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Electrically Reconfigurable Microwave Metasurfaces With Active Lumped Elements: A Mini Review

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Metasurfaces, a kind of two-dimensional artificially engineered surfaces consist of subwavelength unit cells, have recently attracted tremendous attention, owing to their exotic abilities for tailoring electromagnetic responses. With active lump elements incorporated into the design of metasurfaces, dynamic reconfigurabilities enabled by external stimuli could be realized, offering opportunities for the dynamic manipulation of electromagnetic waves. In this mini review, we present a brief review on the recent progress of electrically reconfigurable metasurfaces at microwave frequencies. A brief discussion will also be given with our outlook on future development direction and possible challenges in this interesting field.

Keywords: Metasurface, Meta-devices, PIN diodes, Reconfigurable metasurface, Varactors

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1 INTRODUCTION

Metamaterials (Liu and Zhang, 2011; Zheludev and Kivshar, 2012), a kind of artificial electromagnetic media constructed with sub-wavelength units, have attended considerably increasing interests in both scientific and engineering communities. Metasurfaces (Yu et al., 2011; Sun et al., 2012; Chen et al., 2016; Sun et al., 2019; Akram et al., 2020) are the two-dimensional equivalents of metamaterials, formed by periodic or non-periodic arrangement of sub-wavelength elements in an ultrathin film, which possess flexible capability to control the amplitude, phase, and polarization state of electromagnetic(EM) waves. Versatile functionalities, such as perfect absorption, anomalous reflection, and focusing, can be realized with the help of metasurfaces (Akram et al., 2019; Shao et al., 2019). While metasurfaces could be artificially designed with various functionalities, the particular functionality is typically fixed after the design of the metasurface (Li Z. et al., 2020). The functionalities of metasurfaces are able be adjusted by loading active elements into the designs (Cui et al., 2014; Luo et al., 2016; Zhang et al., 2020a). On account of the possibilities to independently control each meta-atom by the embedded active lumped element, these meta-atoms can be assembled to form electrically reconfigurable metasurfaces with tunable amplitude/phase profiles. For example, it is suitable for reconfigurable metasurfaces to be constructed with meta-atoms incorporated with voltage-driven elements (such as PIN diodes (Ghosh and Srivastava, 2016), varactors (Wang et al., 2019), graphene (Zhang et al., 2020b)), so that electromagnetic characteristics can be dramatically tuned through varying applied voltages. By accurately determining the voltages applied on different meta-atoms, these meta-devices can realize desired functions for dynamical wave manipulation. In this mini review, we briefly review the major achievements in electrically reconfigurable microwave metasurfaces with different loaded active lump elements. We will also give a brief discussion with our perspectives on future developments and challenges in this area.

2 METASURFACES WITH PIN DIODES

2.1 Uniformly Tuning With PIN Diodes

The tunablity of microwave metasurfaces can be enabled by incorporating PIN diodes in the structure design. A tunable circuit analog absorber whose equivalent thickness is electronically changed by employing PIN diodes to control the RF signal path, which results in absorbing frequency switching between 0.85–1.88 and 2.66–5.23 GHz (Qi et al., 2012). Xu et al. demonstrated a tunable metamaterial absorber, whose reflection responses can be adjusted over 2–18 GHz frequency range by changing the bias voltage on the PIN diode array (Xu et al., 2012). Recently, switchable perfect absorber/reflectors with a PIN diode integrated active frequency selective surface have attracted enormous interest (Yoo and Lim, 2014; Ghosh and Srivastava, 2016). In 2019, Zhao et al. proposed an electrically reconfigurable metasurface that can be switched between reflection and absorption modes by loading PIN diodes (Zhao et al., 2019). Perfect absorption occurs when the impedance of the dielectric substrate matches well with the free-space impedance while total reflection occurs when they mismatch. Similarly, switchable transmissive/absorptive metasurfaces have also been reported

