Metasurfaces are ultrathin metamaterials consisting of planar electromagnetic (EM) microstructures (e.g., meta-atoms) with pre-determined EM responses arranged in specific sequences. Based on careful structural designs on both meta-atoms and global sequences, one can realize homogeneous and inhomogeneous metasurfaces that can possess exceptional capabilities to manipulate EM waves, serving as ideal candidates to realize ultracompact and highly efficient EM devices for next-generation integration-optics applications. In this paper, we present an overview on the development of metasurfaces, including both homogeneous and inhomogeneous ones, focusing particularly on their working principles, the fascinating wave-manipulation effects achieved both statically and dynamically, and the representative applications so far realized. Finally, we also present our own perspectives on possible future directions of this fast-developing research field in the conclusion.© 2019 Optical Society of America

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1. INTRODUCTION

Manipulating electromagnetic (EM) waves in the desired manners is one of the most important tasks in photonics research, as photons are believed to be alternative information carriers that may play crucial roles in the next-generation industry revolution. According to Maxwell’s equations, permittivity and permeability of a medium dictate the behavior of EM waves propagating inside it. However, naturally existing materials exhibit only limited abilities to control EM waves, since their permittivities lie in a narrow variation range, and, even worse, their permeability is all very close to 1 at high frequencies (e.g., the visible range), due ultimately to the weak interactions between natural molecules/atoms and the magnetic fields of EM waves. As a result, conventional EM devices typically need to be thick enough (compared to the operation wavelength) and exhibit certain curved shapes to ensure appropriate propagation phases accumulate to realize the desired wave-manipulation functionalities (say, focusing). In addition, efficiencies of conventional devices can also be an issue caused by impedance mismatch between air and natural materials that typically do not exhibit magnetic responses. Such limitations (i.e., size, shape, and efficiency) significantly hinder the applications of conventional optical devices in next-generation on-chip photonics scenarios, which are typically flat, ultracompact, and energy saving.

Metamaterials, artificial composite materials made by subwavelength microstructures (e.g., meta-atoms) with tailored EM properties can in principle possess arbitrary values of permittivity $\varepsilon$ and permeability $\mu$, and therefore provide a promising platform to solve the issues mentioned above [1–4]. The much expanded parameter ranges offer metamaterials significantly improved capabilities to control EM waves in different frequency regimes, leading to many fascinating new physics and wave-manipulation effects being proposed and demonstrated, such as optical magnetism, negative refraction, super lensing, and even invisibility cloaking [5–7] and optical illusion [8]. However, despite great successes, metamaterial-based EM devices are still bulky in size since they rely on the propagation phases of light accumulated inside the devices. More seriously, they suffer from grand challenges in efficiency and fabrication, since they are typically constructed by metallic/plasmonic microstructures with complex geometries, which are lossy and difficult to make, particularly in mass production [9].

Metasurfaces are two-dimensional (2D) versions of metamaterials constructed by identical or distinct planar meta-atoms with predetermined EM responses arranged in some specific global orders. They offer a much better platform to overcome the issues faced by natural materials and bulk metamaterials [10]. In contrast to metamaterial-based EM devices relying critically on the propagation phases of EM waves, metasurfaces fully exploit the abrupt phase changes of EM waves at meta-atom interfaces, so they can be much thinner than the working wavelength. Meanwhile, since EM waves do not typically stay inside metallic structures for a long time, the loss issue can be significantly alleviated in metasurface-based devices. Also, the flat configuration makes such systems easy to fabricate. Most importantly, by tailoring the “order” on which the meta-atoms are arranged, one can realize metasurfaces that exhibit desired inhomogeneous distributions of amplitude and phase for transmitted/reflected EM waves, enabling diversified fascinating wave-manipulation effects far
beyond those realized with metamaterial-based devices [11–13]. These unique features make metasurfaces ideal candidates to realize flat and miniaturized metadevices that exhibit powerful wave-manipulation capabilities, being particularly suitable for on-chip photonic applications.

In this paper, we present an overview on metasurfaces, focusing particularly on the working principles, practical realizations, and potential applications of such ultrathin EM systems. This paper contains the following five sections. In Section 2, we review the available mechanisms to use homogeneous metasurfaces, constructed by identical sub-wavelength-size planar meta-atoms arranged periodically, to manipulate the key characteristics of EM waves, including phases, amplitudes, and polarizations, both statically and actively. Understanding these mechanisms not only helps us construct homogeneous metasurfaces to achieve certain immediate applications (conducting electrodes, perfect light absorbers, polarization-control devices, etc.), but more importantly, provides a solid basis for further studies on inhomogeneous metasurfaces that require meta-atoms with particular EM properties. Equipped with this basic knowledge, we next review in Section 3 the working principles and practical realizations of inhomogeneous metasurfaces constructed with plasmonic or dielectric materials for controlling EM waves with different polarizations. In particular, we highlight a very unique role played by gradient metasurfaces, which is the bridge to link propagating waves and surface waves efficiently, as well the latest exciting theoretical developments on new mechanisms to achieve extreme-condition anomalous EM wave bending. With these mechanisms understood, we then summarize in Section 4 several representative applications of inhomogeneous metasurfaces, including metalenses, metaholograms, metasurface-based cloaking, special beam generation, multifunctional metasurfaces, and tunable/active inhomogeneous metasurfaces. Finally, Section 5 concludes this review, followed by our own perspectives on future directions of this fast-developing research field.

2. HOMOGENEOUS METASURFACES: ROLE OF META-ATOMS

We start from studying metasurfaces constructed by identical meta-atoms arranged periodically in a 2D plane. In many cases, the lattice constants of these ultrathin structures are much less than wavelengths of interest, and thus one can consider these systems homogeneous metasurfaces with EM properties determined by constitutional meta-atoms. Early efforts along this direction are mainly devoted to using homogeneous metasurfaces to control the key characteristics of EM waves, such as phases, amplitudes, and polarizations. To achieve these goals, apparently one needs to first understand how different meta-atoms interact with EM waves, based on which one can choose appropriate meta-atoms to design metasurfaces to realize the desired wave-manipulation functionalities. In this section, we briefly summarize available mechanisms to control phases, amplitudes, and polarizations of EM waves, both statically and dynamically, based on homogeneous metasurfaces.

2.1. Phase Modulation

Dramatic phase changes are induced when EM waves excite certain resonances. These resonances can be classified as electric and magnetic ones, depending on the dipole moments possessed by the structures. On the other hand, systems exhibiting these resonances can be constructed with metallic/plasmonic or dielectric materials. Here, we summarize the features of these resonances and the typical structures supporting them.

2.1a. Electric Resonances

The simplest structure supporting an electric resonance is a metallic bar, as depicted in Fig. 1(a). When an EM wave hits the bar with polarization along its long axis, electric...
current will be driven to flow along the bar, oscillating back and forth at the driven frequency, giving rise to an inductance \((L)\). Meanwhile, because of the finite length of the bar, electric charges can be accumulated at two ends of the bar, with magnitudes oscillating with the driven field thus contributing to a capacitance \((C)\). The co-existence of \(L\) and \(C\) dictates that the structure must resonate at a frequency \(\omega_c \sim 1/\sqrt{LC}\). A careful examination of charge/current distribution reveals that the structure supports an electric dipole moment at resonance. As two typical features of a Lorentz-type resonance, the scattered electric field reaches a maximum as frequency hits \(\omega_c\), and its phase undergoes a variation of \(\pi\) as frequency passes through \(\omega_c\) [Fig. 1(a)]. In principle, \(\omega_c\) of different structures can be accurately computed by solving the charge/current distributions self-consistently [15], but one can alternatively use an empirical formula to estimate it, that is, the resonance wavelength is roughly twice of the total length of the bar. The accuracies of such an empirical formula are better for metallic thin wires at low frequencies, but get worse at optical frequencies, particularly when approaching the plasmon resonance of metals. We note

Figure 1

Phase manipulations with metasurfaces. (a) Metallic electric resonance. Top panel: schematic of a free-standing gold nanorod illuminated by impinging light. Middle panel: simulated electric field distributions around the nanorod at electric resonance frequency. Bottom panel: simulated reflection (red solid line)/transmission (red dashed line) amplitudes and reflection phase (black solid line) spectra of the gold nanorod array. (b) Metallic magnetic resonance. Top panel: schematic of one MIM-type meta-atom consisting of a gold nanopatch and a continuous gold thin film (yellow) separated by the MgF\(_2\) spacer (blue). Middle panel: simulated electric current induced inside the MIM meta-atom illuminated by the input light at magnetic resonance frequency. Bottom panel: simulated reflection (red solid line)/transmission (red dash line) amplitudes and reflection phase (black solid line) spectra of the MIM meta-atom array. (c) Dielectric electromagnetic resonances. Top panel: schematic of a silicon (Si) nanosphere resonator. Bottom panel: scattering efficiency versus dielectric permittivity \(\varepsilon\) (lossless particle) for plasmonic (\(\varepsilon < 0\)) and dielectric (\(\varepsilon > 0\)) materials. Middle panel: simulated electric field distributions of the electric dipole (ed) and magnetic dipole (md) resonances of the Si nanosphere resonator [14]. (c) From Kuznetsov et al., Science 354, aag2472 (2016) [14]. Reprinted with permission from AAAS.
that the phase tuning enabled by such a single-mode electric resonator is limited by $\pi$, which is also tightly connected with amplitude modulation [see Fig. 1(a)]. These restrictions can be released through designing multimode resonators, as introduced with more detail in the following subsections.

2.1b. Magnetic Resonance

Quite a few different structures can support magnetic resonance. In fact, optical magnetism is an important topic in early years of metamaterials research and plays an important role in achieving negative refraction [16]. For example, a split ring resonator (SRR) [2], a topological variant of a metallic straight wire, exhibits a magnetic resonance contributed by the currents flowing along the ring. The EM response of a SRR is similar to that of a metallic bar, only with the electric field changed to a magnetic one. As a result, phase modulation enabled by an SRR possesses the same restrictions as an electric resonator. An alternative structure supporting magnetic resonance is the metal–insulator–metal (MIM) structure [17] consisting of a planar metallic microstructure (say, a metallic bar) and a continuous metal film separated by a thin dielectric spacer [see Fig. 1(b)]. As the MIM structure is illuminated by an EM wave, antiparallel electric currents can be induced on two metallic layers due to the coupling between them, which forms a magnetic mode with a strongly enhanced magnetic field inside the spacer layer. The resonance wavelength is roughly 4 times the bar length, since now the path on which current flows is doubled as compared to that of an electric resonator [see Fig. 1(b)]. Different from a single-mode electric or magnetic resonator, the MIM structure can modulate the phase over a full $2\pi$ range, which inherent physics explained below. When the frequency of the incident wave is far away from the magnetic resonance frequency $\omega_m$, the resonant response dies off, and thus the EM wave is directly reflected back by the metallic ground plane. As a result, the reflection phase is $\pm \pi$. However, when the incident-wave frequency approaches $\omega_m$, the magnetic resonance is strongly excited, making the whole MIM structure behave like a perfect magnetic conductor (PMC) and exhibiting a divergent effective permeability. The EM wave is thus reflected by the PMC with a reflection phase of 0. Therefore, as the frequency passes through $\omega_m$, the reflection phase of the whole structure changes continuously from $-\pi$ to 0 and then to $\pi$, covering the full range of $2\pi$[see Fig. 1(b)]. In fact, no matter how complex the top metallic microstructure is, such MIM structures can always be modeled by a double-layer system consisting of a homogeneous magnetic material put on top of a metal plane [18]. Such a theoretical model can well describe all EM properties of the MIM structure. At optical frequencies, such a magnetic resonance is also called gap surface plasmon (GSP) resonance, as proposed in Ref. [19], since it can be viewed as a cavity mode of a GSP. In addition to the full-range phase modulation capability, MIM structures also de-link the modulations on phase and amplitude, which is another advantage compared to common electric and magnetic resonators. Most importantly, the metallic ground plane can ensure total reflection of EM waves (neglecting material losses), indicating that the reflection amplitude is always 100% independent of the phase variation. At high frequencies where metallic losses are inevitable, reflection amplitude is reduced from 100%, particularly at the resonance frequency. However, one can still use MIM structures to realize phase-modulation-related applications efficiently, through carefully designing the scattering and absorption quality factors of the MIM structure, as discussed in Subsection 2.3.

2.1c. Dielectric Resonance

The resonators discussed in the previous two subsections are all constructed by metals, inside which electric currents oscillate with frequency and resonate at certain frequencies. However, while metals behave as perfect electric conductors (PECs) at low
frequencies, ohmic losses inevitably exist in metals at high frequencies, which can significantly degrade the performances of such resonators. Alternatively, one can use high-index dielectric materials to construct EM resonators to overcome the loss issues [20]. Moreover, since dielectrics are naturally more compatible with current complementary metal-oxide semiconductor (CMOS) technologies, dielectric-resonance-based optical devices exhibit further advantages in applications compared to their metallic counterparts. We choose a spherical nanoparticle (with permittivity $\varepsilon$) as an example to explain the working mechanism of dielectric resonances. According to Mie theory [21,22], we understand that a particle with a given diameter can exhibit a series of EM resonances at certain frequencies for certain values of $\varepsilon$, evidenced by strongly enhanced scatterings. Such resonances can happen not only for negative values of $\varepsilon$ corresponding to plasmonic resonances, but also for positive values of $\varepsilon$, which are the dielectric resonances that we are discussing. Different from plasmonic resonances where conducting currents are strongly enhanced, dielectric materials do not have free electrons to support conducting currents. Instead, incident electric fields can penetrate inside the dielectric medium to induce strong displacement currents, which play similar roles as their conducting counterparts and can resonant under certain conditions. Analyzing the distributions of displacement currents shows that both electric and magnetic modes exist in a single particle, but under different conditions [14]. As shown in Fig. 1(c), the magnetic dipole response results from the circular displacement currents of the electric field, while the wavelength inside the particle is comparable to the diameter of the particle. Also, the electric dipole response is formed by the straight electric displacement current flowing along the diameter direction appearing at higher frequency. Moreover, high-order resonance modes, e.g., magnetic and electric quadrupoles, are also supported by dielectric nanoparticles at high frequency domains. In principle, such dielectric resonances exhibit similar wave-manipulation properties as their metallic counterparts in terms of both phase and amplitude modulations, but with significantly reduced losses. However, compared to metallic resonators, dielectric ones have larger sizes (even comparable to wavelength, depending on the refraction index) in order to achieve the desired optical manipulations.

2.2. Amplitude Modulation

We now introduce available mechanisms to control the amplitudes of EM waves using homogeneous metasurfaces, at both the transmission and reflection sides.

2.2a. Enhanced Optical Transmission

Making optically opaque media transparent is always fascinating. Understanding such mechanisms can greatly facilitate designing metasurfaces to manipulate EM waves at the transmission side. Meanwhile, such effects can find many applications in practice. For example, transparent conducting metals with both high optical transmittance and high conductivity are highly desired in optoelectronics. However, while metals exhibit good static conductivities, they exhibit negative permittivity at frequencies below plasmon resonance frequency and can strongly reflect EM waves. In 1998, Martín-Moreno et al. reported, rather surprisingly, that an optically thick metal film drilled with a periodic array of subwavelength air holes can allow extraordinary optical transmission (EOT), which is orders of magnitude larger than that predicted by standard aperture theory [see Fig. 2(a)] [23]. Such an unusual effect was tightly associated with the excitation of surface plasmon polaritons (SPPs) on the metal surfaces, aided by Bragg scattering enabled by the air-hole array. Here, SPPs denote EM eigenmodes bounded at dielectric/metal surfaces associated with collective oscillations of free electrons, and can be excited when the following momentum matching condition is satisfied: $k_{\text{SPP}} = k_0 \sin \theta_i + mG_x + nG_y$, ($k_0$ is the wavevector in vacuum; $G_x, G_y$ are
the reciprocal wavevectors provided by the periodicity) [27,28]. To understand the microscopic origin of EOT, Liu and Lalanne proposed a SPP coupled-mode model considering all crucial processes, such as the excitation, propagation, and interference of SPP modes [29]. The model can well describe all important features of EOT. However, strictly speaking, such an effect happens only in large systems containing

**Figure 2**

Enhanced optical transmission (EOT). (a) Top panel: schematic of the surface-plasmon-polariton-aided EOT effect through a structural metal. Middle: sample picture of an optically thick metal film perforated with a periodic array of subwavelength apertures. Bottom panel: zero-order transmission of 200 nm thick Ag film (periodicity of air holes, 900 nm; hole diameter, 150 nm) at normal incidence [23]. (b) Top panel: schematic of the localized plasmonic-resonance-aided EOT effect. Middle panel: part of the sample picture of the random arrays of holes. Bottom panel: normalized transmission amplitude of the sample at normal incidence [24]. (c) Top panel: schematic of the scattering-cancellation-induced EOT effect through a homogeneous B layer (yellow, \(\varepsilon < 0\)) sandwiched by two other homogeneous A layers (dark, \(\varepsilon > 0\)). Middle panel: normalized magnetic field distribution inside the ABA structure at the high transmission frequency obtained by effective-medium level calculation. Bottom panel: measured (circles) and calculated (lines) transmission spectra of a practical ABA sample. Following the spirit of metamaterials, subwavelength metallic mesh structures and H-shaped resonators (inset) are adopted to realize, respectively, the desired B layer with negative \(\varepsilon\) and A layers with positive \(\varepsilon\) at the working frequencies [25]. (d) Top and middle panels: interference model and practical design of the metamaterial antireflection coating. Middle panel: experimentally measured reflectance and transmittance spectra for the normal incidence case. The solid and dashed lines represent the reflectance and transmittance of a bare GaAs surface [26]. (a) Figure 1 reprinted with permission from Martín-Moreno et al., Phys. Rev. Lett. 86, 1114–1117 (2001) [23]. Copyright 2001 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.86.1114. (b) Figure 1 reprinted with permission from Lee et al., Phys. Rev. Lett. 99, 137401 (2007) [24]. Copyright 2007 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.137401. (c) Figures 2 and 3 reprinted with permission from Zhou et al., Phys. Rev. Lett. 94, 243905 (2005) [25]. Copyright 2005 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.94.243905. (d) Figures 1 and 4 reprinted with permission from Chen et al., Phys. Rev. Lett. 105, 073901 (2010) [26]. Copyright 2010 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.105.073901.
enough number of apertures, since Bragg scatterings play very important roles. This restriction makes the mechanism difficult to use directly in metasurface design.

Later, scientists discovered that EOT can also happen in metallic films drilled with complex-shape apertures, where localized plasmonic resonance (or termed “shape resonance” and “waveguide cutoff modes” in different literature) supported by these apertures play more important roles than the global Bragg scattering [see Fig. 2(b)]. For example, in 2013 Wen et al. experimentally demonstrated that a metallic plate drilled with fractal-shape apertures exhibits multiple high-transmission bands in the infrared (IR) regime, contributed by the self-similar multiple shape resonances supported by such apertures [30]. Such localized resonances exhibit deep-subwavelength and multiband responses, making them particularly suitable for meta-atom designs [31,32]. Later, Huang et al. further utilized the deep-subwavelength responses of such fractal apertures to realize a metadevice that can achieve subwavelength imaging, thanks to the local-resonance-enabled EOT effect [33,34]. Apparently, similar high transmission can also be achieved through apertures with other shapes [35–38]. In addition to these mechanisms, enhanced transmission can also be induced by the Fabry–Perot (FP) resonance of waveguide modes inside nanoapertures. For example, in 1999 Porto et al. numerically demonstrated that metallic gratings with very narrow and deep enough slits can exhibit high transmission resonance via coupling with the waveguide mode in the slits [39]. Ruan and Qiu numerically demonstrated that such a waveguide-mode-aided high-transmission effect is quite independent of the period of the structure, manifesting its nature of localized resonance [40]. Lee et al. experimentally observed the EOT effect at terahertz (THz) frequencies in random arrays of single rectangular holes [24]. Such a research field has become extremely active since 1998, and readers can learn more from several excellent review articles [41–43].

The EOT mechanisms, while being scientifically inspiring, suffer from several issues in practical applications. For example, SPP-aided EOT is sensitive to both incidence angle and polarization of the excitation wave, and the apertures inevitably degrade the conductance of metals. In 2005, Zhou et al. proposed a new mechanism to make an opaque slab perfectly transparent [25]. Consider a plasmonic metal slab with a negative permittivity ($\varepsilon_2 < 0$). Instead of structuring it by making holes and grooves, the authors proposed to add two identical layers with positive permittivity ($\varepsilon_1 > 0$) to form an ABA structure. Simple calculations show that the whole structure becomes perfectly transparent when the following criterion is met:

$$\left(\frac{k_1}{k_0} - \frac{k_0}{k_1}\right)2 \tan(k_1d_1) - \left(\frac{\alpha_2}{k_0} + \frac{k_0}{\alpha_2}\right)\tanh(\alpha_2d_2)$$

$$- \left(\frac{k_1^2}{\alpha_2k_0} + \frac{\alpha_2k_0}{k_1^2}\right)\tan^2(k_1d_1) \tanh(\alpha_2d_2) = 0,$$

(1)

where $k_j = \sqrt{\varepsilon_j\omega/c}$, $k_2 = i\alpha_2$, and $d_j$ denote the thickness of the $j$th layer. The first two terms in Eq. (1) are contributed by individual A and B layers, while the third term is a multiple scattering contribution of the whole system. Equation (1) clearly reveals that the transparency is governed by cancellation of scatterings from two layers. In the long wavelength limit ($k_1d_1 \rightarrow 0$), Eq. (1) is reduced to $\bar{\varepsilon} = (2\varepsilon_1d_1 + \varepsilon_2d_2)/(2d_1 + d_2) = 1$, in consistency with the prediction based on effective-medium theory (EMT). Moreover, even $k_1d_1$ and $\alpha_2d_2$ are not so small; one can still find solutions of Eq. (1) numerically, going beyond the EMT predictions. Such a mechanism was experimentally demonstrated in the microwave regime, with the “plasmonic” metal mimicked by a metallic mesh with subwavelength openings and layer A represented by a metasurface consisting of H-shaped electric resonators. Perfect transmission of
EM waves was found at frequencies where Eq. (1) is met, in excellent agreement with both full-wave simulations and EMT calculations. Such a mechanism exhibits certain unique features as compared to the SPP-aided ones. First, the perfect transmission is largely governed by the “local” EM properties of the system. Second, the effect is quite insensitive to incident angles, since $|e|_i$ is very large in both layers so that varying the incidence angles (and thus varying the parallel wavevectors) does not change Eq. (1) significantly. Third, the magnetic field is highly amplified inside the ABA system due to the coupling between two metallic layers (as depicted in Fig. 2(c)), which plays a very important role in designing transmissive metasurfaces later (see Subsection 3.2). Soon after such a scattering cancellation mechanism was proposed, experiments were performed in different frequency domains to demonstrate this concept [44,45]. For example, Hooper et al. fabricated such an ABA structure in the optical frequency domain, and experimentally demonstrated the desired high optical transmission [45].

Closely related to the above mechanism, one can also place an antireflection coating layer on a target interface to enhance the optical transmission through it. However, it is not easy to find appropriate coating materials that satisfy the index-matching requirement in low-frequency domains (e.g., far-IR and microwave), and fabricating such antireflection layers is also challenging. In 2010, Chen et al. proposed a new strategy to realize antireflection coatings based on metasurfaces [26]. For an optical interface between air and GaAs, the authors designed an antireflection layer consisting of an array of gold cross-shaped microstructure and a gold mesh separated by a dielectric spacer [see Fig. 2(d)], and then experimentally demonstrated that it can significantly suppress the reflection and thus enhance the transmission into the GaAs medium. The measured maximum transmittance under normal incidence was 90% near 1.2 THz as compared to 68% through a bare air–GaAs interface [dashed line in Fig. 2(d)]. Moreover, the anti-reflection effect is also polarization insensitive even for oblique incident cases. To elucidate the mechanism, the authors modeled the SRR array and the mesh layer as individual metasurfaces with EM characteristics computed as they stand alone, and then calculated the reflection and transmission of the whole system by considering the multiple reflection/transmission effects [Fig. 2(d)]. In the lossless case, the total reflection coefficient can be simplified as

$$\bar{r} = \frac{r_{21} \exp(i\phi_{12}) - r_{23} \exp[i(\phi_{12} + \phi_{21} + \phi_{23} + 2\beta)]}{1 - r_{21}r_{23} \exp[i(\phi_{21} + \phi_{23} + 2\beta)]},$$

(2)

where $2\beta$ represents the phase accumulated for a wave traveling inside the dielectric spacer in a round. Clearly, through tuning the spacer thicknesses and the EM characteristics of individual layers, one can make $\bar{r} = 0$ under certain conditions, yielding complete antireflection. Here, the destructive and constructive interferences are responsible, respectively, for suppression of reflection and enhancement of transmission. The concept was intimately related to the scattering cancellation mechanism, but was established here in an asymmetrical scenario. Experiments were performed to verify the idea in different frequency regimes and to significantly enlarge the working bandwidth [46,47]. For example, Huang et al. report bilayer metasurfaces for accomplishing dual- and broadband optical antireflection in the THz and mid-IR regimes. The dispersions of individual metasurface layers are carefully tailored to provide similar reflection amplitudes and opposite phase dispersions to expand the antireflection operational bandwidth. By exploiting the self-aligned bilayer metallic metasurfaces, this antireflection scheme avoids the deposition of thick dielectric films and is applicable to substrates with arbitrary refractive indices [48].
2.2b. Perfect Absorption

Absorption is another way to control the amplitudes of EM waves. Moreover, efficiently absorbing EM waves are important in many applications, such as enhancing the efficiency of radar detection, photodetectors, and solar cells. However, natural materials cannot efficiently absorb light due to their weak interactions with light. Conventional perfect-absorption devices, such as Dallenbach and Salisbury screens [49,50], are too bulky in size, as they usually consist of resistive sheets placed at quarter-wavelength distances above a metal ground plane. Recently, metasurfaces were widely used to realize EM absorbers in different frequency domains that are ultrathin and highly efficient. Here we briefly review the developments along this line.

To maximize light absorption within a medium, one must simultaneously minimize both transmission and reflection from it. Transmittance through an optical material can be easily diminished if the system is thick enough and exhibits certain losses. However, eliminating the reflection is not easy. Consider a plane EM wave impinging normally on an interface between two homogeneous media, the reflection coefficient can be written as

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \]

with \( Z_i = \sqrt{\mu_i/\varepsilon_i} \) being the impedance of the \( i \)th medium. Equation (3) shows that eliminating the reflection requires matching the impedances of two media, namely, \( Z_2 = Z_1 \). Such a condition is difficult to meet based on natural materials that lack magnetic responses at high frequencies. Metamaterials, which can in principle possess arbitrary values of permittivity and permeability upon design, are the ideal candidates to realize perfect absorbers [51,52].

The idea of using metasurfaces to design thin absorbers was first proposed in 2002 by Engheta [53], who predicted that combining an MIM structure (also called a “high-impedance surface”) with a resistive sheet can efficiently absorb EM waves under appropriate conditions. In contrast to a Salisbury screen, here the distance between the resistive sheet and the ground plane can be much smaller than the working wavelength. Since an MIM structure exhibits a magnetic mode at resonance, it can reflect EM waves without any phase changes, resulting in a strongly enhanced electric field on its surface. As a result, by placing a resistive sheet with proper impedance on top of such a structure the reflected wave can be reduced to zero, leading to perfect EM wave absorption since there is no transmission through the system [53,54].

In 2008, Padilla’s group experimentally demonstrated the first metasurface-based absorber [55], which consists of two metallic layers separated by a dielectric spacer. The top metallic layer is composed of an array of electric ring resonators (ERRs) as shown in Fig. 3(a), which primarily provides electric responses to the system. The bottom layer contains an array of metallic cut wires, which, coupled with the ERR on the top layer, contribute strong magnetic responses to the device. The whole system thus possesses both electric and magnetic responses, which can be tuned independently by varying different structural parameters. Through adjusting geometrical parameters, the authors successfully designed a perfect absorber with impedance matching that of air. Microwave experiments demonstrated that the fabricated device exhibits an absorption peak 88% at 11.5 GHz, though theoretical results predicted near perfect absorption [see Fig. 3(a)].

