Metasurfaces provide a novel strategy to manipulate electromagnetic (EM) waves by controlling the local phase of subwavelength artificial structures within the wavelength scale. So far, many exciting devices have been developed and most of them are based on passive metasurface, which can only perform a specific functionality. It is still very challenging to simultaneously achieve multiple EM functionalities and real-time reconfigurability in one design. This study reports a reconfigurable metasurface for multifunctional control of EM waves. By controlling tunable elements, the proposed metasurface can dynamically change its local phase distribution to generate pre-determined EM responses. Here, the metasurface can generate beam-splitting performance that can be used to reduce backward scattering waves, and its scattering reduction frequency is tunable. In addition, such metasurface can also achieve dynamical beam deflection and polarization transformation through reconfigurable design of the phase distribution. The above EM functionalities have been experimentally demonstrated at microwave frequencies, which can be switched in real time by a computer-controlled voltage source. This study paves the way toward the realization of multifunctional metadevices with real-time and programmable control, showing great potential in applications of smart materials and devices for EM-wave manipulation.

Recently, the rapid progress in the manipulation of electromagnetic (EM) waves has been achieved owing to the emergence of metasurface.\cite{1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18} As a 2D metamaterial, metasurface made of periodically or nonperiodically arranged subwavelength metaparticles on a ultrathin surface has the strong capability of controlling wavefront of light by introducing abrupt phase changes over the wavelength scale. Compared with 3D bulky metamaterial, metasurface significantly relaxes the requirement of complicated fabrication process, thus permitting substantial advantages, such as lower loss, lighter weight, and high degree of integration. So far, metasurfaces have shown great promises for novel applications, and a variety of intriguing devices with the specific functionality have come forth, such as flat lens,\cite{4,5} beam deflector,\cite{6,7} polarizer,\cite{8,9} low-scattering materials,\cite{10,11} and holographic plates.\cite{12,13} Nevertheless, most of aforementioned metasurfaces are composed of passive metaparticles and generally behave one EM functionality, which cannot satisfy the largely increasing demand of multifunctional devices. Although several substantial efforts have been dedicated to combine the multiple EM functionalities into one single metasurface, the realized multifunctionalities can only be acquired at different polarization states or frequencies.\cite{14,15,16,17,18}

More recently, much more attention has been focused on the design of reconfigurable metasurfaces by employing tunable metaparticles driven by thermal effect,\cite{19,20} electrical tuning,\cite{21,22} mechanically stretching,\cite{23,24} and so on. The realistic possibility of reconfigurable metasurfaces has been demonstrated in optical, terahertz, and microwave regions, accompanied by the emergence of interesting applications, such as beam steering,\cite{25,26} tunable absorbing,\cite{27,28} chiral polarization switching,\cite{29,30} and so on. The reconfigurability of metasurface in optical and terahertz domains is generally realized by exploiting the active media, including graphene,\cite{31} liquid crystal,\cite{32} vanadium dioxide,\cite{33} and Ge$_2$Sb$_2$Te$_5$ (GST).\cite{34,35} In the microwave region, metasurfaces achieve the tunable EM responses through the general method of integrating discrete elements such as varactor diodes,\cite{36,37} PIN diode switches,\cite{38,39} and MEMS switches\cite{40} within the metaparticles. In ref. [28], the metasurface with varactor diodes was dedicated to tune the absorbing frequency. In ref. [38], the PIN diodes were adopted to design the polarization-reconfigurable metasurface that can dynamically control the handedness of the circularly polarized wave. The above lumped components have also been used to achieve the dynamical control of EM wavefront.\cite{40} However, most of the realized tunable metasurface focused on the reconfiguration of a single function (e.g., absorbing frequency, polarization feature, and beam deflection angle). The latest efforts started to be devoted to the design of multifunctional metasurface that integrates diversified functionalities into a monolayer metastructure.\cite{39,41} In ref. [39], microelectromechanical system (MEMS) technology was utilized to construct the metasurface with tunable resonance for obtaining 360° phase span, and based on the phase modulation, the multifunctionalities, including polarization control, wavefront deflection and holograms, have been numerically demonstrated. In ref. [41], a programmable metasurface was reported...
to dynamically manipulate the polarization and beam-forming by switching the PIN diodes, but it can only realize a two binary coded phase, which is inevitable to produce quantization loss in the beam steering.\[^{[42]}\] In addition, the 180° reflection phase difference of this metasurface only exists at a single frequency, making all the EM functionalities limited to a narrow band.

