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POLARIZATION INSENSITIVE METAMATERIAL ABSORBER WITH WIDE INCIDENT ANGLE

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Abstract—This paper presents the design, fabrication and measurement of a polarization insensitive microwave absorber based on metamaterial. The unit cell of the metamaterial consists of four-fold rotational symmetric electric resonator and cross structure printed on each side of a print circuit board to realize both electric and magnetic resonances to achieve efficient absorption of the incident microwave energy. Both the full wave electromagnetic simulation and the measurement on the fabricated absorber demonstrate high microwave absorption up to 97% for different polarized incident electromagnetic waves. To understand the mechanism, analysis is carried out for the electromagnetic field distribution at the resonance frequency which reveals the working mode of the metamaterial absorber. Moreover, it is verified by experiment that the absorption of this kind of metamaterial absorber remains over 90% with wide incident angle ranging from 0° to 60° for both transverse electric wave and transverse magnetic wave.

1. INTRODUCTION

Metamaterials are artificial structural materials composed of metals and dielectrics arranged in a periodic way. The electromagnetic (EM) parameters of metamaterials, e.g., permittivity and permeability, defined by effective medium theory (EMT) can be tailored through the design of unit cells of the metamaterials. Owing to this tailorable property, metamaterials with permittivity or permeability less than that of vacuum or with negative values have been successfully achieved over a significant range of EM spectrum ranging from radio to optics [1–8], which are not available with natural materials. Metamaterials

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with these unique properties have been applied to create novel microwave devices [9] with better performances and will find more EM applications such as invisibility cloaks, sub-wavelength imaging [10–13].

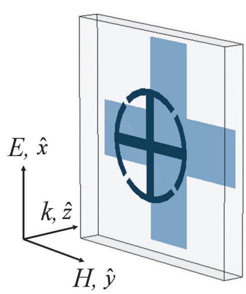
The unit cell of metamaterials is required to be much smaller than the working wavelength so that the electromagnetic properties of metamaterials can be characterized by an effective permittivity $\varepsilon(\omega) = \varepsilon_1(\omega) + i\varepsilon_2(\omega)$ and permeability $\mu(\omega) = \mu_1(\omega) + i\mu_2(\omega)$ according to EMT. By carefully designing the unit cell structures, both the real and imaginary parts of these two parameters could be tailored to the target values so as to exhibit desired electromagnetic features. This property has been successfully utilized to realize EM absorbers with nearly perfect absorption recently in microwave and terahertz region [14–19]. The idea is to independently tune the $\varepsilon(\omega)$ and $\mu(\omega)$ of the absorber through individually adjusting the dimensions of the electric and magnetic resonant components in the unit cell to make the impedance of absorber match to that of free space and possess a large imaginary part of refraction index simultaneously. Therefore, the reflection and transmission of incident waves by the absorber will be minimized at a certain frequency range due to the impedance matching and large losses in the absorber and the absorption will be maximized with the incident energy being converted into heat. However, the metamaterial absorbers recently proposed in [15–17] are polarization sensitive, which only works for EM waves with one particular polarization, and the chiral metamaterial absorber in [18] has a non-planar structure which may complicate the fabrication and installation.

In this paper, a polarization insensitive metamaterial absorber is presented by integrating symmetric electric and magnetic resonators into the unit cell. The impedance of the metamaterial absorber is designed to match that of the free space and the incident EM energy is absorbed through resonant losses inside the absorber. Simulation and experiment are carried out to explore the absorbing characteristics for different polarizations of normal incident EM waves. Moreover, the performance of the absorber for both transverse electric (TE) and transverse magnetic (TM) waves with the oblique incident angle up to 60° is investigated in the experiment. EM field and current distributions are analyzed to demonstrate the physical mechanism of the absorber.