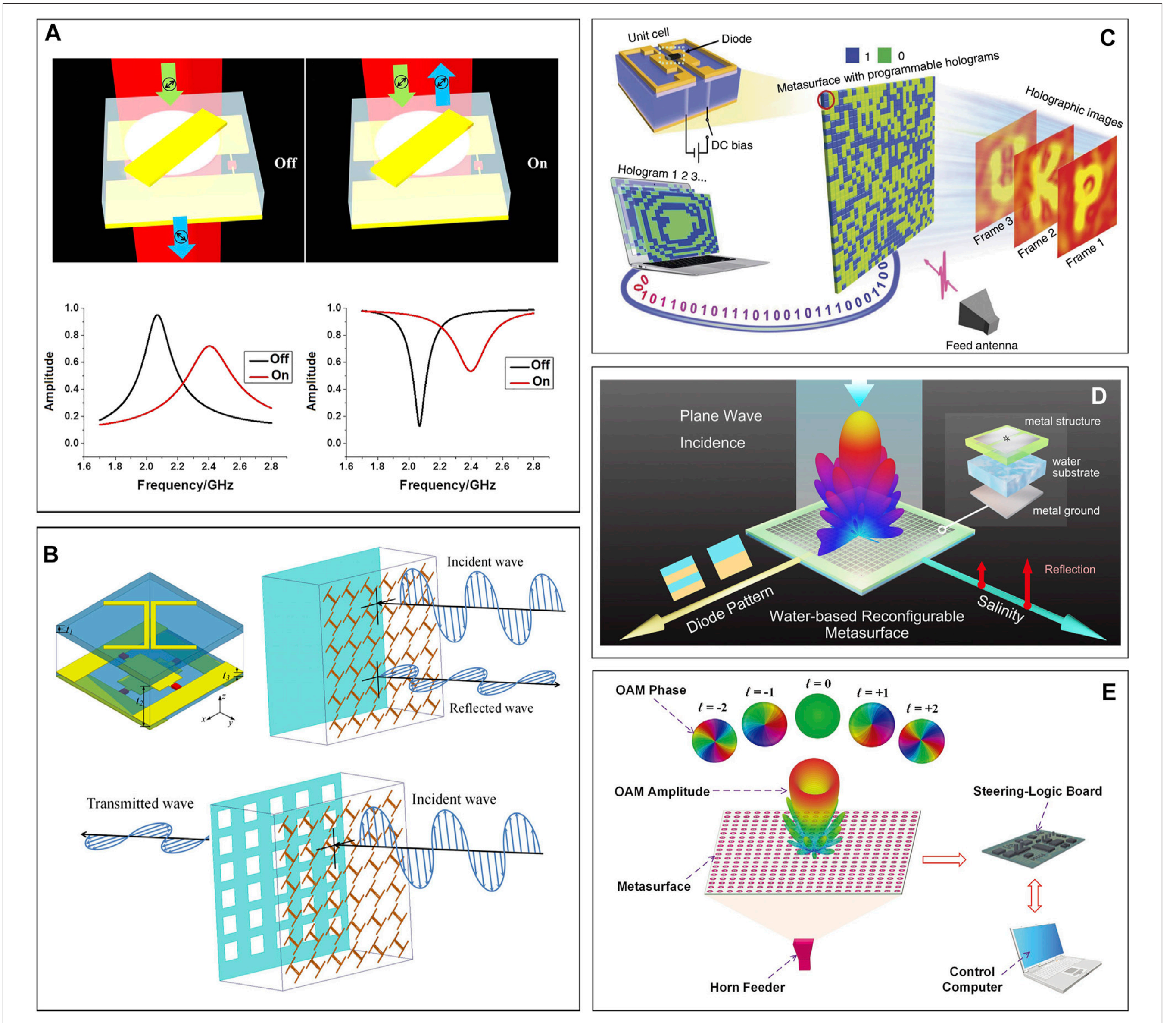

FIGURE 1 | (A) Active metasurface for reconfigurable transmissions/reflections and cross polarization conversions. Reproduced from Tao et al. (2017) with permission from AIP Publishing. **(B)** Reconfigurable metasurface for polarization and propagation Manipulation. Reproduced from Li Y. et al. (2019) with permission from IEEE. **(C)** Reprogrammable coding metasurface holograms. Reproduced from Li et al. (2017) with permission from Spring Nature. **(D)** Reconfigurable water-based metasurface integrated with PIN diodes. Reproduced from Chen et al. (2019a) with permission from AIP Publishing. **(E)** Transmissive programmable metasurface for multimode OAM generation. Reproduced from Bai et al. (2020) with permission from John Wiley and Sons.

