasing the pump power which increases the density of photocarriers in the silicon resonators. Such a transition will shift the local radiation phase of resonators so that we could control the pretested phase gradient and switch the deflection angle. Using the aforementioned phase transition mechanism, an ultrafast (14 ps) reconfigurable beam steering of terahertz waves was demonstrated with the silicon metasurface pumped by femtosecond laser pulses. A similar approach could be applied for other interesting physics, such as bound states in the continuum (BIC) where the quality factors could be actively modulated (Figure 5(e)) [73] and ultrafast “photon brake” effect which leads to asynchronous mode separation and linear frequency change [80]. The active modulation of sharp resonances may find applications in lasing, biosensing, and mode multiplexing.

2.6. Applications in the THz Wavefront Modulation. The metadevices are mainly focused on synchronized modulation of all the unit cells in the entire metamaterial array, which induces a collective modulation of optical properties such as amplitude, phase, polarization, and/or resonant frequency. However, emerging applications of terahertz waves would require local modulation with spatial resolution, such as terahertz imaging and hyperspectral sensing, which could be realized by programmable metasurfaces. At microwave, programmable metasurfaces could usually be realized by integrating with lumped electronic components such as varactors as
control elements due to the relatively large size of unit cells. However, these bulky active components are difficult to be integrated with unit cells of a smaller scale operating in THz frequencies. Therefore, novel solutions should be searched for the development of terahertz programmable metasurfaces.

At present, graphene, MEMS, liquid crystals, and phase change materials could be employed for programmable metasurfaces in the terahertz regime together with drive units such as feed networks and field-programmable gate array (FPGA) as shown in Figures 6(a)–6(f).

Patterned graphene has exhibited great potential in the terahertz regime, and hybrid metasurfaces integrated with graphene were reported with independently addressable drive (Figure 6(a)) [81]. The local voltage could be adjusted by external bias that shifts the conductivity of graphene and thus changes the reflection response of the incident terahertz radiation. By precisely controlling the bias voltage, the reflection phase was dynamically switched between 0 and π that performs as the binary elements of programmable metasurfaces. By encoding each column of the array, beam steering, beam shaping and reconfigurable phase hologram were achieved. This work reveals broad prospects of programmable metasurfaces in the fields of Lidar, adaptive optics, and electro-optical modulators. MEMS-based metasurfaces could also provide a feasible solution for programmable metasurfaces [82]. By designing a MIM configuration of the MEMS metasurface, reflection spectra could be modulated by shifting the resonant frequency while tuning the effective angle of cantilevers. When the MIM metasurface operates in an underdamped regime, a full phase modulation covering 2π can be obtained by tuning the effective angle of cantilever from 0° to 2° which was controlled by external bias voltage as shown in Figure 6(b).

Based on the controllable local phase, programmable polarization control, wavefront deflection and hologram were envisioned.

Programmable control with electrical bias is straightforward with the mature large-scale fabrication and drive technique, but all-optical control with programmable operation could enable faster response and more flexible patterning approach. As shown in Figure 6(c), the conductivity of silicon could be modulated by a pump laser inducing plasmonic resonances, and by patterning the pump beam, a spatially resolved conductivity pattern on the silicon film could be projected from the pump beam. A recent report realized the idea by combining with a digital micromirror device (DMD) to pattern the pump beam, and the pattern was then projected to a thin film silicon (10 μm) wafer [83]. With such a flexible configuration, most metasurface applications could be realized in real time such as streaming holographic images and lenses of variable focal lengths.

Recently, complementary metal-oxide–semiconductor (CMOS) based chip tiles were integrated into conventional split ring resonators for individually addressable and digitally programmable metasurfaces (Figure 6(d)) [84]. C-shaped resonators were split with 8 gaps that were reconfigured by the integrated transistors so that transmission amplitude and phase were modulated according to the 8-bit encoding sequence in each resonator. The device was demonstrated with individually addressable and digitally programmable performance for 25 dB amplitude modulation and phase modulation covering 270°. Based on the proposed resonators, programmable metasurfaces were demonstrated with applications for dynamic beamforming covering angles of ±30°, and programmable holographic projections at 0.3 THz. This technology is very promising.
for terahertz sensing and imaging systems, and communications for multi-gigabits-per-second wireless links with GHz modulation speed.