After such a meta-absorber was demonstrated, follow-up investigations were quickly carried out in the THz regime [56,61,62]. Compared with microwave absorbers, the design presented in Ref. [56] exhibits several new traits. First, the absorber has a
Enhancement of absorption by metasurfaces. (a) Microwave metasurface absorber [55]. Left panel: schematics of an electric ring resonator, cut wire, and the unit cell of the microwave metasurface absorber. Right: simulated (red line) and measured (blue line) absorbance spectra of the microwave absorber. The inset displays the simulated angular dependence of the absorbance at the peak absorption frequency of 11.5 GHz [55]. (b) THz metamaterial absorber. Left panel: schematic (top) of the THz absorber, and photograph (bottom) of a portion of the experimental sample. Right panel: measured absorptivity as a function of frequency for TE (top) and TM (bottom) modes at three different incident angles [56]. (c) Mid-IR metasurface absorber. Top-left panel: simulated reflection (blue line), transmission (green line), and absorption (red line) of the device. Bottom-left panel: a comparison between the experimental absorption (red line) and simulated absorption (dashed gray line). Right panel: simulated energy dissipation in the mid-IR metasurface absorber structure at a wavelength of 6 μm. Energy dissipation distribution in cross (upper left corner), dielectric spacer (upper right corner), ground plane (lower left corner), and cross view of the whole structure (lower right corner) [57]. (d) and (e) NIR metasurface absorbers [58,59]. Metasurfaces in MIM configurations were used in both works, with the top resonator being a gold disk [58] (the left of Fig. (d)) or a patch [59] (the left of Fig. (e)), respectively. The maximum absorptions reported in these two works are 99% and 88%, respectively, while the working wavelengths are both roughly at 1.6 μm. (f) Visible metasurface-based absorber. Upper left corner: unit cell of the absorber. Upper right corner: schematic of the device. Lower left corner: scanning electronic microscopy image of the fabricated sample. Lower right corner: experimental reflectance for normal incidence, normalized to the gold film, for Ag nanocube surface coverages of 7.3% (thin solid line) and 17.1% (thick solid line) [60]. (a) Figures 1 and 3 reprinted with permission from Landy et al., Phys. Rev. Lett. 100, 207402 (2008) [55]. Copyright 2008 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.100.207402. (b) Figures 1 and 4 reprinted with permission from Tao et al., Phys. Rev. B 78, 241103 (2008) [56]. Copyright 2008 by the American Physical Society. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.78.241103. (c) Figures 2 and 4 reprinted with permission from Liu et al., Phys. Rev. Lett. 104, 207403 (2010) [57]. Copyright 2010 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.104.207403. (f) Reprinted with permission from Liu et al.,
flexible polyimide substrate with only 16 μm thickness, making it particularly suitable in conformal applications [see Fig. 3(b)]. Second, the device can absorb THz waves under a wide range of incidence angles with both transverse electric (TE) and transverse magnetic (TM) polarizations [see Fig. 3(b)]. For the TE measurement, the absorption peak is 95% for 30° incidence, reducing slightly to 88% at 60°. For TM radiation, the maximum absorption value reaches 96.8% at 30° and falls by only 0.024 upon increasing to 60°. Third, the bottom layer of the absorber is replaced by a continuous metallic film, forming an MIM structure. Such a configuration cuts off the transmission and thus only the reflection needs to be worried about, which simplifies the design process. In addition, the new configuration is also favored in fabrications, as precise alignment between top and bottom metallic layers is no longer necessary.

The concept was soon pushed to even higher frequencies, with perfect absorbers designed essentially through down-scaling the dimensions of their low-frequency counterparts predominantly in MIM configuration, only with top resonators replaced by new designs. The first mid-IR perfect absorber was again demonstrated by Padilla’s group in 2010 [57], with the top resonator being a metallic cross. The group experimentally achieved an absorbance of 97% at 6 μm and found that the majority of power is dissipated by dielectric losses [see Fig. 3(c)]. Still in 2011, two groups independently reported near-IR perfect absorbers, again in MIM configurations, with the top resonator being a gold disk [58] [Fig. 3(d)] or a patch [59] [Fig. 3(e)]. The maximum absorptions reported in these two works are 99% and 88%, respectively, while the working wavelengths are both roughly at 1.6 μm. The absorption effect is tunable by adjusting the nanostructure dimensions and is robust against varying incident angles. In contrast to their low-frequency counterparts, Hao et al. revealed that, for the near-IR absorbers, the power carried by light is predominantly dissipated through ohmic losses in metals rather than in a dielectric spacer. Visible absorbers were proposed in 2011 [63–65], but experimental demonstrations are rarely seen mainly due to fabrication challenges, although one theoretical work numerically predicted that the absorbance can be as high as 99% at the wavelength 596 nm. To overcome fabrication challenges in the top-down approach, researchers turned to using the chemical self-assembly method to realize perfect absorbers [60,66,67]. In 2012, Moreaus et al. employed a colloidal approach to chemically synthesize silver nanocubes onto a nanoscale-thick polymer spacer layer, which was then put on a metal film, forming a visible metasurface absorber, as shown in Fig. 3(f) [60]. Experimental results showed that measured light reflectance can be reduced to 7% at 637 nm, for a sample with 17.1% Ag nanocube surface coverage.

Finally, we note that MIM metasurfaces were also widely used to control EM polarizations, which will be discussed in detail in the next subsection. To understand why MIM metasurfaces can exhibit two such distinct functionalities, Zhou’s group has established a complete phase diagram by considering the intriguing interplays between losses from radiative and absorptive channels [68]. Intuitively, the phase diagram reveals that perfect absorption is achieved when the two losses are equal to each other, which is also known as the critical coupling condition. This actually provides an alternative yet more inspiring interpretation on the underlying physics of perfect absorption, which will be discussed with more detail in Subsection 2.3a.
2.3. Polarization Control

Polarization is a fundamental characteristic of EM waves, and polarized light is of great importance for various applications, ranging from sensing and photography to optical communications. In practice, it is greatly desirable to have full control on polarization. However, conventional devices to manipulate light polarization are either too bulky in size (say, dichroic crystals) or less efficient (say, optical gratings), which limit their application in certain optical scenarios. Metasurfaces provide an ultrathin and efficient platform to control EM wave polarization. Here, we briefly review the efforts in employing homogeneous metasurfaces to manipulate EM wave polarizations in both reflection and transmission geometries.

2.3a. Manipulating Polarization in Reflection Mode

We start from studying the reflection property of a homogeneous anisotropic metasurface. Suppose a linearly polarized wave is normally incident on a metasurface, with the E vector lying at an angle $\phi$ with respect to the x axis. The incident electric field can be written as (the IEEE definition for EM wave phase is adopted in all of the equations in this paper)

$$\vec{E}_i = (\cos \phi \hat{x} + \sin \phi \hat{y})e^{ikz+iot}. \tag{4}$$

Assume that $r_i = |r_i|e^{i\Phi_i}$ ($i = x, y$) denote the complex reflection coefficients of such a metasurface, then the reflected wave can be obtained as

$$\vec{E}' = (|r_x|e^{i\Phi_x} \cos \phi \hat{x} + |r_y|e^{i\Phi_y} \sin \phi \hat{y})e^{(-kz+iot)}. \tag{5}$$

We see immediately that the polarization state of the reflected wave is determined by three items, azimuthal angle $\phi$, the ratio of $|r_y|/|r_x|$, and the phase difference $\Delta \Phi = \Phi_y - \Phi_x$. Consider the case of $\phi = 45^\circ$ and $|r_y|/|r_x| = 1$. If the phase difference satisfies $\Delta \Phi = 90^\circ$, the polarization state of the reflected wave is circular polarization, indicating that the metasurface functions as a quarter-wave plate. Meanwhile, if $\Delta \Phi = 180^\circ$, the resultant polarization is still linear polarization (LP), but the polarization direction changes to the cross direction of the original one. In such a case, the metasurface is essentially a half-wave plate but with ultrathin thickness. Therefore, the reflection phase difference between two orthogonal polarizations is essential in designing metasurfaces for polarization manipulation [69, 70].

In 2007, Hao et al. initiated the idea of using anisotropic metasurfaces to manipulate EM wave polarization in reflection geometry [69]. Understanding the difficulties of using conventional materials (exhibiting purely electric responses) to modulate the EM wave phases in wide ranges, the authors proposed and then theoretically studied the EM properties of a model system consisting of an ultrathin metamaterial slab with a dispersive permeability $\mu$ tensor placed on a perfect metal substrate. Theoretical calculations predicted that all possible polarization states (circular, linear, elliptic polarizations) are realizable for a LP wave being reflected by such a model system. A simple argument was used to understand these unusual phenomena. Since the permeability is anisotropic ($\mu_{xx} \neq \mu_{yy}$), the reflection coefficients $r_x$ and $r_y$ are different for incident waves polarized along two directions. In most cases where $\mu_{xx}(\mu_{yy})$ is not large, we have $\phi_x(\phi_y) \sim \pm180^\circ$, since the top metamaterial layer is transparent and light can directly “see” the metallic ground plane that is reflecting out of phase. However, at the resonances where $\mu_{xx}(\mu_{yy}) \rightarrow \pm\infty$, we get $\phi_x(\phi_y) = 0$ since light is reflected directly by the opaque metamaterial layer, which possesses infinite impedance (the right panel of Fig. 4(b)]. Therefore, in general we can obtain arbitrary values for $\Delta \Phi$ by adjusting the geometric and material properties of the metamaterial layer. The authors found that MIM structures are the ideal candidates to realize the proposed
Manipulating polarization in reflection mode. (a) Left panel: polarization conversion ratio (PCR) as a function of frequency, obtained by theoretical calculations (solid lines), numerical simulations (solid stars), and experimental measurements (open circles). The inset shows an image of part of the experimental sample. Right panel: frequency dependences of the reflection phase changes on the metamaterial reflector surface for normally incident waves with different polarizations, obtained by theoretical calculations (solid lines) and numerical simulations (solid stars) [69]. (b) The calculated PCR as a function of wavelength using the experimental data. The inset shows a SEM image of a part of the experimental sample [71]. (c) Top panel: reflectivity for three different incident angles. Inset shows SEM image of the fabricated structure. Curves correspond to numerical calculations; markers are experimentally measured values. Bottom panel: reflectivity as a function of analyzer angle measured from the x axis when incident angle $\beta = 40^\circ$. The legend “Reference” refers to reflection from a 50 nm thick SiO$_2$ layer on top of a gold substrate [72]. (d) Left panel: SEM image of the array of gold L patterns fabricated by electron beam lithography. Right panel: experimentally measured reflectance of the fabricated broadband half-wave plate [73]. (e) Phase diagrams of the on-resonance absorption $A$ (left panel) and the span of reflection phase $\Delta \Phi$ (right panel) versus $Q_r$ and $Q_a$ calculated with coupled-mode theory for the single-port model [68]. (a) Figures 2 and 4 reprinted with permission from Hao et al., Phys. Rev. Lett. 99, 63908 (2007) [69]. Copyright 2007 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.063908. (b) Figures 1 and 3 reprinted with permission from Hao et al., Phys. Rev. A 80, 23807 (2009) [71]. Copyright 2009 by the American Physical Society. https://journals.aps.org/pra/abstract/10.1103/PhysRevA.80.023807. (c) Reprinted with permission from [72]. Copyright 2013 Optical Society of America. (d) Reproduced from [73] under the terms of the Creative Commons Attribution 3.0 License. (e) Figure 1 reprinted with permission from Qu et al., Phys. Rev. Lett. 115, 235503 (2015) [68]. Copyright 2015 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.115.235503.
model [69], and they then designed/fabricated an MIM structure in the microwave regime with the top resonator being a metallic “H” [see the inset of the right panel of Fig. 4(a)]. Microwave experiments show that an LP beam indeed converts its polarization completely to the cross direction after being reflected by the metasurface at frequencies near resonance [see the left panel of Fig. 4(a)]. Both the absolute working efficiency and the polarization conversion ratio (PCR) of the device are nearly 100%, since here the system has \(|r_x| \approx |r_y| \approx 1\) with very weak absorptions. Other predicted polarization control effects were also experimentally realized by such a MIM device.

Such concept was soon pushed to optical frequencies. The first reflection-type metasurface half-wave plate was again demonstrated by Zhou’s group in 2009 [71]. The device is also a tri-layer structure consisting of a gold nanorod array and a continuous gold film separated by a \(\text{SiO}_2\) spacer [see the inset of Fig. 4(b)]. Experimental results revealed that the maximum PCR of such a device can reach 96% at the wavelength of 685 nm, as shown in Fig. 4(b). Although the designed structure looks like its microwave counterpart [69], in fact the underlying physics is a bit different. In the optical design, the thickness of the continuous gold film is only 15 nm, implying that the bottom metallic layer is no longer perfectly reflective since metal exhibits a finite penetration length in the optical domain. Therefore, here the couplings between nanorods and the gold continuous film generate not only magnetic resonance similar to the microwave case, but also electric resonance that does not exist in the microwave device. With both magnetic and electric modes fully considered, the authors established an effective-medium model to quantitatively describe the experimentally observed effects. The key physics is that the designed metasurface can exhibit desired permittivity and permeability (in turn, desired impedance) for light polarized along two principle axes, resulting in the \(\pi\) phase difference requested by a half wave-plate. However, although possessing an ultrathin thickness, the realized optical device exhibits a degraded working efficiency compared to the microwave device, since it allows substantial light transmission. Many follow-up works were subsequently performed to demonstrate the polarization conversion effects at optical frequencies with enhanced working efficiencies. The realized devices either have thicker bottom metallic films, and thus block the transmitted signals [72,74,75], or have top resonators taking other shapes [76] or with more carefully tuned space layers [75]. In 2013, Bozhevolnyi’s group utilized a similar MIM-type metasurface [72], but with a thicker bottom gold substrate, to realize a more efficient wave plate [see Fig. 4(c)]. The fabricated structure functions as a half-wave plate at the wavelength of 780 nm with a relative bandwidth of 160 nm. A reflectance of 50% is experimentally obtained.

In the THz regime, Chen’s group demonstrated a reflection-type metasurface polarization converter in 2013 [77]. The device is similar to the microwave one but with H-shaped top resonators replaced by metal cut wires. An important contribution of this work, apart from the actual device realization in the THz regime, is the significantly enlarged working bandwidth (0.73–1.88 THz). The working principle is slightly different from those of the microwave and optical devices, although all of them are in MIM configurations. Here, the authors argued that two metallic layers form an FP-like cavity in which THz waves are multiply reflected before leaving the device. Therefore, THz waves polarized along two orthogonal directions can experience distinct interference upon multiple reflection inside the cavity, generating a significant phase difference for the reflected THz waves. It is such difference in FP modes supported by the cavity that eventually helps realize the desired half-wave plate functionality. The obtained broadband performance results from the superposition of the multiple polarization conversion effect [78,79]. In 2014, Jiang et al. introduced a new mechanism to construct broadband wave plates. Basically, the designed structure is also composed of a layer of metallic metastructure and a continuous metallic film separated
by a dielectric layer [see Fig. 4(d)] [73]. In contrast to the previous works, here the dielectric layer is dispersive over the region of interest, which can perfectly compensate the intrinsic dispersion of the metallic structures. Experimental results demonstrated that, for the half-wave plate sample, the \( x \)-polarized (\( y \)-polarized) incident light is almost entirely converted to its cross polarization after being reflected by the metasurface in a wide frequency band (70–145 THz) [see right panel of Fig. 4(d)]. Very recently, using Jones matrix and Poincaré sphere analyses, Ma et al. derived a set of criteria to help design high-efficiency ultra-wideband THz wave plates using anisotropic metasurfaces [80], and further experimentally demonstrated three different wave plates, all exhibiting excellent polarization manipulation capabilities within ultrawide bandwidths (relative bandwidths larger than 100%).

It is intriguing to note that MIM structures can support distinct resonant modes (e.g., magnetic resonance or FP modes) and exhibit completely different functionalities (perfect absorption in Subsection 2.2b and polarization control in this section). One naturally asks the question: Why does the same type of structure behave so distinctly and what determines their physical behaviors? In a series of works published in 2015–16, Zhou’s group provided answers to these questions [68,81]. In [81], the authors employed a rigorous mode expansion method to analytically study the resonance properties of MIM systems. They found that an MIM system supports magnetic resonant modes when the spacer is thinner than a critical thickness, while the mode changes to a vertical FP mode as the spacer thickness enlarges. The near-field couplings between two metallic layers play the most important role to differentiate these distinct modes. Furthermore, the authors established a complete phase diagram to fully understand the functionalities of MIM structures [68]. They found that all MIM structures can be described by a one-port cavity with a supported mode described by two factors, i.e., the absorptive and radiative quality factors defined as \( Q_a = \frac{\omega \tau_a}{2} \) and \( Q_r = \frac{\omega \tau_r}{2} \), where \( \tau_a \) and \( \tau_r \) denote the mode lifetimes due to absorption and radiation, respectively. Based on such a simple model, the authors found that the optical properties of MIM systems are fully controlled by the ratio between these two parameters, which is, in turn, dictated by the geometrical or material properties of the underlying structures. Specifically, a MIM metasurface behaves as a perfect absorber when \( Q_r/Q_a = \frac{\omega \tau_r}{2}/\frac{\omega \tau_a}{2} = 1 \), but turns to being a strong reflector (i.e., \( |r| \to 1 \)) when \( Q_r/Q_a \) is far away from 1, as shown in the left panel of Fig. 4(e). Moreover, in the \( Q_r < Q_a \) region, the MIM structure represents an underdamped resonator with phase variation covering \( 2\pi \) as frequency passes through the resonance, while in the \( Q_r > Q_a \) region, the resonator become overdamped with small variation range of reflection phase (i.e., less than 180°) [see the right panel of Fig. 4(e)]. Such a phase diagram can greatly facilitate the design of appropriate metasurfaces with tailored functionalities, demonstrated by experimental results on a series of THz MIM metasurfaces realized by the authors. We need to mention that several other groups also noted the fascinating interplay between absorptive and radiative losses in such MIM structures, although presented in different forms [82,83]. Moreover, such a generic phase diagram establishes a solid basis for achieving dynamically tunable metadevices based on MIM systems, as we will discuss in Subsection 2.4.

2.3b. Manipulating Polarization in Transmission Mode

After the first demonstration of polarization manipulation in reflection mode, many efforts were devoted to extending the concept to transmission mode, which is more desired in practice. However, such a task is much more difficult to fulfill than that in reflection mode, since now both transmission and reflection need to be considered.

In 2008, Beruete et al. designed a metadevice consisting of multilayers of EOT slabs [see Fig. 5(a)], and experimentally demonstrated that it can select an EM wave with a
Figure 5

Manipulating polarization in transmission mode. (a) Left panel: photograph of the fabricated hole array metasurface plate. Right panel: measured phase for the negative refractive index (NRI) component, two plates (solid red) and three plates (solid blue), and for the positive refractive index (PRI) component, two plates (dashed red) and three plates (dashed blue) [84]. (b) Left panel: SEM image of the fabricated L-shaped holes metasurface plate. Right panel: measured transmission spectra with the polarization analyzer set at four different angles (upper panel). Phase difference between the detected phases in the $x$ and $y$ directions as a function of wavelength (lower panel), where insets are the calculated polarization states of the transmitted light at two eigenfrequencies [85]. (c) Left panel: focused-ion-beam cut of a polymer structure partially filled with gold (upper left) and oblique view of a left-handed helix structure after removal of the polymer by plasma etching (upper right); top-view image revealing the circular cross section of the helices and the homogeneity on a larger scale (lower panel). The lattice constant of the square lattice is $a = 2$ mm. Right panel: normal-incidence measured transmittance spectra. LCP and RCP are depicted in red and blue, respectively. Pitches of left-handed helices (upper panel) and right-handed helices (lower panel) [86]. (d) Left panel: layer A (upper panel) is periodically arranged electric resonators; layer B (lower panel) is metallic mesh. Right panel: simulated (solid curves) and measured (circles) spectra of transmission amplitudes and phases for two incident polarizations [87]. (e) Left panel: schematic of the unit cell of the broadband THz transmission-type linear polarization converter. Right panel: cross-polarized transmittance obtained through experimental measurements, numerical simulations, and theoretical calculations, and with the numerically simulated copolarized reflectance [77]. (f) Left panel: experimentally measured degree of linear polarization (DoLP) and angle linear polarization (AoLP) for circularly polarized excitation. The inset is an SEM image of silver nanorods. Right panel: experimental measurement of the transmission coefficients for linearly polarized excitation along the two nanorod axes [88]. (a) Reprinted with permission from Beruete et al., J. Appl. Phys. 103, 053102 (2008) [84]. Copyright 2008 AIP Publishing LLC. (b) Reprinted with permission from Li et al., Appl. Phys. Lett. 93, 021110 (2008) [85]. Copyright 2008 AIP Publishing LLC. (c) From Gansel et al., Science 325, 1513–1515 (2009) [86]. Reprinted with permission from AAAS. (d) Reprinted with permission from [87]. Copyright 2011 Optical Society of America. (e) From Grady et al.,
particular polarization to pass through [84]. For an incident wave with arbitrary polarization, any type of polarization state can be obtained at the output by simply adjusting the number of stacked plates. The phase shift between two orthogonally polarized eigenwaves is dictated by the negative and positive indices for two different modes traveling inside. However, such a device still needs a large enough thickness since it relies on propagation-phase accumulations, as shown in the right panel of Fig. 5(a), and the working efficiency of the device is quite low. Soon, Li et al. proposed a single-slab polarization-control device that is a silver film drilled with an L-shaped aperture array [see Fig. 5(b)] [85]. Since the aperture exhibits different “shape resonances” for two polarizations controlled by the lengths of two arms of the L [see Subsection 2.2], naturally the EOT through such a device exhibits distinct behaviors for two polarizations, which can be fully utilized to control the polarization state of light transmitted through it. Indeed, nearly 45° polarization rotation was experimentally observed with relatively strong transmission for a polarized light with a specific incidence angle at the wavelength 1200 nm [see Fig. 5(b)]. The optical rotation is high considering that the sample is only 80 nm thick. In the same year, Chin et al. demonstrated a microwave transmission polarizer based on an anisotropic metasurface [89] consisting of an array of electric resonators exhibiting designable effective electric permittivity. A device consisting of two layers can function as a quarter-wave plate, while a four-layer device functions as a half-wave plate. However, while these devices do not need wavelength-scale thicknesses, their working efficiencies are not perfect, not only due to absorption, but more importantly, also due to reflection caused by lacking magnetic permeability in the designed systems.

In addition to using anisotropic metasurfaces, researchers also proposed to use chiral metasurfaces to control EM-wave polarization at the transmission side [86,90,91]. Also in 2008, Li et al. investigated the transmission of microwaves through a chiral metasurface [90], formed by an array of square single SRRs. They found that an elliptically polarized transmitted wave was achieved at the resonant frequency of the metasurface, with major polarization axes approximately perpendicular to that of the incident wave. The optical activity of such a medium is due to the hybridization effect of magnetic resonances. Such a device can be ultrathin, but both the PCR and the working efficiency of the device do not approach 100%. In 2009, Gansel et al. investigated the propagation of light through an anisotropic photonic metamaterial [86] composed of a three-dimensional (3D) array of gold helices [see Fig. 5(c)]. For light propagating along the helix axis, the circular polarization with the same handedness as that of the helices is blocked by the structure, whereas light with another circular polarization is transmitted. The measured spectra revealed that a large transmittance ratio appears in the wavelength range (3.5–7.5 μm), as shown in the right panel of Fig. 5(c).

In 2011, Zhou’s group proposed a new device configuration to achieve 100% efficiency polarization control on a transmitted wave. The device is a tri-layer structure in an ABA configuration [87], where layer A consists of periodically arranged electric resonators, while layer B is a metallic mesh [see Fig. 5(d)]. Such ABA structure supports perfect transmission for an x-polarized EM wave at a frequency interval centered at 5.1 GHz [see the right panel of Fig. 5(d)], dictated by the scattering cancellation mechanism introduced in Subsection 2.2a. Moreover, the proposed device also allows perfect transmission for y-polarized EM waves within the same frequency interval, but with physics governed by the EOT mechanism assisted by Bragg scatterings. Different
transparency mechanisms generate a $\pi/2$ difference in transmission phases for two polarizations, making the device an ideal half-wave plate working in transmission mode. The whole device is much thinner than wavelength but exhibits a nearly 100% working efficiency. Extensions to THz frequencies are possible, but with significantly degraded efficiency due to strongly enhanced material absorptions [92].

However, the proposed device still exhibits a narrow working bandwidth. In 2013, in addition to realizing a reflection-type THz polarizer, Chen and co-workers [77] also presented a scheme to realize a broadband transmission polarization convertor for THz waves. The fabricated device contains three metallic layers, in which the top and bottom ones are orthogonally orientated metallic gratings, which ensure that only cross-polarized THz waves can pass through the whole device. The middle metallic layer contains an array of cut wires oriented at an angle 45° with respect to the two gratings. The role of cut wires is to efficiently convert the energy of an incident wave to that of the cross-polarized transmitted wave. The distances between two adjacent metallic layers are carefully chosen to diminish the reflection (thus to enhance the transmission) based on multiple scatterings. Experimental results revealed that $x$-polarized incident THz waves can be completely converted to $y$-polarized transmitted waves, with a conversion efficiency exceeding 50% from 0.52 to 1.82 THz, as shown in Fig. 5(e).

Such an elegant approach was further used to design high-efficiency inhomogeneous metasurfaces in transmission mode, which will be introduced with more detail in Subsection 3.1. Inspired by this work, a variety of similar structures have been realized in other frequency domains to demonstrate broadband, high-efficiency polarization converters [93–95]. Also in 2013, Alù’s group realized a broadband optical metawave-plate using a single, planar metasurface [88], as shown in the inset of the left panel in Fig. 5(f). The device is based on interleaved silver nanorods with properly tailored frequency dispersion that introduces an abrupt flat $\pi/2$ phase shift for two orthogonal polarizations over an ultrathin thickness. The achieved quarter-wave plate can work in a large frequency portion of the entire visible spectrum.

2.4. Tunable Homogeneous Metasurfaces

The metasurfaces/metadevices introduced in previous subsections are all passive systems, whose fascinating wave-manipulation functionalities are fixed once they are fabricated out. However, in real applications it is more desirable to have tunable devices with properties/functionailities controllable by external knobs. Much effort has been devoted to realizing tunable metasurfaces through integrating active elements into corresponding meta-atoms, which can thereby be controlled by appropriate external stimuli. In this subsection, we briefly summarize the available mechanisms to make tunable (homogeneous) metasurfaces, classified by different external stimuli adopted to control the EM responses of meta-atoms. We emphasize that the mechanisms described below actually lay a solid basis for designing functional metadevices based on inhomogeneous metasurfaces with individually controlled meta-atoms, which will be introduced in Subsection 4.6.

2.4a. Electrically Tunable Metasurfaces

As a commonly adopted approach, one can integrate electrically sensitive materials functioning at different frequency domains, such as varactor diodes, liquid crystals (LCs), doped semiconductors, and two-dimensional (2D) materials, into the meta-atom designs. At microwave frequencies, varactor and PIN diodes are frequently adopted in designing tunable metasurfaces, since their EM responses (e.g., capacitances) can be dramatically tuned by applying external voltages. For instance, in 2011 Zhu et al. experimentally demonstrated a microwave metadevice composed of MIM meta-atoms with PIN diodes incorporated. By varying the voltage applied across these diodes,
the authors can control the “on” and “off” states of the diodes and thus switch the functionality of the device from a reflector to a perfect absorber [96]. Based on similar mechanisms, many other tunable microwave metadevices were experimentally demonstrated, such as a tunable polarization controller [97,98] and a frequency switchable absorber [99,100]. However, such a scheme cannot be directly extended to frequencies higher than gigahertz (GHz), where diodes typically do not work.

