Switchable Metasurface With Broadband and Highly Efficient Electromagnetic Functionality

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Electromagnetic metasurface is a kind of artificial electromagnetic structure, which can control the transmission, reflection, polarization and beam of electromagnetic wave within sub-wavelength thickness. Efficiency, bandwidth and dynamic control are very important in the application of metasurface. The bandwidth of electromagnetic transparency can be broadened by interlayer coupling of local resonance modes of the stacked layers. In this paper, we propose that the electromagnetic wave could be switched on or off in a broadband frequency range by metasurface which consists of three layers of metal microstructures with PIN diodes. When the diodes are biased with forward voltage, the switching diodes are in the on state, and the slab reflects electromagnetic wave completely, just like a perfect metal. When the diodes are biased with backward voltage, the switching diodes are equivalent to a capacitor, and all the electromagnetic wave energy passes through the sample. The simulation results show that the transmissivity is <1% when the sample is loaded with forward voltage in the frequency range of 8–12 GHz, while the transmittance is more than 96% when the sample is loaded with reverse bias. We have fabricated the corresponding samples and measured the reflection and transmission in the waveguide. The measurements verify the properties of broadband highly efficient electromagnetic transparency and perfect reflection.

Keywords: metasurface, switchable, broadband, high efficiency, PIN diode

INTRODUCTION

Manipulating the amplitude and phase of the electromagnetic waves in a desired manner has broad applicability in areas such as imaging, sensing, and communication [1]. In practical applications, full control of transmitted wave with high efficiency covering a wide frequency range is of great importance [2, 3]. In recent years, metasurfaces with subwavelength thickness of artificial structures have attracted great interest and yielded ground-breaking electromagnetic and photonic phenomena [4–13]. Among them, active devices have attracted much attention for their key role in communication and imaging systems in recent years [14–24]. Phase change materials (GST and VO2), graphene and PIN diodes are proposed to realize tunable metamaterials [25–28]. However, due to the resonant feature of artificial structures, it is very difficult to manipulate the electromagnetic wave in a broadband frequency range, and metasurfaces only exhibit fascinating
physical properties at specific frequencies [29–33]. Such a narrowband feature dramatically restricts the application of the metastructures in versatile areas.

The resonant tunneling of surface plasmon polaritons (SPPs) can effectively enhance the transmissivity of metal slab perforated with an array of subwavelength-sized holes, which has been widely studied as a phenomenon of extraordinary optical transmission (EOT) [34–38]. It is reported that, in the EOT of metallic films, perfect transparency only occurs at a single or a set of discrete frequencies, and is sensitive to the incident angle of the electromagnetic wave. Then it is further revealed that, local resonance modes of specific hole arrays also lead to EOT phenomena which are robust to the incident angle [39, 40]. And the bandwidth of EOT passband was broadened by the evanescent coupling of the local resonance modes of the cascaded multi-layer system that is perforated with an array of coaxial annular apertures [41–46].

In this paper, a cascaded design is proposed to realize electrically switchable metasurface with high efficiency over a continuous frequency range from 8 to 12GHz. The electromagnetic metasurface exhibits tunable transmission and reflection properties which can be freely controlled by changing the state of the loaded PIN diodes. The simulation of finite-difference-time-domain (FDTD) method indicates that the incident wave perfectly transmits through the multilayer when the PIN diodes are switched off, and the transmission efficiency is above 96% within the whole frequency range. When the PIN diodes are loaded with forward bias voltage, the transmission is suppressed below 1%, while the reflectivity reaches 88%. It can be observed from the field distributions that the electromagnetic transparency comes from the near-field coupling of the magnetic resonance modes [23, 47–51]. We fabricated the corresponding samples in the microwave frequency regime, and measured the transmissivity and reflectivity for different states in the waveguide. The experimental results are in good agreement with the simulations. This research is expected to have a good application prospect in imaging, communication and other fields.

MODEL DESCRIPTION

As schematically shown in Figure 1A, the broadband metasurface for electromagnetic manipulation is composed of three layers of metallic structure (colored in yellow) separated by two layers of dielectric medium (colored in blue). The thickness of dielectric layers and metallic layers is \( h = 1.575 \text{ mm} \) and \( t = 0.035 \text{ mm} \), respectively. Figure 1B presents the top view of the metallic structure in upper surface, which is the same as that in bottom surface. They are periodically arranged gratings with a period of \( p = g + b = 2.1 \text{ mm} \), and a gap width of \( g = 1.5 \text{ mm} \). Lumped PIN diodes are loaded on the gratings to switch the state of the metasurface by changing the DC bias. The structure in the middle layer is metallic mesh with periods of \( p_x = 7.62 \text{ mm} \) in \( x \) direction and \( p_y = 4.98 \text{ mm} \) in \( y \) direction, as shown in Figure 1C, and the width of metallic wire is \( w_m = 0.7 \text{ mm} \).

SIMULATIONS AND MEASUREMENTS OF HIGHLY EFFICIENT SWITCHABLE METASURFACE

The state switch of the metasurface is achieved by changing the voltage loaded on the PIN diodes. The diodes are conductive when loaded with forward bias voltage (On-State) that the gratings behave as metallic mesh. Therefore the metasurface is equivalent to three-layered meshes with cutoff frequency much higher than the operational frequency, so that the electromagnetic incidence is strongly reflected. In contrast, the diodes work as capacitors while they are not biased or loaded with reverse bias voltage (Off-State). In this instance, the gratings together with the metallic mesh in the middle layer form a kind of magnetic resonant structure. Although the working frequency is below the cutoff frequency of the mesh in the middle layer that the incident wave cannot directly pass through the structure, near-field coupling between the magnetic modes leads to electromagnetic wave tunneling, similar to the electronic tunneling effect. Therefore, we...
achieved transmittance manipulation through the control of bias voltage.