As illustrated in Figure 6(e), metasurfaces integrated with liquid crystals could also be applied for programmable applications [85]. High quality factor Fano resonances were utilized to achieve a large phase variation while sustaining the transmittance, which dramatically expands the phase difference with an acceptable transmission intensity (≤6 dB). The maximum phase difference between the biased (10 V) and unbiased conditions (0 V) of the LC-metasurface is 178.9° at 0.408 THz with a nearly constant transmittance. Based on the LC-metasurface configuration, beam steering was experimentally demonstrated with a maximum angle of 30°.

In 2022, programmable metasurfaces was realized by integrating with phase change materials actuated by current pulses [86]. The work shown in Figure 6(f) presents a programmable memory metadevice based on vanadium dioxide (VO2) with 8 × 8 pixels operating as a terahertz spatial light modulator. The current pulse can efficiently trigger phase change of VO2, resulting in a remarkable change of conductivity which enables more than 65% amplitude modulation with a current bias <60 mA. The memory effect of VO2 (could hold for more than 5 hours) was also probed in writing and erasing data by the current pulses in the hybrid metasurfaces. The nonvolatile property of VO2 provides solutions of serial driving of pixels which significantly reduces the density of bias lines, especially benefiting large-scale metasurface array.

Recently, interesting band engineering of Moiré graphene stacked at a magic angle was observed to enable a flat band, which has an important role in superconductivity under a strong magnetic field [48, 56]. Soon, similar magic angle was applied in cascaded metasurfaces that have recently attracted a lot of attentions [87–89]. In fact, the multilayer metasurfaces have been investigated for various applications with extraordinary performance. For example a tri-layer metasurface was employed to rotate the polarization direction of THz waves to its orthogonal one in a broadband range [61]. In order to realize an arbitrary output polarization state, the similar tri-layer (cascaded) metasurface was adopted, and any direction of linear polarization state could be obtained by mechanically adjusted the rotation angle of each metasurface layer [90]. Recently, Cai et al. proposed a new mechanism for dynamical control of terahertz wavefronts without using local active metamaterials [87]. Cascaded metasurfaces were employed that have different rotational speeds with each other, which causes the relative phase variation over time. Wavefront and polarization of light were modulated dynamically in the rotating process (Figure 6(g)). Such a configuration is very interesting to manipulate light for dynamic and complex applications, and would push the development of the next-generation metadevices.

In the preceding sections, we have summarized some typical configurations of active metadevices that manipulate terahertz waves in free space for a complete control of wave properties such as amplitude, phase, frequency, polarization, and wavefront. Overall, we focused on different combinations of active materials and metasurfaces, and discussed the current developments, advantages and disadvantages in each combination from the aspect of applications. In order to expand the functionality and improve the performance of metasurfaces, exploring new physics is essential. Recently, topological insulators of electronics have attracted lots of attentions, and research of the photonics analog is rapidly developing. Photonic topological insulators are currently an emerging area which would benefit terahertz on-chip communications with high-efficiency and robust transmission. Although PTIs commonly focus on band engineering under the light line in a band diagram, the robust properties of topologically-protected edge states would find applications in free-space applications by leaking the mode [91], and guide the design of stable, high quality free-space modes [92, 93]. The active or reconfigurable strategies applied in metadevices as discussed in the preceding part could also be applied in PTIs for versatile applications. We envision that the topological photonics would find groundbreaking development in terahertz applications, both in free space and on chip, especially for the next-generation communications. Therefore, we would also provide some overview of the area of PTIs, and introduce the concept and milestones of development. Since most progress in PTIs was in optics, microwaves or acoustics, we will present the progress mostly in these areas, and finally summarize the recent works in terahertz regime. We also note that we define the term “metamaterial” as a more general concept that covers metasurfaces, metadevices and photonic crystals [94].

Next, we will focus on PTIs. Fundamentals of PTI will be briefly introduced, and more attentions will be paid on the photonic analogue of quantum valley Hall effect (QVHE). Representative works of topological photonic crystals (TPCs) based on quantum Hall effect (QHE), quantum spin Hall effect (QSHE), and QVHE will be discussed. From the aspect of applications, we will concentrate on QVHE due to the ease of fabrication and working without requirement of external stimuli. Finally, we will conclude with the current progress of PTIs in terahertz applications.

