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DUAL BAND SWITCHABLE METAMATERIAL ELECTROMAGNETIC ABSORBER

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Abstract—This paper presents the design, fabrication and measurement of a dual band switchable metamaterial electromagnetic absorber. The unit cell of the metamaterial consists of dipole mode electric resonators coupled by microwave diodes on one side of a dielectric substrate and metallic ground plane on the other side. Simulation and measurement results show that by forward or reverse biasing the diodes so as to change the coupling between the resonators, the absorber can be dynamically switched to operate in two adjacent frequency bands with nearly perfect peak absorption. Field distribution reveals the physical origin of the switchable performance based on the dipole mode of the electric resonator in the unit cell. It is also demonstrated that the frequency difference between the two bands can be tuned by adjusting the loading positions of the diodes with unchanged high absorption, which helps to design absorbers with specific switchable working frequencies in practical applications.

1. INTRODUCTION

Electromagnetic (EM) wave absorbing material is a functional material that absorbs incident EM energy and converts it into heat, which is useful in many areas such as the control of electromagnetic interference (EMI), and electromagnetic compatibility (EMC) purposes. Conventional microwave absorbers are either based on lossy materials such as metal or ferrite powders that can absorb EM waves over a specific frequency range [1–3], or employing one

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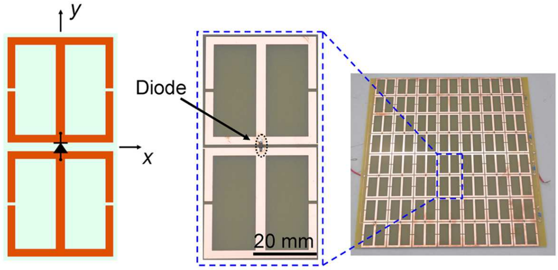
or more thin resistive sheets separated by dielectric spacers, such as the Salisbury screen or multilayer Jaumann absorber [4, 5]. However, the working frequency band is usually fixed and limited by the EM properties of the constituent materials.

Recently metamaterials have been employed to construct EM wave absorbers [6–12]. Through designing the inclusion structures, the effective EM parameters of metamaterials can be tailored and unique values which are less than unity or even negative can be achieved. The idea of metamaterial absorber is to adjust the effective ε and μ independently by varying the dimensions of electric resonant component and magnetic resonant component in the unit cell so as to match the effective impedance of the absorber to free space and achieve a large resonant dissipation at the meantime. Thus, wave transmission and reflection are minimized simultaneously and absorption is maximized [6]. Although metamaterial absorber has relatively narrow bandwidth, it possesses many advantages such as high absorption, low density, and thin thickness. Moreover, the frequency response can be tailored or scaled from microwave to terahertz and infrared regimes through carefully designing the constituent resonant structures [6–8].

With the trend of multi-band operation in current wireless electronic devices, there is increasing demand for tunable and multi-band control of EM radiation [13]. In this paper, a dual band switchable metamaterial absorber is presented that is realized by integrating microwave diodes into the resonant structure of the metamaterial. Simulation and measurement are conducted to investigate the switchable microwave absorbing property between two frequency bands. Field distribution is given to explore the working mode and the physical origin of the property. It is also shown that by tuning the loading position of the diodes, it is able to adjust the frequency difference between the two switchable absorbing bands.

2. METAMATERIAL STRUCTURE AND RESONANCE MODES

Figure 1(a) shows the unit cell of the proposed metamaterial absorber. Two single polarized electric-LC resonators (ELCs) [6] are used as the unit cell, which are coupled together by microwave diode and integrated on the top layer of a dielectric substrate with a metallic ground plane on the bottom layer. For incident EM wave with electric field polarized along y axis, the ELC couples strongly to the electric field but weakly to magnetic filed, supplying an independent electric response. The ELC and metallic ground plane form the



(a) (b)

Figure 1. (a) A schematic of the unit cell of the switchable metamaterial absorber, and (b) the fabricated sample sheet.

parallel conducting structure [14] and couple to magnetic field, supplying independent magnetic response. Therefore, by adjusting the dimensions of the ELC and substrate thickness, the effective impedance of the metamaterial absorber can be matched to that of free space and high EM loss can be obtained owing to the electric and magnetic resonances of the unit cell. As a result, EM wave reflection of the proposed absorber is minimized and EM wave absorption is maximized within a certain frequency band.

