Metamaterial is a kind of material/structure that is artificially designed and has exceptional electromagnetic properties and/or other physical properties, not found in nature. A class of electromagnetic metamaterial with only one or a few layers of periodic or aperiodic arranged cell structures in the direction of electromagnetic waves propagation can be referred to as a metasurface. Metasurface can be considered as a two-dimensional representation of metamaterial and can realize the controlling of the amplitude, phase, and polarization state/direction of the incident electromagnetic wave. According to the novel electromagnetic characteristics of metasurface and its big advantages, a series of new planar devices and systems based on metasurface can be developed. The goal of this review article is firstly to provide introductions for basic metasurface, its significance properties, and application principles. Meanwhile, the main research progresses of regular metasurfaces and the newly developed reconfigurable metasurfaces are analyzed, focusing on the types of amplitude modulation, phase modulation, polarization modulation, and multidimensional modulation. Finally, the research significances of metasurface development trend and important engineering practical applications are analyzed in the end.

Keywords: metamaterial, metasurface, reconfigurable, wave-front manipulation, applications

INTRODUCTION

Metamaterial is a kind of synthetic structural material with singular electromagnetic, acoustic, or mechanical characteristics [1–6]. One can select the appropriate substrate types according to different application requirements and design subwavelength-scale structure (meta-atom) with different shapes, sizes, and rotation directions. According to the subwavelength period or nonperiodic array arrangements, the designed metamaterial can control independently/coherently the amplitude, phase, polarization state/direction, and other parameters of the incident electromagnetic/acoustic wave as needed. In correspondence to this, novel planar functional devices and systems working in different frequency bands such as low frequency, high frequency, microwave, THz, and visible light can be developed [7–16]. Therefore, metamaterials have important application prospects in the fields of science and engineering such as acoustics/mechanics, electromagnetics, optics, and thermodynamics. A class of electromagnetic metamaterial consisting of only one layer or a few layers of periodic or aperiodic elements in the direction of electromagnetic wave propagation is also called electromagnetic metasurface [17–21]. The electromagnetic metasurface has subwavelength thickness in the direction of electromagnetic waves propagation.
wave propagation, small size, and light weight, but it can realize
the similar electromagnetic wave characteristic controlling
abilities as the classical three-dimensional electromagnetic
metamaterial. In recent years, therefore, the research on
metasurface has become one of the hotspots in the academic
and industry areas [22–35].

Based on the Huygens’ principle, each subwavelength
structure unit of the electromagnetic metasurface will generate
a spherical wave packet at the metasurface-air interface under the
action of incident electromagnetic waves. The spherical wave
packets generated by all metasurface units form a new
electromagnetic wave-fronts [36]. Therefore, each metasurface
unit can be reversely designed according to the required
electromagnetic wave-fronts. And accordingly the
electromagnetic wave-fronts can be controlled by adjusting the
shape, size, and direction of the metasurface unit [36–40].
Different from conventional large-scale planar optical
components or microwave phased array antennas, the
metasurface can control and adjust the characteristics of near-
field electromagnetic wave in the subwavelength range. It is
possible to develop several new high-performance thin-film,
ultraminiature planar electromagnetic or optical devices
including spatial filters [41, 42], focusing lens [43, 44], beam
polarization deflection/converters [45, 46], special beam shaping
devices [47, 48], and holographic imaging plates [49, 50].
Therefore, it is of great scientific value to explore and develop
a new mechanism, new method, and process technology of
artificially synthesized electromagnetic metasurface in the
advanced electromagnetic community. In the past decade,
many good review articles have been published to summarize
the developments of metasurfaces [40, 51–60]. However, those
review articles only focused on some parts of the research aspects,
like the fundamentals and the specific applications. Most
importantly, only a few review articles summarized the
research developments of the basic metasurfaces and the
tunable/reconfigurable metasurfaces. In this review, therefore,
we would like to summarize the recently developed different
kinds of electromagnetic metasurfaces and reconfigurable
electromagnetic metasurfaces and devise some new research
directions.

Research Progress on Basic Metasurfaces
The main technical realization ways of synthetizing metasurface
can be divided into plasmonic-like structure based on metallic
materials [36, 37], full dielectric photonic structure based on high
refractive index materials [33, 38–40], and other novel structures
based on novel thin film materials, semiconductor materials,
quantum dots, etc. [33, 36–40, 61, 62]. Most of the reported
metasurfaces are used to realize the manipulations of the
amplitude, phase, and polarization together with other
parameters of the incident electromagnetic waves.