In the THz and IR regimes, doped semiconductors can be used as the active elements to design tunable metasystems, since their conductivities (and thus optical responses) can be dramatically modified via electrical gating [101,102]. Such a mechanism features broad bandwidth and high modulation speed, and is compatible with CMOS technology. In 2006, Chen et al. experimentally demonstrated the first THz tunable metasurface, which consists of electrically connected SRRs placed on a semiconductor substrate. By varying the bias voltage applied across the Schottky diode formed at the metal–semiconductor interface, a modulation of 50% on transmission through the device was experimentally realized [101]. Three years later, the authors further realized a tunable metadevice based on the same configuration but with optimized design for SRR resonators, and experimentally demonstrated that it can achieve real-time active amplitude (55%) and phase ($\pi/6$) modulation on the transmitted wave at 0.81 THz with a speed of up to 2 MHz [see in Fig. 6(a)] [102]. After this work, many other tunable metadevices were proposed to achieve larger modulation depths, higher modulation speeds, and/or broader tuning ranges, based on a similar mechanism but

Figure 6

Homogeneous tunable metasurfaces. (a) Semiconductor-hybridized electrically tunable metasurfaces (ETMs) (bottom inset) for THz phase and amplitude modulations. Upper inset: measured transmission spectra at different bias voltages [102]. (b) Measured relative change in transmission and phase change as a function of gate voltage and frequency for graphene-based ETMs. Inset: schematic rendering of a gate-controlled active graphene metamaterial [103]. (c) MIM graphene ETMs for full-range phase modulations (inset). Experimental results on relative change in reflection and phase for THz beams [104]. (d) Optically tunable metasurfaces (OTMs) based on semiconductors for THz wave modulation. Experimental transmission spectra with different powers of pump light. Inset: SEM picture of a meta-atom of proposed OTMs [105]. (e) Schematic of OTMs based on optically sensitive polymer to manipulate the polarization of transmitted light in the optical regime [106]. (f) Right panel: mechanically tunable metasurfaces (MTMs) based on MEMS technology. Left panel: reflection

with different geometries and active materials [111,112] (e.g., transparent conducting oxides [113–115] and transition metal nitrides [116]).

Graphene, a zero-bandgap 2D material with conductivity tuned efficiently via an external gating, is another excellent candidate to help realize tunable devices in the THz or mid-IR regimes [117,118]. In 2011, Ju et al. showed that the plasmon resonance of a graphene ribbon array can be dramatically tuned through gating the graphene [119]. However, the graphene alone has weak optical responses, since it is only a single atomic layer. In 2012, Lee et al. combined gate-controlled graphene with a transmissive metasurface and experimentally achieved active amplitude (47%) and phase (32.2°) modulations on the transmitted THz wave [103], as shown in Fig. 6(b). Recently, many graphene–meta-hybridized tunable metadevices were demonstrated in both the THz [120–124] and IR regimes [125–131], which exhibit diversified functionalities, such as tunable absorbers [120,123,130], phase modulators [128,129], active polarization controllers [124], and beam steering [131]. Unfortunately, the phase tuning ranges of these graphene–metasurfaces are all very limited. Recently, Miao et al. combined graphene with a MIM metasurface, and experimentally demonstrated that the whole system can modulate the phase of a THz wave in a range much wider than those realized before. The physics is well explained by the coupled mode theory, which shows that graphene essentially plays the role of tunable loss, which drives the system to transit from an underdamped resonator to an overdamped one as the graphene is gated [see the generic phase diagram of MIM systems in Fig. 6(e)]. Wide-range phase changes occur at two different frequencies covering ±π. By designing two meta-atoms with slightly different working frequencies, the authors further demonstrated that using two “phase
bits” can enable THz phase modulation with a maximum range of 243° at 0.48 THz [see Fig. 6(c)] [104].

LCs are also widely used as “active elements” to help realize tunable metasurfaces. The orientation angles of molecules in an LC can be controlled by external electric fields, leading to significant modulations on the refractive index of the LC. As a result, the resonant properties of metasurfaces with LCs incorporated can be efficiently tuned by applying an electric field across the LC [110,132,133].

Epsilon-near-zero (ENZ) thin films, made by transparent conducting oxide or doped semiconductor materials, provide a promising platform to realize ETMs [113,134]. Thanks to the strongly enhanced density of the optical mode at the permittivity near zero regime, the optical properties of ENZ materials can be efficiently tuned with different external stimuli.

2.4b. Optically Tunable Metasurfaces

By hybridizing optically sensitive materials with passive metasurfaces, we then realize optically tunable metasurfaces (OTMs), whose properties can be controlled by ultrafast light pulses. In 2008, Chen et al. experimentally demonstrated that a semiconductor-incorporated OTM, constructed by an SRR array on a silicon-on-sapphire substrate could realize a 20% frequency switching at frequencies around 0.85 THz with an optical pump fluence of 0.5 \( \text{mJ/cm}^2 \) [Fig. 6(d)] [105]. Recently, Gu et al. experimentally demonstrated an optically controlled electromagnetically induced transparency with actively tuned EM wave group delay through a carefully designed THz metasurface, which consists of a metallic cut wire and two SRRs with photoconductive silicon islands positioned in their gaps [135]. Optically responsible phase change materials [106,136–138] are also good candidates to realize OTMs. Very recently, Ren et al. designed/fabricated an OTM by combining a plasmonic metasurface (consisting of a periodic array of L-shaped slits) with an Ethyl Red switching layer, and experimentally demonstrated that the device can actively modulate the polarization of transmitted light. The tunability is achieved by controlling the coupling conditions between the plasmonic resonant modes and the binary isomeric states of the ethyl polymer switching upon light stimulation [see Fig. 6(e)] [106]. Chalcogenide phase-change materials, composed of alloys of germanium (Ge), antimony (Sb), and tellurium (Te), have also been widely used to realize OTMs in the IR regime, through combinations with carefully designed plasmonic meta-atoms [137,139].

2.4c. Mechanically Tunable Metasurfaces

Exerting mechanical forces on a metasurface can also efficiently tune its optical properties, since the meta-atom structure or its local environment can be dramatically modified [107,108,140–142]. Micro-electro-mechanical-systems (MEMS) or nano-electro-mechanical-systems (NEMS) are widely used technologies to realize mechanically tunable metasurfaces in different frequency domains [107,140,143]. In 2013, Ou et al. experimentally demonstrated an electromechanical light modulation in the near-IR regime based on an electrically reconfigurable metasurface, which is composed of a continuous metallic “meander near the wire” pattern manufactured on a grid of flexible dielectric strings, as shown in Fig. 6(f). With the help of MEMS, the inter-position change of metastructures can lead to a continuous reflection modulation up to 8% at 1500 nm. In addition, the modulation rate of such a 100 nm thick metadevice can reach as high as several megahertz [107]. Very recently, based on the generic phase diagram of MIM systems [Fig. 4(e)] [68,81], Cong et al. experimentally demonstrated wide-range active phase modulation on THz waves based on an MIM metadevice with an inter-layer gap dynamically controlled by MEMS technology [144].
Microfluidics is another technology widely used to achieve mechanically tunable metasurfaces at different frequency domains \[141,108,145,146\]. For instance, Sun et al. experimentally realized real-time tunable colors with all dielectric (TiO\(_2\)) metasurfaces embedded in a polymeric microfluidic channel \[108\]. As shown in Fig. 6(g), the narrowband reflection peaks of the metasurfaces (corresponding to distinct colors) can be well controlled with the injection of different solutions with different refraction indices into the channel. Based on the rapid color transition (less than 16 ms) and high spatial resolution of such an approach, the clearance and restoration of information and images encoded in the microfluidic reconfigurable metasurfaces was also demonstrated experimentally.

Mechanically tunable metasurfaces (MTMs) based on stretchable and flexible substrates have been proposed to achieve various dynamic effects (e.g., color tuning \[147,148\], switchable holograms \[149\], and varifocal lenses \[150\]). The tunable capability of such approach is based on dynamical control on the interspacing distances among meta-atoms with applied force, which can efficiently modify their interactions and result in significant modification of the EM properties of the metasurfaces. However, mechanically tunable metadevices usually suffer from the issues of slow speed, limited device size, and/or restricted tuning range.

2.4d. Thermally Tunable Metasurfaces

Incorporating thermally responsive materials (e.g., phase change materials (PCMs) \[109,151\], LCs \[110\], and superconductors \[152,153\]) into metasurfaces is another approach to realize tunable metasurfaces. Vanadium dioxide (VO\(_2\)) is a typical PCM that exhibits a metal–insulator transition at 340 K. In 2008, Driscoll et al. experimentally demonstrated a TTM by patterning metallic structures on a VO\(_2\) substrate \[154\]. By varying the temperature to induce the phase transition, the authors demonstrated a 20% modulation on light transmission through the system at 1.5 THz. As shown in Fig. 6(h), they further utilized the hysteresis of such metal–insulator phase transition to demonstrate a TTM-based memory device \[109\]. In 2015, Wang et al. experimentally demonstrated a switchable quarter-wave plate in the THz regime, based on a VO\(_2\)-hybridized metasurface \[151\]. The tunability of such a metadevice arises from the effective length change of the designed resonator, induced by the phase change of the VO\(_2\) inserted inside the meta-atom. Since LCs exhibit temperature-dependent refractive indices, many LC-based TTMs were also proposed to achieve different functionalities at different frequency ranges, such as tunable absorbers and spatial light modulators. For instance, Sautter et al. fabricated a metasurface consisting of silicon nanodisks with LCs incorporated, and demonstrated that its EM resonance can be dynamically tuned at telecom wavelengths by varying the temperature \[110\]. As shown in Fig. 6(i), a 40 nm shift in resonance wavelength with a pronounced transmittance change was achieved with room-temperature tuning. In addition, superconductors are another intriguing material to realize TTMs, especially in the THz regime \[153,155\]. Very recently, Ding et al. experimentally demonstrated an electrically and thermally tunable silicon metasurface for broadband THz antireflection application. Composed of interdigitated p–n junctions, such an active metadevice exhibits thermally tuned reflection and electrically tuned transmission properties, enabled by the bias voltages applied across the p-n junctions \[156\].

2.4e. Tunable Metasurfaces Based on Other Tuning Mechanisms

In addition to the mechanisms introduced above, there are many others that have been successfully used to realize tunable metadevices in different frequency ranges. For example, one can incorporate ferroelectric materials into the meta-atom design, which can be tuned by applying a magnetic field \[157\]. Meanwhile, it is also possible to use a chemical approach to change certain chemical components of the constituent
materials forming the metadevices, thus yielding the desired tunable optical responses (e.g., hydrogenation-based metadevices [158]).

3. GRADIENT METASURFACES: PRINCIPLES AND REALIZATION

In the last section, we discussed how to employ homogeneous metasurfaces to control EM waves, where the crucial role played by meta-atoms is highlighted. Recently, scientists gradually realized that metasurfaces are not necessarily homogeneous, but rather, the “macro-order” on which meta-atoms are arranged in a specifically designed inhomogeneous metasurface can play an important role. Indeed, such an artificially designable “macro-order” is another important feature of metasurfaces, apparently not belonging to natural materials, that can significantly expand the capabilities of metasurfaces to manipulate EM waves. In this section, we summarize the physical principles established for designing gradient metasurfaces, constructed with metallic or dielectric materials, to control EM waves with linear or circular polarizations, including recently proposed new mechanisms for designing metadevices with perfect efficiencies at extreme conditions.


Guiding light to propagate along a predetermined direction is always desired in optics. A simple approach is to use a flat mirror to reflect light. Alternatively, the propagation direction of light can also be bent at an interface between two media with different refraction indices. Light reflection/refraction at an interface, the basis for nearly all kinds of optics devices, are governed by Snell’s law [159]:

\[
\begin{align*}
\sin \theta_r &= \sin \theta_i \\
n_t \sin \theta_t &= n_i \sin \theta_i,
\end{align*}
\]

where \(\theta_i, \theta_r, \theta_t\) denote, respectively, the angles of incidence, reflection, and refraction, while \(n_i, n_t\) denote the refraction indices of two media. The physics behind such an elegant law is the conservation of a tangential wave vector of light at the interface, which is ultimately dictated by the translation invariance symmetry of the system. However, such a conservation also imposes unavoidable restrictions on light manipulation based on reflections/refractions. For instance, the angle of reflection must precisely equal the angle of incidence, implying that one has to vary the orientation angle of a mirror to change the direction of reflected light. While the refraction angle can be different from the incidence one, such difference is tied with the index contrast at the interface, which significantly limits the light-manipulation capabilities since the index variation range of natural materials is quite narrow.

In 2011, Yu et al. proposed a new concept to control the directions of the reflected/refracted light at optical interfaces, which breaks the constraint imposed by the conventional Snell’s law [160]. Instead of studying the interfaces with translation invariance symmetries, the authors considered an artificial interface exhibiting abrupt phase changes \(\Phi(x, y)\) for waves reflected and/or transmitted through the interface at the position \((x, y)\). The behavior of light reflection/refraction at such an interface can be understood based on the Fermat–Huygens principle. As shown in Fig. 7(a), consider a light beam traveling from far-field point A at medium 1 to far-field point B at medium 2 through the artificial interface. According to the Fermat–Huygens principle, the right optical path of light should take a minimized accumulated phase. Therefore, the phase accumulated along an optical path near the right one (the red line in Fig. 7(a)) and that along the right path [the blue line in Fig. 7(a)] must be identical. Considering both the propagating phases and the abrupt phase changes at the interface, one can easily derive the following equation:
$$n_i \sin \theta_i - n_i \sin \theta_i = \frac{\lambda_0}{d} \frac{d\Phi}{dx}$$  \hspace{0.5cm} (7)

to describe light refractions at the interface, with $\lambda_0$ being the light wavelength. Based on similar arguments, we have

Figure 7

Generalized Snell’s law. (a) Schematics used to derive the generalized Snell’s law. At the interface between the two media, an ideal surface structure is adopted to introduce a gradient abrupt phase shift in the light path. (b) Illustration of the symmetric (top panel) and antisymmetric (bottom panel) plasmonic modes defined by the induced current patterns inside the V-antenna. The angle between the incident polarization and the antenna symmetry axis is 45°. (c) Refraction angle versus incidence angle for the ordinary (black) and anomalous refraction (red) for the V-antenna sample with a periodicity of 15 μm. The curves and symbols are the results obtained by the theory [Eq. (8)] and experiments, respectively. (d) The envelope of the scattered waves of the eight V-antennas with an oblique equal phase plane. According to Huygens’ principle, the interference of these scattered waves will give rise to an anomalous refraction beam. (e) A metasurface combining a thin gradient-index metamaterial layer with a PEC. Under illumination of a normally incident wave, the induced currents inside the metasurface will generate an obliquely reflected beam. (f) Measured (circle) and simulated (line) scattering patterns for the metasurfaces (see inset) with phase gradient of $\xi = 0.8 k_0$. (g) Measured scattered field intensity profiles for the V-antenna array designed for the NIR regime and illuminated with x-polarized light, with the dashed line representing the theoretical prediction based on the generalized Snell’s law. (h) Schematics of a high-efficiency reflective metasurface with the unit cell (inset) consisting of an Au nanorod (yellow) and a continuous Au film (yellow) separated by the MgF$_2$ spacer (blue). (i) Measured and simulated scattered field intensity for the gradient metasurface depicted in (h) illuminated by y-polarized light at $\lambda = 850$ nm with different incident angles. (a)–(d) From Yu et al., Science 334, 333–337 (2011) [160]. Reprinted with permission from AAAS. (e), (f) Reprinted with permission from Macmillan Publishers Ltd.: Sun et al., Nat. Mater. 11, 426–431 (2012) [161]. Copyright 2012. (g) From Ni et al., Science 335, 427–427 (2012) [162]. Reprinted with permission from AAAS. (h), (i) Reprinted with permission from Sun et al., Nano Lett. 12, 6223–6229 (2012) [163]. Copyright 2012 American Chemical Society.
\[ n_i \sin \theta_r - n_i \sin \theta_i = \frac{\lambda_0}{2\pi} \frac{d\Phi}{dx} \]  \hspace{1cm} (8)

to describe light reflections at such an interface. Equations (7) and (8) are called the generalized Snell’s law for light reflections/refractions, which, compared with the original Snell’s law [Eq. (6)], contain an important new term proportional to the phase gradient \( d\Phi/dx \) provided by the artificial interface. Alternatively, we can also rewrite Eqs. (7) and (8) as a more physical version:

\[ \vec{k}_r^i = \vec{k}_i^i + \nabla \Phi, \quad \vec{k}_r^f = \vec{k}_i^f + \nabla \Phi, \]  \hspace{1cm} (9)

which states that the parallel wave vector of light does not conserve at the interface after reflection/refraction, but rather gains an additional term contributed by the artificial interface. Such an additional term significantly expanded our capabilities to control light propagation. For example, even for normally incident light (i.e., \( \theta_i = 0^\circ \)), one can bend the reflected/refracted light to arbitrary directions dictated by the phase gradient. Moreover, since \( \nabla \Phi \) is solely determined by the artificial interface, its direction is not necessarily parallel to \( \vec{k}_i^i \), indicating that off-plane reflection/refraction can easily happen at a carefully designed artificial interface.

The question is then how to realize an interface with a desired phase profile \( \Phi \). This is, however, quite nontrivial since any single-mode resonator exhibits a Lorentz-type response to incident light, and thus can provide a phase modulation only over a \( \pi \) range. Yu et al. proposed to adopt V-shape nanoantennas to modulate the phase over a \( 2\pi \) range on a subwavelength scale [160,164]. As shown in Fig. 7(b), such V-shape antennas consist of two arms with length \( h \) joined at their ends, forming an angle of \( \Delta \). In contrast to a single-mode structure, such antennas naturally support two resonant modes with different symmetries and at different frequencies. While the effective resonance wavelength of the symmetric mode is roughly \( 2h \), that of the anti-symmetric one is roughly \( 4h \), dictated by the currents flowing inside the two arms. Therefore, as LP light strikes on the antenna, both modes can be excited, with substantially different amplitudes, by the electric-field components along the symmetry axis \( \hat{s} \) and the anti-symmetric axis \( \hat{a} \). A simple calculation shows that the cross-polarization component of scattered light contains two Lorentz terms exhibiting an additional \( \pi \) phase difference. It is such a unique feature that motivates Yu et al. to use cross-polarized scatterings of such V-shape antennas to modulate the phase of incident light over a full \( 2\pi \) range. By setting the working wavelength to 8 \( \mu m \), the authors successfully found four V-shape antennas with different geometrical parameters \( h \) and \( \Delta \) that can scatter incident light to the cross-polarization component with nearly equal amplitudes, but with phases changing linearly over a \( \pi \) range. By simply taking the mirror structure of the existing V-antennas, the authors got another set of four antennas whose cross-polarized radiation have phase shifts covering another \( \pi \) range [Fig. 7(d)]. Yu et al. then fabricated a metasurface consisting of a periodic array of eight such V-shape antennas, which, as argued before, must exhibit an abrupt phase distribution \( \Phi(x) \) linearly varying in space. According to the Fermat–Huygens law, light reflection/refraction at such an interface must follow the generalized Snell’s law given by Eqs. (7) and (8), which can be understood by the Huygens’ wave interference picture, as shown in Fig. 7(d). Yu et al. performed angle-resolved optical measurements in the mid-IR regime to unambiguously demonstrate such unusual behaviors [see Fig. 7(c)]. Several months later, Ni et al. fabricated a metasurface through down-scaling the sizes of V-shaped antennas and experimentally demonstrated that the anomalous reflection and refraction effect held in the near-IR regime [162]. Moreover, the authors showed that such effect can work within a very broad wavelength region [see Fig. 7(g)].
in sharp contrast to the narrowband resonance-induced effects in periodic metasurfaces/metamaterials. Furthermore, Aieta et al. experimentally demonstrated out-of-plane anomalous reflections and refractions based on a similar metasurface [165] by purposely setting $\vec{k}_i$ not parallel to $\nabla \Phi$.

Despite the great successes achieved, such V-antenna metasurfaces exhibit certain shortcomings. First, the working mechanism of a V-antenna dictates that one can utilize only its cross-polarized scattered field, which is quite inconvenient for some applications. Meanwhile, since the co-polarized scattered fields do not exhibit the desired phases, they will be normally reflected and refracted governed by the original Snell’s law, as shown in Fig. 7(c) by the black curves. Finally, since V-antennas can radiate to both sides symmetrically as electric dipoles, so the scattered fields form transmitted and reflected beams simultaneously. Therefore, there exist altogether four different channels to scatter light by the V-antenna array, which are normal/anomalous reflection/transmission modes. As a result, the efficiency of the desired anomalous refraction, being only one of these four channels, is quite low (about 10%) [164]. Moreover, in designing such metasurfaces, one needs to choose V-antenna arrays exhibiting nearly equal amplitudes but different phases for the cross-polarized scattered field. This is again not a trivial task since one needs to carefully balance the influence of structural optimizations on amplitude and phase, which are usually tightly correlated.

Half a year later, Sun et al. [161] proposed an alternative approach that can overcome most of the deficiencies of V-antenna metasurfaces mentioned above, particularly the efficiency issue. More importantly, the authors also developed a new scheme to couple propagating waves (PWs) to surface waves (SWs) with nearly 100% efficiency based on gradient metasurfaces. We will discuss the PW–SW couplings in Subsection 3.3 with more detail, and here we focus only on efficiently controlling PWs using metasurfaces. The new strategy is based on a reflection geometry for which one does not need to worry about transmission. The key idea can be understood by the following argument [Fig. 7(e)]. As a plane EM wave strikes on flat metal, electric currents are excited on different parts of the metal surface, which, in turn, work as secondary sources to radiate to free space. The interference among waves radiated from those sub-sources form the wavefront of the reflected light. Under normal incidence, these sub-sources all exhibit the same initial phases and, thus, their interference must form specular reflection. Suppose we put an ultrathin slab with appropriate $\varepsilon(x)$ and $\mu(x)$ onto the metal [see Fig. 7(e)], and reconsider the reflection properties of the system. Now the initial phases of sub-sources can be tailored to arbitrary values depending on exact values of $\varepsilon$ and $\mu$ at each local position. As a result, one can tune the forms of $\varepsilon(x)$ and $\mu(x)$ to make the reflection phase $\Phi(x)$ of the whole device satisfy a linear distribution. The existence of a metal ground plane ensures that the reflection amplitudes at different local positions are all 100%, which already implies the high (nearly 100%) efficiency of the device. Indeed, the authors employed a rigorous mode expansion method to calculate the scattering properties of such a model system [161,166], showing that it can inherently support nearly 100% efficiency anomalous reflection. Sun et al. further designed/fabricated two realistic gradient metasurfaces with different phase gradients based on the effective-medium model, and performed microwave experiments to demonstrate that they support nearly 100% efficiency anomalous reflection to different angles dictated by the designed phase gradients [see Fig. 7(f) for one example). The building block of these metasurfaces is a MIM meta-atom, as was discussed in Subsection 2.2, consisting of a metallic H-shape antenna and a metal plate separated by a 1 mm thick dielectric spacer. As such a meta-atom is illuminated by an LP wave, anti-parallel currents are induced on two metallic layers, resulting in magnetic resonance (see Subsection 2.1). The whole structure can be modeled as a double-layer effective-medium system consisting of a flat metal
capped by a homogeneous layer exhibiting a highly dispersive $\mu$ [18]. As argued in Subsection 2.1b, the reflection phase $\Phi$ of such a meta-atom can vary in the whole $2\pi$ range as frequency changes, which is highly desired for metasurface designs. By setting the working frequency as 15 GHz, the authors carefully tuned the arm length of the H to find a set of MIM meta-atoms exhibiting different reflection phases, and adopted them to realize a series of gradient metasurfaces with different phase gradients $\xi (= d\Phi/dx)$. A picture of a metasurface fabricated with $\xi = 0.8k_0$ (with $k_0 = \omega/c$) is depicted in the inset of Fig. 7(f). The authors then characterized the scattering patterns of these metasurfaces under illumination of normally incident microwaves. Clearly, the normally incident wave is deflected to a non-specular direction with $\theta_r = 53^\circ$ by the metasurface with $\xi = 0.8k_0$, which is consistent with the theoretical prediction based on Eq. (7) [see Fig. 7(f)]. The authors also demonstrated, through both numerical simulations and experiments, the generalized Snell’s law by measuring the relation between $\theta_r$ and the incident angle $\theta_i$ on samples with different $\xi$. The high efficiencies of these metasurface devices can be clearly seen from the measured scattering patterns. Several months later, Sun et al. successfully pushed the idea forward, and experimentally demonstrated a highly efficient reflection-type gradient metasurface in the near-IR regime [163]. The fabricated device is still based on MIM meta-atoms, only with the H resonators replaced by gold nanorods to alleviate the fabrication challenges [Fig. 7(h)]. The authors experimentally characterized the scattering patterns of such a device at different incident angles and wavelengths [Fig. 7(i)], and the results obtained show that the anomalous reflections exhibit very high efficiencies ($\sim 80\%$) and a wide working band (750–900 nm). In addition, such metasurface was also proposed as a polarization beam splitter [163], which was soon experimentally realized by Bozhevolnyi’s group [167]. Compared with the V-antenna metasurfaces, such MIM metasurfaces exhibit the following apparent advantages: 1) their working efficiencies are intrinsically high, since all transmission channels are blocked and the normal reflection mode can also be suppressed through careful design, 2) the anomalous mode exhibits the same polarization as that of the incident light, and 3) they are relatively easy to design since one does not need to worry about the amplitude fluctuation of these meta-atoms.