3. Topological Photonic Crystals

3.1. Fundamentals of Photonic Topological Insulators. Topology is a mathematic tool that mainly resolves the conserved and quantized quantities of substances known as topological invariants. For instance, a complex closed surface can be continuously deformed into a geometrically distinct but topologically equivalent form that is characterized by the number of holes (also called genus). Figure 7(a) illustrates the transformation process by assuming a closed surface deforming along with time whose geometric parameters change continuously while topological parameters change discretely. In addition to mathematics, topology plays a key role in condensed matter physics, phononics, mechanics, cold atomic gases, and photonics [95–98]. One of the most interesting properties lies at the topologically protected edge states in the interface between insulators with different topological invariants according to bulk-boundary corresponding theory [99]. As a physical consequence of the
nontrivial band topology, backscattering-immune edge states reside at interfaces between two topologically distinct media. By virtue of band structure theory [100–102], PTIs possess similar bulk band structures as traditional photonic crystals, but have one or more gapless edge states within the bandgap as illustrated in Figure 7(b). Based on whether time-reversal symmetry is broken, PTIs can be mainly classified into two categories: time-reversal symmetry broken PTIs (Figure 7(b)) and time-reversal symmetry invariant PTIs (Figures 7(c) and 7(d)). The preceding scenario is based on QHE [103] where the topological invariant is characterized by Chern number (also called TKNN invariant); and gapless chiral edge states exist in the interface of insulators with different Chern numbers. The latter one has a zero Chern number but involves a new degree of freedom, i.e., spin (valley), characterized by spin (valley) Chern number in analogy to QSHE [104] (QVHE). According to Kramer’s degeneracy theorem [105], electrons possess half-integer spin and all relative eigenstates of the system are at least doubly degenerate under time-reversal symmetry. In the interface of insulators with different spin Chern numbers, spin-up electrons experience different forces with the spin-down ones, and thus propagate in opposite directions as the band diagram shown in Figure 7(c). In contrast to fermions, photons are bosons without the benchmark of Kramer’s degeneracy theorem, and a “pseudospin” degree of freedom is introduced to mimic the spin of electrons. The QSHE can be described as $Z_2$ insulators, which have only two values, 0 or 1, corresponding to spin Chern number $C_{\text{spin}}$ [95, 106, 107], and analogous properties are realized by adopting circular polarizations of photons [108].

In addition to spin-polarized topological edge states in QSHE, there exists a similar binary degree of freedom resembling valley [109–112], which exhibits a degeneracy at $K$ point (Dirac point) in the momentum space. For 2D materials, a valley always arises in a highly symmetric lattice such as a hexagonal lattice of graphene ($C_6$ symmetry) as a result of the time-reversal symmetry ($T$) and space-inversion symmetry (or parity symmetry, $P$). QVHE requires $P$ broken without breaking $T$, which is characterized by Berry curvatures ($\Omega$). The Berry curvature of the $n$th band satisfies $\Omega_n(k) = -\Omega_n(-k)$ under $T$, and $\Omega_n(k) = \Omega_n(-k)$ under $P$ and thus the associated total Chern number is zero with both $T$ and $P$ symmetry conserving. Once breaking the degeneracy and opening a bandgap, the Berry curvature has a non-zero value at the valleys, and the topological invariant of QVHE system is measured by the valley Chern number ($C_{\text{valley}}$) instead of zero Chern number under $T$. There exist two edge modes with opposite propagation directions along the interface at different valleys ($K$ and $K'$, as shown in Figure 7(d)). The band diagram

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**Figure 7**: Schematic diagrams of topology, QHE, QSHE, and QVHE. (a) Continuous geometrical parameter changes and discrete topological parameter changes by deforming the surface over time. (b) Chiral edge states in the bandgap of QHE systems. (c) Helical edge states characterized by “spin up” and “spin down” in QSHE systems which propagate in the opposite directions. (d) Valley edge states by breaking inversion symmetry.
illustrates that a quantum valley Hall insulator exhibits a pair of edge states with opposite group velocities, i.e., opposite propagation directions, at the valleys.