Here, we propose a design of the reconfigurable metasurface for multifunctional control of EM wave. This metasurface uses variable impedance loading technique to extend its frequency range and also achieves continuous reflection phase modulation with a large varying range. The proposed metasurface is composed of a monolayer metallic structure with a pair of PIN switches and varactor diodes involved into the each metaparticle. By independently controlling the biasing voltages applied to these two diodes, such metasurface can dynamically control its surface impedance and thus manipulate the reflection phase at a variable frequency.\[^{[3]}\] We have experimentally demonstrated that the proposed metasurface is able to realize beam splitting at tunable frequency bands through reconfigurable design of the reflection phase distribution, which can be used for backward scattering reduction. Additionally, it is verified to have the capability of realizing dynamical beam deflection and polarization conversion. Therefore, three different EM functionalities are integrated into our metasurface so that it can not only realize low observability in a wideband spectrum, but also achieve single-beam steering and polarization control within the shared aperture. All the EM functionalities can be switched in real time by simply changing the spatial distribution of biasing voltages applied to each diode.

The metaparticle of this metasurface uses a bowtie structure, which is composed of two metallic trapezoid patches and a central continuous strip, as shown in Figure 1a. All the metallic patterns are etched on the F4B substrate (\(\varepsilon_r = 2.65\)) with a thickness of 3 mm. The varactor diode is embedded between the one patch and central strip, while the other patch is connected to the central strip by the PIN switch. The models of MA46H120 and MA4FCP305 manufactured by MA-COM are respectively selected for the varactor diode and PIN switch in the simulation and fabrication. The varactor capacitance can be tuned between 0.17 and 1.1 pF with a parasitic resistance of about 2 \(\Omega\).\[^{[43]}\] The total capacitance of the PIN switch is \(C_t = 0.05\) pF for reverse bias, while the series resistance is \(R_s = 2.1\) \(\Omega\) for a forward biasing current of 50 mA.\[^{[44]}\] We can use transmission line model to analyze the operation mechanism. The metaparticle behaves as the termination load of the transmission line and it can be represented with the LC equivalent circuit. The metallic part is modeled as the inductor \(L\), while the varactor is represented by the capacitor \(C\) that is tunable. Then the load impedance is deduced as \(Z_{\text{eq}}(\omega) = j\omega L + 1/j\omega C + Z_{\text{pin}}\) in which \(Z_{\text{pin}}\) is the impedance of the PIN diode and its switching creates two different surface impedances, making our metasurface generates two different reflection phases. It is generally found that the two reflection phases have 180° phase difference at a narrow band.\[^{[10,22,45]}\] In order to extend the bandwidth of 180° phase difference, we can further change the capacitor \(C\) to tune the impedance, which could obtain more different reflection phases. Therefore, the 180° phase difference is expected to be realized at a variable frequency through appropriate diode configurations. Besides, our metasurface could achieve reflection phase control with large tuning range at some frequency bands, which may be developed for dynamical beam deflection and polarization conversion. So, the proposed reconfigurable metasurface is expected to integrate three diversified functionalities, including beam splitting, beam deflection, and polarization transformation, as shown in Figure 1b. Biasing circuit depicted in Figure S1 (Supporting Information) is designed to control this reconfigurable metasurface. Therefore, we can dynamically switch the above three EM functionalities by simply changing the diodes configuration through a computer-controlled DC voltage source.