It should be emphasized that, in order to achieve absorbing performance switchable between two bands, the ELC is designed to resonate in dipole mode, the second resonant mode of ELC (at higher frequency) [15], which is different from the first resonant mode (at lower frequency) used in the previous metamaterial absorber design [6]. Illuminated by the normal incident EM waves with electric field polarized along y axis, the distribution of electric field component along y axis (E_y) and the surface current is simulated and plotted in Figs. 2(a) and 2(b) respectively at the working frequency on the surface of ELCs without the coupling diode. Because the ELC is designed to resonate in dipole mode, the electric field is strong in the neighboring region where the diode will be loaded so that the upper and lower ELCs are coupled through the distributed capacitor in this region. The surface current on all the ELC strips parallel to y axis flows in the same direction and converges at the places where the central strip and outer ring of the ELC are connected, producing a strong local electric field in this region.

When the upper and lower ELCs are connected by diode, the switchable impedance of the diode is connected in parallel with the distributed capacitor in this region and changes the coupling effect between the two ELCs. Under reverse bias voltage, the diode is

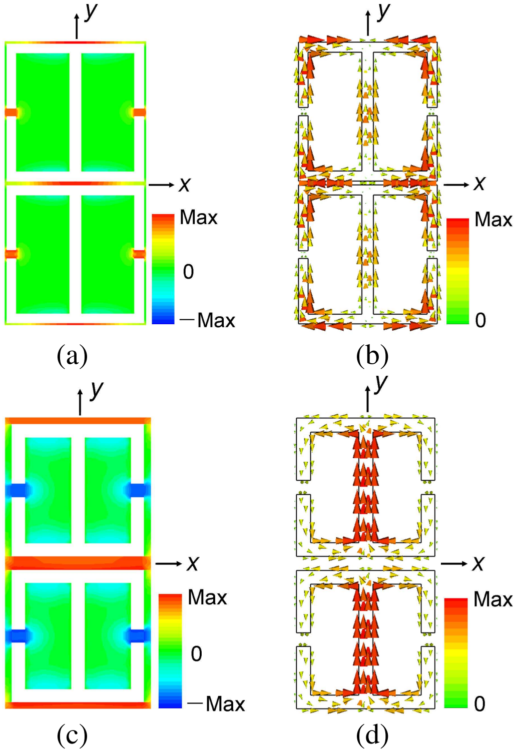


Figure 2. The distributions of (a) electric field component E_y and (b) surface current on the ELCs in dipole resonant mode. The distributions of (c) electric field component E_y and (d) surface current on the ELCs in LC resonant mode.

in OFF state with large capacitive impedance, which lowers the resonance frequency of the ELCs. While under forward bias voltage the diode is in ON state with inductive impedance, which increases the resonance frequency of the ELCs. As a result, the working frequency of the absorber is switchable between two frequency bands through controlling the bias of the coupling diodes.