An effective Hamiltonian provides a concrete numerical explanation of the QVHE taking advantage of \( \mathbf{k} \cdot \mathbf{p} \) method in the vicinity of \( K/K' \) valley [113, 114]

\[
H_{K/K'}(\delta \mathbf{k}) = \pm v_D \delta k_x \sigma_x + v_D \delta k_y \sigma_y + v_D \Delta_p \sigma_z,
\]

where \( v_D \) is group velocity, \( \delta \mathbf{k} = \mathbf{k} - \mathbf{k}_{K/K'} \) is displacement of wave vector \( \mathbf{k} \) to the \( K/K' \) valley indicated by \( \mathbf{k}_{K/K'} \) in the momentum space, \( \sigma_i (i = x, y, z) \) are Pauli matrices associated with orbital degree of freedom, and \( \Delta_p \) is the norm of the displacement of wavevector from \( K/K' \). The value of valley Chern number is analytically calculated from Berry curvature by means of the eigenfrequencies and eigenfunctions of the effective Hamiltonian (Eq. (6)). For instance, eigenvector near the \( K \) valley at the lower band is written as:

\[
u_n(k) = \frac{1}{\sqrt{1 + \left( \frac{\left( \Delta_p - \sqrt{\Delta_p^2 + \delta k_x^2 + \delta k_y^2} \right)^2}{\delta k_{\nu}^2 + \delta k_{\nu}'^2} \cdot \frac{\Delta_p - \sqrt{\Delta_p^2 + \delta k_x^2 + \delta k_y^2}}{\delta k_{\nu} + i \delta k_{\nu}'} }},
\]

with the eigenfrequency

\[
\delta \omega = -\sqrt{\Delta_p^2 + \delta k_x^2 + \delta k_y^2}.
\]

In terms of the conventional definition of the Berry connection, we have

\[
\mathbf{A} = i(u_n | \nabla_k | u_n) = \frac{1 + \left( \Delta_p / \sqrt{\Delta_p^2 + \delta k^2} \right)}{2 \delta k^2} (-\delta k_x \hat{x} + \delta k_y \hat{y}),
\]

and the Berry curvature is

\[
\Omega_k = \nabla \times \mathbf{A} = \frac{\Delta_p}{2 (\delta k^2 + \Delta_p^2)^{3/2}}.
\]

Similar method applies to the Berry curvature calculation at \( K' \) valley, and values of the Berry curvature at valleys are

\[
\Omega_{K/K'}(\delta \mathbf{k}) = \pm \frac{\Delta_p}{2 (\delta k^2 + \Delta_p^2)^{3/2}},
\]

where \( \delta k = |\delta \mathbf{k}| \) is the norm of the displacement of wavevector. From Eq. (11), valley Chern number is obtained by integrating the surface in the half of the first Brillouin zone as:

\[
C_{K/K'}^{K/K'} = \frac{1}{2 \pi} \int_{\text{BZ}} \Omega_{K/K'}(\delta \mathbf{k}) dS = \pm \frac{1}{2} \text{sgn} (\Delta_p),
\]

As indicated by Eq. (12), the valley Chern number has a magnitude of \( 1/2 \) and the sign is determined by \( \Delta_p \). Valley-polarized edge states (helical states) immune to perturbations are expected due to valley-momentum locking in the interface or domain wall between insulators of distinct \( C_{valley} \) [115, 116] with opposite sign.