\[\begin{align*}
\text{Figure 1. Proposed reconfigurable metasurface and its metaparticle.} \\
a) \text{Schematic model of the metaparticle. Its geometric parameters are} \\
\text{optimized as follows: } l = 8\text{ mm, } a = 4.15\text{ mm, } w = 1.5\text{ mm, } c = 3.15\text{ mm, } \\
p = 12\text{ mm, and } h = 3\text{ mm.} \\
b) \text{Illustration of the reconfigurable metasurface and its multiple electromagnetic functionalities. Function I: Beam-splitting performance that can be used to achieve scattering reduction; Function II: Dynamical beam deflection performance that can be used to realize single-beam steering; Function III: Linear-} \\
circular\text{ polarization conversion. All these functionalities are integrated into one metasurface and can be dynamically switched through a computer-controlled DC voltage source.}
\end{align*}\]
are set as (PIN is ON, \( C = 0.17 \text{ pF} \)) and (PIN is OFF, \( C = 0.7 \text{ pF} \)), respectively. By simply changing the diodes configuration, the antiphase difference can be shifted to other frequency bands. It is seen in Figure 2b that the 180° phase difference is tuned to occur at the frequency band ranging from 7.5 to 11.5 GHz if the capacitance value of one element is varied from 0.7 to 0.37 pF. Additionally, by replacing its diode configuration with (PIN is ON, \( C = 0.34 \text{ pF} \)), the surface impedance of the proposed tunable element can be further changed and then the 180° phase difference is realized at the higher frequency band of 11.5 GHz – 13.5 GHz, as seen in Figure 2c. When combining the 0° and \( \pi \) reflection phase elements in a specific distribution, the metasurface can reshape the scattering field distribution, generating beam-splitting effect. The binary digital elements of “0” and “1” are utilized to describe the above 0° and \( \pi \) reflection phase elements, respectively. To verify its beam-splitting performance, the metasurface is endowed with periodic coding sequence of 000111…, and its scattering field distribution is investigated under normal incidence, as displayed in Figure 2d. The “0” and “1” digital elements are realized by applying different diode configurations. Here, all the PIN switches are switched on in these two digital elements, while the capacitance values of varactors are respectively set to be 0.17 and 0.34 pF. Compared with the mirror-reflection of the flat metallic plate, the scattering field along normal is obviously cancelled out and the backward scattering wave is mainly split into “+1” and “−1” order diffraction directions. When applying other periodic coding sequence, the ±1 order diffraction angle would be changed, which is dependent on the lattice size of \( D (D = 3 \times P \text{ at the periodic coding sequence of 000111…}) \) and can be calculated by formula of \( \theta = \arcsin(\lambda/2D) \) (\( \lambda \) is the incident wavelength in free space). The lattice size should be larger than \( \lambda/2 \) in the frequency range of interest, or else there is no beam-splitting phenomenon. This beam-splitting effect is often used for radar scattering section (RCS) reduction, making our metasurface as a low RCS material.\(^{[10]}\) We have demonstrated that the “0” and “1” digital elements can be produced at different frequency bands by tuning the diode configurations. So the frequency reconfiguration for beam-splitting effect could be expected, thus leading to RCS reduction at a variable frequency. In our design, the phase difference within 180° ± 37° is accepted for 10 dB RCS reduction.\(^{[15]}\) The metasurface composed of 22 × 22 unit cells was fabricated, and its experimental setup shown in Figure 2e is adopted to measure RCS for different voltage configurations. Two wideband horn antennas connected to a vector network analyzer are respectively utilized as the transmitter and receiver, and the sample is placed in the center of the arc-shape bracket. The multiway voltage source is adopted to control the voltage configuration for generating the predesigned EM functionality. Here, three groups of voltage configurations are applied to our metasurface, corresponding to three different EM responses. In each voltage configuration, there are two pairs of biasing voltages employed to the proposed metasurface for producing two antiphase elements. For example, one reflection phase element at the first case is realized by respectively applying the biasing voltage of +1.5 and −1 V to the varactor diode and PIN switch, while the biasing voltages of +13 and +16 V are respectively imparted on the corresponding diodes of the other reflection element. As Figure 2f shows, the obvious RCS reduction is observed at a frequency band ranging from

Figure 2. Simulation analysis and experimental verification of the beam-splitting performance for the proposed reconfigurable metasurface. a–c) Simulated reflection magnitude and phase of the tunable elements at three different frequency bands. At each frequency band, about 180° reflection phase difference (see solid and dashed lines) can be obtained between two tunable elements with different diode configurations. d) 3D scattering pattern of the metasurface consisting of two antiphase elements distributed in periodic coding sequence of 000111… at 12 GHz. e) Photography of the RCS measurement setup and fabricated sample. f) Measured RCS reduction performance under three different voltage configurations. The “0” and “1” reflection phase elements at each case are realized by loading the voltage configurations of \((V_1, V_2)\) and \((V_3, V_4)\), respectively. The biasing voltage of \( V_1 (V_3) \) is imparted on the varactor diode, while the PIN switch is applied by the biasing voltage of \( V_2 (V_4) \).
6.3 to 8 GHz at this case, and the maximum RCS reduction value is about 22 dB occurring around 6.8 GHz. When changing the voltage configuration, the RCS reduction range can be dynamically shifted to 8–11.3 and 11.3–13 GHz, respectively. Therefore, the working bandwidth of our metasurface, defined by 10 dB RCS reduction, is about 6.7 GHz (6.3–13 GHz). Compared with the counterparts of the existing reconfigurable coding metasurface,[10,22,41] the RCS reduction bandwidth is significantly increased. It is still reasonable to expect the larger bandwidth for RCS reduction through optimization of the coding sequence in this metasurface.[10]