(Li Y. et al., 2020). Li et al. designed a tunable metadevice based on coupled-mode theory, which can be switched from perfect transparency to perfect absorption under the control of an external voltage applied to the PIN diode. In addition, flexible structures of unit cell offer another straightforward way to realize reconfigurable metadevices. Metasurfaces have shown powerful abilities in controlling the reflections, transmissions, and polarizations of EM waves, independently. A reconfigurable polarization converter is proposed, which based on an active-element-controlled metasurface without extra bias network (Li et al., 2016). It achieves circular-linear polarization conversion when the PIN diodes are switched to OFF. Flexible structures of unit cell offer another straightforward way to realize reconfigurable metadevices. Metasurfaces have shown great abilities in controlling the reflections, transmissions, and polarizations of EM waves, independently. As shown in **Figure 1A**, Tao et al. (2017) proposed a single active metasurface which is exploited to reconfigure propagating states of EM waves. By switching the status of PIN diodes embeded in each unit cell, the metadevice can not only switch its EM properties between the reflection and transmission mode, but also realize cross linearized polarization conversion. Very recently, Li Y. et al. (2019) demonstrated a multi-functional reconfigurable metasurface, which can control both the propagation and the polarization of EM wave. By controlling the bias voltage, it can switch its function among the reflection-type converter, the transmission-type converter and the transparent structure (**Figure 1B**).

2.2 Non-uniformly Tuning With PIN Diodes

In order to achieve more elaborate functionalities, the locally applied uniformly tuning voltages are allowed to be different for each unit cell in the electrically reconfigurable metasurface. It enables more tunable applications to be achieved, such as multi-beam generation (Huang et al., 2017a), tunable reflection (Wan et al., 2016; Yang et al., 2016), beam diffusion (Yang et al., 2016; Huang et al., 2017a), beam focusing (Yang et al., 2016) and hologram (Li et al., 2017). In recent years, Cui et al. proposed the concept of reprogrammable coding metasurfaces, which can be dynamically controlled in microwave regimes (Cui et al., 2014; Li et al., 2017). Controlling the bias voltage applied across the PIN diode loaded on the top of the meta-atom can yield two different reflection phases, i.e., 0 and π to mimic “0” and “1” states, respectively. Then, the phase distribution encoded on the whole metadevice can be controlled by directly reprogramming the bias voltages applied on these meta-atoms using field-programmable gate arrays (FPGA) directly. Therefore, real-time controllable digital beam steering (Cui et al., 2014; Wan et al., 2016) and dynamically switched holographic images can be realized (Li et al., 2017) (**Figure 1C**).

Although these digital reconfigurable metasurfaces can realize various functions, their beam steering ability is greatly limited because of 1-bit digital coding. Compared with them, the beam manipulation capability of 2-bit digital metasurface with two PIN diodes loaded on each meta-atom is obviously enhanced (Huang et al., 2017a). In 2017, Huang et al. proposed a 2-bit digitally controlled coding metasurface, which can dynamically switch between different scattering modes through a programmable electric source, such as beam deflection, multi beam and beam diffusion (Huang et al., 2017a). Moreover, a few recent works show the possibility to load switchable PIN diodes on Pancharatnam-Berry(PB) metasurface (Xu et al., 2016a) and water-based metasurface (Chen et al., 2019a). Xu et al. designed a tunable PB metasurface with frequency reconfigurability. By controlling the external voltages applied to the diodes, the operation band with 180° phase difference between orthogonal reflection coefficients can be dynamically controlled. Therefore, when PIN diodes are “ON” state, the PB metasurface composed of these meta-atoms with orderly rotation angle exhibits a broadband photonic spin hall effect with nearly 100% conversion efficiency, when PIN diodes are “OFF” state, it switches to dual well-separated bands (Xu et al., 2016a). As for reconfigurable water-based metasurface integrated with PIN diodes, the EM wave reflected by the metasurface can be modulated by both the degree of salinity and the diode pattern. Through these two manipulating methods, the metasurface is able to control the amplitude of the scattered beams and the beam deflection angles, which provides a more flexible and economical way for wavefront manipulation (Chen et al., 2019a) (**Figure 1D**). With the deepening of the research, the manipulation of the transmitted electromagnetic wave by the reconfigurable metasurface is realized. Bai et al. (2020) proposed a transmissive reconfigurable metasurface for the generation of multi-mode convergent OAM beams with high efficiency (**Figure 1E**). Liu et al. (2020) demonstrated a dual-band real-time reconfigurable meta-atom with polarization-independent manipulation of reflection and transmission wavefronts.