3.2. Topological Photonic Crystals. One of the most effective ways to realize PTIs is utilizing photonic crystals. The simplest photonic crystal is a one-dimensional structure with periodic and alternating dielectrics of different refractive indices [117] as shown in Figure 8(a). By breaking the symmetry of a given periodic structure, some intriguing properties can be realized, for example, robust transmission against disorders [118, 119, 122–127]. Photonic topological phase based on QHE was originally realized using gyromagnetic photonic crystals subject to external magnetic field to break the time-reversal symmetry as shown in Figure 8(b) [118]. A unidirectional edge state immune to disorders and defects was experimentally observed. However, the strategy is difficult to be extended to shorter wavelength due to the lack of ferromagnets at higher frequencies. As an alternative, QSHE without breaking time-reversal symmetry was adopted by introducing "pseudospin", for example, in the rhombohedral shape unit cells [119] (Figure 8(c)). The pseudospin was achieved by expanding and shrinking the superlattices to lift the degeneracy of four-fold Dirac point at \( \Gamma \) point. By shrinking the unit cells in the lattice, eigenmodes at the lower band and upper band behave as dipole and quadrupole modes, respectively; and they flip when expanding the unit cells where nontrivial topological invariant appears. PTIs based on QSHE have a rapid development due to the easy execution of inversion-symmetry breaking without requirement of external magnetic fields [128]. Extending the application of PTIs from 2D to 3D, the first 3D PTI was reported supporting topologically protected surface states (Figure 8(d)) [129]. The 3D Dirac point was lifted, and a bandgap emerged via breaking the mirror symmetry in \( z \) direction. In 3D momentum space, a Weyl point exists when two bands cross linearly with each other which commonly requires breaking certain symmetry. Inversion symmetry broken is usually applied in non-centrosymmetric Weyl systems, and time-reversal symmetry broken also works. It has been reported that magnetized semiconductor InSb behaves as a magnetized plasma for terahertz waves, and Weyl points and corresponding photonic Fermi arcs were observed [121] (Figure 8(e)). This scheme may enable the topological exotic effects and initiates the demonstration of topological phases in the terahertz band facilitating the terahertz topological devices.

According to bulk-edge correspondence, the \( n \)-dimensional topological insulators can support \((n-1)\)-dimensional
topological states; and for higher-order topological insulators (HOTI), they may support lower-dimensional topological states. For example, a 2D topological insulator would host 1D gapless edge states and 0D corner states. The relevant literatures of HOTI are summarized [129–135]. In contrast to artificial defects in conventional photonic crystals to confine electromagnetic waves, corner states with high quality factor exist spontaneously in corner positions. Both edge states and corner states exist that would lead to applications of compact and robust cavities and waveguides. These intriguing topological phenomena in TPCs are readily scaled to THz band for defect and perturbation immune applications which is one of the most promising candidates to manufacture THz devices. We will discuss related content in section 3.4.

3.3. Valley Hall Topological Photonic Crystals and Applications. Currently, the most developed approach for PTI is based on QVHE. Typical PTIs based on QVHE could be executed with valley photonic crystals (VPCs) with time-reversal symmetry conserved, which could be easily fabricated with conventional lithography for a wide range of applications from waveguides, beam splitters to topological lasers [123, 138]. The typical approach to access nontrivial valley Chern number is breaking inversion symmetry. One example is the tripod-shaped metallic rods suspended between a parallel-plate waveguide in a triangular lattice as shown in Figure 9(a) [122]. This work proposed polarization multiplexing by opening the same bandgap for both TE and TM polarizations and demonstrated topological-protected perfect output coupling behavior for application of directional antennas. After this work, different methods were soon proposed, for example, by replacing the metallic rods with fan-shaped structures (Figure 9(b)) [123]. Via tuning the length of fun arms, inversion symmetry of the metallic structure is broken, and two types of unit cells are defined as pattern A and B. With opposite valley Chern numbers at $K/K'$, gapless edge states appear by forming boundary between the two patterns where opposite propagation directions were supported for AB-type and BA-type interfaces. Another example to access nontrivial valley Chern number is shown in Figure 9(c), where inversion symmetry is broken by tuning the height of metallic rods in a honeycomb lattice [126]. Robustness of the edge states was demonstrated by bending the domain wall with two sharp angles and the transmission was not obviously affected by the sharp angles compared with that of a straight waveguide.

The VPCs discussed above are based on metallic materials suffering from significant Ohmic absorption loss. A better performance would be obtained with dielectric materials with negligible Ohmic loss. An example of valley PTI with dielectric cylinders [136] is shown in Figure 9(d) whose symmetry was broken by introducing refractive indexing contrast between the neighboring cylinders, and thus bandgap opened. Different types of domain walls denoted as armchair type and zig-zag type were discussed for different transport performance. Detailed quantitative study on robustness of various types of domain walls was reported in ref (139). A honeycomb lattice with two air holes of different radii in the silicon slab also supports valley edge states (Figure 9(e)) [137]. Three types of interfaces were designed to show the robustness of the edge states.