However, the MIM metasurfaces, although exhibiting high efficiencies, work in reflection geometry, which is still inconvenient for certain applications. In 2013, based on the general concept of Huygens’ surfaces, Pfeiffer and Grbic proposed a new strategy to design high-efficiency gradient metasurfaces to manipulate the EM wavefronts at the transmission side [168]. Noting that the V-antennas exhibit purely electric responses and radiate to both sides, the authors proposed to adopt meta-atoms exhibiting simultaneous electric and magnetic responses, which, through careful structural optimization, can radiate only to the transmission side after being excited. Equivalently, these meta-atoms can also be viewed to possess impedance matched perfectly with that of air (through tuning their electric and magnetic responses appropriately), so that they can allow perfect transmission of EM waves without reflection. Figure 8(a) depicts a representative meta-atom adopted by the authors, which consists of a metallic cut wire and an SRR to provide the desired electric and magnetic responses, respectively. By carefully tuning the structural parameters, the authors successfully designed a series of meta-atoms with (nearly) 100% transmission amplitudes and linearly varying transmission phases covering the full range of $2\pi$ at a target frequency of 10 GHz. By fabricating a gradient metasurface based on these transparent Huygens’ meta-atoms, the authors experimentally characterized the transmission/reflection properties of the device under normal-incidence excitation. The results obtained clearly demonstrated the anomalous beam bending effect enabled by the metasurface, as shown in Fig. 8(a). In sharp contrast to the V-antenna metasurface, such a Huygens’ metasurface
Generalized Snell’s law. (a) Reflectionless Huygens’ metasurface. Left panel: schematic of one representative Huygens’ meta-atom. Right panel: simulated magnetic field ($H_z$) of a $y$-polarized plane wave normally illuminated on the gradient Huygens’ metasurface [168]. (b) Schematic (left panel) and simulated beam-refraction effect (right panel) of an optically thin, isotropic Huygens’ metasurface working at telecommunication wavelengths [169]. (c) Left panel: schematic of the hybrid bilayer plasmonic metasurface, composed of one layer of gold nanoantennas on the top and its Babinet-inverted pattern at the bottom, separated by conformal dielectric pillars. Right panel: measured anomalous transmitted field intensity as a function of wavelengths and refraction angle [170]. (d) Transmissive metasurface composed of single layer C-antennas for achieving the broadband THz wave bending effect. Left panel: optical image of the fabricated sample. Right panel: transmission amplitude and phase shift of the $y$-polarized component of the proposed structure under $x$-polarized incidence at 0.63 THz [171]. (e) High-efficiency anomalous refraction effect. Left panel: proposed metasurface composed of eight resonators creating a linear phase shift of the cross-polarized transmission over a $2\pi$ range and two orthogonal metallic gratings perpendicular to each other. A normally incident $x$-polarized wave is deflected to the anomalous refraction channel with the cross-polarization. Right panel: measured cross-polarized transmittance as a function of frequency and angle, compared to theoretical prediction (dashed curve) [77]. (f) Beam bending by coding metasurface. Left panel: the 1 bit digital metasurface composed of two types of elements, “0” and “1”. Right panel: simulated scattered field distribution of the 1 bit metasurface [173]. (g) Dielectric meta-reflectarray for the beam bending effect. Left panel: simulated cross-polarized reflection magnitude and phase maps for resonators with different geometry (bottom) and schematic of eight resonators that provide a phase shift from 0 to $2\pi$ (top). Right panel: simulated electric field pattern of the meta-reflectarray illuminated by a normally incident $x$-polarized Gaussian beam. The wavelength is 1550 nm [174]. (h) Left panel: metasurfaces consisting of trapezoid shaped silver plasmonic antenna arrays in an MIM configuration. Right panel: a photograph of various reflection modes of the redirected beam [175]. (a) Figure 2 reprinted with permission from Pfeiffer and Grbic, Phys. Rev. Lett. 110, 197401 (2013) [168]. Copyright 2013 by the American Physical Society. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.197401.
exhibits a maximum efficiency of 86%, which is even comparable to that of the MIM metasurface. However, directly scaling down the microwave sample to optical frequencies is difficult, since the meta-atoms are complex 3D non-flat structures, which are very challenging to fabricate. Alternatively, Pfeiffer et al. adopted a multi-layer metallic structure as building block to design a Huygens’ metasurface working at telecommunication wavelength [see Fig. 8(b)], in which the magnetic response is induced effectively through the inter-layer couplings [169]. Unfortunately, the working efficiency of the fabricated device is only 18% in experiment and is 30% in full-wave simulation. Compared to early microwave realizations, the low efficiency of such optical Huygens’ metasurface is due to strongly enhanced ohmic losses of plasmonic metals at optical frequencies and fabrication imperfections. New structures have also been proposed. For example, Monticone et al. proposed a metasurface configuration to control the transmission wavefronts efficiently [176]. The meta-atoms proposed are essentially parallel-plate waveguides composed of plasmonic and dielectric thin films, which, upon careful optimization, can support high transmission of light with different transmission phases. Full wave simulations demonstrated that 75% of the incident Gaussian beam can be deflected to the off-normal direction after transmission. In 2013, Chen’s group utilized multilayer meta-atoms as building blocks to construct high-efficiency transmissive metasurfaces, but working at THz frequencies, as depicted in Fig. 8(e). Moreover, the newly realized metasurfaces combine the functionalities of wavefront controls and polarization rotation with very high efficiencies and within a broad frequency band, which goes a step further over a standard Huygens’ metasurface [77]. Such improvement is enabled by a series of smartly designed three-layer meta-atoms, each consisting of two orthogonally placed metallic gratings inserted with a cut-wire resonator with the symmetric axis lying between two gratings. Based on the mechanism presented in Subsection 2.3, such meta-atoms can allow high transmission of cross-polarized THz waves with phases tuned by adjusting the structures of the cut-wire resonators. The authors designed and fabricated a gradient metasurface utilizing such meta-atoms, and experimentally demonstrated that the device can enable anomalous refraction and polarization rotation simultaneously for incident THz waves, as shown in Fig. 8(e) [77]. The maximum efficiency of the device is 61% at 1.4 THz with an anomalous refraction angle $\theta_r = 24^\circ$, which is quite remarkable considering the non-negligible losses of metals at this frequency domain, not mentioning the added advantage of polarization-control functionality. Researchers have continued to report new configurations to achieve anomalous deflection of light, and these are briefly summarized here. In transmission geometry, Qin et al. proposed a bilayer plasmonic metasurface to enhance the efficiency for reshaping visible light [170]. As shown in Fig. 8(c), the metasurface consists of
two physically separated plasmonic structures, with top layer being a gold V-antenna array, while the bottom one is its Barbinet-inverted structure. The proposed hybrid metasurface can achieve a high cross-polarization conversion efficiency (36% in simulation and 17% in experiment), with physics governed by strong interlayer couplings that can excite both electric and magnetic responses. Zhang et al. utilized C-shaped resonators to construct a gradient metasurface to tailor the wave fronts of THz waves [171]. By varying the radius \( r \) and the opening angle \( \alpha \) of the split rings, the authors obtained a series of split rings that can allow cross-polarized transmission with nearly constant amplitudes and linearly varying phases, which are used to construct a gradient metasurface, as shown in Fig. 8(d). The fabricated device can achieve a broadband anomalous refraction effect from 0.57 to 1 THz, with a maximum deflection angle of 84°.

In reflection geometry, Cui et al. extended the concept of gradient metasurface to a “digital” metasurface [173]. The key idea is to use meta-atoms with discretized phase values as digital elements to construct metasurfaces. In a 1 bit realization, one needs only two meta-atoms exhibiting 0 and \( \pi \) reflection phases to construct metasurfaces with different functionalities. For instance, a metasurface composed of such 2 bits arranged periodically can deflect the incident wave to two diffraction channels, as shown in Fig. 8(f). By changing the coding sequence or increasing the bit number, the authors realized digital metasurfaces with more functionalities, including beam manipulation and scattering reduction [177]. To reduce the ohmic losses at high frequencies, Yang et al. proposed to replace plasmonic metals with high-index silicon to construct a reflection-type metasurface [174]. As shown in Fig. 8(g), the building block consists of eight 45° or 135° oriented silicon short wires and a silver background plane with an ultrathin (200 nm) PMMA spacer. Based on the phase diagram shown in Fig. 8(g), the authors sorted out four silicon antennas, all providing high cross-polarization reflection amplitude but with different reflection phases covering a \( \pi \) range. By rotating those four antennas by 90°, another set of four antennas with reflection phases covering the remaining \( \pi \) range are obtained, which, together with the original four, are used to construct a gradient metasurface, as shown in Fig. 8(g). Such a scheme is quite similar to that of the V-antenna metasurface [160], but realized with dielectric materials. Figure 8(g) shows the simulated cross-polarization reflection field distribution at the wavelength of 1550 nm for the x-polarization incidence case. The calculated working efficiency of such an anomalous deflector is about 83%, which is higher than its plasmonic counterpart, but with the shortcoming of increased device thickness. In 2015, Li et al. reported a simple metasurface design to achieve anomalous reflection for visible light within a broad band. The device consists of trapezoid-shaped silver antenna arrays and a thick silver mirror separated by the thin SiO\(_2\) spacer, as shown in Fig. 8(h) [175]. Compared to metasurfaces composed of multiple antennas, the present design can provide a quasi-continuous local reflection phase shift covering the full 2\( \pi \) range, due to the continuously varied antenna width in a single structure. Meanwhile, the reflection amplitude is very high. The device can achieve a broadband co-polarized anomalous reflection effect (450–850 nm) with the highest measured efficiency of 85%, with loss taken into account.

3.2. Geometric-Phase Metasurfaces for Manipulating Circularly Polarized EM Waves
The metasurfaces described in the last subsection all work for LP EM waves, and are constructed by planar resonators with different structures [160,162,161,163,165]. However, such resonance-based metasurfaces suffer from the following issues. First, the phase profiles provided by such metasurfaces inevitably deviate from the correct ones at frequencies away from the working one at which the meta-atoms are designed, due to the intrinsic frequency dispersions of resonant structures, which
ultimately leads to limited working bandwidths. Second, to design such metasurfaces involving different meta-atoms with distinct EM responses, one has to perform full-wave simulations to optimize the structures of each meta-atom, which are time consuming, particularly for metasurfaces exhibiting sophisticated functionalities. Finally, fabrication of such metasurfaces (especially working at optical frequencies) is challenging and requires precise controls on complex structures with fine differences.

Facing these challenges, scientists have continued to search for new mechanisms to construct metasurfaces. Pancharatnam–Berry (PB) metasurfaces, built with identical meta-atoms oriented with particular angles, thus exhibiting geometry-originated phases for scattered EM waves, are an alternative type of metasurface that can manipulate the wavefronts of circularly polarized (CP) EM waves [178,179]. Because such metasurfaces can largely overcome the issues mentioned above, they have quickly become a widely studied class of systems in parallel with the resonance-based metasurfaces. We first briefly describe the origin of such PB phases. Consider an arbitrary anisotropic planar structure (say, a metallic bar) placed on the $x$–$y$-plane and illuminated by normally incident CP light with a certain spin [spin-up $\sigma = 1$, left CP (LCP); spin-down $\sigma = -1$, right CP (RCP)]. Upon excitation, the resonator can generate electric currents flowing along the $x$ and $y$ axes with different amplitudes and a 90° phase difference. Such differences in response along two orthogonal directions, manifesting the anisotropic nature of the resonator, ensure that the wave scattered by the resonator contains both spin-conserved and spin-reversed components. The spin-conserved scatterings are less interesting, but the spin-reversed scatterings are quite non-trivial. In a pioneering work, Pancharatnam first discovered [180] that spin-reversed scattering can possess an additional phase factor $e^{i2\theta}$ as the planar structure is rotated by an angle $\theta$ with respect to the $z$ axis [see Fig. 9(a)], which was later interpreted as a geometrical phase by Berry in Ref. [184]. The geometrical origin of such an additional phase can be understood with the help of the Poincaré sphere, as shown in Fig. 9(a). Specifically, the spin-reversed scatterings by two objects in Fig. 9(a) can be interpreted as two lines on the Poincaré sphere that connect the north and south poles, and pass through the equator at different points separated by an angle $\theta$. The phase difference between these two processes is the solid angle surrounded by two curves, which is precisely twice of $\theta$. Such a phase can be interpreted as a Berry phase carried by a photon moving in an adiabatic process represented by the closed loop on the Poincaré sphere. One unique feature of the PB phase is that it is solely dictated by the orientation angle of the scatter, and thus it is frequency non-dispersive. Moreover, the PB phase changes its sign as the incident spin state changes from $\sigma = 1$ to $\sigma = -1$. Finally, one should bear in mind that the spin-reversed scattering actually contributes to the spin-maintained reflection, since the definition of spin is associated with the wavevector of the EM wave, which is reversed after reflection.

Even before the concept of metasurface appeared, Hasman’s group had already done a series of pioneering works utilizing such a mechanism to build spin-dependent optical devices [178]. As shown in Fig. 9(a), the first device realized in 2002 consists of subwavelength dielectric gratings with local periodic direction varying linearly in space. Because the local period is much smaller than the wavelength, the grating can be effectively regarded as a uniaxial crystal at every local point. Now illuminate the device with CP light with different spin. Since the local uniaxial axis of the system changes continuously from 0 to $\pi$ within one supercell, the spin-reversed wave transmitted through the device at a local position must carry a PB phase, which is linearly varying in space covering the full $2\pi$ range over a supercell [see Fig. 9(a)]. The spatial phase gradients are of opposite signs for incident CP light with different spin. Therefore, the spin-reversed components of waves transmitted through such a device, formed by interference among those locally transmitted waves possessing different PB phases,
must propagate to two opposite oblique directions depending on the input spin, generating a spin-dependent diffraction, which is now called the photonic spin-Hall effect (PSHE). The authors then fabricated a sample with a periodicity $\Lambda = 3.2$ $\mu$m and a periodicity $\Lambda_0 = 0.136$ $\mu$m.

**Figure 9**

Pancharatnam–Berry (PB) metasurfaces. (a) PB phase optical elements with computer-generated subwavelength gratings. Left panel: illustration of the origin of PB phase based on the Poincaré sphere. Right panel: geometry of the subwavelength grating as well as the PB phase profiles for LCP and RCP illumination [178]. (b) PSHEs in plasmonic chains. Left panel: SEM images of two different plasmonic metasurfaces for achieving PSHE. Right panel: the spin-dependent momentum deviation for a metasurface composed of spatially orientated rectangular apertures for different input spin states at a wavelength of 730 nm [179]. (c) Left panel: SEM image of a PB metasurface composed of gold nanorods fabricated on the SiO$_2$ substrate. Right panel: phase distributions of both incidence and refraction with different spins obtained by full wave simulations. Here, the wavelength is 1020 nm [181]. (d) PSHE with nearly 100% efficiency in reflection geometry. Left panel: schematics of the 100% efficiency PSHE realized at our reflective metasurface. Right panel: measured normalized scattered-field intensities versus frequency and reflection angle for one high-efficiency metasurface under different spin polarized illuminations [182]. (e) PSHE with nearly 100% efficiency in transmission geometry. Top: illustration of the principle of the 100% efficiency transmissive PB meta-atoms with both electric and magnetic dipolar responses (left panel) and measured electric field distributions (real part) of the vortex beam with topological charge of $q=1$ (right panel) generated by the metasurface depicted in the bottom right panel. Bottom: part of the image of the fabricated high-efficiency vortex beam metasurface generator (right panel) formed by ABA meta-atoms (left panel) [183]. (a) Reprinted with permission from [178]. Copyright 2002 Optical Society of America. (b) Reprinted with permission from Shitrit et al., Nano Lett. 11, 2038–2042 (2011) [179]. Copyright 2011 American Chemical Society. (c) Reprinted with permission from Huang et al., Nano Lett. 12, 5750–5755 (2012) [181]. Copyright 2012 American Chemical Society. (d) Luo et al., Adv. Opt. Mater. 3, 1102–1108 (2015) [182]. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission. (e) Figures 3 and 7 reprinted with permission from Luo et al., Phys. Rev. Appl. 7, 044033 (2017) [183]. Copyright 2017 by the American Physical Society. https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.7.044033.
performed optical measurements at the wavelength 10.6 μm. Experimental results clearly verified the predicted effects, showing that spin-reversed diffraction modes appear at the desired angles for RCP and LCP illumination, respectively.

The rapid advances in plasmonics offer abundant choices to design PB optical elements. In 2011, Hasman’s group further demonstrated a plasmonic device that can realize the PSHE [179]. As shown in Fig. 9(b), the device is a 200 nm thick gold film etched with a collection of air holes arranged in a curve such that the direction of the air-hole chain varies spatially as $\theta = \pi x / a$. Although every individual nanoaperture possesses an *isotropic* shape, the transmission spectra at different positions do exhibit *anisotropic* responses, caused by inter-aperture couplings that result in distinct plasmonic coupled modes for transverse and longitudinal excitation. Therefore, the curved plasmonic chain can be regarded as a collection of anisotropic meta-atoms with spatially varying orientations, generating a linearly varying phase profile for the spin-reversed scattered light, which, in turn, results in the PSHE. The authors performed optical experiments to clearly demonstrate the desired PSHE enabled by the fabricated device [see Fig. 9(b)]. In addition to utilizing the coupling-induced anisotropy, Hasman’s group further directly utilized a nanoaperture with *anisotropic* shape to generate the desired PB phases. In the same work [179], Hasman’s group fabricated another plasmonic device consisting of *identical* rectangular apertures with orientation angles linearly varying in space, arranged in a straight line instead of a curved one [see Fig. 9(b)]. Optical experiments nicely demonstrated the PSHE realized by the device. Such an excellent series of pioneering works laid a solid basis for future developments along this direction. However, these early-version PB devices either exhibit very low efficiencies or have thicknesses comparable to wavelength (the dielectric devices), and exhibit only beam-bending functionalities (i.e., PSHE).

The emergence of the metasurface concept significantly stimulated the development of PB metadevices based on geometric phases. In 2012, Li’s group theoretically proposed a more efficient PB device utilizing a split-ring slot antenna as the building block to achieve spin-dependent wavefront control [185]. A complex-shape antenna can provide more degrees of freedom to tailor spin-reversed scattering strengths, thus yielding a more efficient wave-control effect. Several months later, Zhang’s group further proposed to use a nanoparticle with *anisotropic* shape as the building block to build PB devices, which exhibit further enhanced working efficiencies because less metal is adopted as compared to previous devices [181]. Moreover, Zhang’s group fabricated a device consisting of an array of rectangular patch antennas with orientation angles linearly varying in space [see Fig. 9(c) for the sample picture], and then experimentally characterized its angle-resolved transmission properties under the illumination of CP light with spin $\sigma$. Indeed, experiments revealed clearly that the spin-reversed transmission modes are refracted to two off-normal directions at two different sides of the surface normal. In fact, within a unified framework developed for metasurfaces in Subsection 3.1, the anomalous transmission (and reflection) on such PB metasurfaces can be described by the following (spin-dependent) generalized Snell’s law:

\[
\begin{align*}
\begin{cases}
    n_i \sin \theta_r - n_i \sin \theta_i &= \sigma \frac{2\pi}{\lambda} \frac{d\phi}{dx} \sin \theta, \\
    n_i \sin \theta_r - n_i \sin \theta_i &= \sigma \frac{2\pi}{\lambda} \frac{d\phi}{dx},
\end{cases}
\end{align*}
\]  

where $\sigma \frac{d\phi}{dx} = \sigma \frac{2\theta}{S}$ is the phase gradient with $\sigma$ denoting the spin of incident light, and $\theta, S$ denote, respectively, the orientation-angle difference and spatial distance between two adjacent meta-atoms. Compared to Eqs. (7) and (8) in Subsection 3.1, now $\sigma$ is another degree of freedom to control the generated physical effects (e.g., PSHE).
Now consider another slab with all meta-atoms rotated by an angle of \( \times 2 \). Interestingly, these Jones matrices can be expanded to linear combinations of four basic matrices, i.e., the unit matrix and the Poincaré sphere. Suppose that a generic slab formed by a periodic array of PB meta-atoms is placed on the \( x-y \) plane. The transmission/reflection properties of the slab can be generally described by two Jones matrices, \( T(0) = \begin{pmatrix} t_{uu} & t_{uv} \\ t_{vu} & t_{vv} \end{pmatrix} \) and \( R(0) = \begin{pmatrix} r_{uu} & r_{uv} \\ r_{vu} & r_{vv} \end{pmatrix} \), where \( u, v \) denote two principle axes of the meta-atoms. By changing the basis from LP to CP via defining two unit vectors \( \hat{u} \) and \( \hat{v} \), one obtains the forms of two Jones matrices in CP bases \( \hat{T}(0) \) and \( \hat{R}(0) \).

Now consider another slab with all meta-atoms rotated by an angle of \( \phi \) with respect to the \( z \) axis. One can easily derive its Jones matrices in CP bases as \( \hat{T}(\phi) \) and \( \hat{R}(\phi) \).

Interestingly, these Jones matrices can be expanded to linear combinations of four basic \( 2 \times 2 \) matrices, i.e., the unit matrix \( \hat{I} \) and three Pauli matrices \( \{\hat{\sigma}_1, \hat{\sigma}_2, \hat{\sigma}_3\} \). For example,

\[
\hat{R}(\phi) = \frac{1}{2} (r_{uu} + r_{vv}) \hat{I} + i \frac{1}{2} (r_{uv} - r_{vu}) \hat{\sigma}_3 + \frac{1}{2} (r_{uu} - r_{vv}) (e^{-i\phi} \hat{\sigma}_+ + e^{i\phi} \hat{\sigma}_- + i (r_{uv} + r_{vu}) (e^{-i\phi} \hat{\sigma}_+ + e^{i\phi} \hat{\sigma}_-),
\]

where \( \hat{\sigma}_\pm = (\hat{\sigma}_1 \pm i \hat{\sigma}_2) / 2 \) are two spin–flip operators satisfying \( \hat{\sigma}_\pm |\pm\rangle = 0 \) and \( \hat{\sigma}_\pm |\mp\rangle = |\pm\rangle \), with \( |\pm\rangle \) denoting the spin-up and spin-down states, respectively.

Equation (11) revealed the underlying physics clearly. Obviously, the first two terms in Eq. (11) represent the spin-conserved scattering, while the last two terms change the spin state of incident light. While the spin-conserved scatterings do not carry any additional phase, the spin-flipped ones do carry PB phases \( e^{\pm 2\phi} \) depending on the incident spin. Thus, any PB metadevice formed by such a meta-atom must simultaneously contribute a normal reflection mode and an anomalous reflection mode, with power efficiencies given by \( R_n \equiv (|t_{uu}|^2 + |r_{uv}|^2) / 4 \) and \( R_d \equiv (|t_{uu} - t_{uv}|^2 + |r_{vu} - r_{vv}|^2) / 4 \), respectively. The same argument applies to the transmission Jones matrix \( \hat{T}(\phi) \), only with \( \{r_{uu}, r_{uv}, r_{vu}, r_{vv}\} \) replaced by \( \{t_{uu}, t_{uv}, t_{vu}, t_{vv}\} \). Therefore, in pure reflection geometry, the criterion to achieve 100% efficiency PB device is then

\[
r_{uu} + r_{vv} = r_{uv} - r_{vu} = 0,
\]

implying that the normal reflection channel should be terminated, leaving all the incident power transferred to the anomalous reflection channel in the ideal lossless case.

Based on these criteria, the authors designed two microwave PB metasurfaces, constructed with meta-atoms either with mirror symmetry or not, but both with Jones’
matrices satisfying the criteria [Eq. (12)]. Designing the symmetric meta-atom is straightforward, as now the criterion [Eq. (12)] is reduced to $r_{uu} = -r_{vv}$, implying that the desired meta-atom is nothing but an ideal wave plate. Such a task is easy to finish as one already gained lots of experience in designing polarization-control devices using periodic metasurfaces (Subsection 2.3). Indeed, the symmetric meta-atom is just an MIM structure with an anisotropic-shaped top resonator. Such a meta-atom naturally totally reflects EM waves for two polarizations, and one needs only to carefully adjust the structure to make the reflection-phase difference $(\phi_{uu} - \phi_{vv})$ stay at $\sim \pi$ within a wide frequency window. Designing the asymmetric meta-atom is a bit complicated and will not be described in detail here. With two meta-atoms successfully designed, the authors then fabricated two wave-bending PB metasurfaces, and performed microwave experiments to characterize their reflection properties. Far-field measurements clearly demonstrated that nearly all LCP components of an incoming wave are reflected to the left side of surface normal, while all RCP components are reflected to the right side, within a frequency band of 10–14 GHz. In particular, the normal reflections are completely suppressed, which ensures the high working efficiency of the device (>90%). The performance of another metasurface is similar to that of the symmetric metasurface. Such criteria are important as they make possible the design of high-efficiency PB metadevices, which are highly desired for future applications. We note that at a similar time, Zhang’s group also independently discovered a similar criterion, and they further utilized the criterion to design/fabricate an optical PB metasurface to achieve hologram imaging with exceptionally high efficiency (~80%) [188]. We will discuss it with more detail in Subsection 4.2.

100% efficiency PB metasurfaces in transmission geometry are even more desirable in applications, but are also more difficult to realize [183]. In 2017, Luo et al. examined the problem and found that 100% efficiency metasurfaces can be obtained as long as we get appropriate meta-atoms exhibiting Jones-matrix elements that satisfy

$$r_{uu} = r_{vv} = 0, \quad |t_{uu}| = |t_{vv}| = 1, \quad \arg(t_{uu}) = \arg(t_{vv}) \pm \pi. \quad (13)$$

However, a single-layer resonator exhibiting an electric response only can never fulfill the above condition [31], since it will radiate to both sides, and thus we cannot independently tune the reflected and transmitted waves. Such a constraint can be released if the meta-atom exhibits both electric and magnetic responses. As shown in Fig. 9(e), the electric fields radiated from an electric (magnetic) dipole are symmetrical (antisymmetrical) at two sides of the dipole. Therefore, one can independently control the radiation at two sides of the meta-atom by tuning its electric and magnetic responses appropriately. In further adding appropriate anisotropy, one thus obtains a transmissive meta-atom with Jones-matrix elements satisfying Eq. (13). Inspired by Ref. [25], Luo et al. adopted the ABA structure to design a 100% efficiency PB meta-atom [Fig. 9(e)], in which the magnetic response is induced by the couplings between two metallic layers. Here, layer A contains an array of metallic bars, while layer B is a holey metallic film loaded with metallic bars, and two dielectric spacers are adopted to separate them. Through careful optimization, the authors obtained an ABA meta-atom with Jones-matrix elements satisfying Eq. (13) within a frequency window centered at 10.5 GHz. With such a building block at hand, the authors fabricated two microwave PB metasurfaces and experimentally demonstrated that they can realize PSHE and vortex beam generation [Fig. 9(e)] with very high efficiencies (~91%).
Before concluding this subsection, we would like to compare the two widely studied metasurfaces:

1) PB metasurfaces work for CP light, while the resonance-phase ones work for LP light.
2) The phase responses of PB metasurfaces are usually non-dispersive, while those in resonance-phase ones suffer from strong frequency dispersion. However, the working efficiencies of PB metasurfaces strongly depend on frequency, indicating that such systems still have frequency dispersion.
3) PB metasurfaces usually exhibit correlated functionalities under illumination with different spin, while the resonance-phase ones do not have such a constraint.
4) PB metasurfaces are usually easy to design and fabricate, while the same things are not true for the resonance-phase metasurfaces.

3.3. Linking PWs and SWs with Metasurfaces

Most optical devices are based on manipulating propagating waves (PWs) in the free space. There is, however, another type of wave propagation mode called “surface wave” (SW), which plays an important role in modern photonics research, particularly for on-chip applications. SWs generally denote fundamental EM eigenmodes, bounded at certain interfaces between two different optical media, that can transport only on the interface, with field strength exponentially decaying as they leave the interface. An SPP is an important type of SW, existing on dielectric/metal interfaces at near-IR (NIR) and optical frequencies typically associated with charge oscillations inside the plasmonic metal. Because of their extraordinary properties, i.e., subwavelength lateral resolution and a strongly enhanced near field at the interfaces, SPPs have drawn intensive interest in physics, chemistry, and biology [189], and have been widely used in superresolution imaging [190,191], biosensing and chemical sensing [192,193], enhanced Raman [194] and nonlinear effects [195], solar cells [196], and so on. In low-frequency domains (e.g., THz and GHz) where metals usually behave as PECs lacking plasmonic responses, one can design structured metal surfaces that can support spoof SPPs [197,198], which exhibit similar wide-range applications as natural SPPs. Although SWs have many important applications, their efficient excitation is challenging, since far-field light cannot couple directly with SWs due to the inherent momentum mismatch [189]. Many approaches have been proposed to excite SWs, such as using grating and prism couplers. However, these devices are either bulky in size or exhibit intrinsically low frequencies caused by normal reflection at device surfaces and decoupling effects, making them unfavorable for modern photonic applications [199]. Although metamaterials have been used to control PWs and SWs separately, based on, say, transformation optics theory, an efficient bridge to link these two wave-propagation modes is still lacking.