3 METASURFACES WITH VARACTORS

3.1 Uniformly Tuning With Varactors

Thanks to its variable capacitance with more flexibility than PIN diode, varactor diode, a different electrically sensitive element, is an alternative excellent candidate for reconfigurable metasurfaces in microwave regime. The meta-atom could integrate a varactor diode to manipulate the electromagnetic response, where the capacitance of the varactor diode can be adjusted in a continuous way. In the simplest case, all varactors are controlled by the same voltage, which effectively provides frequency tunability for the metasurface (Mias and Yap, 2007; Zhu et al., 2013; Dincer, 2015). The most widely investigated functionality is tunable perfect absorption.By adjusting the reverse bias voltage loaded on the varactor diode, the absorption frequency of the designed unit can be controlled continuously (Zhao et al., 2013; Lin et al., 2014; Zhu et al., 2015). For instance, in 2016, Luo and coworkers (Luo et al., 2016) experimentally demonstrated an electrically tunable metasurface absorber in the GHz regime based on dissipating behavior of embedded varactors (**Figure 2A**). Due to the varactors and biasing circuits embedded in the unit structure, the absorptivity can be tuned with a wide range by changing DC biasing voltage. In addition, employing varactors on metasurfaces enables tunable frequency and phase properties (Zhu et al., 2013).