In traditional waveguides, light is usually scattered or coupled to adjacent components when propagating through
sharp bends with serious scattering and reflection losses in an integrated photonic circuit, PTIs could solve this problem with topologically protected edge state [136, 142–144]. In recent years, PTIs based on QVHE have shown great potentials in designing optical components such as channel intersections [145, 146], topological lasers [147] and communication chips [137, 148, 149], taking advantage of the intriguing properties such as valley-locked transport [118, 150, 151], robustness against perturbations [115, 118, 148, 152–154], and corner states with high quality factors [131]. In 2017, Wu et al. elucidated a concrete method to realize a beam splitter in microwave region (Figure 10(a)) [123], which consists of four domain walls with two distinct patterns. According to the valley-locked transport properties, the transport channel selectively depends on the input ports. In 2020, a novel topological acoustic waveguide was reported with a larger transport area instead of a narrow interface [145], where the middle layer with a Dirac point was sandwiched by two inversion-symmetry-broken layers with opposite valley Chern numbers. The analogous structure was extended into valley Hall PTIs, which could improve energy capacity in the domain improves with a larger number of $x$. The strategy could be applied in designing a beam splitter, light harvesting devices, and topological cavities.

A more complex frequency-selective router could be realized by VPC with more than one bandgap. In preceding works, only one Dirac point was realized, and thus only one pair of valley edge states exist in the single bandgap. By designing two bandgaps, two pair of edge states appear. Dual-bandgap valley topological phononic insulators were recently reported with frequencies at approximately $f$ and $2f$ based on nano-electromechanical metamaterials [141] as shown in Figure 10(c). The structure consists of some etching holes located at the vertices of a regular triangle, and inversion symmetry was broken by changing the distance to the triangular cores. The dual-band valley Hall PTI was applied as a router with dual-band transmission [138] where selective routing path dependent on both operating frequency and input port was observed. The dual-band valley Hall PTIs may lead to further development of multiband integrated photonic circuits with logical operation.

3.4. Progress of VPC for Terahertz Applications. VPCs in the terahertz band have recently attracted many attentions with potential applications in on-chip communications [158–162]. Terahertz waves would offer a considerable
broad bandwidth for a higher data rate of wireless communications at a rate of terabits per second [163] and THz links for high-speed, energy-efficient and low-cost inter-chip communications are essential. However, traditional hollow metallic waveguides [164], photonic crystal waveguides [165], metallic transmission lines [158], THz fibers [166] and metallic wires [167] would commonly exert a nonnegligible impact on transmission due to bending losses at a sharp corner and scattering losses of fabrication imperfection. VPCs would provide a simple and promising route to address these problems.

In 2020, the first VPC waveguide for terahertz on-chip communications was reported [149]. Inversion symmetry of unit cells was broken to introduce nontrivial valley Chern number which was fabricated with high-resistivity silicon, as shown in Figure 11(a). A negligible loss of THz waves was observed in transmission spectra even with multiple sharply bended domain walls. Based on the high transmission efficiency and large bandwidth, a high-quality real-time uncompressed 4K HD video transmission test was performed through the VPC waveguide. Recently, electrically pumped topological THz laser [91] was also experimentally realized based on the active VPCs [168, 169]. As shown in Figure 11(b), a closed triangular loop was designed where THz waves could propagate immune to the existence of shape corners and defects. The bandwidth of gain medium overlaps with the photonic bandgap, and terahertz waves could be tightly confined in the closed loop with large quality factors, and THz lasing occurs at sufficient large pumping currents. Unlike the conventional QCLs, topological lasers with valley edge modes circumvent the impact of spatial hole-burning effect.