In 2012, Sun et al. proposed that gradient metasurfaces are the very bridge to link these two important modes with essentially 100% efficiency [161]. The working principle is schematically depicted in Fig. 10(a), and is closely related to the discussion of anomalous reflection by MIM metasurfaces in Subsection 3.1. Suppose a reflection-type gradient metasurface is illuminated by a normally incident light. Each meta-atom on the metasurface then radiates to free space as a secondary source with a unitary amplitude and an initial phase linearly depending on its position. When the phase gradient $\xi = d\Phi/dx$ is smaller than $k_0$, interference among these sub-sources can generate an obliquely outgoing beam, leading to the anomalous reflection effect [see Fig. 7(f)]. Intriguingly, when $\xi > k_0$, radiation from these sub-sources cannot construct any PW with an equal-phase plane [see Fig. 10(a)] [161], but rather form an SW bounded by the metasurface. Such an argument can also be understood from the generalized Snell’s law, which is explicitly written as
Gradient metasurface SPP couplers. (a) Schematic of PW–SW conversion processes for gradient metasurfaces with $\xi > k_0$. (b) Left panel: schematic of the near-field scanning technique to demonstrate SW generation. Right panel: $E_z$ field (phase information included) on part of the $\xi = 1.14k_0$ metasurface under $x$-polarized normal illumination, obtained with experiments (top) and simulations (bottom). (c) Measured [including far-field (FF) and near-field (NF)] and simulated parallel $k$ vectors ($k'$) of the waves reflected by the $\xi = 0.8k_0$ metasurfaces, illuminated by $x$-polarized waves of different incident angle $\theta_i$. (d) Top: experimental setup for demonstrating the process of guiding driven SWs outside the metasurface. Bottom: measured $E_z$ distribution on both the metasurface and the mushroom surface. (e) Left panel: sketch of 1D periodic metasurface illuminated by a TM-polarized (i.e., $x$-polarized) normally incident light. Right panel: amplitude and phase of reflected light from the metasurface as a function of strip width $w$ when $\lambda = 1500$ nm, periodicity $\Lambda = 489$ nm, and $d = t = 50$ nm. (f) Simulated $E_z$ field patterns inside the gradient metasurface SPP coupler based on the unit structures in (g), illuminated by $x$-polarized normally incident light at $\lambda = 1500$ nm. (g) SEM images of the fabricated 1D (left) and 2D (right) SPP metasurface couplers. (h) Leakage radiation microscopy images showing polarization-controlled SPP excitation inside the 2D SPP coupler at $\lambda = 1500$ nm. (i) Left panel: key issues that degrade the efficiencies of conventional SPP couplers (e.g., grating and prism couplers), the initial reflection loss, and the decoupling loss from SPPs to free space. Right panel: configuration of the SPP metacoupler. A transparent gradient metasurface is placed at an optimized distance above the plasmonic metal. The incident wave is first converted into a driven SW bound on the metasurface and is then resonantly coupled to the eigen SPP wave on the plasmonic metal. Neither reflection loss at the metasurface nor decoupling from the SPP to free space occurs. (j) Simulated $H_y$ field distribution showing SPP excitation by the effective-medium-based metacoupler with 94% efficiency. (k) Left panel: schematic of five designed ABA-type meta-atoms,
Now, with an additional wavevector \( \xi \) provided by the gradient metasurface, the “reflected wave” exhibits a tangential wavevector larger than \( k_0 \) even under normal excitation, making it an SW bounded at the interface. Different from conventional PW–SW conversion schemes, here the momentum mismatch between PW and SW is compensated by the phase gradient provided by the metasurface. In addition, the scheme is intrinsically of high efficiency since the SW is the only channel for the wave to go, while there are many channels in other couplers (say, the grating coupler). Indeed, numerical simulations based on an ideal model system (a PEC capped with a thin dielectric layer with continuously varying refraction index) without super-periodicity demonstrated that the PW–SW conversion efficiency can be as high as 98% [161].

To experimentally demonstrate this prediction, Sun et al. designed and fabricated an MIM metasurface with \( \xi = 1.14k_0 \) at the frequency 15 GHz, using meta-atoms similar to those described in Subsection 3.1. By shining an \( x \)-polarized microwave normally onto the metasurface, the authors found that no “reflected” far-field signals can be detected, verified also by simulations on realistic structures. They next used a monopole antenna to directly probe the local \( E_z \) fields (with both amplitude and phase) on an \( x-y \) plane 2 mm above the metasurface [see Fig. 10(b)]. The measured pattern [upper panel in Fig. 10(b)] unambiguously revealed that the SW nature of the generated “reflected wave,” which has a parallel wavevector larger than \( k_0 \) (very close to \( \xi = 1.14k_0 \)). Finite-difference time-domain (FDTD) simulations [lower panel in Fig. 10(b)] agree well with experimental results.

An important feature of such PW–SW conversion is that it is a non-resonant scheme, which can happen at any incident angle exceeding a critical value \( \theta_i > \theta_c = \sin^{-1}(1 - \xi/k_0) \), as predicted by Eq. (14). This is quite different from the usual PW–SW conversion processes (say, using grating or prism couplers), which typically happen only at particular incident angles. Taking the \( \xi = 0.8k_0 \) sample as an example [Fig. 6(f)], the authors experimentally demonstrated that PW–SW conversion can take place at oblique angles exceeding a critical value [Fig. 10(c)], demonstrating the validity of Eq. (14). However, one should notice that the SW excited with this scheme is not an eigenmode as is a usual SPP, but is in fact a “driven” SW, which can exist only under the illumination of an impinging PW. This also explains why such a PW–SW conversion works for a wide range of incidence angles, since a “driven” SW can take any wavevector not restricted by the SPP dispersion relation.

Such a new mechanism paves the way to realize many SW-related applications, such as high-efficiency SPP couplers, anti-reflection coatings, and light absorbers.
Knowing that the excited SW is still not the desired SPP, Sun et al. designed and fabricated an artificial plasmonic metal (a mushroom structure [202]) supporting an eigen spoof SPP at this frequency, and placed it to the right-hand side of the gradient metasurface to guide the excited “driven” SW out of the metasurface [see Fig. 10(d)] [161]. In their experiments, the authors illuminated only the gradient metasurface by an x-polarized microwave, and used a monopole antenna to measure the $E_z$ distribution on the entire $x$–$y$ plane covering both the metasurface and the “plasmonic” metal. Figure 10(d) depicts the measured $E_z$ distribution, showing clearly that the “driven” SWs on the metasurface are indeed guided out to spoof SPPs on the mushroom structure. Compared to conventional SPP couplers, such a metasurface-based coupler exhibits many advantages, such as much enhanced efficiency, unidirectional excitation, incidence-angle insensitivity, and a miniaturized device size. One year later, Pors et al. pushed the concept forward, demonstrating a unidirectional polarization-controlled SPP metacoupler working at telecommunication wavelength [200]. The fabricated coupler is constructed by the same type of MIM meta-atoms, only with sizes scaled down for high frequencies. Since metals exhibit finite penetration lengths and losses for light in this frequency domain, the authors carefully considered the reflection-amplitude fluctuations of meta-atoms in their design [see Fig. 10(e)]. They first fabricated a one-dimensional (1D) SPP coupler [left-panel in Fig. 10(g)] with phase gradient matching the wavevector of the eigen SPP on the plasmonic metal (without the top metallic patches), and experimentally demonstrated that SPPs can be excited with an efficiency of 27% (47% in simulations [Fig. 10(f)]). The authors next realized a 2D metacoupler exhibiting phase gradients along two orthogonal directions [right panel in Fig. 10(g)]. Experiments show that such a device can excite SPPs flowing along two directions on the plasmonic metal, as illuminated by incident light with different polarizations [see Fig. 10(h)]. However, the measured SPP excitation efficiency is only 15%, which is possibly caused by fabrication imperfections and enhanced material losses at optical frequencies.

In a theory paper, Qu et al. analyzed the key issues that most influence the working efficiency of such SPP couplers [203]. The authors found that, while an ideal gradient metasurface (exhibiting continuously varying permittivity/permeability) can indeed yield light-bending effects with nearly 100% efficiency, practically realized metasurfaces are all composed of supercells exhibiting truncated reflection-phase distributions. Therefore, scatterings naturally exist at the boundaries between adjacent supercells. Such effect is particularly significant for the PW–SW–SPP conversion process, which can decouple the generated SWs back to PWs, since the generated SWs have to flow on the inhomogeneous metasurface before reaching the homogeneous part (i.e., the plasmonic metal). Indeed, calculations show that as the coupler’s size increases, the SPP excitation efficiency gradually decreases, caused by the above-mentioned decoupling effects. As a result, while such SPP couplers are particularly useful in highly miniaturized applications (say, on-chip photonics devices), they are not convenient for SPP excitation with incident light with large beam widths.

Facing these challenges, in 2016 Sun et al. discovered a new strategy to realize SPP metacouplers with very high efficiencies [201]. The authors first sorted out two issues that limit the performance of conventional SPP couplers, which are the reflection losses at the devices’ interfaces and the decoupling of SPPs on metasurfaces, as shown in Fig. 10(i). Having understood these origins, the authors then proposed a new metasurface-based configuration for PW–SPP conversion, which consists of a perfectly transparent gradient metasurface (with $\xi > k_0$) placed at an optimized distance above the target plasmonic metal. The working principle can be described as follows: the metasurface first converts an incident PW to a driven SW bounded at the metasurface, which is then resonantly coupled to an eigen SPP on the plasmonic metal.
The efficiency of such a coupler must be very high since the metasurface is perfectly transparent without reflection, and more importantly, the generated SPP cannot decouple back to a PW due to the broken inversion symmetry of the system. Full-wave simulations on an ideal system verified the concept, showing that the SPP coupling efficiency reaches 94% as the gap distance takes an optimized value, as shown in Fig. 10(j). Such a distance plays a dual role in affecting the conversion efficiency—decreasing it can enhance the efficiency of the PW–SW coupling process but diminish that of the SW–SPP conversion process—and thus one must carefully optimize it to balance the two effects. The authors experimentally demonstrated the concept by making a transparent microwave metacoupler at the frequency 9.2 GHz, based on ABA-type of meta-atoms. Aided by effective-medium analyses, the authors successfully designed five different ABA structures, all allowing high transmission for EM waves but exhibiting different transmission phases covering the entire $2\pi$ range [Fig. 10(k)]. The authors then fabricated a transparent gradient metasurface and put it at 1 mm (an optimized value obtained via full wave simulations) above an artificial plasmonic metal (a mushroom structure), as shown in Fig. 10(l). Illuminating the metacoupler by an $x$-polarized microwave at 9.2 GHz, the authors performed near-field scanning experiments to demonstrate that the incident PW has indeed been successfully converted to an SPP flowing on the “plasmonic” metal [see the well-defined SPP field pattern depicted in Fig. 10(l)]. Far-field experiments further indicate that the SPP conversion efficiency of the device reaches 73%, which is the highest among all SPP couplers available in this frequency domain. These findings point out a new direction to design high-performance SPP couplers, but realizing them is challenging in high-frequency domains.

We note that the SPP excitation directions are fixed (dictated by the signs of phase gradients) once the metacouplers mentioned above are fabricated. Meanwhile, PB metasurfaces can exhibit helicity-controlled phase profiles, which offer the possibility to realize unidirectional SPP excitation. Two papers independently demonstrated this idea at a similar time. In 2013, Huang et al. proposed a spin-controlled directional SPP coupler based on a PB metasurface [204]. As shown in Fig. 11(a), the fabricated device is a gold film drilled with an array of rectangular air holes with orientation angle $\alpha$ linearly varying as a function of $x$, thus providing a PB phase $\varphi_\sigma(x) = \sigma\theta(x)$ for incident CP light with spin-$\sigma$. However, the gradients on PB phases are not large enough to convert a PW to a SPP, and the authors have to seek help from Bragg scatterings, which provide reciprocal wavevectors $G = \pm m2\pi/s$ for the impinging light, with $m$ being the diffraction order and $s$ the inter-hole distance. Therefore, as the wavevector matching condition

$$m \cdot 2\pi/s + \nabla \varphi_\sigma = \pm k^{\text{SPP}}_s$$

(15)

is satisfied, with $k^{\text{SPP}}_s$ being the wavevector of the eigen SPP, an SPP mode can be excited on the metal surface. Suppose for the $\sigma = 1$ (LCP) excitation, one can adjust the structural details (i.e., the $\theta(x)$ distribution) to make Eq. (15) satisfied with $m = +1$, then naturally the combination of $\{\sigma = -1, m = -1\}$ is also the solution of Eq. (15), only with the sign in front of $k^{\text{SPP}}_s$ changed. Therefore, such a device naturally supports spin-controlled unidirectional SPP excitations, which is an advantage in comparison with previously realized SPP metacouplers. The authors performed both experiments and simulations to demonstrate spin-controlled unidirectional SPP excitation at the desired wavelength [see Fig. 11(b)]. At a similar time, Lin et al. demonstrated that a metal film drilled by two arrays of air apertures with orthogonal orientations can achieve similar spin-controlled directional SPP excitations [see in Fig. 11(c)] [205]. The key idea is quite similar to that adopted in Ref. [204], but is now demonstrated in a simpler structure. When illuminated by normally incident CP light, the single aperture array can selectively couple with the component polarized
Gradient metasurface SPP couplers. (a) Top panel: schematic of a unidirectional SPP coupler consisting of an array of rectangular apertures with spatially varying orientations on a metal film. Bottom panel: ordinary and anomalous refraction and diffraction illuminated by the normally incident spin state $\sigma = 1$. (b) Experimental observation of the SPP excitation along the right direction inside the metacoupler for an incident beam with $\sigma = 1$ [204]. (c) Configuration of the polarization-controlled directional SPP coupling. The unit cell consists of two columns of apertures with orientations of $\theta_1 = 45^\circ$ and $\theta_2 = 135^\circ$ and a spacing $S$. (d) SEM image of a circular coupler (top left panel) based on the design shown in (c). The measured NSOM images of the coupler under RCP (top right panel), LCP (bottom left panel), and linearly polarized (bottom right panel) illumination, resulting in radially inward, outward, and both inward and outward couplings, respectively, of SPPs [205]. (e) Top panel: picture of the fabricated chirality-modulated spoof surface plasmon metacoupler and experimental setup to demonstrate the SPP excitation performance. Bottom panel: measured electric ($E_z$) and magnetic ($H_z$) field patterns above PB metacoupler under LCP illumination at frequency of 10 GHz [206]. (f) The schematic (top panel), sample image (middle panel), and measured electric field (bottom panel) for the high-efficiency and broadband converter linking a conventional coplanar waveguide and an ultrathin corrugated metallic strip (the plasmonic waveguide) [207]. (g) Left panel: schematic and sample picture (inset) of the plasmonic metaslit for achieving asymmetric SPP focusing. Middle and right: NSOM images of surface fields generated from the metaslit for LCP and RCP illumination [208]. (h) Top panel: conceptual schematic of a 1D PEC waveguide covered by a gradient-index metasurface (gradually changing blue regions) for asymmetric transportation of light. Middle and bottom panels: numerical demonstration of the asymmetric propagation for an EM wave incident from the left and right sides [209]. (a), (b) Reproduced from [204] under the terms of the Creative Commons Attribution NonCommercial-NoDerivs 3.0 Unported License. (c), (d) From Lin et al., Science 340, 331–334 (2013) [205]. Reprinted with permission from AAAS. (e) Reproduced from [206] under the terms of the Creative Commons Attribution 4.0 License. (f) Ma et al., Laser Photon. Rev. 8, 146–151 (2014) [207]. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission. (g) Reproduced with permission from [208]. Copyright 2015 Optical Society of America. (h) Reprinted with permission from Macmillan Publishers Ltd.: Xu et al., Nat. Commun. 4, 2561 (2013) [209]. Copyright 2013.
along the short axis and excite the SPPs on both sides of the array. By carefully choosing the separation distance and the orientation angles of the double-aperture arrays [Fig. 11(c)], the SPP beams emitted from the two aperture arrays can constructively interfere at one side and destructively interfere at the other side, leading to a directional SPP excitation. Furthermore, as the helicity of incident CP light changes, the interference conditions are changed accordingly, thus switching the SPP excitation direction. Near-field experiments nicely demonstrated the predicted effects, in good agreement with theoretical results based on a dipolar model. Moreover, such an effect can be extended to cylindrical SPP excitations, as shown in Fig. 11(d), where the double-aperture arrays are now arranged on a circle. As the spin of incident CP light is flipped, SPP beams can be excited to propagate either inward or outward on the plasmonic metal. Recently, Zhang et al. modulated the orientation angles of the nano-apertures inside the array along the $y$ direction, giving rise to a phase profile to further control the wavefront of the excited SPP beam, achieving oblique SPP excitations and SPP focusing [210].

Although these PB couplers enable spin-controlled SPP excitations, their working efficiencies are unfortunately quite low. Recently, Duan et al. theoretically analyzed the inherent issues limiting the performance of these PB couplers: (i) the adopted meta-atoms do not satisfy the 100% efficiency criterion [Eq. (12)], so that normal modes inevitably exist to degrade the device performance; and (ii) while the incident CP light contains both TE and TM components, the converted SPP modes usually take only a TM polarization, and such polarization mismatch further decreases the SPP conversion efficiency [206]. The authors then proposed a new scheme to design high-efficiency PB metacouplers, consisting of the following two steps. First, they designed a high-efficiency PB meta-atom based on the criterion in Eq. (12), so that it can perfectly convert incident CP waves to driven surface waves with nearly 100% efficiency. Second, they designed an artificial metal supporting both TE- and TM-polarized eigen SPPs so that it can efficiently guide out SPPs with two polarizations. Based on this scheme, the authors successfully constructed a high-efficiency PB metacoupler for microwave frequencies, and experimentally demonstrated that both TE- and TM-polarized SWs are efficiently guided out as eigen SPPs [see Fig. 11(e)]. Far-field measurements further demonstrated that the realized coupler exhibits a very high conversion efficiency (78%), which can be further enhanced based on careful optimization. Although so far the concept has been demonstrated only in the microwave regime, we expect that extending it to high-frequency domains is possible.

The concept of using metasurfaces to link far-field and near-field can find many applications. In 2014, Ma et al. utilized a gradient metasurface as a bridge to link a transmission line and a plasmonic waveguide in the microwave regime [207]. Usually, guided-wave (GW) modes in the transmission line possess smaller wavevectors compared to spoof SPP modes in the plasmonic waveguide. Such wavevector mismatch causes significant scattering losses at the junction of these two systems. To solve this issue, the authors designed a gradient metasurface that possesses an effective wavevector smoothly varying in space, to link the two systems as a convertor. Microwave experiments demonstrated a broadband and high-efficiency conversion between GW and spoof SPP, as depicted in Fig. 11(f). Lee’s group proposed several plasmonic nanoslit structures, composed of single or double arrays of nanoslit segments with specific tilting angles, to manipulate the SPPs. By designing the focal lengths of two nanoslits differently, such plasmonic device can achieve the asymmetric SPP focusing effect, as depicted in Fig. 11(g). Such a concept can also be applied to more complex SPP manipulation, such as multiple focusing, arbitrary beam shaping, or plasmonic vortex generation [208]. Meanwhile, Xu et al. proposed to cap a gradient-index metasurface on one sidewall of a waveguide to achieve an asymmetric waveguiding effect [209].
As shown in Fig. 11(h), a mode transporting along the $+x$ direction obtains an additional wavevector ($\xi = d\Phi/dx > 0$) from each reflection at the metasurface, and finally turns to a SW propagating through the device. Conversely, a mode transporting along the $-x$ direction is reflected back because its wavevector continuously decreases after reflection and finally changes sign. Clearly, the phase gradient breaks the lateral inversion symmetry leading to the fascinating asymmetric waveguiding effect. Microwave experiments nicely demonstrated this concept. Several years later, Li et al. adopted a similar idea to realize asymmetric transmission, but for dielectric waveguide modes in the IR regime [211]. Moreover, the authors also experimentally demonstrated that such gradient metasurfaces can work as mode converters in the dielectric waveguide, and are more miniaturized in size and/or efficient than other mode converts. These excellent examples revealed the strong potential of integrating metasurfaces with conventional EM devices, which are highly desired for future applications.

3.4. Dielectric Metasurfaces

While metals behave as PEC in the GHz regime, they become lossy as frequency increases particularly to the visible regime. As a result, ohmic losses can significantly degrade the performance of metasurfaces constructed with plasmonic metals, especially for those working in the transmission mode at optical frequencies. On the other hand, at optical frequencies dielectrics exhibit much smaller losses than metals, which stimulated rapid developments of dielectric metasurfaces with high performance. As presented in Subsection 2.1, dielectric nanoparticles support both electric and magnetic resonances [212–214]. In 2013, Staude et al. [215] demonstrated that disk-shaped dielectric resonators can select either electric or magnetic mode as their lowest-order resonances, and the spectral positions of these two modes can be tuned in dramatically different ways through changing the geometry of the disk array [see Fig. 12(a)]. This allows us to achieve a spectral overlap between electric and magnetic resonances, leading to a suppression of backward scattering and a high optical transmission [222]. Moreover, the phases of light transmitted through such transparent nanoparticles can be continuously tuned to cover the whole $2\pi$ range, through careful structural adjustments. In addition, dielectric resonators with complex geometries exhibit expanded degrees of freedom to modulate light in terms of both amplitude and phase. Thus, such dielectric nanoparticles are the best candidates to build meta-atoms for designing functional metasurfaces with high efficiencies and broad operating bandwidths. Many dielectric metasurfaces were recently realized to manipulate light in both transmission and reflection geometries for LP and CP excitations, which will be briefly reviewed here.

In reflection geometry, a simple approach to achieve dielectric-based metasurfaces is to replace the top metallic resonators in plasmonic MIM metasurfaces with dielectric Mie resonators. In 2014, Yang et al. fabricated a dielectric metasurface, consisting of a periodic array of high-index silicon cut wires and a metallic ground plane separated by a low-index polymer spacer, and experimentally demonstrated that it can achieve high-efficiency LP conversion over a 200 nm bandwidth around 1550 nm. They further used such meta-atoms to design another metasurface exhibiting an azimuthally varied phase profile [see Fig. 12(b)], and demonstrated that it can generate an optical vortex beam efficiently within a wavelength range of 1500–1600 nm [174]. Based on a similar idea, Sun et al. fabricated a reflective metasurface based on TiO$_2$ nanoblocks with aspect ratio around 1–1.5, and demonstrated that it can achieve efficient cross-polarized anomalous reflection at 632 nm (with conversion efficiency around 50%) and holograms in red, green, and blue with absolute efficiencies of 36.7%, 24.5%, and 13.9%, respectively [223].

To manipulate light wavefronts at the transmission side, Mie-resonant meta-atoms (with tailored electric and magnetic resonances) were widely used to construct
dielectric metasurfaces exhibiting desired phase profiles [216,224–226]. For example, in 2015, Yu et al. reported that dielectric metasurfaces constructed by supercells consisting of eight silicon nanodisks with tailored sizes can efficiently deflect arbitrarily polarized incident light into the desired diffraction order. As shown in Fig. 12(c), the deflection efficiency can reach \( \sim 45\% \) over the wavelength range of 665–755 nm [216]. Similar configurations were also implanted to achieve efficient vortex beam generation in transmission geometry at the NIR regime [224,225].

A related yet slightly different approach to construct dielectric metasurfaces is to utilize upright dielectric nano/micro-post/pillars with high aspect ratios, which operate as low-\( Q \) FP resonators. By adjusting the cross sections of such dielectric waveguides, one can tune the effective indices of the waveguide modes to obtain the desired phase shifts for the transmitted light. Many fascinating effects and functional devices were realized based on such a scheme, such as metaholograms [217], metalenses [227,228], and vortex beam generators [229]. For instance, Wang et al. experimentally demonstrated high-efficiency transparent holograms based on dielectric metasurfaces formed by silicon nanopillars. The achieved metaholograms can produce high-resolution grayscale images and transmit over 90\% of light with diffraction efficiency over 99\% at 1600 nm, and operate with a working bandwidth of 375 nm [Fig. 12(d)] [217]. Very recently, Fan et al. experimentally demonstrated a divergent metalens with near-unity numerical aperture (NA) based on a dielectric metasurface constructed by SiN hexagonal nanopillars [227]. High transmission (about 80\%) and subwavelength resolution were achieved by the metalens over the wavelength range of 480–780 nm. Moreover, polarization-dependent phase shifts can be achieved in dielectric waveguides with asymmetric cross sections, which provide an ideal platform to realize polarization-dependent light manipulation [218]. Recently, Faraon’s group experimentally demonstrated several polarization-dependent metadevices based on elliptical-cross-section high-contrast dielectric nanoposts, functioning as wave plates, polarization beam splitters [Fig. 12(e)], metalenses, and metaholograms. These metadevices typically work in the NIR regime and exhibit relatively high efficiencies [218].

Meanwhile, the PB mechanism has also been widely employed in designing dielectric metasurfaces to manipulate CP light with high efficiencies [219–221,230–233]. The key step is to design dielectric meta-atoms exhibiting high PCR according to the criteria introduced in Subsection 3.2. For instance, Capasso’s group experimentally demonstrated that PB metasurfaces consisting of rotated silicon nanofins can produce chiral holograms with chirality-dependent functionalities in the NIR regime. Each pixel of such a metadevice is composed of two phased arrays (arranged along the \( y \)-axis direction, as shown in Fig. 12(f)) that couple to CP light with different chirality, thanks to the PB phases introduced by the rotated nanofins [219]. In addition, such a metadevice exhibits an absolute efficiency of \( \sim 20\% \) and extinction ratio of \( \sim 10 \) at 1350 nm, with working bandwidth of \( \sim 200 \) nm. Recently, based on a transmissive metasurface with eight-level modulation on geometric phases by precisely control of the geometries and orientations of the constituted Si nanorods, Huang et al. experimentally realized multiple holographic images at three different \( z \)-planes excited with spin-polarized light in the visible regime, as shown in Fig. 12(g) [220]. Although the working efficiency of such a device is quite low (about 3\%), it exhibits a wide working band ranging from 480 to 680 nm, and does not suffer from high-order diffraction and twin-images issues. In a parallel line, Capasso’s group experimentally demonstrated that PB metasurfaces constructed with high-aspect-ratio TiO\(_2\) nanofins can realize metalenses [231], chirality-distinguishable beam splitters [232], and vortex beam generators [Fig. 12(h)] [221], all working in the optical regime with high efficiencies.
3.5. New Mechanisms for Constructing Metasurfaces with Nearly Perfect Efficiency

In previous subsections, we have introduced several mechanisms to design gradient metasurfaces for manipulating EM waves with different polarizations. These mechanisms are all based on Huygens’ principle. However, while metasurfaces designed in such a way work very well in most cases, severe problems exist in certain limiting conditions. Let us take a beam-bending reflective metasurface as an example to explain the physics. According to the common design strategy, ideally such a metasurface should be designed to exhibit a linearly changing reflection-phase profile \( \Phi(x) = \Phi_0 + \xi \cdot x \) to achieve the desired anomalous reflection to an angle determined by \( \xi \). However, while metasurfaces designed following this criterion do exhibit nearly 100% efficiencies (efficiency drops a bit in plasmonic cases due to absorption) when the bending angle is small, the efficiency of the metasurface drops significantly when the designed bending angle is large (typically larger than 70°) [161,163]. Such an issue intrinsically exists in all metasurfaces designed with the common Huygens principle, which poses an obstacle for using metasurfaces in those applications that need large-angle bending, such as blazing gratings and interferometers. In fact, it was theoretically analyzed [161,166] that the metasurface needs to provide appropriate perpendicular electric or magnetic responses to perfectly construct the desired redirected beam when the bending angle is different from the incident one. Unfortunately, usually metasurfaces are ultrathin and exhibit only in-plane EM responses. It is clear that the large-angle efficiency issue is an inherent limitation of metasurfaces designed with a common approach, which exhibit local, passive, and in-plane EM responses.

Recently, many new design schemes have been proposed to solve the issue. In 2016, Mohammadi Estakhri and Alù [234] re-analyzed the correct boundary conditions imposed on a metasurface to yield a perfect wave bending effect. They pointed out that the EM properties of a local part on the metasurface should be governed by total (or local) EM fields, including both the incident and the out-going waves, rather than considering only the incident wave, as in the common design approach. Specifically, now the boundary conditions at each point on the metasurface \( (S) \) should be expressed as

\[
\hat{n} \times (\tilde{H}_{2S} - \tilde{H}_i - \tilde{H}_{1S})|_S = \frac{1}{2} Y_e [(\tilde{E}_{2S} + \tilde{E}_i + \tilde{E}_{1S}) \cdot \hat{n}]|_S,
\]

\[
\hat{n} \times (\tilde{E}_{2S} - \tilde{E}_i - \tilde{E}_{1S})|_S = -\frac{1}{2} Z_m [(\tilde{H}_{2S} + \tilde{H}_i + \tilde{H}_{1S}) \cdot \hat{n}]|_S,
\]  

(16)

where \( Y_e \) and \( Z_m \) denote the desired admittance and impedance of this local part; and \((\tilde{E}_i, \tilde{H}_i), (\tilde{E}_{1S}, \tilde{H}_{1S})\), and \((\tilde{E}_{2S}, \tilde{H}_{2S})\) denote the incident wave and the scattered waves in regions I and II, respectively. Assuming that \( (\tilde{E}_{1S}, \tilde{H}_{1S}) \) and \( (\tilde{E}_{2S}, \tilde{H}_{2S}) \) can be represented by the desired outgoing waves that are already known, solving Eq. (16) can thus yield the exact material properties (i.e., impedance profile) of the metasurface under design. In reflection geometry, Eq. (16) can be analytically solved. In general, suppose that the metasurface is designed to perfectly reflect an incident wave with parallel wavevector \( k'_x \) to a non-specular direction with parallel wavevector \( k_x \). The surface impedance and admittance profiles are then retrieved as

\[
Z_m = \frac{4}{Y_e} = 2\eta_0 \frac{e^{-ik'_x x} + A_x e^{-ik_x x}}{\cos \theta_i e^{-ik'_x x} - A_x \cos \theta_r e^{-ik_x x}}
\]

(17)

through solving Eq. (16), where \( \theta_i \) and \( \theta_r \) denote the incident and reflection angles, \( \eta_0 = \sqrt{\mu_0/\varepsilon_0} \) denotes the wave impedance of vacuum, and \( |A_x| = \sqrt{\cos \theta_i/\cos \theta_r} \) is the amplitude of the perfectly reflected wave. Equation (17) states clearly that, in order to achieve perfect anomalous reflection, the metasurface must involve local losses in
some parts ($\text{Re}\{Z_m(x)\} = \text{Re}\{4/Y_e(x)\} < 0$) and gains in some other parts ($\text{Re}\{Z_m(x)\} = \text{Re}\{4/Y_e(x)\} > 0$). This is expected, as the impedance of the incident wave and the outgoing wave cannot be matched in a passive metasurface due to their different parallel wavevectors [see Eq. (17)], while with gain and loss on the metasurface, such an issue can be solved. The authors numerically demonstrated that indeed a gain–loss metasurface designed with Eq. (3) can indeed reflect an incident wave to an extreme oblique angle with 100% efficiency [see Fig. 13(a)].