FDTD method is employed to calculate the transmission of the metasurface for both states. In the simulation, perfect electric conductor (PEC) boundaries are set at the x and y directions, and absorbing boundary is set at negative z direction. Waveguide port excitation is imposed at positive z direction with the incident wave propagating along z-direction. Figure 2 shows the calculated transmissivity and reflectivity of the metasurface for the two states. When the diode is loaded with forward bias, it is replaced by a resistor with a resistance of 4.2 Ω in the simulation model. As shown in Figure 2A that, for on-state, the transmissivity is <1% and the reflectivity is more than 88%, implying that the electromagnetic wave is almost completely reflected back in a broad frequency band from 8 to 12 GHz. Due to the thermal effect of resistance, there is about 10% absorption loss in the on-state. Figure 2B presents the spectrum for off-state when no bias voltage is applied. The diode is replaced by a capacitor with a capacitance of 0.02 pF in simulation. It is observed that the metasurface is perfectly transparent with transmissivity >96% and reflectivity <4% within the band.

In order to verify the proposed switchable metasurface for wide-band electromagnetic manipulation, we fabricate the microwave samples by printed circuit board (PCB) technology, as shown in Figure 1D. Taconic TLX-6 is used with a dielectric constant of 2.65, and the geometric parameters of the sample is kept the same as those of simulation model. Then 24 PIN diodes are loaded on the gratings in upper and bottom surfaces. We adopt Aluminum Gallium Arsenide (AlGaAs) flip-chip PIN diodes (MA4AGP907) because of their small geometry and junction capacitance. When applied with forward bias...
voltage, the diode is equivalent to a resistor with a resistance of 4.2 $\Omega$ at 10 GHz, otherwise it behaves as a capacitor with a capacitance of 0.02 pF. The electrodes are leaded from gratings to impose the bias voltage (shown in Figure 1B). The metasurface is placed in standard waveguide with a length of 22.86 mm and a width of 10.16 mm. Then the waveguide is connected to the vector network analyzer (PNA52224) with a coaxial-to-waveguide converter. By measuring the S parameters, we extract the transmissivity and reflectivity of the sample. Figure 3 shows the experimental results for the two states which are in good agreement with the simulation results, confirming the wide-band control of electromagnetic transparency from the metasurface.

The bandwidth and efficiency are key points to the electromagnetic wave control. It has been proved that the working bandwidth can be broadened by near-field coupling of resonance modes between adjacent layers [41]. Due to the mutual coupling of magnetic resonance modes, the transmission peak of the metasurface extends to a transmission band as shown in Figures 2B, 3B. The simulated power transmission is above 96% in the frequency range of 8–12 GHz, and the reflectivity reaches minimum at two resonant frequencies at $f = 8.2$ and $f = 11.1$ GHz, while the simulation transmission is above 80% in the frequency range of 8.4–12 GHz, and the reflectivity reaches minimum at two resonant frequencies at $f = 8.6$ and $f = 11.0$ GHz. The calculated field distributions provide further insight into the cause of wide-band transparency. Figure 4 shows the spatial distributions of the electric field in the $yz$ plane at the two resonant frequencies. Arrows in the field distributions represent the direction of the electric field vector, with their size and color indicating the scale of the field. It can be read from the color bar that the near-field electric field is magnified six times at these two frequencies of perfect transparency, while the magnitude of plane wave incidence is set as unit. It also can be seen from the field distributions that the $y$ component of electric field is symmetric about the $y = 0$ plane at 8.2 GHz and is antisymmetric at 11.1 GHz. Considering the symmetry of these two modes, we can draw the conclusion that the perfect transparency peaks result from the inter-layer coupling of the magnetic resonance modes.

As the bandwidth of transparent state can be broadened by the near-field coupling of the resonance modes in the metasurface, the coupling coefficient can be adjusted by metallic mesh in the middle layer. Inspired by tight binding theory, the weaker the coupling is, the smaller is the energy difference between symmetric and antisymmetric states, vice versa, the stronger the coupling is, the larger is the energy difference. Therefore, it provides a way to control the bandwidth of electromagnetic transparency by adjusting the mesh size in the middle layer. For demonstration, the transmission spectra of $w_m = 0.5, 0.7, 1.0$ mm are calculated and shown in Figure 5. As the value of $w_m$ increases, the transparency bandwidth becomes narrower, which agrees well with the theoretical prediction.

**CONCLUSION**

In this paper, we have proposed a general scheme to design broadband active metasurface, which switches the transparency and reflection electromagnetic properties by controlling the loaded PIN diodes in the upper surface and bottom surface. The origin of the broadband property is studied in detail, and electric field distributions are presented for the explanation of perfect transparency occurring in the structure. The broadband nature of dynamic manipulation of the transmission and reflection...
states in the proposed structure is verified both numerically and experimentally. The simulated insertion loss of the metasurface on the transparency state is $<0.5$ dB within the frequency range 8–12 GHz, which is benefit from evanescent coupling and hybridization of the magnetic resonant modes. The simulated transmission of the metasurface on the reflection state is $<15$ dB. The proposed structure is suitable for microwave communication, sensing systems.

**DATA AVAILABILITY STATEMENT**

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

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**AUTHOR CONTRIBUTIONS**

ZW conceived the idea and supervised the whole study. XL conducted the numerical calculations and performed the experiments. YC derived the theory, carried out the analysis, and drafted the manuscript. All authors contributed to the review of the manuscript.

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Conflict of Interest: YC was employed by the company Shanghai Mi Xuan Electronic Technology Co., Ltd.

The remaining 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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