The field confinement is an important feature of waveguides, and the properties of VPC were studied in detail in the terahertz band with a honeycomb lattice [155]. In the work shown in Figure 11(c), symmetry was broken by adjusting the diameters \( d_1 \) and \( d_2 \) of the neighboring two holes in one unit cell. It is found that the degree of asymmetry (difference between \( d_1 \) and \( d_2 \)) determines the strength of field confinement of the topological edge modes and the robustness of topological protection. This is in essence originated from the larger bulk bandgaps with a larger lattice asymmetry. Apart from the THz waveguides and lasers, tunable terahertz topological edge and corner states in designer surface plasmon crystals were also reported recently (Figure 11(d)) [156]. In the type of Su-Schrieffer-Heeger lattice, symmetry is broken by modulating the intra-cell coupling strength \( (d_1) \) and inter-cell coupling strength \( (d_2) \). In addition to the in-plane confinement of topological edge states, the designer surface plasmons also enable vertical confinement. From the aspect of fabrication for VPCs, 3D printing was adopted to fabricate metallic THz topological waveguide (Figure 11(e)) [157] which exhibited a larger bandgap (12.5%).
4. Conclusion and Outlook

This review article has summarized the current development of active metadevices and photonic topological insulators in the terahertz regime. For the active THz metadevices, high efficiency, high modulation speed, low power consumption and high integration are the eternal goals. Therefore, many excellent studies have been focused on improving one or more parameters to meet the goals by exploring different active mechanisms and interesting physics of metasurfaces. As a result, active THz metadevices have significantly expanded the ability to control EM waves, and provided a promising platform for different applications, such as switchable filters, polarization controllers, beam steering devices, and tunable metalenses.

Although we have witnessed great achievements in THz active metadevices, several grand challenges still exist in this field. Looking for the most suitable active materials for various specific applications is the toughest challenge in exploring active metadevices with better performance. As discussed in this review, we briefly summarize the shortage of each active medium again. The large thickness of LCs decreases the performance and overall usability of devices while it increases the size of the meta-atoms and thus the actuation voltage. Patterned graphene is an excellent material for THz applications, but the monolayer thin film limits the strength of light-matter interactions. Certain PCMs provide a nonvolatile platform for reconfigurable metadevices, however, high temperature is commonly required for phase transition and loss would be a severe problem after the phase transition. MEMS are limited by the modulation speed of mechanical cantilevers, which is usually slower than other methods. Semiconductors would be an outstanding candidate for active metadevices if they could be integrated with CMOS-compatible fabrication, and more materials and physics should be explored for integrated metadevices to accelerate the relaxation of carrier dynamics for a higher modulation speed. With the development of the next-generation communications, more complex reconfigurable EM metasystems would be indispensable for future daily

**Figure 11**: Progress of VPCs for terahertz applications. (a) Sample of terahertz VPC for on-chip communications with experimental setup for 4K video transmission tests [149]. (b) THz topological laser and the relevant emission spectra [91]. (c) Unidirectional transmission with different types of VPCs [155]. (d) THz designer surface plasmon crystal with a square lattice of metallic pillars standing on a metal surface. \( E_z \) component of the bulk states (in black dots), edge states (in blue dots), and corner states (in red dots) are shown [156]. (e) 3D-printed terahertz topological waveguides [157].

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applications. Therefore, it is expected that new mechanisms of metasurfaces should be established to manipulate EM waves with better performance such as decoupling between phase and amplitude for independent control of the two properties and high-gain free-space wave propagation by exploring the topological properties of metasurfaces.

Topological phenomena comply with robustness regardless of disturbances, but also rely on rigid adherence to established conditions, where the current challenge is the lack of active topological devices to realize parameter-tunable topological phenomena. In terahertz communications, ultrafast amplitude/phase modulators and multiplexers should be developed. This might be realized by combining the active mechanism with the terahertz topological waveguides to design ultrafast reconfigurable routers. The study of active metadevices might provide some guidance. Based on the active topological metadevices, tunable topological THz lasers would significantly push the development of terahertz sources. With high order topological insulators, promising applications would emerge by engineering the local field hot spots for strong light-matter interactions. With the rapid development of compact terahertz sources and efficient modulators, it is envisioned that terahertz technology would revolutionize our daily lifestyle soon.

Data Availability

The data are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no competing interests.

Authors’ Contributions

L.C. initiated the idea of the review and supervised the project. H. X. prepared the part of photonic topological insulators, and J. F. prepared the part of active metadevices. L.C., J. F., H. X., and D. L. discussed and wrote the manuscript with inputs from Z. G. and P. S. All authors read and commented on the manuscript. Hongyang Xing and Junxing Fan contributed equally to this work.

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