While the idea proposed by Estakhri and Alù is inspiring, it has several intrinsic limitations. First, gain–loss metasurfaces are difficult to realize in practice, and a simplified design (say, dropping the gain parts in metasurfaces) does not yield the desired 100% working efficiency [234,236,239,240], which is expected since gain material plays a crucial role here. Second, it is not entirely convincing to represent the local EM fields by the sum of the incident and far-field forms of the reflected waves in Eq. (16), which completely neglects the contribution of non-radiative near-field components. Inspired by this work, scientists continued to explore other approaches that are more practically realizable. In 2017, Epstein and Eleftheriades noticed that the non-radiative evanescent waves on the surface can actually help match the local impedance without necessarily involving gain and loss in the design. Using evanescent waves as auxiliary fields to help achieve local power conservation, the authors proposed a new scheme to design passive and lossless metasurfaces that can realize 100% efficiency large-angle wave bending [see Fig. 13(b)] [235]. On the other hand, Tretyakov’s group fully utilized the guided surface waves trapped on the metasurface to help design passive metasurfaces that exhibit nonlocal responses to achieve the 100% efficiency large-angle anomalous reflection [see Fig. 13(c)]. Such a nonlocal metasurface can well mimic a gain–loss metasurface as seen at a plane above the metasurface, solving the impedance mismatch issue.

The authors fabricated a microwave sample based on MIM meta-atoms and experimentally verified its ability to achieve nearly perfect anomalous reflection [237]. Such conceptually new mechanisms for high-efficiency wavefront manipulation allows the design of thin perfect reflectors, offering versatile design methods applicable to other scenarios, such as focusing reflectors, surface wave manipulation, or metasurface holograms, extendable to other frequencies.

Despite the several mechanisms proposed, challenges still exist in realizing wide-angle high-efficiency metadevices in practice. For example, in all these mechanisms, interparticle near-field couplings are completely overlooked, and, thus, applying such strategies in practical design still needs large-scale numerical optimization. Very recently, Ra’di and co-workers proposed a new concept—the metagrating—to realize metasurfaces that achieve 100% efficiency large-angle anomalous reflection, in which a supercell contains only one resonator that exhibits in-plane and/or perpendicular responses [238]. Almost at the same time, Wong and Eleftheriades proposed a more practical design approach to realize metagratings with a supercell consisting of two resonators with different reflection phases [241]. They demonstrated that a fine-tune of the reflection response of two planar resonators can also approach unitary efficiency under certain conditions, and they verified this concept experimentally in the microwave regime [241]. Later on, Shvets’ group brought the concept to transmission geometry and the high-frequency domain. They used a bianisotropic metamolecule supporting four different types of resonance as a building block to construct a metagrating at mid-IR wavelengths. As the result of destructive interference of these four modes, only one diffractive order is expressed in transmission, while all reflections are strongly suppressed, leading to nearly 100% efficiency anomalous transmission [242]. Sell et al. demonstrated that silicon-based metagratings capable of large-angle deflection with multifunctional performance can be realized. Such metagratings contain non-intuitive nanoscale patterns and support a large number of spatially overlapping optical modes per unit area. The quantity of modes, combined with their optimized optical responses, offers enough degrees of freedom to design high-efficiency metadevices [243]. Packo et al. described an inverse design approach to construct a metagrating that can channel the incident energy toward the desired direction [244]. The grating is composed of a cluster of resonators whose properties can be derived by the inversion of a given matrix. Using this design strategy, the authors numerically demonstrated an anomalous refractor and an anomalous reflector, both exhibiting very high efficiencies [244]. In addition to such theoretical approaches, numerical optimization is also frequently used to help find optimized metastructures with high working efficiencies [237]. Based on numerical optimization, Lin et al. have demonstrated metasurfaces working both in transmission and reflection modes based on conventional thin-film silicon processes that are suitable for the large-scale fabrication of high-performance devices [245]. All these newly proposed mechanisms share the same key physics. First, the systems are purposely designed (via varying the incident angle or lattice constant) in such a way that only a small number of diffraction channels are “alive” while all others are evanescent. Then, by fully exploiting the differences in radiation symmetries of different resonant modes, one can “tune” the EM responses of the meta-atom to completely suppress the radiation to all channels except the desired one, resulting in a 100% efficiency extreme wave control. These newly proposed strategies can significantly simplify the designing processes to realize large-angle bending metasurfaces with nearly 100% efficiencies, which may stimulate much follow-up work in metasurface research.

4. APPLICATIONS OF INHOMOGENEOUS METASURFACES

Having understood different working principles of using metasurfaces to control EM waves, we turn to describe the key applications of metasurfaces, including metalenses,
metaholograms, metacloaking, special-beam generation, and multifunctional and tunable metadevices.

4.1. Metalenses

Lenses play important roles in optics as they are the most crucial components in nearly all complex optical systems. Conventional lenses are usually made of transparent dielectric materials (say, glass). To realize the desired functionality, a conventional lens must exhibit a certain curved shape so that waves transmitted through (or reflected by) it at different local positions can gain required phases. Such strict requirements make them bulky in size, difficult to make, and possess only limited functionalities, which hampers their application in modern integrated-optics applications.

Metamaterials can partially resolve the above issues [246–250]. In 2008, Lin et al. proposed a flat metamaterial slab, with effective refraction index varying in space to generate the desired phase for a locally transmitted wave, to realize the same focusing functionality as a conventional lens. The building block of such a metamaterial lens is a metallic rod embedded inside a high-index dielectric block [246], which can exhibit both electric and magnetic resonance upon excitation, yielding an effective index that can be tuned by varying the height of metallic rods. Two years later, Paul et al. proposed a gradient-index metamaterial lens for THz waves [247], using an annular slot aperture as a building block with effective refractive index dictated by the slot radius. Broadband focusing that is insensitive to polarization and incident angle of external radiation was experimentally demonstrated. In 2009, Verslegers et al. demonstrated a plasmonic flat lens for visible light. The device is a 400 nm thick metallic film perforated with nanoslits with appropriate widths [see Fig. 14(a)] [248] that can control the waveguide cut-off frequencies to yield different transmission phases for light passing through them. However, this metalens can focus incident light with only one particular polarization to a focal line (i.e., a 2D focusing). Such an issue was soon solved by Lin et al., who fabricated a plasmonic lens based on 2D cross-shaped apertures [249] that can realize a polarization-insensitive 3D focusing effect at the 850 nm wavelength. Compared to conventional lenses, all these metamaterial lenses are flat and can exhibit reduced thickness. However, since these devices still exploit the propagation phases inside the metamaterials, they are inevitably bulky and complex and/or exhibit low working efficiencies.

Metasurfaces that exploit interfacial phase changes, rather than propagating phases, provide an excellent platform to overcome the issues mentioned above, boosting the fast development of metalenses. The key idea is to arrange meta-atoms in such a way that the transmission/reflection phase profile on the metasurface satisfies

$$\Phi_{\text{Lens}}(r) = k_0 \left( \sqrt{F^2 + r^2} - F \right), \quad (18)$$

which can ensure waves transmitted through (or reflected by) the metalens can constructively interfere at the designed focal point. Here $F$ is the designed focal length. Readers should distinguish these two different definitions clearly in all metadevices to prevent achieving the opposite functionalities. In 2012, Li et al. experimentally demonstrated a high-efficiency reflective metalens in the microwave regime [253] based on MIM meta-atoms with H-shaped top resonators [see Fig. 14(d)]. By tuning the structural details of the H structures, the authors found a set of meta-atoms yielding the desired reflection phases, and then assembled them to construct a 2D metalens with a focusing length of 100 mm at frequency 10 GHz. Similar to other MIM metasurfaces, such a device is ultrathin ($\sim \lambda/12$ thickness) and exhibits nearly 100% efficiency. Nearly at the same time, Bolzhevolnyi’s group realized a broadband reflective
Flat metalenses based on metasurfaces. (a) Planar lens based on a nanoscale slit array in metallic film. Left panel: geometry and SEM image of the lens, consisting of a 400 nm optically thick gold film with air slits of different widths (80–150 nm) milled therein on a fused silica substrate. Middle and right panels: focusing patterns measured by confocal scanning optical microscopy and FDTD simulation [248]. (b) Focusing flat mirrors based on plasmonic metasurfaces. Left panel: SEM image of a part of a fabricated metalens designed for 800 nm wavelength, with the building block shown in the inset. Right panel: optical focusing image obtained for the sample illuminated by light at 800 nm [251]. (c) Metasurface-based terahertz flat lens. Left panel: schematic of light focusing analysis by the metasurface. Right panel: schematic of the desired metasurface lens and the imparted phase distribution. Bottom: partial optical image of the proposed metalens [252]. (d) Flat microwave metalens in reflection geometry with the building block shown in the inset [253]. (e) Babinet-inverted plasmonic metalenses. Left panel: SEM image of the fabricated plasmonic metalens with a focal length of 2.5 mm at wavelength of 676 nm. Right panel: measured cross-polarized focusing field patterns on the transmission side of the metalens [254]. (f) Schematic of a dielectric metalens operating in transmission mode with its building block (a TiO$_2$ nanopillar on a glass substrate) shown in the insets [231]. (g) Dual-polarity plasmonic metalens for visible light. The lens consists of an array of plasmonic dipole antennas (S = 400 nm) on a glass substrate with orientations varied along the x direction [255]. (h) SEM image of the fabricated dielectric metalens based on a silicon nanobeam with a focal length of 100 $\approx$ m at $\lambda$ = 550 nm. The insets depict the measured field intensity profiles in the focal plane and along the optical axis [256]. (i) Metasurface based on high-aspect-ratio TiO$_2$ metasurfaces. Left panel: SEM image of the metalens edge. Right panel: focal spot intensity profiles at $\lambda$ = 532 nm measured by a metalens (top) and a conventional commercial optical lens (bottom) [257]. (a) Reprinted with permission from Verslegers et al., Nano Lett. 9, 235–238 (2009) [248]. Copyright 2009 American Chemical Society. (b) Reprinted with permission from Pors et al., Nano Lett. 13, 829–834 (2013) [251]. Copyright 2013 American Chemical Society. (c) Wang et al., Adv. Opt. Mater. 3, 779–785 (2015) [252]. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission. (d) Reprinted with permission from [253]. Copyright 2012 Optical Society of America. (e) Reproduced from [254] under the terms of the Creative Commons Attribution NonCommercial-NoDerivs 3.0 Unported License. (f) Reprinted with permission from Khorasaninejad et al., Nano Lett. 16, 7229–7234 (2016) [231].
metalens in the NIR regime [251]. The meta-atoms that they adopted are also MIM structures [Fig. 14(b)] with the top resonator being gold patches with different lateral sizes, yielding the desired parabolic reflection phase profile. The authors fabricated a metalens with a size of $17.3 \times 17.3$ mm and experimentally characterized the 2D focusing functionality of the metalens. Their experiments revealed that the focal length of the device changes from 15 to 11 mm as wavelength varies from 750 to 950 nm, with experimental (theoretical) efficiency lying in the range of 14%–27% (50%–78%). Compared to its microwave counterpart, such an optical metalens has relatively lower efficiency, which is mainly due to fabrication errors and material losses.

However, reflective lenses are inconvenient in certain applications where transmissive metalenses are more desired. Soon after V-shaped metasurfaces were proposed, Ni et al. demonstrated a Babinet-inverted plasmonic metalens working in transmission mode at the NIR regime [254]. The building meta-atom is a V-shaped aperture on a 30 nm thick gold film, which, based on Babinet’s principle, can control transmitted light (including both amplitude and phase) in the same way as a V-shaped antenna controls reflected light. Figure 14(e) shows an SEM image of one of the fabricated metalenses, with $F = 2.5 \mu m$ for $\lambda = 676$ nm. An optical microscope connected with a CCD was adopted to map the field distributions for the cross-polarized light transmitted through the sample, clearly demonstrating the focusing effect [Fig. 14(e)]. Similarly, Wang et al. proposed to use C-shaped split ring resonators (CSRRs) [252], being topological equivalents of V-shaped antennas, to build THz metalenses, as depicted in Fig. 14(c). They demonstrated a 5.52 mm diameter metalens with an NA of 0.27, exhibiting nice focusing effects within the frequency range of 0.5–0.9 THz. Moreover, the authors also fabricated a 5 × 5 metalens array to quantify the wavefront aberrations of impinging THz beams. When the device is illuminated by a THz beam with a distorted wavefront, the metalenses in the device can create a series of focal points located at different planes, based on which one can retrieve the wavefront distortion of the incident beam. However, the working efficiencies of these metalenses are very limited, due ultimately to the common issues existing in such single-layer ultrathin metasurfaces [186]. In principle, a metalens based on a Huygens metasurface [168] can achieve high-efficiency focusing effects in transmission mode. However, it is difficult to scale down such metasurfaces with complicated structures to high-frequency regimes.

Understanding the difficulties in enhancing the working efficiencies of plasmonic metalenses at high frequencies, scientists turned to studying dielectric metalenses. In 2016, Capasso’s group demonstrated high-efficiency transmissive metalenses for visible light [231], with meta-atoms being nanopillars made by high-index TiO$_2$ on a glass substrate [Fig. 14(f)]. By varying the diameters of nanopillars with tall-enough height, the authors can control the phases of transmitted light within the full $2\pi$ range, yet with transmission amplitudes remaining at reasonably high values, based on the dielectric-resonance mechanism introduced in Subsection 2.1. Three different metalenses were fabricated, working respectively at 405, 532, and 660 nm, all exhibiting a diameter of 300 mm and focal length of 200 mm and thus an NA of $\sim 0.6$. Experiments demonstrated the excellent focusing performance of these metalenses, exhibiting efficiencies of 30%, 70%, and 90%, respectively. Metalenses with even higher NAs (0.85) were also fabricated, and they exhibit slightly decreased working
efficiencies due to increased fabrication errors in such high-NA metalenses. One advantage of such metalenses is that their performance is essentially independent of the incident polarization. However, it is very challenging to make such metalenses, which involve nanostructures with very high aspect ratio.

Alternatively, the PB mechanism has also been widely employed to design metalenses. Such PB metalenses are sensitive to excitation light with CP instead of LP, and the phase distribution, designed for a particularly spin-polarized light, may change to a defocusing profile yielding a virtual image, when the excitation field changes its chirality. The latter naturally offers the PB metalens an attractive property of bifunctionality. In 2012, Chen et al. fabricated a PB metalens [see Fig. 14(g)] consisting of plasmonic dipole antennas with orientation angles designed to realize a 1D focusing phase profile with $F = 60 \cong m$ at $\lambda = 740$ nm [255] for excitation light with RCP. Optical measurements demonstrated that the device realizes a real and a virtual images as the incident light changes its chirality from RCP to LCP. However, such a metalens exhibits very low efficiency, since the meta-atom is not designed to satisfy the criterion in Eq. (13). In fact, it was theoretically predicted that such a single-layer PB meta-atom cannot exhibit working efficiency higher than 25% [186], which was proved experimentally by Ding et al., who demonstrated a transmissive PB metalens in the microwave regime, with efficiency approaching the 25% limit [187]. Although one can use the high-efficiency trilayer PB meta-atom [183] to design transmission-mode microwave PB metalenses with very high efficiencies, such structures are very difficult to fabricate at optical frequencies, and the enhanced metallic losses will also diminish the devices’ efficiencies. Alternatively, Lin et al. demonstrated a dielectric metalens with an NA of 0.43 working at $\lambda = 550$ nm [Fig. 14(h)] [256]. The authors employed a 100 nm high Si-nanobeam antenna (put on a quartz substrate) as a basic PB meta-atom, which is carefully designed to possess a $\pi$ phase difference for transmitted light with two perpendicular polarizations and thus exhibit a high PCR. However, substantial difference in the transmission amplitudes for the two polarizations still limits its working efficiency. Very recently, Khorasaninejad et al. reported high-NA and high-efficiency dielectric metalenses working in the visible, based on a PB meta-atom being a high-aspect-ratio TiO$_2$ nanofin [see Fig. 14(i)] [257]. The highly transparent nature of TiO$_2$ and excellent sample quality significantly reduce the losses of the devices and boost the efficiencies. More importantly, the meta-atom is designed to yield a very high PCR and thus a high working efficiency. Three metalenses working respectively at the wavelengths of 660, 532, 405 nm were fabricated, exhibiting focal lengths of $90 \cong m$ and high NA of 0.8. The metalens designed at 405 nm shows the highest efficiency of 86%. The authors experimentally compared the performance of their metalens with a commercial one and found that the metalens shows a better resolution at the central wavelength. However, in contrast to a commercial lens exhibiting broadband performance, the metalens has a relatively narrow bandwidth.

Although metalenses exhibit many attractive properties, they unfortunately suffer from severe chromatic responses that are unfavorable for applications. One can understand the origin of such chromatic responses by analyzing Eq. (19). Suppose two adjacent meta-atoms on a metalens are separated by a distance $d$. Then, the difference in the abrupt phase shifts provided by them should be

$$\Phi_1 - \Phi_2 = \frac{d\Phi_{\text{Lens}}}{dr} \cdot d,$$  

where $\Phi_{\text{Lens}}$ is the desired phase profile of the metalens described by Eq. (18) and $d$ is the periodicity of the metasurface. While one can easily design a metalens to Eq. (18) for a particular wavelength $\lambda_0$, it is not easy to satisfy Eq. (19) at all wavelengths.
Obviously, the right-side term in Eq. (19) exhibits linear wavelength dependence \( \propto k_0 \) due to its propagating-wave nature. However, \( \Phi_1 \) and \( \Phi_2 \), being the abrupt phase changes of the two adjacent meta-atoms on the surface, exhibit either Lorentz-type dispersions (for resonance-phase meta-atoms) or are totally dispersionless (for PB meta-atoms), both of which cannot compensate for the dispersion of the right-side term. Note that such chromatic responses exist in all metasurface-based devices, which can be understood from Eq. (19) only with its left-side term changed accordingly to enable the meta-atoms to exhibit different linear phase retardations. To realize achromatic metadevices, the key issue is then to design meta-atoms with engineered dispersions that can precisely compensate for the dispersions of propagating phases, so that Eq. (19) can be satisfied in a wavelength range as wide as possible.

In 2015, Capasso’s group proposed a scheme to realize multiwavelength achromatic metadevices (including metalenses), as depicted in Fig. 15(a) [258]. They proposed to use multimode composite meta-atoms that exhibit frequency dispersions different from the Lorenz form of a single-mode resonance to compensate for the propagating-phase dispersions at three discrete wavelengths. The composite meta-atoms consist of two coupled dielectric resonators with different widths \( w_1, w_2 \). By sweeping \( w_1, w_2 \) and the separation \( g \) between two resonators, the authors sorted out a series of meta-atoms exhibiting correct phases at three discrete wavelengths, yet with nearly uniform transmission amplitude. They first demonstrated a metasurface that can bend incident light to the same deflection angle \( \theta = -17^\circ \), at three wavelengths (1330, 1550, and 1800 nm) [see Fig. 15(a)]. They further demonstrated a 2D multiwavelength achromatic metalens exhibiting an NA of 0.05 and identical focal length \( F = 7.5 \) mm [see Fig. 15(a) for measured field patterns at three wavelengths]. However, such a scheme can realize achromatic functionalities only at several discretized wavelengths, and the design strategy relies on brute-force simulations to construct a full meta-atom database, which is quite low efficiency.

Such a pioneer work stimulated numerous studies on achromatic metadevices. For example, Hu et al. demonstrated a multiwavelength achromatic metalens [264] based on plasmonic meta-atoms consisting of several nanoparticles with different sizes and shapes. Different from the design strategy based on brute-force simulations [258], the lattice evolution algorithm was adopted to efficiently design a flat optics device. With more degrees of freedom added in the design, such metadevice can help produce desired frequency dispersions for multiwavelength achromatic focusing. Avayu et al. integrated three plasmonic metalenses, individually designed to focus red, green, and blue light to nearly identical focal points, to form a single device that can realize an achromatic focusing effect [Fig. 15(b)] [259]. Such an idea is simple and straightforward, similar to the traditional method based on an optical-element array. The realized metasystem also possesses the advantages of a flat configuration and easy integration.

The next task is to realize broadband achromatic metalenses, which are more useful in practical applications. In 2017, Khorasaninejad et al. proposed a 3D achromatic metalens working in a continuous frequency band [260], as shown in Fig. 15(c). The building block consists of a single 600 nm high square TiO2 nanopillar on an SiO2 substrate with an alumina film at the bottom. Such a phase shifter can provide multiple \( 2\pi \) phase modulation and anomalous phase dispersion, both of which offer extra degrees of freedom for designing achromatic lenses. By optimizing the widths of local nanopillars, the authors designed a metalens satisfying Eq. (18) at several discretized wavelengths within a continuous band (490–550 nm). A 200 \( \equiv \) m diameter achromatic metalens with an NA of 0.2 was experimentally demonstrated to focus LP light to the same focal length of 485 \( \equiv \) m within a 60 nm working band. To further
Achromatic metalenses based on dispersion engineering. (a) Multiwavelength achromatic dielectric metadevices. Left panel: mechanism for achromatic focusing lens at three different wavelengths. The phase shifts $\phi_{m,i}$ and $\phi_{m,j}$ imparted by the metasurface at points $r_i$ and $r_j$ of the interface are designed so that the paths $l_i(r_i)$ and $l_j(r_j)$ are optically equivalent at different wavelengths. Right panel: side view of the metasurface for achromatic deflection. The building block consists of two coupled rectangular dielectric resonators of fixed height $t$ and varying widths $w_1$ and $w_2$ [258]. (b) Multispectral achromatic metalens composed of three closely stacked metasurfaces designed individually at wavelengths of 650, 550, and 450 nm, respectively [259]. (c) Schematic of an achromatic metalens over 60 nm bandwidth in the visible (left panel) and the measured intensity profiles of the reflected beam by the metalens at the main-axis plane for different wavelengths (right panel) [260]. (d) Schematic for broadband reflective achromatic metalenses (left panel). The unit elements are single or multiple metallic nanorods with different linear phase profiles [261]. (e) Broadband transmissive achromatic metalenses aiming for providing spatially dependent group delays such that wavepackets from different locations arrive simultaneously at the focus point. The building block is composed of one or more TiO$_2$ nanopillars with different dimensions [262]. (f) Macroscopic optical image (left panel) and local SEM image (middle and right panels) of the broadband transmissive achromatic metalens composed of the GaN nanopillars and the Babinet nanostructures [263]. (a) From Aieta et al., Science 347, 1342–1345 (2015) [258]. Reprinted with permission from AAAS. (b) Reproduced from [259] under the terms of the Creative Commons Attribution 4.0 License. (c) Reprinted with permission from Khorasaninejad et al., Nano Lett. 17, 1819–1824 (2017) [260]. Copyright 2017 American Chemical Society. (d) Reproduced from [261] under the terms of the Creative Commons Attribution 4.0 License. (e) Reprinted with permission from Macmillan Publishing Ltd.: Chen et al., Nat. Nanotechnol. 13, 220–226 (2018) [262]. Copyright 2018. (e) Reprinted with permission from Macmillan Publishing Ltd.: Wang et al., Nat. Nanotechnol. 13, 227–232 (2018) [263]. Copyright 2018.
expand the bandwidth, Wang et al. employed integrated-resonant unit elements, with phases contributed by both resonant and PB mechanisms, to design broadband achromatic optical components [261]. Specifically, a metallic nanorod can support multiple plasmonic resonances including fundamental and high-order modes. The authors noticed that the phase distribution between two resonances exhibits a nearly linear profile against $1/\lambda$, and such slope can be tuned via changing the inter-mode wavelength or introducing more resonances, as shown in Fig. 15(d). Meanwhile, the PB mechanism is also utilized to provide a basic phase profile at the boundary of the wavelength band. Using such a design strategy, the authors experimentally demonstrated a metalens with an NA of 0.268, exhibiting achromatic focusing functionality in a wide wavelength band (1200–1680 nm). However, such a metalens does not exhibit a high working efficiency ($\sim 12\%$), simply because, to achieve achromatic functionality, the authors have to purposely avoid using the high-efficiency meta-atoms, which inevitably exhibit the strongest resonance-induced dispersion. Soon, Wang et al. also demonstrated a transmission-type achromatic metalens working in 400–660 nm [263], as shown in Fig. 15(f). The adopted meta-atoms are solid or inverse GaN nanopillars, which, upon careful design, can support multiple waveguide-like modes, which can be fully utilized to realize dispersion compensation. Aided by brute-force simulations, the authors finally realized a metalens with an NA of 0.106 to achieve achromatic focusing and full-color imaging. Meanwhile, Chen et al. also reported a broadband achromatic metalens in transmission mode for visible light [262]. The involved meta-atoms consist of one or more 600 nm high TiO$_2$ nanofins standing on a SiO$_2$ substrate, as shown in Fig. 15(e). By carefully choosing the dimensions of those nanofins, the authors found a series of meta-atoms that yielded linear phase profiles with different slopes for building up the achromatic metalens. The achromatic focusing effects in the wavelength range of 470–670 nm were experimentally demonstrated by two fabricated metalenses with NAs of 0.2 and 0.02.

Although metalenses working at different frequencies using distinct materials [265–273] have already been demonstrated, research along this line is still underway, since many issues need to be solved before such devices can finally replace currently available commercial counterparts.

4.2. Metaholograms

Holography denotes such a technique that one encodes the information of a target image into an optical medium (i.e., hologram), which later, upon excitation, can reconstruct the original image. In a conventional approach, a reference beam is used to interfere with the light emitted from the target object, generating an interference pattern that is then recorded as the permittivity distribution on a holographic plate [274,275]. As the plate is illuminated by the same reference beam, scatterings can reconstruct the desired image. Alternatively, one can also employ a computer-generated-hologram (CGH) technique to numerically design a holographic plate without necessarily performing the interference experiment [276]. The key step in CGH is to determine the requested transmission/reflection amplitude/phase distributions at a holographic plate by solving an inverse problem with both the incident field and final image fixed. However, although holograms have found many applications in practice (display [277], optical detection [278], beam shaping [279], etc.), holographic plates made by conventional materials suffer from the issues of bulky size, less efficiency, the twin-image effect, and limited resolution, due ultimately to the narrow permittivity range of naturally existing materials and large (wavelength scale) pixel size. Recently, metamaterials/metasurfaces have offered us an ideal platform to overcome these challenges, thanks to their powerful abilities to control the local transmission/reflection properties at the subwavelength scale. In this subsection, we briefly review the development of metaholograms.
In 2012, Smith’s group demonstrated the first metamaterial-based hologram in the IR regime [280]. At a working wavelength of $10.6 \approx m$, the authors designed a set of metallic structures that exhibited different values of effective refraction indices, while the multilayer configuration can further enhance the variation range of transmission phases through these structures. Fifteen distinct meta-atoms were designed to yield the requested transmission phases, aided by full wave simulations. The final sample was formed by assembling an array of phase pixels, each consisting of $5 \times 5$ meta-atoms, selected to exhibit the desired transmission phases based on a CGH phase distribution calculated for a target hologram image. Optical experiments were performed to demonstrate the desired holographic image [Fig. 16(a)]. While this work paves the way to using metamaterials for hologram applications, it exhibits several limitations. For example, the multilayer metamaterial is quite complicated and thus difficult to fabricate. In addition, the device is still thick and exhibits very low efficiency.