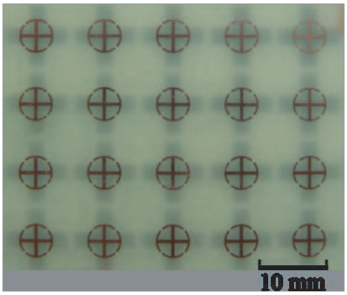
2. PRINCIPLE, DESIGN AND SIMULATION

Figure 1(a) shows the unit cell geometry of the proposed absorber with the volume of $10\,\mathrm{mm} \times 10\,\mathrm{mm} \times 1\,\mathrm{mm}$ which is designed and optimized at around 10 GHz. It consists of a metallic electric-LC (ELC) resonator in the front side of the dielectric substrate and metallic cross in the back side of the substrate. The inner and outer radius of the ELC are 2.2 mm and 2.5 mm, respectively, the gaps in the ELC are 0.28 mm and the width of the central cross in ELC is 0.5 mm, the back cross is 2.5 mm in width and 9 mm in length. The ELC couples strongly to the electric field of the incident waves but weakly to the incident magnetic field, providing a frequency dependent electric response $\varepsilon(\omega)$. The magnetic field of incident waves will penetrate the space between the ELC and back cross and generate countercurrents on these conductors, leading to a frequency dependent magnetic response $\mu(\omega)$. By carefully adjusting the dimensions of the ELC, back cross as well as the space between them, $\varepsilon(\omega)$ and $\mu(\omega)$ can be tuned individually. Thus, the impedance of the absorber can be matched to that of free space and high EM losses can be achieved in the unit cell through a large resonant imaginary part of refraction index so as to minimize the reflection and transmission of the incident waves simultaneously at a certain frequency band.

A full wave EM simulation based on finite integration technique (FIT) is performed to study and design the proposed absorber. The material of the ELC and cross is modeled as copper with 17 μm in thickness and frequency independent conductivity $\sigma = 5.8 \times 10^7$ S/m. The dielectric board is modeled as a FR4 board with $\varepsilon = 4.3$ and $\tan\delta = 0.02$. In order to demonstrate the polarization insensitivity of the absorber, two different polarizations of a planar normal incident EM waves are considered. One is the case with electric component polarized along x axis, the other is the case with electric component rotated for 45° in x-y plane. The simulated transmission, reflection as well as absorption are compared in Figs. 2(a) and (b) as the



(a)



(b)

Figure 1. (a) Unit cell geometry of the metamaterial absorber, and (b) photograph of the fabricated sample sheet.

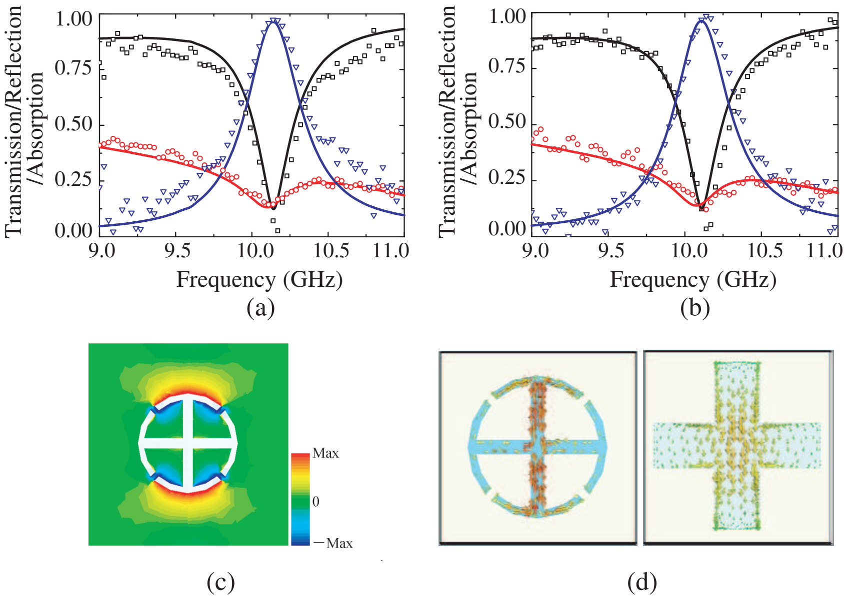


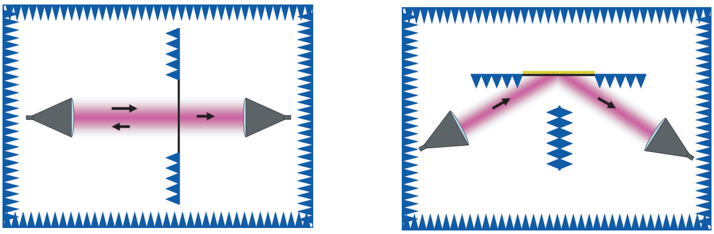
Figure 2. Simulated (solid lines) and measured transmission (circle), reflection (square) and absorption (triangle) of the metamaterial absorber for normal incidence. (a) Electric filed polarized along x axis. (b) Electric field rotated for 45° in x-y plane. (c) Simulated E_x at the surface of ELC at 10.14 GHz. (d) Simulated surface currents on ELC and back cross at 10.14 GHz.