In this section, the beam deflection functionality of our metasurface is examined. Figure 3a shows the simulated reflection phase in the frequency band of 11–13 GHz for different capacitance configurations. It is seen that the total phase difference reaches about 300° around 12 GHz with a phase step of 60°. When placing these six reflection elements with the constant progressive phase shift in a periodic distribution along the electric field direction, the reflected beam of our metasurface under normal incidence is redirected to the angle of 20°, as seen in Figure 3b. By varying the gradient phase difference of Φ from 60° to 120°, the number of reflection phase elements per each period is changed to be 3, that is to say, only three kinds of elements are adopted as the gradient phase cells in one period, which can make the beam angle deflected to 44°, as displayed in Figure 3c. In order to verify the beam steering performance of our metasurface in experiment, the reflection phase should be first measured for different biasing voltages applied to the varactors. As Figure 3d shows, the reflection phase varying range is between –75° and 150° at 12 GHz when all the PIN diodes are switched off and the biasing voltage imparted on varactors is changed from 0 to 15 V. If the PIN diodes are switched on, the reflection phase can be tuned from –45° to 245° for the different biasing voltages. Therefore, the total phase varying range of our metasurface reaches as high as 320° (–75°–245°), and its reflection loss is less than 3 dB within all the reflection phase angles. The fabricated metasurface can be divided into 22 rows, and all the reflection elements in each row share the identical voltage configuration, corresponding to a specific reflection phase. The gradient reflection phase distribution changes along the electric field direction periodically, and its period is 360°/Φ.

We adopt three groups of the voltage configurations to control the reflection elements of the sample, and their gradient phase difference of Φ is set as 60°, 90°, and 120°, respectively. The experimental verification was carried out in anechoic chamber, as seen in Figure 3e. The fabricated metasurface and the transmitting horn are fixed on a rotation equipment. When moving the rotation equipment, the sample is always illuminated by the normal incident wave emitted from the transmitting horn, and the receiving antenna captures the reflection signal for the rotating angles of –90° to +90°. Figure 3f shows the measured far field radiation patterns at 12 GHz. It is seen that the reflection beam is obviously deflected from normal and its deflection angle is dependent on the voltage configuration. Here, the reflection beam is respectively redirected to 20°, 30.5°, and 43° by applying the voltage configuration 1, 2, and 3 to the sample in turn. Thus, the single-beam steering performance of our metasurface is validated. More beam-deflection angles could be expected through ingenious design of the voltage configuration imparted on diodes. In order to make the metasurface

Figure 3. Simulation analysis and experimental verification of the beam deflection performance for the proposed reconfigurable metasurface. a) Simulated reflection phase of the tunable element under different diode configurations. b) Simulated electric field distribution of the metasurface consisting of the periodically arranged phase gradient elements with a phase step of 60° at 12 GHz. c) 3D radiation pattern of the metasurface with the gradient phase difference varying from 60° to 120° at 12 GHz. d) Measured reflection magnitude and phase of the metasurface for different biasing voltages. e) Photography of the measurement setup for radiation pattern. f) Measured 2D radiation patterns at 12 GHz under three different voltage configurations. The voltage configuration 1 in a period is set as (0.1 V, –1.0 V), (2.2 V, 1.6 V), (3.45 V, 1.6 V), (4.54 V, 1.6 V), (6.05 V, 1.6 V), and (11.0 V, 1.6 V). The voltage configuration 2 in a period is set as (0.1 V, –1.0 V), (2.85 V, 1.6 V), (4.54 V, 1.6 V), and (7.6 V, 1.6 V). The voltage configuration 3 in a period is set as (2.2 V, 1.6 V), (4.54 V, 1.6 V), and (11.0 V, 1.6 V).
possess 2D beam deflection capability, one should remodify the geometry of the metaparticle and make it individually controlled, which inevitably brings in the extra technical challenge of the design for the complicated biasing network.