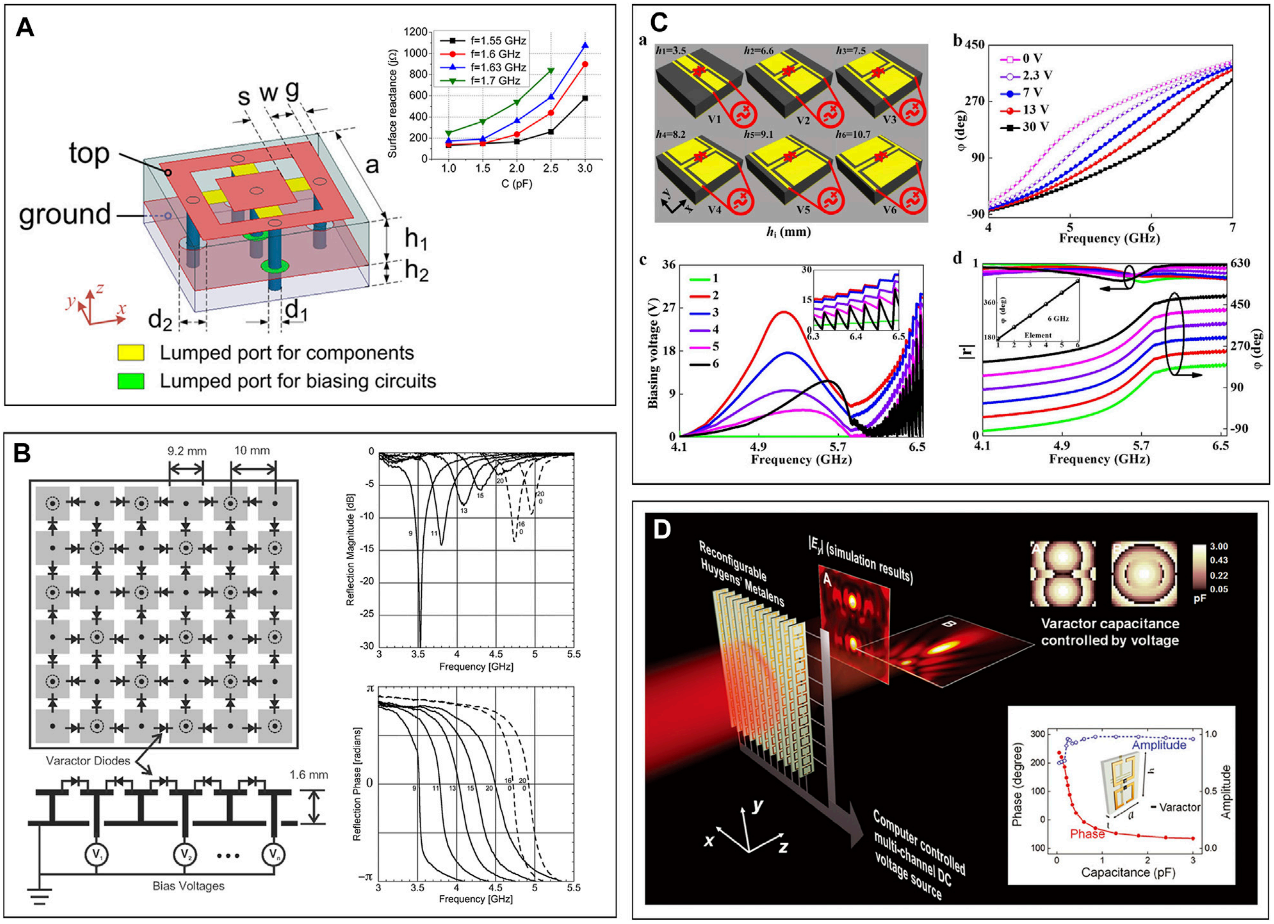

FIGURE 2 | (A) Electrically tunable metasurface absorber with embedded varactors. Reproduced from Luo et al. (2016) with permission from AIP Publishing. **(B)** Active metasurface with full 360° reflection phase tuning. Reproduced from Zhu et al. (2013) with permission from Spring Nature. **(C)** Tunable microwave metasurfaces with dynamical switch. Reproduced from Xu et al. (2016b) with permission from Spring Nature. **(D)** Reconfigurable Huygens' metalens. Reproduced from Chen et al. (2017) with permission from John Wiley and Sons.

In this case, the meta-atom, a multiple resonance structure with two resonance poles and one resonance zero, is capable of providing full 2π reflection phase variation, active tuning in finite frequency and linear reflection phase tuning (**Figure 2B**). Zhu et al. (2010) demonstrated a tunable metamaterial reflector/absorber for polarization modulation, which is made of ELC resonators with varactor diodes. The EM reflections for orthogonal polarized incident waves can be tuned independently by adjusting the bias voltages on the corresponding diodes. Because of this characteristic, the reflected waves can be electrically controlled to a linear polarization with polarizaiton azimuth angle tunable from 0° to 90° at the resonant frequency. When off the resonant frequency, an elliptical polarization with tunable azimuth angle of the major axis can be generated.

3.2 Non-Uniformly Tuning With Varactors

The locally applied tuning voltages could be different for each unit cell of the metasurface with non-uniformly tuning varactors. Nearly 20 years ago, Sievenpiper and coworkers (Sievenpiper et al., 2003) proposed an electrically steerable reflector based on a resonant textured surface loaded with varactor diodes in the microwave regime. Researchers demonstrated that by programming the reflective phase gradient on the meta-device, the reflected beam can be electrically controlled over ±40° for both polarizations. Inspired by this work, many other microwave metasurfaces were proposed to perform different functionalities, such as tunable frequency and phase properties (Burokur et al., 2010; Dai et al., 2018), beam scanning (Ratni et al., 2018a), beam focusing (Xu et al., 2016c; Lv et al., 2019; Wang et al., 2019), hologram (Zhang K. et al., 2018), pre-designed scattering field generation (Huang et al., 2018; Li T. et al., 2019) and vortex beam generation (Guo et al., 2020). Xu et al. (2016b) established a tunable scheme to overcome the dispersion-induced issues in microwave metasurfaces. By adding tunable elements to our meta-atoms, the phase response of each meta-atom can be precisely controlled via external knobs, so as to correct the inevitable phase distortion at any frequency (**Figure 2C**). Ratni et al. (2018a) experimentally demonstrated an active metasurface for reconfigurable reflectors, which can produce anomalous reflection properties within a broad frequency range and scan the direction of the reflected beam in a certain angle range. In addition, this kind of reconfigurable planar metasurface is of frequency agility and can realize beam focusing (Ratni et al., 2018b).