solid lines. It can be observed that the reflection of the absorber is high in low frequency region, then drops to a minimum at 10.14 GHz denoting impedance matching with the free space, and finally goes up again. The transmission is relatively lower than the reflection over the entire frequency range, and reaches a minimum value at 10.14 GHz. The absorption is calculated by $A = 1 - |S_{11}|^2 - |S_{21}|^2$. Both the transmission and reflection is simultaneously minimized at 10.14 GHz so that a nearly perfect absorption is achieved at this frequency. Moreover, the results for the two different polarizations are nearly identical with each other, which imply that the proposed metamaterial absorber is insensitive to the polarization of incident EM waves.

Parameter retrieval has been carried out based on standard algorithm [20] which shows that the retrieved effective $\varepsilon(\omega)$ and $\mu(\omega)$ are equal to each other and large imaginary part of effective refraction index is observed at 10.14 GHz. To better understand the physical mechanism of the absorber at the frequency where the peak absorption is achieved, electric field component along x axis (E_x) at the surface of the ELC and the current distribution on the metals for the incident wave polarized along x-axis are plotted in Figs. 2(c) and (d), respectively. The front ELC is excited by the incident electric field so that opposite charges are accumulated at the upper and lower arches of the ELC, which can be determined by opposite directions of electric field at the edge of each arches shown in Fig. 2(c), and the current flows along the vertical conductor of the central cross of the ELC as shown in Fig. 2(d). The ELC works as a dipole for this kind of polarization. Surface currents on the ELC and the back cross are compared in Fig. 2(d). It is observed that the currents are flowing in opposite directions along x axis owing to the magnetic flux between the two metallic elements along y axis. The absorber interacts with the incident EM field as both an electric resonator and a magnetic resonator in this way and exhibits effective EM parameters ensuring high energy absorption.

3. EXPERIMENTAL VERIFICATION

Based on the optimized dimension of the unit cell, a 300 mm × 300 mm metamaterial absorber sheet as shown in Fig. 1(b) is fabricated by integrating the metallic structures onto an FR4 dielectric substrate using print circuit board (PCB) technique to experimentally verify the EM absorbing characteristics. The measurement is carried out in a microwave anechoic chamber. Two horn antennas with focusing dielectric lens mounted on the aperture are used to transmit EM beam onto the sample sheet and receive both the transmitted and reflected signals so as to obtain the absorption for normal incidence, as shown in Fig. 3(a). Microwave absorbing material is placed surrounding the



(a) (b)

Figure 3. Schematics of transmission and reflection measurement in an EM anechoic chamber for (a) normal incidence or (b) oblique incidence. Triangles represent microwave absorbing material and the thick black line covering the hole of the absorbing screen indicates the planar absorber sample sheet. The yellow (or gray) line in (b) denotes the metallic conductor placed at the back of the sample sheet.

sample sheet to eliminate the unwanted direct coupling between the horns for transmission measurement. The transmission and reflection spectra from 9 to 11 GHz are recorded by a vector network analyzer (Agilent E8363C) connected to the two horns. To test the polarization insensitivity of the absorber sheet, the horns are rotated for 45° around the main radiation direction to generate and receive EM waves with different polarization. In the experiment, transmission measurement is calibrated with that when the position of the sample is left as hollow (unit transmission) and reflection measurement with that the sample is replaced with an aluminum board as perfect reflector (unit reflection).