The proposed metasurface is still found to have the capability of manipulating polarization states of the reflection wave since it is anisotropic. The reflection phase can be continuously tuned along y-axis, while it is fixed along x-axis. By controlling the phase difference between these two orthogonal directions ($\Delta \phi = \phi_{xx} - \phi_{yy}$), the metasurface could achieve linear–circular polarization transformation when it is illuminated by a linearly polarized (LP) wave with electric field polarizing along the diagonal of the tunable elements. Assuming there is no material loss, a left-handed circular polarized (LCP) wave can be obtained at the case of $\Delta \phi = +90^\circ$, while it is right-handed circular polarized (RCP) wave at the case of $\Delta \phi = -90^\circ$. In order to verify the polarization conversion performance of this metasurface, the experiment is performed with the same measurement setup utilized for acquiring RCS. Two pairs of biasing voltages are respectively applied to all the varactors and PIN switches. Both the transmitting and receiving horns are first polarized along x-axis, in parallel with the diagonal of the tunable elements, and then we can measure the amplitude and phase of the $x$-component reflection wave. After that, the receiving horn turns to y-polarization, and the corresponding results of the $y$-component reflection wave can be obtained. Figure 4a presents the measured phases of the $x$- and $y$-component reflection waves at two different voltage configurations. It is seen that the phase difference between the $x$- and $y$-component reflection waves is about $+90^\circ$ at state 1 and $-90^\circ$ at state 2 around 12.0 GHz. The characteristics of the circular polarized (CP) waves can be then calculated by formula of $R_{xx} = R_{yy} \pm i R_{yx}$, where the subscript “+” indicates the RCP wave and “−” indicates the LCP wave. The polarization conversion performance of our metasurface is displayed in Figure 4b. The incident LP wave is transformed to LCP reflection wave at state 1 in the frequency band ranging from 11.7 to 12.2 GHz where the isolation between RCP and LCP outgoing wave is larger than 15 dB. Its reflection loss varies between 0.3 and 1.9 dB with an average of 1 dB. When the sample operates at state 2, the similar result is obtained from 11.8 to 12.2 GHz where the RCP reflection wave is generated with the cross-polarization ratio over 15 dB. Therefore, such metasurface is experimentally demonstrated to achieve the dynamical control of the reflection polarization by changing the voltage configurations. In reality, it is still seen in Figure 3a that the tuning range of the $y$-polarized reflection phase is very large between 11 and 13 GHz. So by further tuning the diode configuration, it is possible to realize the frequency reconfigurability for polarization conversion. In addition, it should be pointed out that the proposed metasurface is severely dependent on the incident polarization. To achieve polarization-independent control of the metasurface, more lumped components are required into each metaparticle, and at this situation, active media may be considered as a good candidate to replace the lumped components for constructing the polarization-independent metasurface.

In conclusion, we have proposed a novel reconfigurable metasurface that integrates multiple EM functionalities into itself. By controlling the varactor and PIN diodes loaded on each metaparticle, the different EM functionalities can be dynamically switched as desired. The beam-splitting performance of the proposed metasurface is validated by constructing aniphasic distribution, and its frequency reconfiguration property can be also realized by further changing voltage configurations imparted on the diodes. This functionality can make our metasurface achieve RCS reduction at variable frequency bands. Additionally, through ingenious design of gradient phase distribution, our metasurface is still verified to achieve single-beam steering and each of the steering angles is dependent on the gradient phase difference that is tunable. Another functionality of the proposed metasurface is polarization conversion due to its anisotropic structure. By employing the phase difference between two orthogonal directions, the incident LP wave can be transformed to the CP wave with different handiness. All the above functionalities have been experimentally confirmed, which fully demonstrates the excellent performance of our metasurface in multifunctional EM manipulation within a shared aperture. Such concept could be scaled to the higher frequency regions where the active media such as graphene and phase change material may be a good choice to achieve the dynamical control of EM wave.© 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
functionalities, which has tremendous application potentials in smart and reconfigurable devices and systems.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

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