



Dynamic Control of Ultrathin Electromagnetic Absorber Using Active High Impedance Metasurfaces

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In recent years, active metasurfaces have induced more interests, which provides great freedom of wave manipulation and gives rise to many novel phenomena. High impedance metasurfaces are a kind of artificial structures characterized by the in-phase reflection at the resonant frequency. It works as a magnetic mirror and can be applied in subwavelength cavity, low profile reflector antenna, etc. When introduce in tunable components, it possesses versatile functionalities and broader application. In this paper, we proposed an active high impedance metasurface which exhibits highly efficient absorption to the electromagnetic incidence. As an array of diodes are loaded between the gap of periodic gratings and applied with positive bias, the absorption frequency can be dynamically controlled by the level of bias voltage. At the resonant frequency, the reflection from the metasurface can be less than 1%, implying that most of the incidence is absorbed by the magnetic resonance of high impedance metasurface. When the bias voltage is tuned from 0 to +1.33 V (the forward voltage), the resonant peak rises from 8.5 to 9.1 GHz, providing a flexible control of electromagnetic wave absorption in X band.

Keywords: high-impedance, metasurface, dynamic control, equivalent circuit model, magnetic resonance, absorption

INTRODUCTION

Recently, metasurfaces [1] have attracted a great deal of attention due to their ability to freely manipulate electromagnetic waves within the sub-wavelength thickness, obtaining desirable electromagnetic properties that are not available in nature [2–5]. They have great potential for applications in microwave communication, integrated circuits, antennas, and so on [4, 6–9]. When combined with tunable mechanism, metasurfaces present variable electromagnetic properties with respect to the external condition and provide dynamic control of the incident waves [10, 11]. Metasurfaces based on tunable mechanisms such as optical [12, 13], thermal [14], electrical [15–19], and MEMS [20, 21] have been proposed to enable the dynamic control of electromagnetic waves.

High impedance surface (HIS) [22, 23] is a kind of sandwich structures comprised of periodical metallic patterns, dielectric spacer and metallic ground plane. They behave as a highly efficient magnetic conductor (PMC) to the incident wave at resonant frequency with high surface impedance, giving zero phase shift to the reflected wave [24, 25]. HIS is widely investigated and found to be an electromagnetic band gap (EBG) material which suppresses the propagation of surface waves. These properties can be utilized for low-profile antenna, and back lobe suppression, etc [26, 27]. Meanwhile, it is worth noting that the local field is enhanced by several orders around the

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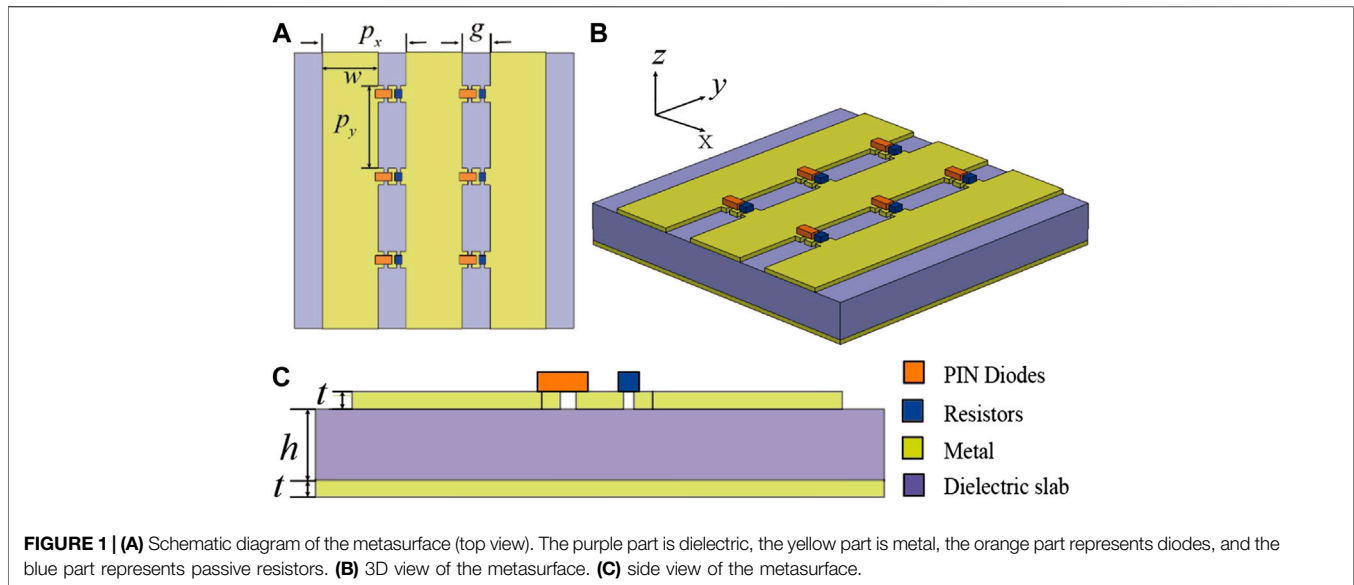
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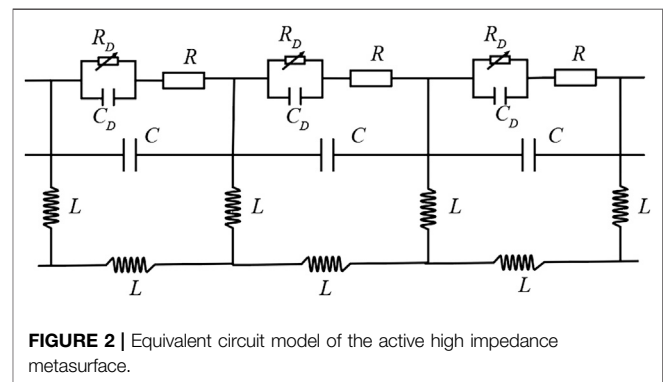