Metasurface for Amplitude Modulation
The metasurface that realizes the amplitude control of
electromagnetic waves is mainly used to reflect, absorb, or
transmit the incident electromagnetic wave energy. In recent
years, a large number of related results have been reported, such
as the broadband metasurface absorber [12–15, 63], metasurface
space filter [64, 65], metasurface color printing [66], graphene
metasurface anomalous refraction plate [67], dielectric
metasurface for selective diffraction [68], and metasurface for
near-field plasmonic beam engineering [69], as concluded in
Figure 1.

Specifically, the representative broadband metasurface
absorber shown in Figure 1A is fabricated on a flexible
substrate by using the nanoscale metal particles arranged in a
nonperiodic manner so that the entire metasurface can be
conformally mounted on a nonplanar carrier [63]. When the
metal particles resonate, the equivalent impedance of the entire
metasurface is matched with the free-space wave impedance.
The high dielectric loss and magnetic loss generated by the resonance
absorb the incident electromagnetic wave energy and the square
metal particles have polarization insensitive ability. Thereby the
entire metasurface absorber can achieve high-performance
absorptions in the near-infrared band and wide angle of
incidence. The structure in Figure 1B consists of a layer of
dielectric metasurface and two layers of distributed Bragg
reflectors which can be integrated into various planar optical
components [64]. The upper and lower distributed Bragg
reflectors form a typical Fabry–Pérot resonator. The
metasurface of the middle layer realizes the control of the
resonance frequency and constitutes a high-performance (high
frequency-selectivity) space electromagnetic wave signal filter.
The metasurface in Figure 1C consists of a metal plasmonic cell
that reproduces the color pattern captured by the camera [66].
Each metal unit resonates with different electromagnetic wave
reflection coefficients in the visible frequency region so the
human eye can observe different colors. Based on this
characteristic, the original color pattern can be reproduced by
designing the corresponding metal unit and array, according to
the color information of each pixel in the previously taken color
photograph.

Moreover, as can be seen in Figure 1D, an active metasurface
can be formed by integrating graphene into a U-shaped aperture
size via a single layer configuration [67]. The hybrid graphene
metasurface composed of the artificially constructed two-
dimensional metal hole array at the subwavelength scale and
the naturally occurring graphene constitutes an electrically
steerable amplitude anomalous refraction. Based on the
Pancharatnam–Berry phase and the suitable spatially linear
phase differences, the amplitude modulation for circularly
polarized terahertz wave with anomalous refraction can also
be achieved by the effective modulation of the gate voltage.
Advanced applications for the dynamic control of
electromagnetic waves by electrically tunable graphene
metasurfaces such as amplitude tunable active focusing lenses
are proposed [67]. More research progress for the dynamic
controllable metasurfaces will be discussed in details in the
next section. In Figure 1E, a complex amplitude modulation based
on the ultrathin dielectric metasurface is used to create a new
method for independently selecting diffraction orders based on
the adjustment of the geometric parameters of the custom
nanostructures [68]. Figure 1F also shows a near-field
plasma beam engineering of metasurface using nanoaperture
arrays to effectively control the complex amplitude of the surface plasmon polaritons in the near-field region [69]. In such a design, each individual nanoaperture is determined pixel by pixel. As a result, the amplitude can be determined by the different lengths of the nanoaperture and the complex amplitude modulation of the surface plasmon polaritons is realized.

Those metasurfaces mentioned above are designed according to the specific application requirements. Each metasurface unit is arranged in a periodic or aperiodic manner to realize the control of the amplitude of the electromagnetic wave. However, when such metasurfaces are designed and developed, their electromagnetic wave amplitude control characteristics are fixed and cannot be changed.

**Metasurface for Phase Modulation**

On the other hand, the phase response characteristics of metasurface are also closely related to the size, shape, rotation mode, and the substrate material type of the metasurface unit. Therefore, each metasurface unit can be reversely optimized as well as designed according to the specific phase distribution requirements to achieve the phase control of the electromagnetic wave. As early as 2011, N. Yu et al. used eight metasurface elements of different shapes to effectively achieve phase manipulation in the range of 0-2π based on the principle as shown in Figure 2A [70]. And a metasurface having flat focusing function and vortex electromagnetic wave generating function based on the phase manipulation has been developed as can be seen in Figure 2B [36, 70, 71].