Metasurfaces can largely overcome the issues mentioned above, and many metasurface-based holograms appeared soon after this pioneering work. In 2013, Shalaev’s group experimentally demonstrated a metahologram in the visible regime, as shown in Fig. 16(b) [281]. Here, the metasurface consists of V-shaped apertures perforated in a metallic thin film. Through geometry sweeping, the authors first numerically obtained a database for designing meta-atoms with desired transmission amplitudes and phases, based on which they then successfully designed a holographic plate for creating a desired image according to the CGH-calculated phase distribution. The working principle of such V-shaped apertures is essentially the same as that discussed in Subsection 3.1 for the V-shaped antenna, according to Babinet’s principle. Therefore, only the cross-polarized component of the scattered field can form the desired image, which is an apparent shortcoming. In addition, the efficiency is still low, persisting in all V-antenna-based metasurfaces due to the inevitable multimode generation. Almost at the same time, Tsai’s group presented a reflection-type metahologram for visible light that can overcome the issues mentioned above [282]. The basic meta-atoms are MIM structures with the top resonators being gold nanocrosses, which inherently possess much higher efficiencies than the V-antennas, as discussed in Subsection 3.1. By tuning the structural details, one can easily obtain a set of meta-atoms that yield different reflection phases to cover the full $2\pi$ range, yet with reflection amplitudes staying at high values. Moreover, the lengths of two orthogonal nanorods are free parameters to independently control the reflection phases for two LPs, which allowed the authors to design a single metasurface encoding two distinct hologram images (i.e., “NTU” and “RCAS”) when illuminated by light with different polarizations [see Fig. 16(c)]. The realized metaholograms can work within a broad band (width $\approx 880$ nm) under a wide range of incident angles. The measured efficiency of the device is about $18\%$ at the wavelength of $780$ nm, while the simulated value is even higher ($28\%$). Compared to the transmission-type metaholograms [281], this scheme yields a much higher efficiency and does not require polarization conversion for detection. The working efficiency can be further improved by introducing more phase levels and reducing the material losses. For instance, Yifat et al. later demonstrated a high-efficiency and broadband metahologram at telecommunication wavelength by adopting MIM meta-atoms with the top structures being patch-dipole nanoantennas [see Fig. 16(d)] [283]. Here, each meta-atom consists of two nanostructures (i.e., a nanopatch and a nanodipole), providing more freedom to tailor the reflection coefficients. Via geometric-parameter sweeping, the authors sorted out six different meta-atoms with reflection phases varying from $0^\circ$ to $360^\circ$ with a constant step, yet exhibiting quite uniform and high reflection amplitude, thanks to the expanded design freedom. These meta-atoms were used to construct a metasurface that can generate the same hologram image at two different detecting angles ($20^\circ$ and $45^\circ$). Optical measurements
Metaholograms based on (a)–(d) resonance phase or (e)–(h) geometric phase. 
(a) Schematic of the IR multilayer phase holograms (left) and the reconstructed holographic image of “DUKE” (right panel) [280]. (b) Holographic images of “PURDUE” produced by the metasurface hologram (see inset) illuminated by a 676 nm laser [281]. (c) SEM image (left panel) of the metahologram for projecting the polarization-controlled dual images of “NTU” and “RCAS” [282]. (d) Left panel: schematic of the structure and experimental concept of the highly efficient and broadband wide-angle hologram projected to an angle $\theta$ in the far field [283]. (e) Left panel: hologram structure and reconstruction procedure for projecting a 3D optical image of a jet. Right panel: measured holographic images of a 3D helix at different focal planes [285]. (f) Left panel: illustration of the reflective nanorod based high-efficiency metahologram. Right panel: experimentally obtained optical efficiency for both the image and the zeroth-order beam, showing a maximum efficiency of 80% at 825 nm [188]. (g) Helicity multiplexed hologram composed of two different sets of metasurface patterns, operating with opposite incident helicities and merged together with a displacement vector of (d/2, d/2) [286]. (h) Left panel: SEM image of the fabricated high-efficiency broadband dielectric metahologram. Right panel: holographic images covering the visible spectrum with the input wavelengths being 480, 520, 540, 600, 620, and 640 nm [287]. 
demonstrated that the generated holographic image has high fidelity, high efficiency (40%–50%), and works in a wide wavelength range (180 nm).

After the PB mechanism was identified, many groups soon realized metaholograms based on PB metasurfaces. By using a plasmonic nanobar as a meta-atom, Huang et al. demonstrated the first PB metahologram on which each nanorod is orientated to achieve the local phase desired for creating 3D holography, as shown in Fig. 16(e) [285]. Note that rotating a nanorod changes only the local phase (without affecting the amplitude) of the transmitted CP light, which is an important advantage of such a scheme. As a proof of concept, the authors designed/fabricated a metahologram encoding the image of a 3D jet with a size of hundreds of micrometers, at the wavelength of 810 nm. Under illumination of CP light with the correct spin (RCP light), a 3D image was formed, which was carefully captured by a CCD by tuning the distance between the sample and objective. In addition, by tuning the observation plane and the angle of view, the authors clearly demonstrated the 3D nature of the formed holographic image experimentally [see Fig. 16(e)]. We should emphasize that only the LCP components of scattered waves can form a real image, dictated by the PB mechanism working only for spin-reversed mode (see Subsection 3.2). Interestingly, reversing the spin of excitation light may add a minus sign [see Eq. (11)] to the encoded phase profile, which creates a virtual image at the reflection side. Real and virtual images were successfully observed, located symmetrically on two sides of the sample, as the sample is illuminated by RCP and LCP light, respectively.

However, low efficiency is still a bottleneck issue of PB metaholograms. In addition, the created holographic image in such PB scheme can be “seen” only by spin-sensitive detectors, while the scattered field with another CP contributes to “background noise,” which is very inconvenient in realistic applications. In a work parallel to Ref. [182], Zhang’s group independently discovered the criterion to make high-efficiency PB meta-atoms in reflection geometry. They further experimentally demonstrated a PB metahologram with high efficiency (~80%) in optical wavelengths [see Fig. 16(f)] [188]. The adopted meta-atom is a MIM structure with the top resonator being a simple nanorod, which, upon careful structural optimization, can function as a half-wave plate as desired [see Eq. (12)]. The PCR of the designed PB meta-atom stays at over 80% within a broad wavelength range (550–1000 nm). The authors utilized such a PB meta-atom to construct a hologram that encoded the image of Einstein’s portrait, in which the orientation angles of PB meta-atoms are determined by CGH-calculated phase distribution. In contrast to metaholograms based on resonant meta-atoms [280–282], here the local phases can be precisely and continuously controlled, an important advantage of the PB scheme that also partially explains why it can exhibit high performance. Experiments verified high-efficiency and high-fidelity holographic imaging within a wide wavelength range. Wen et al. further experimentally demonstrated helicity-modulated multiplexed holography based on a high-efficiency PB metasurface [286]. As shown in Fig. 16(g), the sample was made by two sets of MIM meta-atoms, with orientations independently controlled to encode two different holographic images (i.e., a flower and a bee), for excitation of LCP or RCP light [Fig. 16(g)]. Therefore, the image projected can be switched between flower and bee, as the chirality of incident light is tuned. Such chirality-multiplexed holography was experimentally verified in the wavelength range of 475–1100 nm, with maximum efficiency reaching 40% at 960 nm. In addition to metallic losses, cross talk between two sets of nanorods is another factor to affect the device’s performance, which is the key issue persisting in all bifunctional devices based on such a “merging” concept (see also Subsection 4.5).

However, the high-efficiency metaholograms mentioned above are all for reflection geometry, which is sometimes inconvenient for realistic applications. To realize
high-efficiency metaholograms in transmission geometry, we need to first design a transmissive PB meta-atom exhibiting a high PCR, which is, unfortunately, not an easy task, particularly at optical frequencies when using plasmonic metals (see Subsection 3.2). Meanwhile, researchers have found that dielectric meta-atoms can exhibit high working efficiencies at optical frequencies. In 2016, Capasso’s group reported a high-performance dielectric PB metahologram working at visible wavelengths [287] soon after their seminal work on dielectric metalenses [257]. The building block is essentially the same high-aspect-ratio TiO$_2$ nanofin, which, owing to its geometric anisotropy and wavelength-scale height, can generate a phase difference of $\pi$ for waves passing through it with two orthogonal polarizations. Three metaholograms were designed and fabricated, working at wavelengths of 480, 532 and 660 nm [Fig. 16(h)]. The maximum working efficiencies of these devices are measured as 82%, 81%, and 78%, respectively, which is quite remarkable.

With physical mechanisms clearly established, researchers continued to explore more applications of metaholograms. Huang et al. reported a plasmonic metahologram that can reconstruct a multicolor image under the illuminations of white light [285]. To ensure the device worked in the whole visible regime, the authors purposely selected aluminum, which has an exceptionally high plasmon frequency, as the material to build the metahologram. The device consists of three different sets of nanoantennas that carry desired phase distributions responsible for holographic images in the three primary colors. Wavelength-dependent diffractions are utilized to project images with different colors to specific locations. Soon, Wan et al. fabricated a plasmonic metasurface composed of subwavelength nanoslits and demonstrated that it can construct 2D and 3D full color images [288]. Wavelength-multiplexed metasurface holograms with both amplitude and phase modulations can faithfully produce not only the three primary colors, but also their secondary colors. Full-color holographic images were successfully reconstructed, but with relatively low efficiencies ($\sim$2%) caused by the low transmission through the subwavelength nanoslits. Deng et al. proposed a diatomic metasurface to achieve vectorial optical metaholograms [289]. The building block is based on an MIM trilayer design consisting of two orthogonal silver nanorods. Both the spatial displacement and orientation angle of the two nanorods in each metamolecule are modified for achieving full and dispersionless phase and polarization control. Active reconstruction of vectorial holographic images was experimentally demonstrated, and was found to be robust against both incident angles and wavelengths. Recently, Yue et al. extended the metahologram concept to use Sb$_2$Te$_3$ (a topological insulator material) to build a 60 nm thick metahologram [290]. Since Sb$_2$Te$_3$ thin film has different refractive indices at the surface and in the bulk, it can serve as an intrinsic cavity for large phase tuning through multiple reflections. Such mechanism explains why Sb$_2$Te$_3$-based metaholograms can work in the deep-subwavelength scale. The fast development of this field [291] has opened up a new direction for complicated wavefront control, which has great potential in future applications.

We believe that metasurfaces can potentially be very useful in display applications in the future, based on the promising progress already achieved on metaholograms. However, many practical issues (cost, tuning speed, mechanical stability, etc.) need to be addressed from the application point of view, before such technologies and products can finally be accepted by the industry.

4.3. Metasurface-Based Cloaking

Rendering an object invisible to external observers is always fascinating and has important applications in practice. Such a goal can be achieved if the object is surrounded or covered by an invisible cloak that can redirect impinging light to the desired directions, as if the object does not exist for an observer in the far field. Obviously, such
a cloak cannot be made by natural materials that exhibit very limited capabilities to control light. In 2006, Pendry [5] and Leonhardt [6] independently proposed a framework based on transformation optics (TO) theory to design invisibility cloaks, which were soon implemented in different frequency domains [7,292,293]. In a parallel fashion, many other schemes were also proposed to achieve invisibility, such as perfect absorption [55,58,59] and scattering cancellation [294]. However, these schemes have their own disadvantages. For example, TO-based cloaks are bulky in size and require complicated metamaterials with extreme EM parameters, and the invisibility achieved by scattering cancellation sensitively depends on the shape of the object being hidden.

Metasurfaces offer a new platform to achieve optical invisibility. In 2013, Zhang et al. proposed a microwave carpet cloak based on a reflective metasurface built with MIM meta-atoms with H-shaped top structures [295]. The metasurface is placed at a tilt angle $\theta$ with respect to the ground plane, below which an object can be hidden [see Fig. 17(a)]. The device is essentially a gradient metasurface with an appropriate reflection-phase gradient so that it can reflect normally incident EM waves back to the normal direction, according the generalized Snell’s law [160,161,163]. In such a way, an object hidden inside the triangle region below the device cannot be detected by external observers, since the reflected wave is identical to that reflected from the ground plane. Microwave experiments demonstrated that such a metasurface carpet cloak can work within the frequency band 9.9–10.6 GHz and for incident angles $<5^\circ$.

In principle, the concept of the metasurface-based carpet cloak is quite generic and can be realized in different frequency domains for objects with arbitrary shapes. In 2015, Ni et al. demonstrated an ultrathin carpet cloak for visible light based on a reflection-type metasurface [296]. As shown in Fig. 17(b), a skin-level conformal metasurface made by MIM meta-atoms is used to cloak an arbitrarily shaped object hidden below. By carefully tuning the geometrical parameters, each local part of the metasurface can possess an appropriate phase gradient that can help reflect normally incident light back to the normal direction, no matter how this local part is tilted against the ground plane. As a result, the reflected light is the same as that reflected from a flat ground plane so that the object cannot be discovered. The authors performed optical experiments to nicely demonstrate the carpet cloaking effect, with several macroscopic 3D bumps and dents hidden in the region below the cloak. The cloaking effect persists within a wide wavelength band (710–810 nm) and for a wide range of incident angles (0–30°). The total thickness of the cloak is only 80 nm ($\lambda/8$), which is a huge advantage of the present scheme. After this work, a series of studies [297,300–306] have been conducted to realize polarization-independent, wide-incidence-angle, and/or broadband carpet cloaks based on metasurfaces. For example, Chen’s group experimentally demonstrated a full-polarization arbitrarily-shaped 3D metasurface cloak in the microwave regime [297], as shown in Fig. 17(c). Both simulations and experiments show that such a cloak can completely restore the polarization, amplitude, and phase of input light as if the light was incident on a flat mirror.

Despite great successes achieved along this direction, we note that these metasurface-based cloaks are all in reflection geometry, which makes them inconvenient to implement in certain application scenarios (say, without a ground plane). However, making a transmissive metasurface cloak is very challenging, as the cloak should not only prevent reflection but also redirect the incident wave to pass around the hidden object without touching it. Recently, Chu et al. proposed a new device configuration that integrates a transparent gradient metasurface with an ultrathin zero-index material (ZIM) as a cloak working in transmission geometry [298]. The cloaking effect is realized through the following three steps, enabled by the metasurfaces and the ZIM [Fig. 17(d)]. First, the gradient metasurface at the device entrance can redirect the locally incident light to propagate along the normal direction after transmission.
Metasurface based cloaking. (a) An ultrathin directional carpet cloak based on generalized Snell’s law. Left panel: schematic of the directional carpet cloak composed of metasurfaces with the whole structure shown in the inset. Right panel: simulated total electric field for the tilted metasurface illuminated by a normal incident wave [295]. (b) A skin level invisibility cloak for visible light. Left panel: illustration of a metasurface skin cloak made of nanoantennas covering the arbitrarily shaped object. Right panel: simulated scattering electrical field distributions for an object without (top) or with (bottom) a metasurface skin cloak at normal incidence [296]. (c) Schematic of a full polarization 3D metasurface cloak in THz regime (left panel, whole structure; right panel, building block) [297]. (d) Hybrid invisibility cloak in transmission mode. Left panel: conceptual illustration of the cloak based on the integration of metasurfaces and ZIM. The black lines indicate the ray paths of light and the red arrows indicate the flow of electromagnetic flux inside the ZIM. Right panel: electric field distribution for the case with the cloaking shell (green rectangle region, experiments; outside region, simulations) [298]. (e) Diffusion-induced cloak with coding metasurfaces. Left panel: schematic of a coding metasurface for achieving THz diffusion (inset: simulated 3D scattering pattern) in reflection mode. Right panel: measured and simulated backward reflection spectra of the metasurface [173]. (f) A deterministic approach to achieving broadband polarization-independent diffusive scatterings. Left panel: three key design steps are (i) design a reflective PB meta-atom with nearly 100% efficiency, (ii) form a set of subarrays providing focusing phase profiles but with different initial phases, and (iii) arrange these subarrays based on a certain coding sequence. Inset shows a typical Fourier-transform spectrum of a subarray. Right panel: the wave-diffusion behaviors achieved by such metasurface [299]. (a) Reprinted with permission from Zhang et al., Appl. Phys. Lett. 103, 151115 (2013) [295]. Copyright 2013 AIP Publishing LLC. (b) From Ni et al., Science 349, 1310–1314 (2015) [296]. Reprinted with permission from AAAS. (c) Yang et al., Adv. Mater. 28, 6866–6871 (2016) [297]. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission. (d) Reproduced from [298] under the terms of the Creative Commons Attribution 4.0 License. (e) Reproduced from [172] under the terms of the Creative Commons Attribution NonCommercial-ShareAlike 3.0 Unported License. (f) Reprinted with permission from Xu et al., ACS Photon. 5, 1691–1702 (2018) [299]. Copyright 2018 American Chemical Society.
Second, the ZIM is designed such that it can redirect any normally incident light to flow around it, due to the wave-tunneling effect [307]. Finally, the tunneled wave is then bent back to the original direction after passing through the metasurface at the exit side. This way, the incident wave can never touch the central region, where an arbitrary object can be hidden, and pass through the whole device as if the hidden object does not exist at all. The authors first numerically validated such idea based on an effective-medium model system. They next designed and fabricated a ZIM based on a photonic crystal with a Dirac-cone-like dispersion following Ref. [308], and a transparent gradient metasurface based on ABA meta-atoms that exhibits a phase gradient to refract a normally incident wave to an angle 45° after transmission following Ref. [201], both working at the frequency of 10.2 GHz. Figure 17(d) depicts the electric field distribution inside the rhombic cloak device illuminated by a plane wave at 10.2 GHz, verifying the nice EM wave cloaking effect. While this work provides a new concept for realizing skin-level cloak devices in transmission geometry, many problems need to be solved in future studies. For example, although the designed metasurface has a subwavelength thickness, the ZIM made of photonic crystal is still bulky, leading to a wavelength-scale hybrid cloak device. Also, the device exhibits a limited bandwidth and is quite sensitive to the incidence angle of external illumination. Such issues can possibly be solved later by employing recently developed coding/programmable metasurfaces [173] or nonlocal metasurfaces [309].

Other mechanisms have also been proposed to achieve invisibility based on metasurfaces. In 2014, Cui’s group proposed a coding metasurface that possesses a significantly reduced radiation cross section (RCS) for EM waves within a broad frequency band [173], which is an ideal cover layer to hide an object. As shown in Fig. 17(e), the metasurface is composed by two distinct types of MIM meta-atoms, which are designed to have nearly 100% reflection amplitudes, but with reflection phases $0 \equiv \theta \equiv \phi$, denoted as “0” and “1” particles, respectively. By optimizing the arranging sequences of these two meta-atoms in an $N \times N$ lattice, the authors designed a metasurface that can redirect the normally incident EM wave to many different directions in 3D space, leading to significant RCS reductions, particularly for specular reflection. The reported device exhibits a $-10$ dB level RCS reduction within a relatively broad bandwidth (7.8–12 GHz). Such diffusive metasurfaces can be realized with more meta-atoms exhibiting finely discretized phase levels working in different frequency domains [172–313]. Despite significant progress achieved in this field, the realized diffusive metasurfaces suffer from the following key issues: 1) the RCS reduction is achieved mainly for the specular reflection but not for all directions, and 2) the design process involves optimization that is very time-consuming and non-reproducible. Very recently, Zhou’s group proposed a deterministic and straightforward method to design diffusive metasurfaces to achieve full diffusion of incident EM waves to all angles, within an ultrawide frequency band and independent of incident polarization [299]. The design strategy consists of three key steps, which are adopted to overcome the issues mentioned above [Fig. 17(f)]. The authors first design an MIM PB meta-atom that exhibits high-efficiency PCR within an ultrawide band. They then use such a meta-atom to construct a set of subarrays (i.e., bits) that exhibit the same parabolic phase distributions but with different initial phases. Finally, the bits are arranged in an arbitrary coding order to form a diffusive metasurface. The most important improvement is that the present design strategy combines the advantages of different mechanisms, i.e., PB phase, focusing, and coding metasurfaces. Specifically, using a PB mechanism can make the device insensitive to incident LP, while a metalens can naturally diffuse an incident EM wave to difficult directions. In addition, adopting an arbitrary coding sequence can further enhance the performance and make the device compatible with complex shapes, as requested in practice. The authors performed
extensive numerical and experimental studies to demonstrate the robustness of their newly proposed approach. In particular, their experiments show that a metasurface designed with such an approach can reduce the RCS for all directions by more than 10 dB within an ultrawide band (6–18 GHz) for incident EM waves with arbitrary polarizations. Recently, Liu et al. proposed a new approach for designing external cloaks through combining a surface admittance approach and a TO approach with complementary media as a seed simulation. The metadevice can hide an object on top of a reflective metasurface, mimicking a flat mirror, which is similar to a TO-based external cloak that uses a negative index medium to cancel out the scattering field of the object. Here, a metasurface is used to replace the negative index medium [314].

Except for EM cloaking, conformal metasurfaces can be utilized to achieve other fascinating physical effects, which form important research directions [315–320]. For instance, Faraon’s group proposed to decouple the optical properties of an object from its physical shape by capping a thin and flexible metasurface on the object conformally. Such a conformal metadevice is composed of silicon nanoposts embedded in a polymer substrate that are able to tailor the local wavefront of impinging light. As a proof of concept, the authors experimentally demonstrated that a cylindrical lens covered with a carefully designed conformal metasurface can effectively function as a spherical lens [315]. Recently, Genevet’s group proposed the concept of “conformal boundary optics,” which is an analytical method based on first-principle derivation that can help tailor the reflection and transmission fields at will. For any given object, one can use the developed theory to design an appropriate metacoating to cover it, in order to achieve the desired optical effects, such as anomalous diffraction and optical illusion [316]. Moreover, conformal metasurfaces can also be employed to realize even more complex functionalities, such as displays [317] and holograms [318,319].

4.4. Special Beam Generation

Beams with special patterns (e.g., vortex beams, Bessel beams, vector beams) can find many applications in applied optics, but conventional devices to generate them (e.g., spiral phase plates and light modulators) are either too bulky and/or have low efficiencies, which makes them unfavorable for integration-optics applications. Metasurfaces provide new opportunities to design optical devices to generate these special beams. These devices are flat and of subwavelength sizes, which may find important applications in integration optics. In this subsection, we briefly review the development along this direction.

4.4a. Vortex Beam Generation

The field profile of a vortex beam can be simply described by \( \vec{E}(\vec{r}) = \vec{E}_0 \exp(-ikz) \exp(-im\phi) \), with \( k \) being the wavevector in a background medium. Because of the azimuthally dependent phase factor \( \exp(-im\phi) \), a vortex beam can carry an optical angular momentum (OAM) with a topological charge \( m = 0, \pm 1, \pm 2, \ldots \) and, hence, can increase the channels for information communication. In addition, the doughnut-like intensity profile of vortex beams is highly desired for numerous applications, such as stimulated emission depletion microscopy [321] and optical tweezers [322].

Along with their pioneering work on establishing the generalized Snell’s law, Yu et al. [160] and Genevet et al. [323] already utilized V-shaped nanoantennas to build metasurfaces that serve as optical vortex beam generators. As shown in Fig. 18(a), the fabricated device consists of eight different types of V-shaped antennas that can scatter light with different phases, arranged in different azimuthal angle regimes, to finally create a spiral-like phase profile on the metasurface. As incident light strikes the metasurface, light transmitted through different local parts can gain phases, and the interference

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Special beam generation with metasurfaces. (a) Plasmonic optical vortex plate based on a metasurface. Left panel: SEM image of such metasurface. Right panel: measured vortex patterns created by the interference of the vortex beam and a co-propagating Gaussian beam [323]. (b) Vortex beam generator based on a plasmonic waveguide. Top panel: schematic of a nanowaveguide array that induces a vortex wavefront. Bottom: SEM picture of the fabricated nanowaveguide array (left panel) and the spiral interference pattern for a LP illumination case (right panel) [324]. (c) Vortex beam generation based on a PB metasurface (left panel, SEM image of the sample; right panel, measured field patterns of the vortex beams for different wavelengths [181]. (d) Left panel: schematic of an aberration-free ultrathin flat axicon for generating Bessel beams at telecom wavelengths. Right panel: measured field patterns along the main-axis plane of the generated Bessel beam [325]. (e) Catenary nanostructures for Bessel beam generation. Sketch of the Bessel beam generators for \( l = 2 \) and 3 with the measured interference patterns depicted in the insets [326]. (f) The plasmonic metasurface (right panel) used to generate radially polarized beams combines subwavelength apertures for polarization control (left panel) and wavelength-scale diffracting apertures (middle panel) [327]. (g) Schematic of a high-efficiency anisotropic Huygens’ metasurface for converting a circularly polarized Gaussian beam into a vector Bessel beam [328]. (h) Left panel: schematic of vector vortex beam generation through a single metasurface. Right panel: polarization and phase distributions of the normal mode (bottom panel), anomalous mode (middle panel), and the interfered vector vortex beam (top panel). The anomalous mode has the same circular polarization as that of the incident beam and a spiral phase change with the topological charge of 2, while the normal mode has opposite helicity but no phase change, upon illumination by RCP light. The interference of two modes gives rise to radial polarization distribution with the topological charge of \( l = 1 \) [329].

among them can generate a vortex beam with a topological charge of $m = 1$. In their experiments, the authors utilized a co-propagating Gaussian beam to interfere with the transmitted beam, generating a spiral-like interference pattern [see Fig. 18(a)], which is direct evidence of vortex beam generation. In 2014, Sun et al. proposed a different metasurface to generate a vortex beam [Fig. 18(b)] [324]. The device is a plasmonic metal drilled with circular nanowaveguides with appropriate sizes located at different azimuthal positions on a circle. By varying the radii of the waveguides, the authors can precisely control the phases of light transmitted through the apertures to make them follow the equation $e^{im\theta}$, thus providing an OAM to the incident light. An optical vortex beam was produced experimentally at the wavelength of 532 nm. The structural symmetry guarantees that the present OAM generator is polarization independent, which is highly desired in applications.

PB metasurfaces can generate spin-polarized vortex beams with both spin and orbital momentum. In 2012, Huang et al. fabricated a PB metasurface to generate an optical vortex beam [181]. A helical phase front carrying an OAM can be produced upon illumination by a normally incident CP Gaussian beam. Thanks to the non-dispersive nature of the geometric phase, the metasurface can work within a broad band ranging from the visible to NIR regimes, as shown in Fig. 18(c). Similar vortex beam generators based on different PB meta-atoms were subsequently proposed in various frequency domains [330,331]. Since most PB metasurfaces are constructed by meta-atoms with a finite number of orientations, they can provide discretized phase shifts only for the input light, which limits the performance of vortex beam generation. To solve this issue, scientists proposed certain plasmonic structures that can provide phase shift continuously in space to generate optical vortices with better qualities. For example, Chimento et al. proposed a vortex generator that is a metal film etched with a circular subwavelength nanoslit [332]. Upon illumination with CP light, a straight slit allows only LP light with a particular polarization to pass through, thus acting as an effective quarter-wave plate. Thanks to the circular configuration, the orientation of the local wave plate changes from 0 to $2\pi$ along the curved slit, thus providing a phase of the form $e^{\pm 2i\theta}$, which helps generate vortex beams with topological charges $\pm 2$. Based on similar structures, Guo et al. proposed to utilize another freedom, i.e., the local aperture’s width, to provide an additional continuous phase shift to the incident light, resulting in vortex beams with integer or fractional topological charges [333].