The measured results for two different polarizations of normal incidence are plotted as dotted lines in Figs. 2(a) and (b), respectively. The measurement agrees with the simulation quite well with peak absorption of 97% and a full width at half maximum (FWHM) of 4.7% for both polarizations, which verifies the nearly perfect absorption and polarization insensitivity of the proposed design. The transverse field of normally incident EM waves with any polarization can be decomposed into two orthogonally polarized components. Owing to the orthogonal symmetry of the proposed absorber in x-y plane, it couples and responds to each component equally which ensures that this absorber can work for incident EM waves with all polarizations, including circularly polarized waves.

The absorbing characteristics for oblique incident angles are also investigated. Considering the relatively small transmission value from both simulation and measurement results for normal incidence as well as the fact that microwave absorber is often used with a conducting back in practical application, the absorbing characteristics for off normal incidence is tested by putting the sample sheet on a square aluminum board with the same size and measuring the reflection only since the transmission under this arrangement is almost zero, as shown in Fig. 3(b). In the measurement, oblique incidence is realized by adjusting the positions of the two horns. Specular reflection is measured to calculate the absorption because both the experiment and the simulation indicate that the reflected field strength will decrease about 10 dB when the receiving horn is deviated 10° from the specular direction, which means that the reflected energy mainly distributes at the specular direction.

Figure 4 shows the measured absorptions for both TE and TM waves with an oblique incident angle ranging from 0° to 60°. For incident angle larger than 60°, the measurement will be affected by the unavoidable direct coupling between the two horns in the experimental setup, so that the absorbing characteristics for larger oblique angles are not obtained. It is observed from Fig. 4(a) that for TE waves,

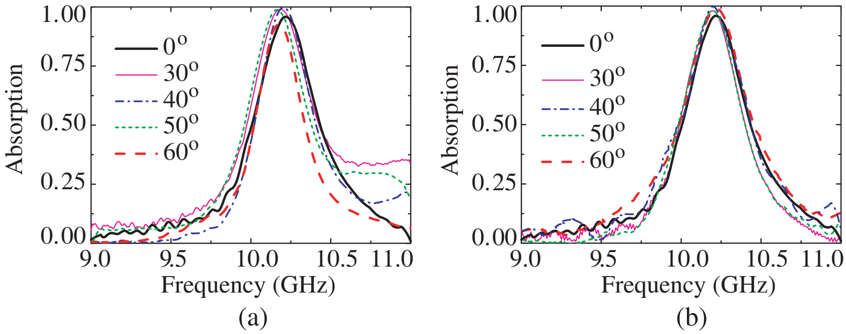


Figure 4. Measured absorptions at different oblique incident angles for (a) TE and (b) TM modes. The Labels for different curves indicate the incident angles.

the peak absorption remains greater than 95% and the FWHM larger than 4% for incident angle ranging from 0° to 50°. For incidence angle of 60°, the peak absorption and FWHM drop to 92% and 3.3% respectively, since the incident magnetic field can no longer efficiently induce the resonant currents on ELC and back cross. For TM waves, absorptions are almost unchanged for all of the incident angles with peak absorption above 95% and FWHM larger than 4% as shown in Fig. 4(b). Since any oblique incident EM waves can be decomposed into TE and TM modes, these measurement results indicate that the proposed absorber can work well for oblique incident EM waves over a large range of incident angles.

The absorbing capability of the proposed absorber is directly resulted from the resonant structures of the unit cell. Through simply scaling up and down the dimensions of these structures, it is possible to tune the absorbing frequency over a significant EM frequency spectrum. Furthermore, conformal installation of this absorber can be achieved by integrating the metallic structures onto flexible dielectric substrate.

4. CONCLUSION

In this paper, a metamaterial absorber sheet for all polarizations has been successfully fabricated and tested, using PCB technique. Polarization insensitivity has been verified with nearly identical responses for different polarized EM waves in both simulation and measurement. Peak absorption of 97% with a 4.7% FWHM has been achieved for normal incident waves. Investigations into the EM field distribution in the unit cell have revealed the working mode of the absorber. Moreover, the measurement results for oblique incidence have indicated that the absorption remains above 92% for a large range of incident angles up to 60° for both TE and TM modes. With geometrical scalability, this absorber could be designed to work at other EM frequency range with nearly perfect absorption. These remarkable features suggest many potential applications, including EM wave spatial filter, frequency selective thermal emitter [19] owing to the narrow band character as well as the bolometric pixel element for its perfect conversion from EM energy to heat [16].

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