The phase-modulated metasurface initially reported controls only the crosspolarization component of the incident electromagnetic wave, but most of the common polarization components of the incident electromagnetic wave are not effectively utilized. As a consequence, its electromagnetic wave conversion efficiency is extremely low [62, 72]. To solve this problem, researchers have proposed several kinds of new structures such as Pancharatnam-Berry (P-B) phase metasurface, reflective-type metasurface, Huygens’ metasurface, double-layer and multilayer metasurface to realize high-efficient electromagnetic wave manipulation.

**P-B phase metasurface.** The P-B phase metasurface is a type of structure that can continuously control the phase of electromagnetic waves by changing the rotation angle of the metasurface unit. In 2015, X. Ding et al. designed the P-B phase metasurface structure as shown in the first subplot in Figure 2C, and a high-performance flat-focus lens has been developed which achieves nearly 25% electromagnetic wave control efficiency [73]. The same year D. Wen et al. designed a high-efficient holographic imaging plate based on another P-B phase metasurface structure [74], as shown in the second subplot of Figure 2C. Moreover, based on the geometric P-B phase, the intracavity laser mode is controlled topologically to achieve a high modulus purity of ~95% [75]. Following the transmissive ultrathin P-B metasurfaces, the photonic spin Hall (PHSE)

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**FIGURE 1 |** Amplitude-modulated metasurface design and its typical applications. (A) Broadband absorber [63], (B) spatial filter [64], (C) color printing [66], (D) graphene metasurfaces [67], (E) selective diffraction with a dielectric metasurface [68], and (F) a single nanoaperture in one period [69].
effect can be observed and the efficiency is close to 100%. At the same time, the microwave metasurface with a three-layer structure (total thickness still much smaller than the operating wavelength) is designed (the maximum PSHE efficiency can reach up to 91%), stimulating other P-B metadevices with high efficiency and high performance [76].

**Reflective-type metasurface.** Moreover, the magnetic resonance characteristics can be formed between the metasurface unit and the metal back-plate in the reflective-type metasurface structures so that the control efficiency of incident electromagnetic waves can be greatly improved. Based on the previously reported P-B phase, a reflective-type P-B phase metasurface with different phases is used combined with different predesigned coding sequences to control the terahertz wave. The coded P-B phase metasurface provides the ability to reduce broadband radar cross section and proposes a flexible way to manipulate reflected terahertz waves [77] as shown in the first subplot of Figure 2D. In 2015, G. Zheng et al. designed an I-shaped reflective-type metasurface holographic imaging plate as can be seen in the second subplot of Figure 2D, which realized phase control of incident electromagnetic waves with its control efficiency reaching up to 80% [78].

**Huygens' metasurface.** Based on the Huygens' principle, the Huygens' metasurface which can produce both electric and magnetic resonance was designed to control the electric and magnetic field components of the incident electromagnetic wave. As a result, it has a nearly nonreflecting and completely matching transmission characteristics to maximize the control efficiency of the electromagnetic wave. In 2013, within this frame, C. Pfeiffer et al. designed and developed a Huygens' metasurface with electromagnetic wave control efficiency up to 86% in microwave frequency band [79], as shown in the last subpicture of Figure 2D. They also realized the transmission direction control of electromagnetic beam and the Gauss-Bessel beam conversion. Subsequently, C. Pfeiffer et al. further developed a Huygens' metasurface in the near infrared band.
In 2016, L. Wang et al. designed a grayscale metahologram as can be seen in the first subpicture of Figure 2E, based on the Huygens’ principle. They realized phase control and its control efficiency is up to 99% [81]. In 2018, following the developments of Huygens’ metasurface with complete phase shift coverage, Z. Wang et al. proposed a novel Huygens’ metasurface hologram at microwave frequency, with detailed studies for the electromagnetic field distribution at the control interface and the energy distribution between the modulation focal points and microwave imaging. This proposed Huygens’ metasurface extends the approach of holographic microwave applications [82] as shown in the last subpicture of Figure 2E.

In recent years, researchers have also proposed double-layer and multilayer metasurface designs, for further improving the efficiency of controlling the phase of electromagnetic waves. A variety of flat functional devices are reported, e.g., in [83, 84].