resonant frequency. HIS can also be used as an electromagnetic absorber when appropriate loss is introduced. It works with small loss factor and electrically thin thickness, while gives high absorption efficiency [28–30]. In 2019, Liu et al. introduced PIN diode into a HIS, making a reconfigurable metasurface with multiple applications [31].

In this paper, we have designed and measured for the first time the highly efficient absorption effect of an active high-impedance metasurface. we fabricated a HIS which consists of a metallic grating and a ground plane, with a dielectric substrate sandwiched between them. Then a diode and a passive resistor are loaded on each gap of the grating. Highly efficient electromagnetic absorption can be achieved by dedicated design of the resistance of passive resistor; and the absorption frequency can be dynamically changed with the tunable characteristics of the diode. It is observed with finite-difference time-domain (FDTD) simulations that, the absorption efficiency is 99% at 8.5 GHz without the DC bias; while applied with positive bias voltage, the series resistance of the diode decreases, resulting in a higher resonant frequency of HIS; and at the forward voltage +1.33 V of the diode, the absorption frequency increases to 9.7 GHz. Reflection from the sample is measured with microwave experiments. The tuning range is from 8.5 to 9.1 GHz with a minimum reflection of -30 dB observed during the measurements, which agrees well with the theoretical predictions. This work can make good contributions to instrument protection, electromagnetic wave shielding and other areas.

STRUCTURE AND SIMULATIONS

The proposed active HIS is a three-layered periodic structure as schematically shown in **Figure 1**. A metallic grating is on the top surface with a period of $p_x = 12.2$ mm and a gap of $g = 3$ mm, so that the width of the grating is $w = 9.2$ mm. Then a diode and a



passive resistor are loaded in series across each gap and periodically arrayed along y direction with an interval of $p_y = 12$ mm. We adopted Aluminum Gallium Arsenide (AlGaAs) flip-chip PIN diodes (MA4AGP907) with a small junction capacitance of 0.025 pF, and the resistance of the passive resistor is $R = 100 \Omega$. On the bottom layer is a metallic ground plane. The thickness of the dielectric layer is $h = 0.78$ mm, and that of each metallic layer is $t = 0.017$ mm, giving rise to a total thickness of 0.814 mm of the sample. The dielectric constant of the substrate is $\epsilon_r = 2.65$.

According to the equivalent circuit model theory [23], a HIS can be modeled as a parallel RLC resonant circuit. The gap of grating behaves as a capacitor and the resonant loop forming among the top and the bottom layer provides an equivalent inductance, giving rise to a constant resonant frequency determined by the structural geometry. When the gap is loaded with a diode and a passive resistor, it turns into an active HIS with equivalent circuit model as shown in **Figure 2**. The diode forms a parallel RC circuit with the junction capacitance C_D and a variable resistance R_D , in series with the passive resistor R , integrated into the HIS circuit. The variable

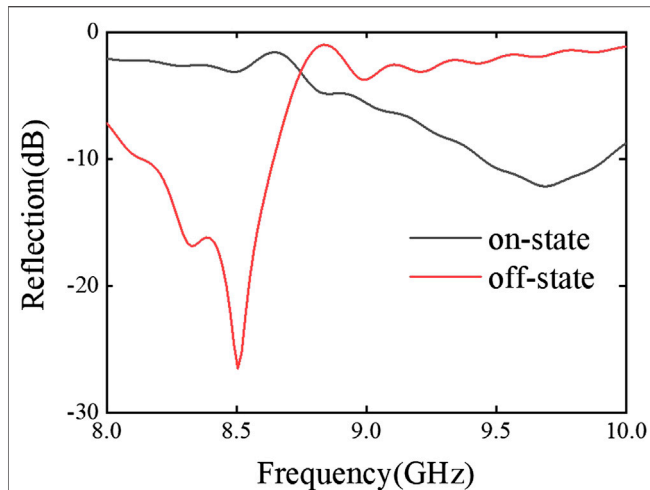


FIGURE 3 | The simulated reflection spectra of the active high impedance metasurface when the loaded PIN diodes are on-state (black line) and off-state (red line).

