Design of Broadband Metamaterial Absorber Based on Lumped Elements

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Abstract- **An enhanced broadband metamaterial based on lumped elements is presented. The structure is composed of lumped elements and two conductive layers with a single substrate (FR-4) between them. The simulation results show that the bandwidth of absorption of 80% is about 10.58 GHz and the full width at half maximum (FWHM) can be up to 92%. The further simulations of the proposed MA can operate at a wide range of incident angles under both transverse electric and transverse magnetic polarizations.**

I. Introduction

Electromagnetic metamaterials (MMs) have produced many exotic effects and devices, which are usually defined as a class of artificial media with unusual properties not found in nature, such as negative refraction [1], sub-wavelength imaging super-lens [2], and cloaking [3]. Recently, Landy et al. have proposed a thin metamaterial absorber (MA), in which electric and magnetic resonance makes the absorber possess matched impedance to eliminate the reflection and strongly absorb the incident wave [4]. Since then, many MAs have been proposed and demonstrated from microwave to optical frequencies [5-7]. However, the bandwidth of these MAs is usually narrow, and is not applicable in some areas. Generally, MAs are composed of periodic arrays of sub-wavelength metallic elements. Various approaches have been proposed to extend the absorption band, the purpose of which is to make the MA units resonate at several neighbouring frequencies [8-12]. These MMs obtain high absorption properties primarily through dielectric loss and impedance matching at resonance for incident EM waves. MA could be founded have various potential applications in thermal imaging, thermal bolometer, wavelength-selective radiators, stealth technology, and nondestructive detection.

In this paper, in contrast to the broadband absorbers in the previous studies, we proposed a simple broadband MA based on lumped elements. The proposed MA is composed of lumped elements and two conductive layers with a single substrate (FR-4) between them. The top layer consists of a ring and a deformed cross (RDC) embedded in the ring which loads the lumped elements, whereas the bottom layer has a metallic ground plate without patterning. The absorption bandwidth can be broadened by changing the lumped elements. The design and simulations for the proposed MA have been presented in the paper.

II. Structures and Design Guidelines

According to the effective medium theory, MMs can be characterized by a complex permittivity $\tilde{\varepsilon}(\omega)$ and permeability $\tilde{\mu}(\omega)$. In practice, loss is measured by the amount of electromagnetic power absorbed, where absorbed power is $A(\omega)=1-R(\omega)-T(\omega)$, where $R(\omega)$ and $T(\omega)$ is the reflection and the transmission as functions of frequency ω, respectively. To achieve unity absorption of the MA, minimizing $R(\omega)$ and $T(\omega)$ to near zero simultaneously is necessary. The frequency dependent $R(\omega)$ and $T(\omega)$ are dependent on the complex refraction and relative wave impedance on the complex refraction $\tilde{n}(\omega)=\sqrt{\tilde{\mu}(\omega)\cdot\tilde{\varepsilon}(\omega)}$ and relative wave impedance $\tilde{z}(\omega)=\sqrt{\tilde{\mu}(\omega)/\tilde{\varepsilon}(\omega)}$. Therefore, it is possible to absorb both the incident electric and magnetic field tremendously by properly tuning $\tilde{\varepsilon}(\omega)$ and $\tilde{\mu}(\omega)$, and achieving perfectly impedance-matched to the free space.

In order to design the broadband MA, we firstly proposed a two-band MA; the two-band MA is composed of two conductive layers with a single substrate (FR-4) between them. The top layer consists of a ring and a deformed cross (RDC) embedded in the ring, whereas the bottom layer has a metallic ground plate without patterning. A substrate (FR-4) with a relative permittivity ε_r=4 (loss tangent, 0.025) and thickness h= 0.8 mm is chosen. The chosen metal is copper with the thickness of 0.035 mm and the electric conductivity of 5.8×10^7 s/m. The optimal parameters of the two-band MA are as follows: the outer diameter of the ring is r=3.9mm, and the distances of the inner cross shown in the structure are d=0.3mm and t=0.2mm. The width of the structure W=0.2mm, and the length of the inner cross is l=2.9mm, which is shown in Fig.1 (a). And then the lumped elements are loaded on the two-band MA to expand the bandwidth, eventually, the broadband MA can be achieved, which is shown in Fig.1 (b). Because of loading the lumped elements, the thickness of the substrate (FR-4) is increased to h=3.2mm. As to the two-band MA, the two resonant peaks can be shifted closely through optimizing the geometric parameters carefully.