As can be seen above, a variety of novel planar devices with beam focusing, transmission direction control, vortex electromagnetic wave generation, holographic imaging, and other functions have been developed using phase-modulated metasurfaces. It is the most well-developed metasurface research areas in recent years. However, the phase-modulated metasurfaces and the realized electromagnetic wave control characteristics based on the planar functional devices have also been defined to be incapable of real-time dynamic tuning.

**FIGURE 3 |** Polarization-modulated metasurface design and its typical applications. (A) All-dielectric metasurface [85], (B–E) multilayer metasurface [86, 87], (C) holographic metasurfaces that depend on polarization [88], and (D) topology of metasurface antenna [90].

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**Metasurface for Polarization Modulation**

By designing an asymmetric metasurface unit, the phase difference of the transmitted or reflected electromagnetic waves in the orthogonal direction can be realized. As a result, the control of the polarization direction of the electromagnetic wave and the conversion between various polarization states of the electromagnetic wave were achieved [62, 72]. For example, in 2014, C. Wu et al. developed an all-dielectric metasurface as shown in Figure 3A which has Fano’s asymmetric resonance characteristics. It can convert linear polarization wave into circular polarization wave radiation [85]. In the same year, C. Pfeiffer et al. developed a multilayer metasurface unit structure as can be seen in Figure 3B which can realize the asymmetric transmission of circularly polarized waves and achieve the reversal of polarization states [86]. In 2016, C. Pfeiffer et al. continued to develop a multilayer metasurface structure as shown in Figure 3E which can realize the control of the polarization direction of linear polarization waves [87]. In 2017, based on this type of metasurface, J. Mueller et al. designed a holographic metasurface that exhibits different response characteristics for different polarized electromagnetic wave excitations [88] as directed in Figure 3C. In the same year, based on the anisotropic metasurfaces, X. Huang et al. achieved the polarization of circularly polarized waves with high conversion efficiency over a wide frequency range [89]. In 2018, W. Yang...
et al. proposed a low-profile broadband double-circularly polarized metasurface antenna and thus it can be extended to construct a $2 \times 2$ dual circularly polarized antenna array [90] as shown in Figure 3D. The working state of the above-reported metasurface, however, also fails to achieve on-demand real-time dynamic tuning.

**Metasurface for Multidimensional Modulation**

All the above-mentioned metasurfaces are only able to control one single degree of freedom, e.g., amplitude, phase, or polarization of incident electromagnetic waves. In order to achieve more precise control of electromagnetic waves for high-performance holographic imaging and special beam generation, it is necessary to simultaneously control the amplitude and phase (or phase and polarization) of incident electromagnetic waves. For examples, in 2014, L. Liu et al. proposed a combination of amplitude-modulated metasurface units with phase-modulated metasurface units to achieve simultaneous control of amplitude and phase of electromagnetic wave and also developed a broadband metasurface in the THz band [91]. Subsequently, Z. Li et al. designed and developed the nondiffracting beam radiation metasurface in the near-infrared frequency band [92, 93] based on I-shaped metasurface units and C-shaped metasurface units for simultaneous control of electromagnetic wave amplitude and phase. In 2018, G. Lee et al. proposed a new metasurface consisting of X-shaped meta-atoms to achieve full complex amplitude and phase modulation in the broadband visible wavelength region. It was almost comparable to an ideal 3D hologram, and the beam shaping, 3D bioimaging, optical computing, and optical chips can be developed based on such kind of metasurface [94].

Furthermore, in 2015, J. Li et al. proposed a metasurface unit with different rectangular channels which can control simultaneously the polarization and phase of electromagnetic waves so that the circularly polarized incident electromagnetic waves can be converted to linearly polarized waves after passing through such metasurfaces and can deflect the transmission direction of the linear polarized wave [95]. In the same year, A. Arbabi et al. proposed an elliptical all-dielectric metasurface unit structure by designing the ellipticity and with different rotation angles of the metasurface unit. Moreover, they adopted the honeycomb periodic arrangement to realize precise control of the phase and polarization of electromagnetic waves. Based on this metasurface configuration, a variety of high-performance planar functional devices with electromagnetic wave utilization efficiency of up to 97% have been developed, which can realize polarization separation and focusing, polarization transformation and focusing, holographic imaging, and vortex electromagnetic wave generation functions [61].