In the previous metamaterial absorber, the ELC structure resonates in the first mode, the LC resonant mode, to achieve perfect absorption [6, 7]. To compare, the distribution of E_y and surface current of the ELC structures working in LC resonant mode is simulated at peak absorbing frequency and illustrated in Figs. 2(c) and 2(d), respectively. It can be observed that the electric fields in the gaps of ELC are out of phase with that in the region between

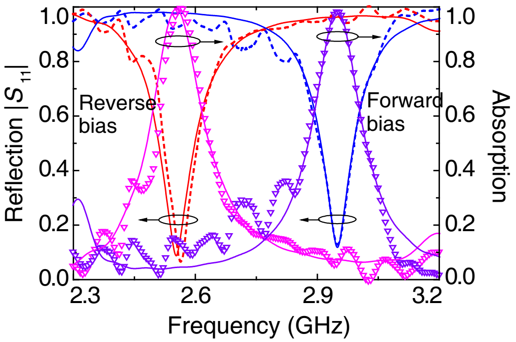


Figure 3. Simulated (solid) and measured reflection coefficient $|S_{11}|$ (dash) and absorption (triangle) of the metamaterial absorber under different diode biasing state for normal incident EM waves.

upper and lower ELCs, which are different from that in the dipole mode where the electric fields in these regions are in phase as shown in Fig. 2(a). Surface current on the ELCs in the LC resonant mode circulates clockwise and counterclockwise in the right and left loops of the ELC respectively as exhibited in Fig. 2(d), rather than flows along the same direction as that in the dipole mode (Fig. 2(b)). Although the ELCs working in LC resonant mode can be utilized to construct the unit cell of metamaterial absorber, it may not be suitable for the proposed switchable dual band absorbers. It is found in our simulation that the switchable impedance of the diode coupling the neighboring upper and lower ELCs would easily destroy the LC resonant mode in each ELC so that the perfect absorbing capability disappears.

3. DESIGN AND MEASUREMENTS

As an example, the metamaterial absorber with dual absorbing band at about 2.6 GHz and 2.9 GHz is numerically designed, physically fabricated and practically measured. A full wave EM simulation based on finite integral method is used to optimize the parameters of the proposed absorber. The dielectric substrate is chosen as FR4 with the permittivity of 4.4, the loss tangent of 0.025 and the thickness of 2 mm. The metallic ELC and ground plane is realized by copper sheet with conductivity of 5.8×10^7 S/m. The unit cell has an area of 36 mm × 72 mm with two ELCs. Each square ELC has the outer edge of 35 mm in length, with the center metallic strip of 3 mm and the other metallic strip of 2.5 mm in width. The gap in ELC and between neighboring ELCs is 1 mm. In simulation, the microwave diode is modeled as a lumped inductor in series with a resistor under forward biasing and as a lumped capacitor in series with a resistor under reverse biasing. The values of these lumped elements are obtained by measuring the diode in different biasing states at working frequency with a RF Impedance/Material Analyzer (Agilent E4991A).

To verify the performance, a 270 mm × 290 mm sample sheet consisting of 7 × 4 unit cells is fabricated using printing circuit board (PCB) technique based on the optimized parameters as shown in Fig. 1(b). The performance of the sample sheet is characterized through free space reflection measurement in a microwave anechoic chamber. A vector network analyzer (Agilent E8363C) and two horn antennas are used to transmit EM waves onto the sample sheet and receive the reflected signals. Since the sample absorber has a metallic sheet on the bottom layer so that EM transmission is zero, we only measure the reflection coefficient $|S_{11}|$ of the sample to obtain its microwave absorption, which is calculated as $A = 1 - |S_{11}|^2$. The measurement is calibrated by replacing the sample with an aluminum board of the same size as perfect reflector (unit reflection). Details about the measurement arrangement have been described in [9].

The measured and simulated reflection $|S_{11}|$ and absorption A for normal incident EM wave under different diode biasing states are exhibited in Fig. 3. When the diode is reversely biased, the measured $|S_{11}|$ is high at low frequencies, undergoes a minimum of 0.06 at 2.56 GHz, and then goes up to nearly unity at higher frequency region, which indicates that a nearly perfect absorption (absorption rate of 99.5%) is achieved at 2.56 GHz with a full width at half magnitude (FWHM) of 5%. When the diode is forward biased, the frequency of minimum reflection shifts to 2.94 GHz with a value of 0.13, which is equivalent to a peak absorption rate of 98% at this frequency and the FWHM is 4.7%. The simulation and measurement are in good agreement, verifying that the microwave absorbing property can be dynamically switched between two frequency bands by biasing the diodes in ON or OFF state.