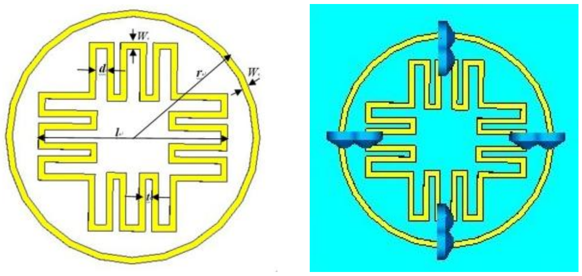


Figure 1. (a) Perspective of the two-band MA; (b) broadband MA based on lumped elements

III. Numerical Results

The proposed MA is designed and optimized based on the standard finite-difference time domain (FDTD) method. Periodic boundary condition is set along the lateral directions of the structure and open boundary condition is set along the *z* direction. Frequency domain solver and hexahedral mesh are applied in our design. The optimized simulate results of the two-band MA are shown in Fig.2, the absorptions of two resonant frequencies are 98.68% and 98.57% at 7.145 GHz and 7.43GHz for structure I; and the absorptions at 6.84GHz and 7.024GHz are 97.24%, 99.47% for structure II, respectively. The two resonant peaks can be shifted closely through optimizing the geometric parameters carefully. The optimized geometric parameters are shown in Tab.1.

Table.1. optimized geometric parameters of structures (unit:mm)

Structure	*r*	*l*	*W*	*d*	*t*
Structure I	3.7	2.7	0.2	0.2	0.1
Structure II	3.9	2.9	0.2	0.3	0.2

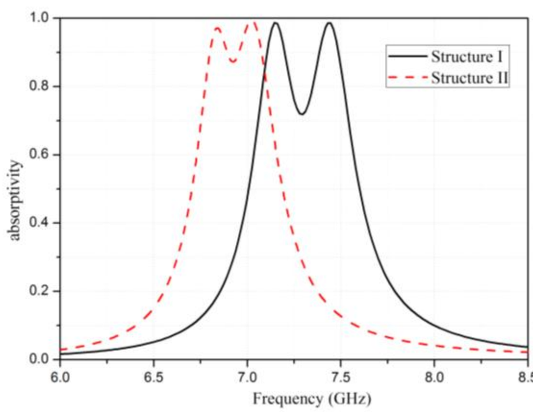


Figure 2. absorptions of the two-band MA.

To achieve broadband MA, the device is composed of the dielectric substrate sandwiched with metal RDC loaded with lumped elements (lumped resistance R)and continuous metal film. The unit cell of composite MA is shown in Fig.1 (b). We load the resisters on the two-band MA. Fig.3 shows the absorptivities of the broadband MA with different lumped resistances. From Fig.3, we can clearly see that when *R*=200Ω, the absorptivity is highest and the absorptivity exceeds 80% from 6.16GHz to 16.74 GHz and the FWHM is up to 92%. We can also see that the lumped resistance mainly influences the magnitude of the absorptivity. These results further confirm the role of the lumped elements to improve performance of the MA and also indicate that lumped parameters have a great influence on the absorbing properties.

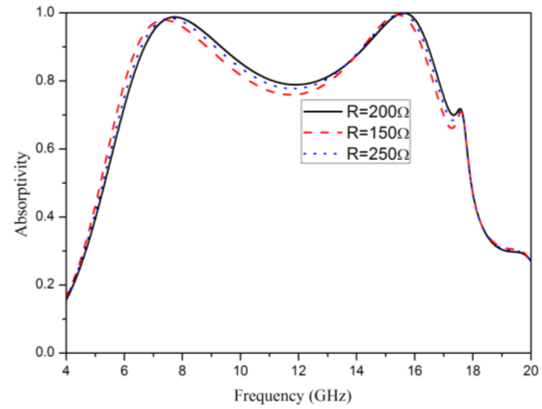


Figure 3. absorptions of the broadband MA loaded on the lumped elements.

We also examine the sensitivity of the broadband MA to the polarization states. The reflection characteristics under a normal incident planar EM wave with different polarizations are plotted in Fig.4. From the figures, the intensity of these reflection dips is nearly unchanged when φ changes from 0° to 45 °.