In 2018, Y. Zhou et al. used lattice design and different arrangements to achieve multifunction reconfigurable metasurface based on amplitude, phase, and polarization modulation fully reflecting the control ability of electromagnetic wave [96]. At the same time, H. Xu et al. developed a multilayer C-shaped chiral metasurface structure, which was able to control the amplitude, phase, and polarization parameters of electromagnetic waves independently, and proposed several functional flat structures, such as dual focus prisms, airy beams, and multibeam shaping [97]. However, these metasurfaces with multidimensional parameters control ability still cannot achieve real-time dynamic control of incident electromagnetic waves.

**Research Progress on Reconfigurable Metasurfaces**

The above-reported metasurfaces can control the amplitude, phase, polarization, and other parameters of the electromagnetic wave as needed, and, therefore, it can develop various planar functional devices with novel functions at different frequency regions. However, when those metasurfaces are designed and fabricated, their specific electromagnetic wave characteristic control abilities are limited and cannot be changed, as concluded in previous section. In recent years, in order to achieve higher degree-of-freedom electromagnetic wave control and utilization, active tunable/reconfigurable/programmable metasurfaces, nonlinear metasurface concepts and design techniques have been proposed [62, 98–103]. As mentioned in the beginning of this review, the electromagnetic response characteristics of the metasurfaces are closely related to the size, shape, rotation direction, and substrate material type of the metasurface unit. As a consequence, the electromagnetic response characteristics of the metasurface can be dynamically controlled by additionally adjusting the metasurface unit structure and the substrate material properties. In turn, the modulations of electromagnetic waves are controlled in real time, that means achieving active tunable, reconfigurable, programmable, and other versatile metasurfaces and versatile optoelectronic devices and systems based on such metasurfaces. The active tunable/reconfigurable metasurface structures that have been reported in recent years include electronic control, light control, temperature control, mechanical control, and power control, which will be discussed in detail in following parts.

**Electrically Reconfigurable Metasurfaces**

For the tunable metasurfaces loaded by diodes [104], transistors [105], MEMS [106–108], graphene [109], and liquid crystals [110, 111], etc., the electromagnetic response characteristics can be dynamically controlled by adjusting the applied bias voltage on the materials/components in those metasurfaces. For examples, in 2017, K. Chen et al. achieved the electromagnetic response characteristic tuning by biasing voltage on each cell in the reconfigurable metasurface array loaded by the independent/joint control diodes. Furthermore, the on-demand controlling of the metasurface to the incident electromagnetic wave front was realized and the adjustable focal length was developed [104] as shown in Figure 4A. In 2018, O. Yurduseven et al. utilized a PIN diode to dynamically tune the “ON” and “OFF” transition states of a slot-type subwavelength metamaterial unit. The waveguide mode was converted to free-space radiation using a binary
adjustment to form a target radiation pattern. Then a dynamically reconfigurable holographic metasurface aperture that allows for electron beam steering purposes was designed. And a synthetic K-band Mills-Cross monochrome microwave camera can be set up to achieve high fidelity images [112], seen in Figure 4B. In 2018, X. Gao et al. proposed an active metasurface composed of a butterfly-shaped unit cells embedded with the voltage-controlled varactor diodes. The reconfigurable polarization converter was dynamically converted from linear to linear, linear to elliptical, and linear to circular by adjusting the bias voltage of the varactor [113]. In 2019, L. Chen et al. proposed a reconfigurable metasurface using the voltage control of the PIN diode and the control of the salinity of the water matrix so that the metasurface can flexibly control the amplitude and deflection angle of the scattered beam. In turn, the X-stage wave front of the reconfigurable water-based metasurface was controlled [114], as shown in Figure 4C. Moreover, in 2017, A. Li et al. developed a broadband absorbing material with adjustable switch control and absorbing power by loading transistors in the absorbing metasurface unit and adjusting the bias voltage applied to each transistor [105], as shown in Figure 4D.

Moreover, in 2018, X. Zhao et al first designed a MEMS-loaded reconfigurable metasurface as can be seen in Figure 4E by controlling the resonant characteristics of the metasurface unit through adjusting the magnitude of the bias voltage, thereby, achieving the control of the polarization state of the incident electromagnetic wave [106]. E. Arbabi et al. prepared a metasurface lens on the MEMS cantilever and controlled the position of the transmitted electromagnetic wave focus by adjusting the bias voltage [107], and, at the same time,
M. Manjappa et al. realized a simple logic signal processing in the THz band based on the MEMS-loaded dual SRR metasurface structure [108].