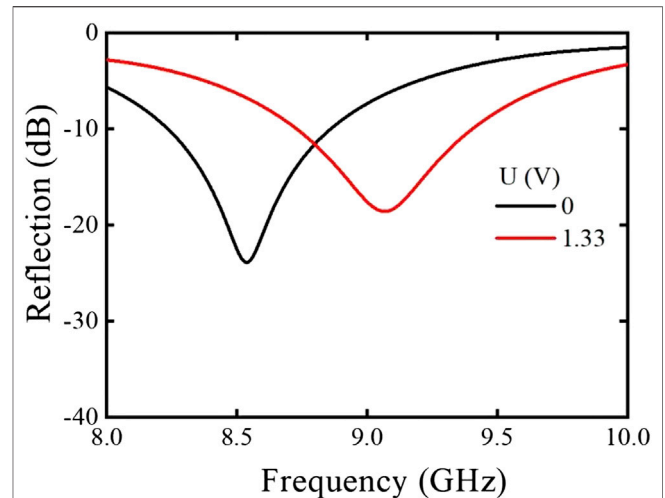


FIGURE 5 | The measured reflection spectra of the active high impedance metasurface when the PIN diodes are loaded with +1.33 V bias voltage (red line) and in open-circuit state (black line).

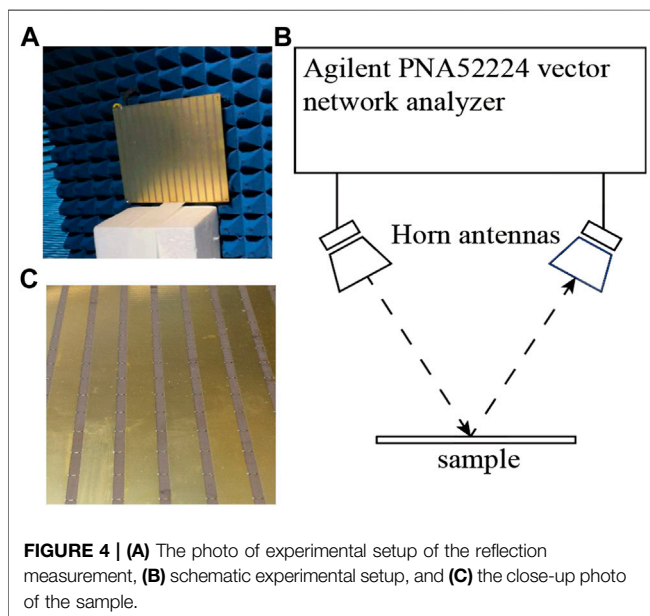


FIGURE 4 | (A) The photo of experimental setup of the reflection measurement, (B) schematic experimental setup, and (C) the close-up photo of the sample.

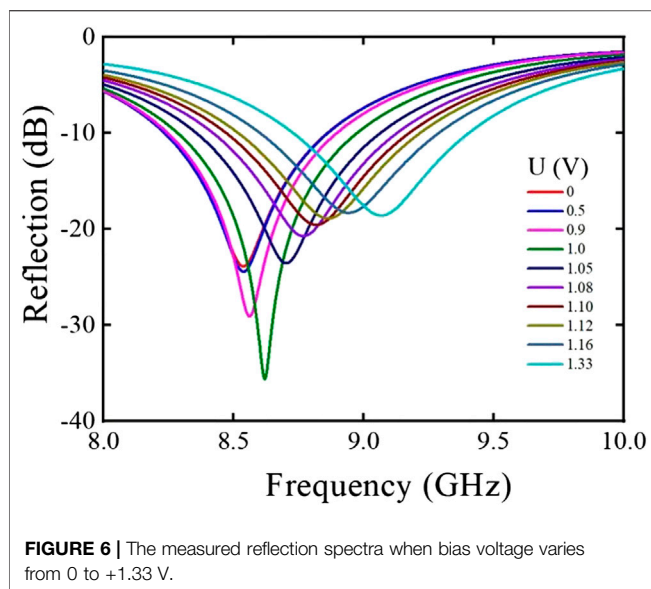
resistance of diode changes from infinite to $R_D = 4.2 \Omega$, while the bias voltage increases positively from 0 to +1.33 V, resulting in an observable shift of the resonant frequency. The value of the passive resistor R is carefully optimized for impedance matching, and highly efficient absorbing the incident power, thanks to the field enhancement on resonant state. FDTD simulations are employed to calculate the reflection for both cases, $R_D = 4.2 \Omega R_D \Omega$ (on-state) and $R_D = \infty \Omega R_D \Omega$ (off-state). In the simulation, periodical boundary conditions are imposed along x axis and y axis. The incident wave propagates along z^- direction and is ensured with no reflection at z^+ boundary by UPML boundary condition. The excitation in time domain is a Gauss pulse. The diode is simulated using passive components