However, these PB devices all exhibit very low efficiencies, since their PB meta-atoms can support both normal and anomalous modes. As a result, the desired anomalous OAM pattern may interfere with the undesired normal mode, causing the vortex beams to blur. To enhance the working efficiency, Yang et al. used a high-index silicon nanowire on a silver ground plane as a PB meta-atom to build vortex generators [174]. Their experiments demonstrated that such dielectric vortex beam generators, with significantly reduced ohmic losses, do show enhanced working efficiencies within the wavelength range of 1500–1600 nm. The efficiency can be further enhanced by carefully designing the PB meta-atom following the criterion of Eq. (13). Indeed, using the ABA-type PB meta-atom designed according to Ref. [25], Luo et al. fabricated three transmissive vortex beam generators, and experimentally demonstrated their excellent ability to generate vortex beams with topological charges $m = 1, 2, 3$ at 10.5 GHz [183]. Field-mapping measurements demonstrated pure OAM beam patterns immune from normal background interference, with a maximum efficiency of $\sim 91\%$. Lu et al. experimentally demonstrated a broadband high-efficiency optical vortex beam generator in the visible regime. A systematic study based on Jones matrix analysis and full wave simulations reveals the relationship between the conversion efficiency and the antenna nature, enabling the realization of a high-performance device [334].
4.4b. Bessel Beam Generation

Bessel beams are a special type of EM radiation with transverse field amplitudes described by Bessel functions of the first kind. In cylindrical coordinates, we can describe a Bessel beam by $E(r, \phi, z) = A \cdot \exp(-ik_z z) \cdot J_n(k_r r) \cdot \exp(\pm im\phi)$, where $k_z$, $k_r$ are the longitudinal and transverse wavevectors, respectively, and $m$ is the order of the Bessel function. It is clear that the amplitude of an ideal Bessel beam is independent of $z$, revealing its non-diffraction property. In addition, high-order Bessel beams can carry OAMs determined by the mode order $m$. The non-diffraction property means Bessel beams have numerous applications in practice, such as particle trapping, near-field probing, and photolithography [335–338]. In traditional approaches, one uses certain devices (such as an annular slit [339] and axicon lens [340]) to diffract or refract the impinging light symmetrically to the main axis, generating the desired Bessel beams through interference. However, such devices are bulky and of low efficiency.

In 2012, Aieta et al. proposed to use V-shaped meta-atoms to construct a Bessel beam generator at the telecommunication wavelength [325]. As shown in Fig. 18(d), the device is essentially a flat version of an axicon with a linearly increasing phase distribution along the radial direction. Specifically, the metasurface is designed to possess a phase distribution $\Phi(x, y) = \frac{2\pi}{\lambda} \sqrt{x^2 + y^2} \sin \beta$, with $\beta$ being the angle of the axicon. Optical measurements clearly revealed a centimeter-scale non-diffraction field pattern along the propagation direction generated by such a flat meta-axicon. However, such a device has a low working efficiency (about 1%). Many different Bessel beam generators were subsequently proposed. For example, Li et al. proposed a compact catenary-shaped nanostructure as a Bessel beam generator [326]. As shown in Fig. 18(e), such a nanoarray behaves like a grating structure with a period $p$, which determines the radial wavevector $k_r = 2\pi/p$ of the Bessel beam. By arranging the nanostructure into a ring or spiral shape, such metasurfaces can generate second-order or third-order Bessel beams, as depicted in Fig. 18(e). Bessel beams with different orders were experimentally created within a broad frequency band.

Much effort has also been devoted to increasing the efficiency of Bessel beam generation [341–343]. Recently, Wang et al. designed and fabricated an ultrathin ($\lambda/6$) transmissive PB metasurface, constructed with the high-efficiency ABA-type PB meta-atom designed following the criterion in Eq. (13). The authors experimentally demonstrated that this metasurface can generate spin-polarized Bessel beams at a frequency window of 10.7–12.3 GHz [341]. The measured maximum efficiency of the device reaches 91%, in consistency with the simulated result (~92%). The self-healing properties of the generated Bessel beam were well demonstrated in experiments with a metallic object purposely put on the propagation path of the beam. In the visible regime, Khorasaninejad et al. fabricated a dielectric PB meta-axicon based on similar TiO$_2$ meta-atoms adopted in constructing metalenses [257], and experimentally demonstrated its capability of generating spin-polarized Bessel beams [344]. Thanks to the high NA (about 0.9) of the fabricated metasurface, the full width at half-maximum of the generated zeroth-order and first-order Bessel beams are as small as ~160 and 130 nm at the central wavelength $\lambda = 405$ nm, with diffraction-free field patterns maintaining for a large distance ($150\lambda$). Bessel beam generators can also be integrated with other functional devices. For instance, Mehmood et al. proposed to combine two distinct functional devices, i.e., a lens and a spiral phase plate, into a single metasurface that can generate Bessel beams with different topological charges focused at distinct focal planes [342].

4.4c. Vector Beam Generation

Polarization, an important characteristic of light wave, plays a vital role in light–matter interaction. Such a degree of freedom has been widely used in many applications, such
as optical detection, displays, and data storage. Different from special beams that possess uniform polarization, vector beams—optical beams with spatially variant polarizations—exhibit expanded degrees of freedom, making them useful in many applications. Recently, much effort has been devoted to designing metasurfaces for generating vector beams, which will be briefly summarized in the following.

In 2013, Lin et al. reported a metadevice to achieve broadband manipulation of vector beams [327]. As shown in Fig. 18(f), such a device consists of a radial polarizer and fork diffraction hologram. Here, the radial polarizer can convert input CP light to radially polarized light with an additional spiral phase $\exp(i\theta)$, while the fork hologram can diffract an incident CP Gaussian beam to a vortex beam with an opposite spiral phase $\exp(-i\theta)$. The whole device can thus be regarded as a combination of two independent structures, owing to their very different length scales, that cooperatively generate the desired radially polarized beams. The fabricated sample was tested at two different wavelengths (633 and 850 nm), exhibiting a conversion efficiency of 3.9%.

Vectorial Bessel beams can also be generated with a single device. For instance, Pfeiffer et al. proposed a multilayer metasurface to efficiently generate a vectorial Bessel beam in transmission mode [see Fig. 18(g)] [328]. The adopted meta-atom consists of three cascaded anisotropic sheets that can manipulate the polarization and phase profiles simultaneously. Owing to the air-matched impedance, the efficiency of the device is very high. Two different metasurfaces were demonstrated experimentally to transform linearly and circularly polarized Gaussian beams to vectorial Bessel beams at a frequency of 9.9 GHz [328]. Based on the PB mechanism, Yue et al. proposed to realize a single plasmonic PB metasurface to generate vectorial vortex beams [329]. Since the adopted MIM meta-atom is not an ideal half-wave plate (see Subsection 3.2), the device can generate both the desired anomalous mode and the undesired normal one, which may affect the final performance of the beam generation. As shown in Fig. 18(h), the resultant beam transmitted through the PB metasurface is a superposition of the co-polarized normal reflection mode with a phase of 0 and the cross-polarized anomalous reflection mode with a PB phase of $\exp(i2\varphi)$, giving rise to a radially polarized $l = 1$ vortex beam with spiral phase of $\exp(i\varphi)$.

Finally, we would like to mention that metasurfaces also provide an ideal platform to generate other types of optical beams, such as Airy beams. These receive intensive research interest because of their unique properties, which include that they are self-accelerating, diffraction-free, and self-healing. Recently, various types of Airy beams, such as plasmonic Airy beams, Airy vortices, and vector beams, have been generated based on plasmonic metasurfaces [345–348], which will not be discussed in detail due to the space limitation of this review.

4.5. Multifunctional Metasurfaces

Facing increasing demands on the speed and memory of EM devices, EM integration is highly desired in modern science and technology. Metasurfaces are ideal candidates to integrate multiple diversified functionalities into single devices with deep-subwavelength thickness and high efficiencies [349]. Various approaches have recently been proposed to achieve this goal, which will be briefly summarized in this subsection.

Polarization is one important degree of freedom that can be used to realize multifunctional metadevices. Based on anisotropic meta-atoms with polarization-sensitive EM responses, various metadevices were realized at different frequencies, exhibiting multiple functionalities triggered by incident EM waves with different LPs [350–356]. In 2014, Chen et al. experimentally demonstrated a metahologram based on anisotropic MIM meta-atoms for achieving polarization-modulated dual holographic images [282]. However, the device still exhibits similar functionalities (e.g., hologram) for two
incident polarizations. In 2016, Cai et al. proposed a general strategy to design bifunctional metadevices that exhibit distinct functionalities with very high efficiencies [350]. They demonstrated two microwave bifunctional metadevices, working in transmission and reflection geometries, respectively, each exhibiting two distinct functionalities [e.g., focusing and beam bending (or even PW-SW conversion)] with very high efficiencies (90% and 72% for reflection and transmission geometries). The adopted meta-atoms are MIM (reflection) and multilayer structures (transmission), both exhibiting anisotropic shapes and thus polarization-dependent responses. Very recently, Ding et al. extended such a concept to the optical regime, demonstrating a bifunctional reflective metadevice that can achieve two distinct functionalities (surface plasmon excitation and beam steering) as being excited by incident lights with two orthogonal polarizations. The device works in a broad band (580–700 nm) and is constructed by anisotropic MIM meta-atoms [see Fig. 19(a)] [352]. In addition to using multilayer meta-atoms, one can also adopt Huygens’ meta-atom and dielectric meta-atoms to construct transmissive multifunctional metadevices. For instance, Arbabi et al. experimentally demonstrated that dielectric metasurfaces constructed by silicon elliptical nanoposts are the ideal platform to design bifunctional metadevices achieving high-efficiency (>72%) polarization-switchable functionalities (imaging, hologram, etc.) in the NIR regime [218]. However, the above-mentioned metadevices work either in pure reflection or pure transmission mode, leaving half of the EM space completely unexplored. To expand the wave manipulation capabilities of metasurfaces, Zhou’s group recently proposed a new type of multifunctional metasurface to manipulate EM waves in the full space [351]. The key improvement is that the designed meta-atoms, consisting of carefully designed multilayers of metastructures so that the whole system can be perfectly transparent or reflective for two polarizations. Using these unique meta-atoms, the authors fabricated several bifunctional microwave metadevices, and experimentally demonstrated that these devices can manipulate EM waves with different functionalities at two sides of the metasurface with very high efficiencies (>85%). As shown in Fig. 19(b), one fabricated metadevice can achieve anomalous reflection for an x-polarized incident wave, and can focus the incident EM wave at the transmission side as the polarization direction changes to the y direction. Employing the same idea, Zhang et al. experimentally demonstrated that a single microwave metasurface can exhibit three different functionalities (beam bending, reducing the radar cross section, and vortex beam generation) and control transmitted and reflected wavefronts simultaneously [363].

Helicity is another degree of freedom frequently exploited to design multifunctional metadevices based on the PB mechanism [357–359,364–368]. A commonly applied scheme is to merge several different PB metasurfaces, each exhibiting a certain functionality as the incident CP light takes a particular helicity, into one single device [365,366]. Although such “merging” strategy is physically straightforward, realized devices exhibit limited working efficiencies and suffer from the issue of functionality cross talk. In 2015, Huang et al. proposed to use PB metasurfaces to record various hologram patterns into helicity-multiplexing channels, as shown in Fig. 19(c) [357]. Although a broadband hologram ranging from 633 to 1000 nm was experimentally achieved, the measured working efficiency was only 4.5% at 810 nm (0.65% at 1000 nm). Recently, Hasman’s group experimentally demonstrated that the alliance of spin-enabled geometric phase and shared-aperture concepts can open a new pathway to implement photonic spin-controlled multifunctional metasurfaces [358,368,369]. Helicity-controlled multiple wavefronts such as vortex beams carrying different OAMs, were demonstrated in the visible regime (780 nm), as shown in Fig. 19(d) [358]. In 2017, Mueller et al. proposed a new approach that combines geometric and propagating phases to encode arbitrary phase profiles on any two orthogonal polarization states (linear, circular, or elliptical), and experimentally demonstrated chiral holograms based on transmissive dielectric
metasurfaces, which can efficiently generate independent far-field images for RCP and LCP excitations at $\lambda = 532$ nm [see Fig. 19(e)] [359].

Wavelength multiplexing is also widely exploited to realize multifunctional metasurfaces. In 2016, Li et al. proposed an approach to realize multicolor metaholography with a single type of plasmonic pixel, based on an off-axis illumination method [360]. As shown in Fig. 19(f), a seven-color metahologram with remarkable image quality was experimentally demonstrated in the optical regime, as well as multicolor 3D metaholography. In a parallel line, dielectric metasurfaces are used to build high-efficiency wavelength-multiplexing metadevices at optical frequencies. As shown in Fig. 19(g), Wang et al. experimentally demonstrated that a metasurface formed by three kinds of silicon nanoblocks multiplexed in a subwavelength super-unit can achieve wavefront manipulations for red, green, and blue light, simultaneously [361]. Again, the experimentally achieved efficiencies of the reconstructed images for highly dispersive color holograms are limited due to the intrinsic issue of the “merging” concept.

Recently, incidence angle was found to be another degree of freedom that has not yet been fully exploited. In 2017, Kamali et al. proposed an angle-multiplexed metasurface composed of reflective high dielectric contrast U-shaped meta-atoms with incidence-angle-sensitive responses, and experimentally demonstrated that it can realize high-efficiency angle-multiplexed diffractions and holograms at the working wavelength of 915 nm, as shown in Fig. 19(h) [362]. Very recently, Zhou’s group established a theory to quantitatively describe the angular dispersion behaviors in metasurfaces [370] and experimentally demonstrated that the angular dispersion is dictated by the plasmonic coupling among meta-atoms inside metasystems. Via “designing” the plasmonic couplings within particles inside composite meta-atoms, the authors proposed a new strategy to design metadevices that exhibit incidence-angle-dependent multifunctionalities, which can possibly stimulate many experimental realizations in the future.

### 4.6. Tunable/Active Inhomogeneous Metasurfaces

The fascinating effects described above are all based on passive metasurfaces, which cannot be changed once the metasurfaces are fabricated. In practical applications, it is highly desired to achieve dynamically tunable manipulation of EM waves. In Subsection 2.4, we have summarized the available schemes to dynamically tune the EM properties of homogeneous metasurfaces in which meta-atoms are controlled uniformly. With the fast developments on inhomogeneous metasurfaces, one can now utilize those schemes to independently control the EM properties of individual meta-atoms in inhomogeneous metasurfaces, thus equipping metadevices with the capabilities to dynamically control EM waves, yielding fascinating applications, such as beam steering and programmable holograms and imaging. This is, however, highly challenging, particularly for frequencies higher than THz. In this subsection, we briefly introduce recent efforts devoted to this field, focusing on both the achievements and challenges.

In the microwave regime, a frequently adopted scheme is to incorporate voltage-driven elements such as diodes and varactors into the meta-atom design. By assembling these meta-atoms to form a metasurface, each meta-atom can be efficiently and independently tuned by the diode/varactor inside its structure, thus offering the whole device desired dynamical wave-manipulation functionalities. Much fascinating progress has been achieved based on such a scheme [371–376]. In 2012, Shadrivov et al. realized a microwave light-tunable metadevice, which consists of arrays of broadside-coupled SRRs, each loaded with a varactor diode connected with a light emitting diode (LED) [371]. By reconfiguring the LED pattern with external light radiation, the authors can individually control the voltages supplied to different varactor diodes, which, in turn, dynamically modulates the responses of those different meta-atoms in the device, finally
resulting in active switching between focusing and defocusing functionality for the fabricated device [see Fig. 20(a)]. Recently, to solve the issue of the chromatic response of all metadevices based on resonant mechanisms, Xu et al. proposed to make tunable metadevices in which the dispersion-induced phase distortion in each meta-atom is precisely rectified by changing the individual external voltage imparted on the varactor diode incorporated in that very meta-atom. A tunable gradient metasurface exhibiting single-mode high-efficiency operation within a wide frequency band was experimentally demonstrated in the microwave regime, as well as a metadevice exhibiting dynamically switchable functionality from a specular reflector to a surface wave converter [372]. Based on such an approach, the authors further experimentally demonstrated a tunable microwave metasurface that can exhibit aberration-free focusing or dynamically switchable focusing performance depending on the gating voltages applied, as shown in Fig. 20(b) [373]. These metadevices are all based on reflection geometry and are relatively easy to realize since one needs to consider only the phase tuning in practical designs. Meanwhile, metadevices working in transmission mode are more difficult to make, as they require precise control of both amplitude and phase of locally transmitted waves. More recently, Feng’s group experimentally demonstrated a reconfigurable Huygens’ metasurface working at 6.9 GHz, which exhibits controllable multiple and complex focal spots by reprogramming the input voltages applied on the loaded dipoles, as shown in Fig. 20(c). The experimentally achieved focusing efficiency is about 36%, with a modulation speed reaching the order of $10^5$ switches/s [374]. In a parallel line, Cui’s group also demonstrated a series of reprogrammable microwave metasurfaces to achieve different EM wave manipulations [375,376]. Figure 20(d) illustrates one fabricated device that which can achieve multiple holographic images in real time through dynamically tuning the voltages applied on loaded diodes [375]. Recently, microfluidics technology has also been widely used to achieve tunable microwave metadevices, such as tunable metalenses [377], dynamic beam deflectors [145], and tunable polarization converters [382]. In 2015, Zhu et al. experimentally demonstrated a reconfigurable metadevice formed by casting microwave resonators through microfluidic channels, which exhibits dynamically switchable focusing functionalities [see Fig. 20(e)], as the EM responses of those resonators were continuously and individually tuned by microfluidic technology [377].

However, these techniques are difficult to implement at frequencies higher than GHz, as no voltage-driven elements work at those frequencies. Much effort has been devoted to exploring new tuning techniques in both the THz and optical regimes, thanks to rapid advances in nanofabrication and material sciences. In 2014, Watts et al. experimentally demonstrated THz compressive imaging based on a metadevice that consisted of $8 \times 8$ dynamic, polarization-sensitive metaspatial light modulators (SLMs). As shown in Fig. 20(f), each meta-SLM is essentially an MIM meta-atom incorporated with n-doped GaAs whose absorption can be actively controlled by the applied voltage. The individual and dynamic control on each pixel makes such metadevice function as a real-time spatial mask for THz radiation [378]. In 2016, Wang et al. proposed a novel approach to realize reconfigurable optical devices based on phase-change materials (Ge–Sb–Te) by inducing a refractive-index-changing phase transition with a diffraction-limited optical writing process. A variety of reversible devices were experimentally demonstrated, such as reconfigurable bichromatic and multifocus Fresnel zone plates for visible light and a gray-scale hologram [see in Fig. 20(g)]. In a parallel line, Huang et al. experimentally demonstrated an electrically tunable MIM metasurface that allows both phase (184°) and amplitude (30%) modulation on the reflected beam at telecommunication wavelength. The tunability arises from the field-effect modulation on the refraction index of conducting oxide layers incorporated into MIM metasurfaces. In addition, they also experimentally demonstrated a dynamically controlled diffraction effect through
Inhomogeneous tunable metasurfaces. (a) Illustration of light-tunable metamaterials. EM wave incident on a metamaterial is reflected at different angles depending on the control light illumination [371]. (b) Aberration-free and functionality-switchable microwave metalenses. Top panel: picture of a fabricated microwave metalens sample and schematics of a tunable meta-atom. Bottom panel: experimental results of achieved metalens with tunable focus length at 5.5 GHz [373]. (c) Reconfigurable Huygens’ metalens and characteristics of a meta-atom. Left panel: active Huygens’ metalens for dynamic EM wave focusing, of which meta-atoms are biased by computer-controlled multichannel DC voltage sources. Right panel: capacitance-dependent phase and amplitude responses of the tunable meta-atom for the transmitted EM wave at 6.9 GHz [374]. (d) EM reprogrammable coding-metasurface holograms in the microwave regime. The metasurface is formed by an array of meta-atoms integrated with a PIN diode independently controlled by a DC voltage. A computer digitally controls the metasurface by dynamically changing the phase distribution for holograms 1, 2, 3, … Under the illumination of a feeding antenna, the metasurface hologram can successively project the holographic images (frames 1, 2, 3, …) at the imaging plane [375]. (e) Microwave metalens with switchable focal length achieved with random access reconfigurable metamaterial formed by loading liquid metal into the ring microcavities based on microfluidic technology. Bottom panel: fabricated sample with schematics of a microcavity filled with liquid metal. Inset: measured field patter of the focusing effect realized [377]. (f) THz SLM with 8 × 8 pixels with individual voltage bias for compressive imaging. Frequency-dependent absorption of a single pixel (referenced to a gold mirror) for two bias voltages of 0 and 15 V. Inset: photograph of the SLM [378]. (g) Optically reconfigurable meta-devices based on phase change materials. Top panel: writing of reconfigurable photonic devices in a phase-change film. Bottom panel: image of the fabricated eight-level gray-scale hologram (left) generating a V-shaped five-spot pattern (right) [379]. (h) Schematic of gate-tunable conducting oxide metadevices based on the MIM metasurfaces incorporated with a thin indium–tin oxide film [380]. (i) Adaptive metalens with simultaneous electrical control of focal length, astigmatism, and shift. Measurement of focal length tuning using the center electrode V5 for double layered devices. Inset: schematic of
the adaptive metalens combining a metalens and a DEA with five addressable electrodes for electrical control over the strain field of the metasurface [381].


electrically controlling different subgroups of meta-atoms in the metasurface [Fig. 20(h)] [380], based on the mechanism described in [68,104]. In the optical regime, researchers also made tunable metasurfaces based on stretchable substrates, which can enable tunable color generation [383] and imaging [381]. In 2018, Capasso’s group experimentally demonstrated electrically tunable large-area metalenses controlled by dielectric elastomer actuators (DEAs), which exhibit tunable focal length and astigmatism and image shift corrections. The achieved adaptive metalens (with a double-layer configuration) working at 1550 nm exhibits focal length modulation of 30% with a high focusing efficiency (62.5%) over the whole tuning range, as shown in Fig. 20(i) [381].

While the past decade has witnessed rapid development in active and tunable metasurfaces, several major challenges need to be overcome before such devices can be used in practice [384]. For instance, most tuning mechanisms simultaneously modulate the amplitude and phase responses of the involved meta-atom, which significantly restricts the achievable functionality. Thus, finding a new tuning mechanism that support wide range but completely decoupled modulation of amplitude and phase remains one of these challenges. In addition, the trade-off between modulation depth and speed is another factor that limits the realizations of high-performance devices. In the matter of material concerns, most tunable metasurfaces realized so far are incompatible with current CMOS technology and exhibit relatively poor chemical and physical stabilities, which could be an obstacle to prevent them from integrating into realistic photonic systems. Despite these challenges, however, we still expect that tunable/active metasurfaces have a promising future that might provide an excellent platform to realize functional photonics devices.

5. CONCLUSIONS AND PERSPECTIVES

We have presented in this paper an overview on metasurfaces, including both homogeneous and inhomogeneous ones, focusing particularly on their working principles, practical realization, and potential application. We started in Section 2 with introducing how to construct homogeneous metasurfaces to control all important characteristics of EM waves, including their phase, amplitude, and polarization, both statically and dynamically, at frequencies ranging from the microwave to the visible. We next discussed in Section 3 how to build inhomogeneous metasurfaces in which
meta-atoms with specific EM responses are arranged in certain pre-designed sequences, which can be used to efficiently manipulate the global wavefronts of incoming EM waves with different polarizations and at different sides of the metasurfaces. The working principles established in Sections 2 and 3 related, respectively, to “local meta-atoms” and “global orders,” and offer researchers powerful capabilities to make metadevices that exhibit diversified functionalities, which were then summarized in Section 4, including metalenses, metaholograms, metacloaking, special beam generation, and multifunctional and tunable/active metadevices. We hope that this review paper can convince the reader that metasurfaces can indeed provide a promising platform to face the challenges of ultracompact, highly efficient, and flat EM devices raised in future applications, and can help the reader to quickly jump into this field without much difficulty. However, due to the restriction on paper length and our limited knowledge, we were not able to cover several interesting sub-branches in metasurfaces, such as nonlinear metasurfaces [385–388], parity-time metasurfaces [389,390], and computing metasurfaces [391–393].

Before concluding this review, we would like to mention some promising future directions for metasurface research, based on our perspectives.

A. **Active/tunable metasurfaces.** While remarkable progress has been achieved along this direction, great challenges exist that also provide opportunities for future studies [384]. For instance, most tuning mechanisms simultaneously modulate the amplitude and phase responses of the involved meta-atom, which significantly restricts the achievable functionality. Thus, to achieve fully free and active manipulation of EM waves, one needs to realize independent and full-range control of both the amplitudes and phases of EM waves at any desired working frequency. In addition, the trade-off between modulation depth and speed is another factor to limit the realization of high-performance devices. Regarding material concerns, most tunable metasurfaces realized so far are incompatible with current CMOS technology and exhibit relatively poor chemical and physical stability, which could be an obstacle to integrating them into realistic photonic systems. Another major challenge is how to independently modulate the EM responses of individual meta-atoms inside arbitrary metasurfaces, at frequencies higher than THz. Existing demonstrations were mostly in the GHz regime, and several trials in the THz and NIR regimes cannot be easily extended to the general cases required in realistic applications. New technologies and materials are needed to overcome this issue. Finally, how to deal with high-degree integration to modulate billions of active elements inside a single device is also a great challenge. New technologies, new design concepts, and new tunable materials are needed to address these issues.

B. **Nonlocal metasurfaces.** Chromatic and angular dispersion can both degrade the performance of optical devices, and therefore are two issues that must be addressed before metadevices can find any meaningful application. While many recent proposals appear to have overcome the chromatic dispersion issue of metasurfaces, the progress on the angular dispersion issue is relatively slow. Recently, Qiu *et al.* established a theory to uncover the origin of such intriguing effect and further provided a useful tool to control it [370]. Based on this approach, one can not only suppress the angular dispersion of metasurfaces, but can also use the angle as a new degree of freedom to realize multifunctional metadevices (e.g., polarizer or metahologram [362]). We expect that studies on angular dispersion form a very active future direction of metasurface research and can stimulate functional devices for diversified applications.

C. **Tailoring light emission by metasurfaces.** Atoms or molecules, after being excited, can relax to their ground states by emitting photons. In practice, it is highly desired to have control of such optical processes, and studies along this line already form an extremely active sub-field following the seminal work of Purcell.
Metasurfaces provide an excellent platform to achieve this end, as they already display great potential to control both the local EM environments for emitters and the far-field channels for the radiation to go. For example, thermal emission of an object can be strongly modified after surrounding it by a carefully designed metasurface that exhibits a desired radiation-absorption spectrum, yielding an amazing energy-saving radiation cooling effect [394,395]. More interestingly, by coupling light to horizontally propagating surface modes, the direction of thermal emissivity can be well controlled [396]. Meanwhile, different metastructures [397–399] have already been used to control the fluorescence of molecules. We expect that more interesting work may appear in this sub-branch, since existing efforts are far from exhausting the full potential of metasurfaces in controlling EM waves.

D. Metasystems. We already see from this review paper the strong potential of single metasurfaces in controlling EM waves. However, in practice facing more complicated application requests, metasystems that integrate several metasurfaces might be required, which is another promising direction in this field. Indeed, several groups have done interesting work along this direction. Faraon’s group proposed a metasystem composed of two cascaded metasurfaces to realize retro-reflection in the IR regime [400]. In addition, a metasystem combining functional metasurfaces (e.g., metalens) with conventional optical elements (fiber, conventional lens, etc.), may possess the advantages of both devices and thus achieve unusual physical effects and functionalities [401–403]. We expect that there will be plenty of room for researchers working along this direction.

E. Metasurfaces for other waves. The concept of metasurfaces can be extended to manipulate other types of waves in addition to propagating EM waves. For example, Lee’s group experimentally demonstrated the generation of surface plasmon vortices based on plasmonic metasurfaces [404]. Dong et al. experimentally demonstrated anomalous reflection, focusing, and even Bessel beam generation of SWs, based on dielectric metawalls [405,406]. Sheng’s group experimentally demonstrated an acoustic metasurface to achieve robust impedance matching and perfect absorption of acoustic waves [407]. Cummer’s group utilized gradient metasurfaces to realize anomalous refraction and SW conversion of acoustic waves [408]. We believe that research along this direction has great potential to explore new physics and applications in the future.

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