The above active meta-devices work in reflection mode. Reflection mode is relatively easy to implement, but sometimes it is not conducive to some applications. In order to achieve tunable/reconfigurable meta-devices in transmission mode, it is necessary to precisely control the phase and amplitude of the locally transmitted wave through each meta-atom. So far, reconfigurable pixel metasurfaces in transmission mode are already available in some areas, such as vortex beam generation (Shi et al., 2019), dynamical focusing (Chen et al., 2017) and so on. In 2017, Chen et al. (2017) experimentally presented a tunable microwave Huygens' metasurface with dynamically controllable focal point (**Figure 2D**). Shi et al. proposed an active metasurface for multiple vortex beams (l = +1, 0, −1) generation (Shi et al., 2019). Different modes vortex beams generation can be realized by changing the transmission phase distribution on the metasurface aperture. Beyond that, Masud et al. proposed a dual-band compact tunable metasurface for EM interference shielding (Masud et al., 2012). By loading varactor diodes on the metasurface, the lower shielding band can be tuned without affecting the resonant frequency of the upper shielding band. The measurement results show that the center frequency of the lower shielding band can be tuned by 80 MHz.

In recent years, the research of tunable devices with inverse design by deep learning has become a hot spot. Yoya et al. (2019) proposed a self-adaptive invisibility metasurface cloak driven by deep learning. At microwave frequency, the reflection characteristics of each meta-atom inside the tunable metasurface can be changed independently by applying different DC bias on the loaded varactor diode. By introducing an embedded pre-trained artificial neural network, the metasurface cloak is capable of responding rapidly to the fast-changing incident wave and surrounding background.

4 DISCUSSION

In this mini review, we have briefly summarized the recent progress on electrically reconfigurable microwave metasurfaces tuned uniformly and non-uniformly by different types of active lumped elements. The tuning mechanism and potential applications of the reconfigurable microwave metasurface were introduced. It is worth noting that a more comprehensive way for designing electrically reconfigurable metasurfaces is to combine multiple tunable elements (e.g. PIN diode and varactor), which provides the possibility to achieve multiple EM functionalities and real-time reconfigurability in one design simultaneously (Wu et al., 2013; Huang et al., 2017b). For example, Wu et al. (2013) presented and experimentally characterized a microwave active absorber which has dual-ability of simultaneous but dividable modulation on absorbing frequency and intensity. Huang et al. (2017b) reported a reconfigurable metasurface for multi-functional control of EM waves. By controlling tunable elements, the proposed metasurface can dynamically change its local phase distribution to generate pre-designed EM responses. Recently, there are many researches on the application of using tunable devices in antenna area (Yoya et al., 2019; Esmaeili and Laurin, 2020). For instance, in 2020, Esmaeili and Laurin (2020) proposed a cylindrical dielectric resonator antenna, which are able to switch between linear horizontal, linear vertical and circular polarizations. Futhermore, active amplifiers provide another option for continuously tunable pixel reconfigurable metasurfaces (Chen et al., 2019b). A spatial-energy digital-coding metasurface with active amplifiers is proposed to realize arbitrary editing of the energy of spatial propagating waves in the microwave frequency range. Meanwhile, the concept of space-time metasurface, which characterized by spatially and temporally variant properties, has been proposed (Zhang L. et al., 2018; Zhang C. et al., 2020; Castaldi et al., 2021). It is meaningful to exploit the temporal dimension by applying a dynamic switching of the coding sequence. Most recently, graphene, a famous electrically sensitive material, has been utilized for designing electrically reconfigurable metasurfaces at microwave frequencies (Zhang et al., 2019; Zhang et al., 2021). However, due to the limited scope of this mini review, we do not summary such types of reconfigurable metasurfaces in this mini review.

The rapid development of reconfigurable metasurfaces from both global and local tuning significantly expands the ability of electromagnetic wave manipulations. The electrically reconfigurable metasurfaces have the potential to automatically adapt to environmental changes. We believe new ideas and new designs will surely emerge in the near future with various new applications, in addition to those described in this review.

AUTHOR CONTRIBUTIONS

LS wrote the first draft and WZ reviewed/edited this paper.

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