with $C_D = 0.025$ pF, and $R_D = 4.2 \Omega$ (on-state) or $R_D = \infty \Omega$ (off-state). z component of Poynting vector is probed at 5 mm above the sample by setting a probe plane. Calculated reflection spectrum is shown in **Figure 3**. For on-state, highly efficient absorption happens at 8.5 GHz with a reflection coefficient of -26.5 dB, while the electromagnetic incidence is mostly reflected back with a reflection coefficient of -1.8 dB at 9.7 GHz. For off-state, the absorption peak is blue shifted to 9.7 GHz with a low reflection level of -11 dB, while the reflection rises to -3 dB at 8.5 GHz. At this point, the dynamic control of resonant absorption peak, that is the switch between absorption and reflection state at 8.5 GHz and 9.7 GHz, can be achieved by using the on-state and off-state of the diode.

EXPERIMENTS AND DISCUSSIONS

For verification, a HIS sample is fabricated with printed circuit board (Taconic TLX-8) with a lateral size of 180×180 mm, as shown in **Figure 4**. 224 chip diodes and an equal number of chip resistors are surface mounted with gold silk bonding technology on the top layer of the sample. By alternatively applying positive and negative DC voltage on adjacent gratings, the diode is biased with tuneable voltage level.

The reflection is measured in a microwave anechoic chamber, with the sample placed on a foam and two standard gain horn antennas placed in front of it. The main lobe of horn antennas is perpendicularly incident on the sample surface, as schematically shown in **Figure 4B**. The horn emitter and the horn receiver are connected to an Agilent PNA52224 vector network analyzer to measure the S parameter S_{21} . At first, a metal plate with the same size as the sample is measured to record the calibration field intensity. When the sample is under test, we get the reflected field intensity. Then the reflection coefficient is derived from the difference between these data.



We measured the reflection spectra for 0 V and +1.33 V bias voltage, corresponding to the off-state and on-state of diode respectively. **Figure 5** shows the normalized reflection coefficient for both states from measurements. It can be observed that, when the bias is not loaded (0 V), the resonant absorption peak appears at 8.5 GHz with a reflection minimum of -24 dB. While applied with +1.33 V bias voltage, the absorption peak shifts to a higher frequency of 9.1 GHz, which agrees well with the theoretical calculation.

In addition to the on-state and off-state, the resistance of the diode will continuously vary during the increase of positive bias voltage from 0 V to +1.33 V. The reflection of the sample is measured at several intermediate levels of bias voltage as shown in **Figure 6**. It is proved that the resonant absorption peak can be dynamically tuned between 8.5 and 9.1 GHz, by adjusting the bias voltage. The reflection of the sample is low than -18 dB during the whole range. When +1 V bias voltage is applied, the reflection coefficient drops below -30 dB, implying a wonderful absorption of incidence.

CONCLUSION

In conclusion, we have designed an active HIS to achieve dynamic control of the electromagnetic absorption. The impedance matching between the HIS and the incident wave is met by

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introducing a passive series resistor on the top surface of the HIS. By adjusting the positive bias voltage of the diode, the resistance of the diode can be tuned in a range to achieve dynamic control of the highly efficient electromagnetic absorption. Experimental samples are fabricated and measured to verify this phenomenon for the first time. Both theoretical simulations and experimental measurements demonstrate that the active HIS can achieve electromagnetic absorption with an absorption efficiency greater than 99% at resonant frequencies. By changing the diode from off-state to on-state, a dynamic switch between the electromagnetic absorption and reflection is observed at 8.5 and 9.1 GHz in experiments. Furthermore, continuous changing of the absorption peak between 8.5 and 9.1 GHz can be achieved by gradually varying the positive bias voltage of the diode. This work has great potential in electromagnetic wave stealth, shielding, and electromagnetic compatibility.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

ZW conceived the idea and supervised the whole study. HL and WX 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 manuscript.

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Conflict of Interest: Author 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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