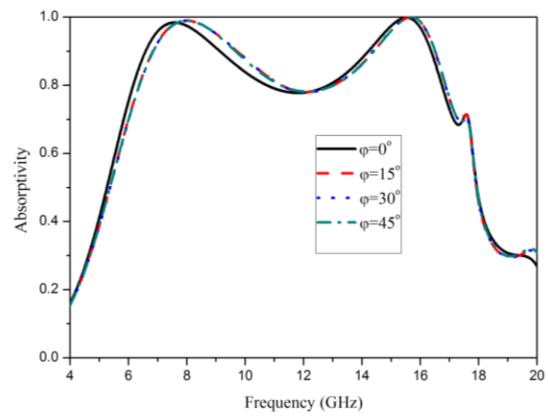
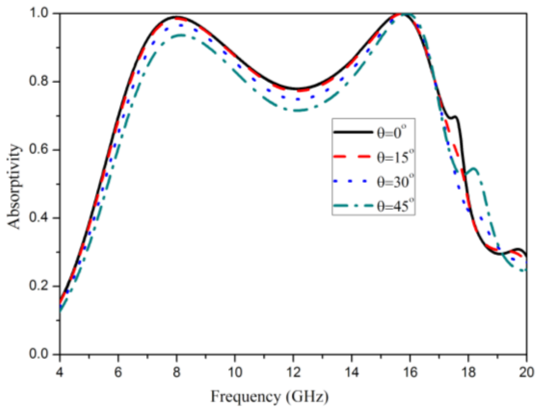
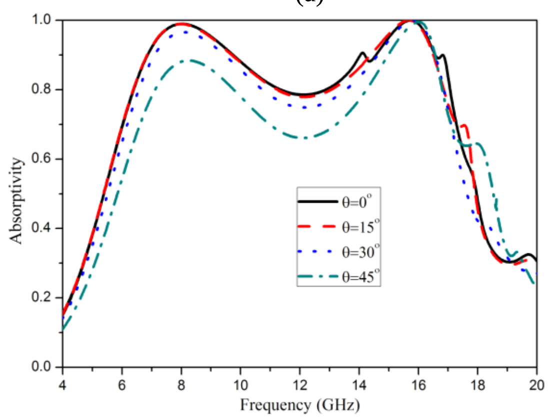


Figure 4. Polarization independence of the reflectivity of the proposed MA

In addition, it is necessary to discuss the situations of large angles of oblique incidence with instable polarization states. Fig.5 shows the simulated results of the proposed MA with frequency for different oblique incident elevation angles (θ, defined as the angle between the wave vector and the normal) for both TE and TM polarizations, respectively. Following the figure, the proposed MA still retains a good performance with broad bandwidths and high absorptions in TE and TM mode, when θ changes from 0°to 45°. When the incident electric field propagates across the MA, the FWHM at normal incident exceeds 80% is up to 92% in TE case; the FWHM at normal incident exceeds 80% is up to 93% in TM case, respectively. Furthermore, when the incident angle reached to 45°, the FWHM at normal incident exceeds 70% is up to 90% in TE case; the FWHM at normal incident exceeds 65% is up to 88% in TM case, respectively. This can be explained by the fact that the position of magnetic-resonance peak is not changed much by increasing the angle of incidence. It is found that the function of this absorber is rarely limited by the direction of incident electric field in a wide angle range.



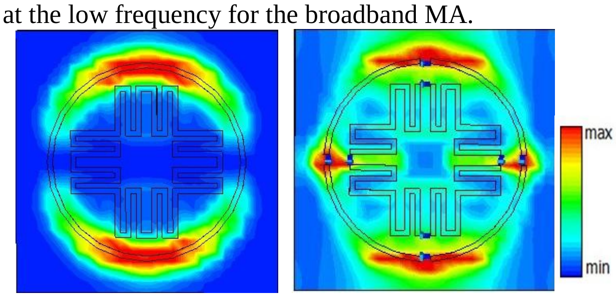
(a)



(b)

Figure 5. Angular independence of the absorptivities of the proposed MA (a) TE and (b) TM modes

To better understand the physical mechanism of the proposed broadband MA, the electric energy density was plotted in Fig.6. Referring to the figure, it can be seen that the electric energy density distributions on the outer ring at the low frequency for the two-band MA, whereas the electric energy density distributions on the lumped elements loaded on outer ring at the low frequency for the broadband MA.



(a) (b)

Figure 6. the electric energy density (a) the two-band MA at 7.145GHz (b) the broadband MA at 7.58GHz.

IV. Conclusions

In conclusion, we have designed and simulated broadband MA with lumped elements. Simulation results demonstrate that the absorptivity of nearly 80% is about 10.58 GHz and the FWHM is up to 92%, and the absorptivity is nearly unchanged for different polarization angles. Compared the RDC structure MA, our design has a wider bandwidth of absorption. Furthermore, the proposed MA is not limited by the quarter-wavelength thickness and relatively thin. The further simulated results indicate that lumped parameters have a great influence on the absorbing properties and there exist optimal values, where the performance of the composite MA is best.

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