In addition, S. R. Biswas et al. theoretically proved that when the graphene material was loaded into the reflective metasurface, by changing the bias voltage of the graphene, the on-demand switching between the beam orientation/focus and electromagnetic cloak can be realized [109], seen in Figure 4F. As a result, the tunable frequency and/or amplitude modulation can be achieved [115, 116]. After that, many high-performance graphene-based tunable/reconfigurable metasurfaces are reported with different kinds of functions, including the tunable polarization switching/reconfigurable metasurfaces are reported with different kinds of functions, including the tunable polarization switching/converting and beam steering [117, 118], broadband and tunable perfect absorber [119–122], and even programmable metasurface [123, 124] which will be discussed later. Moreover, A. Komar et al. and D. Xiao et al. have proposed the designs for integrating liquid crystals into metasurface arrays. By adjusting the bias voltage applied to the liquid crystals, the controlling of the metasurface resonance frequency as well as the on-demand selective absorption of electromagnetic waves of different polarizations was achieved [110, 111], as shown in Figure 4G. A. Howes et al. loaded the ITO material layer in the metasurface array and realized the electromagnetic wave transmittance controlling by adjusting the bias voltage on the ITO material. Finally they realized the reconfigurable focus beam [125], seen Figure 4H. In 2018, O. Tsilipakos et al. used a magnetic dipole with a ring dipole resonator in the metasurface unit made of an elliptical dielectric rod. When the rod dielectric constant is changed, the effect of accurately matching the two resonances can be achieved, realizing the manipulation of constructing a tunable gradient metasurface and reconfiguring its wave front [126], seen in Figure 4I.

This type of reconfigurable metasurface is voltage controlled and has the characteristics of simple tuning abilities. However, it is difficult to achieve on-demand independent control of each single metasurface unit for material-loaded metasurfaces discussed above. Therefore, there are no reports of metasurface applications with better functional performance. Fortunately, in view of the engineering feasibility of electronically controlled reconfigurable metasurface loaded by diodes, the researchers further proposed the idea of coding and reprogrammable metasurface designs. Quite recently, researchers from Southeast University in China have systematically studied the working principle as well as design method of digital coding metasurface and reprogrammable metasurface [99], as shown in Figure 5A. For example, in 2018, L. Zhang et al. proposed the concept of space-time modulated digital coding metasurface to achieve the simultaneous manipulation of electromagnetic wave frequency domain and space; thereby, harmonic beam control was achieved [127], as shown in Figure 5B. The design principle of the space-time digital coded metasurface can be applied to various aspects such as wireless
communication and holographic imaging. Other functional devices such as reconfigurable holographic imaging metasurfaces with transformable multibeam radiation have also been developed [128] as shown in Figure 5C. Based on the breakthroughs obtained by the T. Cui’s research group, the smart metasurface imager and recognizer empowered by a network of artificial neural network (ANNs) for the adaptive control data flow and the smart metasurface that has self-adaptive reprogrammable functions without human participation have been designed [129, 130], as shown in Figures 5D and 5E.

Optically Reconfigurable Metasurface

In recent years, researchers have also proposed to load photosensitive materials as well as devices into metasurface structures to achieve optically reconfigurable metasurface by adjusting the intensity of light sources. For examples, in 2016, Q. Wang et al. used a phase change material (chalcogenide GST) as the metasurface substrate material to realize a light-controlled dual-focus reconfigurable metasurface structure [131], seen in Figure 6A. In 2018, L. Cong et al. used a layer of silicon ring between a conventional C-shaped metasurface unit and a sapphire substrate, as shown in Figure 6B. By changing the intensity of the pump light, fast switching of the polarization state of the incident electromagnetic wave and rapid separation of the copolarized/cross-polarized wave were achieved [132]. In the same year, H. Cai et al. designed an ultrafast tunable metasurface consisting of an array of ion-implant combined with annealed silicon disk using optical pump terahertz probe spectroscopy to perform ultrafast and efficient all-optical tuning of silicon-based metasurfaces, seen in Figure 6C, in turn, achieving ultra-fast effective all-optical modulation of THz waves [133].