Furthermore, it is observed in Fig. 2(a) that, the electric field in the area between the upper and lower ELCs is not evenly distributed along x axis. The field is strong at the center and weak at the two edges, so that the coupling position of the diode has an impact on the property of the metamaterial absorber. This feature allows us some freedom to control the frequency difference between the two absorbing bands through proper choice of the coupling position of the diode. By simulation, the characteristics of the proposed design have been explored with the diode loaded at different positions of $x = 0$ mm (center), 8 mm and 16 mm respectively, while all the other dimension

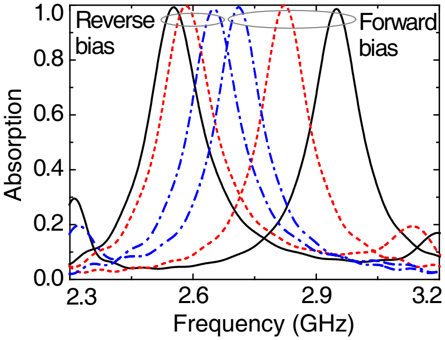


Figure 4. Simulated absorption of the metamaterial absorber with diodes loaded at $x = 0\,\text{mm}$ (solid line), $x = 8\,\text{mm}$ (dashed line) and $x = 16\,\text{mm}$ (dash-dotted line), respectively.

parameters of the unit cell are unchanged. The simulated results are compared in Fig. 4. When the diode is loaded at $x = 0\,\text{mm}$, the peak absorbing frequency is located at 2.55 GHz under reverse biasing state and 2.95 GHz under forward biasing state, the difference between the two peak absorbing frequencies is 400 MHz. As the diode is shifted to $x = 8\,\text{mm}$ where the electric field is weaker than that in the center region, the switching of the diode has a less impact on the resonance frequency of ELC so that the peak absorbing frequency under reverse biasing state increases to 2.58 GHz and that under forward biasing state decreases to 2.82 GHz. The frequency difference is reduced to 240 MHz. Finally, when the diode is positioned at $x = 16\,\text{mm}$ (edge) where the electric field is the weakest, the absorbing frequencies under reverse and forward biasing states change to 2.65 GHz and 2.71 GHz respectively, and the frequency difference is reduced to 60 MHz. The peak absorption is kept above 98% during this process. The above analysis demonstrates that the frequency difference between the two switchable absorbing bands can be adjusted by tuning the coupling position of the diode so as to meet the specific requirements in application. In addition to the scaling of the unit cell structure, this feature allows us more freedom to design the switchable absorber at other frequency spectrums and to adjust the frequency difference between the dual bands.

4. CONCLUSION

In conclusion, a dual band switchable metamaterial electromagnetic absorber is designed and fabricated by employing dipole mode ELC resonators coupled by microwave diode in the unit cells. The resonant inclusions are optimized to match the impedance of the absorber to free space and achieve a large energy dissipation due to resonance simultaneously, leading to nearly perfect wave absorption with very little wave reflection. By applying forward or reverse bias voltage on the diodes so as to change the coupling between the ELC resonators, microwave absorbing performance can be dynamically switched between two frequency bands with nearly perfect microwave absorption. The frequency difference of two bands can be tuned by adjusting the coupling position of the diodes with stable high peak absorption, which allows us to design absorbers with specific switchable frequency bands in practical application. With geometrical scalability, this concept can be applied at other frequency spectrums. The diodes can be replaced with semiconductor thin film devices integrated with the planar metamaterial structure [16] to function at terahertz or optical range. The proposed metamaterial absorber also suggests applications such as bolometric pixel element, spectrum filter with the feature of designable and dynamically switchable dual operating frequency bands.

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