In 2018, K. Fan et al. overcame the static geometric tuning characteristics of traditional dielectric metasurfaces, by controlling the resonant eigenmodes through optical excitation. The optically tunable characteristics of the dynamic dielectric Huygens’ metasurface were proposed and verified, which has great significance for the application of metasurface reconfigurability, as shown in Figure 6D [134]. In addition, the T. Cui’s group from Southeast University integrated the photodiode into the metasurface array to develop the light-controlled reconfigurable metasurface structure by digitally encoding the LED illumination state, as shown in Figure 6F [135]. However, the use of additional light sources to control the electromagnetic response characteristics of metasurface unit to achieve reconfigurable function increases the complexity as well as cost of the system to some extent.

Thermally Reconfigurable Metasurface

It is well known that some of the substrate materials described above such as silicon, liquid crystal, and phase change material GST are sensitive to bias voltage, light intensity, and also the background temperature. Based on the temperature sensitivity of these materials, researchers have proposed thermally reconfigurable metasurfaces in recent years. As can be seen in Figures 7A and 7B, the Y. Kivshar’s Group of the Australian National University has used silicon and liquid crystal as the

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**FIGURE 6** | Optically reconfigurable metasurface. (A) Loaded with phase change material [131], (B) loaded with additional silicon ring layer [132], (C) loaded with ion-implanted silicon layer [133], (D) loaded with specific dielectric materials [134], and (E) loaded with photodiodes [135].
substrate material of the metasurface. By adjusting the temperature around the metasurface, it can realize the dynamic control of the reflection/transmission of incident electromagnetic waves and dynamic control of the transmission direction of incident electromagnetic waves [136, 137]. W. Dong et al. achieved the adjustment of the transmitted electromagnetic wave operating band by using the temperature-sensitive phase-change material GST loaded into metasurface [138]. In 2018, H. Cai et al. proposed a vanadium dioxide-based hybrid metasurface and the hybrid metasurface can realize the control of transmission of terahertz waves by heating, or optical pumping [139]. In the same year, J. Tian et al. used a phase change material such as Ge2Sb2Te5 (GST) to switch the material phase state between a crystal and an amorphous crystal by changing the temperature to switch the response of the meta-atom between an electric and a magnetic dipole. The phase shift generated by the multistage resonance realizes wave front manipulation. It will contribute to the development of future optical communication networks [140]. At the same time, X. Chen et al. used shape memory alloy as the metasurface substrate material and changed the shape of the memory alloy by adjusting the ambient temperature to develop a transmissive metasurface structure with tunable working frequency band [141]. The thermally reconfigurable metasurface provides a solution to a certain extent, but the prepared metasurface was greatly affected by the environmental temperature changings. Aside from that, its practicability and operability are limited.

**Mechanically Reconfigurable Metasurface**

When the metasurface array was prepared on the elastic/flexible substrate material, the shape of the elastic/flexible substrate material can be mechanically adjusted. As a result, the electromagnetic response of the metasurface unit could also be changed, to achieve a mechanically reconfigurable metasurface. In 2018, J. Reeves et al. designed a metasurface as directed in Figure 8A. The C-shaped metasurface unit was prepared on a soft polymer scaffold by additional stretching/compression soft polymerization. The object holder can control the spacing of two C-shaped units in the metasurface unit to realize the mechanically reconfigurable metasurface structure [142]. X. Liu et al. also proposed a noncoplanar metasurface structure as shown in Figure 8B. The two-layer metasurface array was fabricated on a PDMS flexible substrate. The mechanically reconfigurable metasurface was achieved by stretching the PDMS flexible material to change the coupling characteristics between the two metasurface arrays [143].

In addition, Z. Wang et al. prepared a C-shaped metasurface unit on a foldable dielectric substrate as can be seen in Figure 8C. Different chiral responses to incident electromagnetic waves were achieved by changing the folding mode of the dielectric substrate [144]. L. Chen et al. changed the distance of the reflective surface...
of the metasurface metal reflective surface from the metasurface layer by mechanical means to realize the reconfigurable function of the reflected beam [145]. The mechanical reconfigurable metasurface provides a feasible solution for real-time dynamic control of electromagnetic waves. However, its mechanical control system is complex and it is difficult to achieve precise control with the high-performance metasurface applications.

**Power Reconfigurable Metasurface**

In addition, researchers have proposed the design idea of nonlinear metasurface to achieve the generation of higher harmonics and manipulation of its characteristics [100]. In 2014, J. Lee et al. developed an asymmetric cross-shaped unit and a metasurface array using the principle of electron complementary band transition in a semiconductor heterostructure. As a result, a second-order nonlinear harmonic output with high conversion efficiency was achieved [146] as shown in Figure 9A. In 2017, based on the relationship between electromagnetic response characteristics of the nonlinear metasurface and the incident electromagnetic wave intensity, L. Nicholls et al. designed a metasurface that can quickly adjust the polarization direction of the electromagnetic wave as shown in Figure 9B. The nonlinear metasurface was able to realize the polarization deflection of electromagnetic waves of up to 60° under the excitation of electromagnetic waves with different intensities [147]. In 2018, Y. Xu et al. used chalcogenide glass to prepare a full-dielectric metasurface as can be seen in Figure 9C. Based on the high nonlinearity of chalcogenide glass, the switching control of the vortex electromagnetic wave state was achieved by adjusting the incident electromagnetic wave intensity [148]. In 2018, L. Wang et al. proposed a nonlinear all-dielectric metasurface which generates a third harmonic signal and efficiently controls the nonlinear wave front of any complex parameter wave generated by it. Its control efficiency can reach up to 92% [149]. The nonlinear metasurface energy can realize the reconfigurable property of the electromagnetic wave self-control ability simply by adjusting the incident electromagnetic wave intensity. However, in the reported nonlinear metasurface, it is difficult to effectively control each single metasurface unit, so a more versatile reconfigurable metasurface structure is hard to be realized.

In recent years, optomechanical nonlinear metasurfaces [149–151] have received wide attention as a new class of nonlinear metasurfaces. The metal/nonmetal resonant unit in the optomechanical metasurface is prepared on the elastic material matrix or the resonant unit itself is suspended to form an elastic structure. Under the excitation of the incident electromagnetic wave, the field-structure interaction will generate optical gradient force, electromagnetic induction force, and/or thermal expansion force. The optomechanical metasurface can control the self-polarization state of incident electromagnetic waves by adjusting the intensity of incident electromagnetic waves [150, 151]. The nonlinear characteristics of optomechanical metasurfaces are derived from the mutual coupling effect of incident electromagnetic wave energy and metasurface unit structure potential energy.

**DISCUSSION AND PERSPECTIVE**

As can be seen above, the researches on electromagnetic metasurface have made remarkable progress in mechanism discovery, analytical theory breakthrough, application innovation, etc. In recent years, a variety of metasurface implementation methods have been proposed to design metasurfaces with various electromagnetic wave response characteristics to achieve the electromagnetic wave amplitude, phase, polarization direction/state, orbital angular momentum, and spin angular momentum control. Based on the metasurfaces breakthrough, a variety of novel planar function devices and systems with microwave, THz, and optical frequency bands have been developed. For the various metasurfaces, especially the active tunable/reconfigurable/programmable ones, some of them already realized to independently control each metasurface unit.

In the near future, the metasurface can be further widely developed, with more efficient [24, 31, 76, 97, 118], wider operating bandwidth [12, 42, 118, 119] and easier fabrication and lower cost [152, 153]. Most importantly, metasurface can be designed based the cutting-edge techniques, including the artificial intelligent, to achieve the intelligent metasurface and smart metasurface, which are proposed in the past two years.
CONCLUSION

This review firstly discussed the previously well-developed electromagnetic metasurfaces, in terms of the different kinds of modulations, including the magnitude, phase, and/or polarization modulations. Then, based on the analysis of the aforementioned metasurfaces which cannot realize the dynamic control, the active/tunable/reconfigurable metasurfaces based on various materials/components loadsings are analyzed, in terms of the different kinds of control methods, including the electrically, optically, thermally, mechanically, and power reconfigurable/control techniques. In the end, the cutting-edge metasurface design idea based on mechanical learning, deep learning, is pointed out. This review concluded the main research directions in the past several years and it has important value for the metasurface research community.

AUTHOR CONTRIBUTIONS

SZ, LM, WW, JL, and YH discussed together and proposed the review content. LM, YH, and GW modified the review frame. DC, YL, YZ, and NI finished the references collection and figure preparation. SZ and WW finished the whole manuscript writing, and LM, JL, YH, and GW carried out the whole manuscript modification and finalization. All authors contributed to the proofreading. SZ and LM contributed equally to this work.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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