A Wideband Metamaterial Absorber Based on Multilayer Rings and Lumped Resistors

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Abstract— A novel low-frequency wideband and polarization-insensitive metameterial absorber is presented. It is composed of multiple dielectric slabs, lumped resistors, square-circular rings and a metal ground plane, with suitable air spacers sandwiched. An absorptive operating band, determined by absorption $A = 1 - |S_{11}|^2 - |S_{21}|^2 > 90\%$, is demonstrated in the frequency range of 1.96 GHz to 7.44 GHz numerically, up to a bandwidth of 116.6%. The wideband absorption design is based on the destructive interference of the reflection waves from the metamaterial and the magnetic resonance of the square-circular loops. The total thickness of the designed absorber is only $0.094\lambda_L$, where λ_L is the free-space wavelength at the lowest operating frequency.

1. INTRODUCTION

Metamaterials attracts much attention of researchers in the past decade. Various novel theories and applications based on metamaterials were proposed and studied. A metamaterial perfect absorber, proposed by David Smith [1–3], is able to provide a good absorption due to the simultaneous electric and magnetic resonances, however, with a narrower bandwidth. Wideband metamaterial absorbers have been studied using interference theory [4, 5] and implemented at a higher frequency band [5]. Low-profile planar absorbing materials have also been designed by using the left-handed transmission line theory [6, 7], achieving a reduction of 10 dB over a bandwidth of 50% at the center frequency of 2 GHz.

In this paper, a novel low-profile metamaterial absorber, composed of square-circular metal rings and lumped resistors, is proposed for wideband absorptive applications. The proposed structural model is original from the typically square and circular loops, which have strongly magnetic resonance. In addition, the result of the absorber is well explained with the interference theory, which shows that the metamaterial absorber can obtain wide absorptive bandwidth in a low frequency range. Simulated results show that this composite structure metamaterial absorber has a low-frequency wideband absorption in the range of 1.96 GHz to 7.44 GHz, almost 116.6% absorptive bandwidth. Another advantage of this design is that it provides a low profile, about 0.094 free-space wavelength at the lowest operating frequency.

2. ABSORBER CONFIGURATION AND DESIGN PRINCIPLE

The unit cell of the proposed metamaterial absorber is shown in Fig. 1. It consists of a PEC ground and three square-circular rings that have different sizes and are printed on three FR4 dielectric layers. The three FR4 dielectric layers have the same thickness, 2 mm, and their relative permittivity is 4.4. On each square-circular ring, four lumped resistors are employed to connect the square ring and the circular ring, in order to absorb the coupled energy of the magnetic resonance of the square-circular rings. As shown in Figs. 1(a) and (b), the unit cell is square, with side length $W = 32$ mm. The widths of square and circular rings in each layer are the same and denoted by d. The diameter of the circular loop is R_r. W_t and ss are the width and length of the rectangular resistors. The FR4 dielectric slabs are separated by the suitable thickness of air space.

For the analysis of such a periodic structure with an infinite size, the PMC and PEC boundaries are applied to the four sides of the unit cell [8]. The simulated model is shown in Fig. 1(c), where a waveport is applied to feed. Commercial software Ansys HFSS was used to carry out the simulations.

For the metamaterial absorber, the expression of the absorption is $A(\omega) = 1 - T(\omega) - R(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2$, where $A(\omega)$ is the absorption. $|S_{11}|^2$ and $|S_{21}|^2$ are the reflection coefficient and transmission coefficient respectively that are the function of frequency ω.

For better understanding, the equivalent circuit of the metamaterial absorber is presented in the Fig. 2. The square-circular rings are equivalent to a parallel LC loop, and lumped resistors are connected in series to it. Dielectric layers and free space are replaced by the transmission line with different characteristic impedance. Through tuning the parameters of the metamaterial

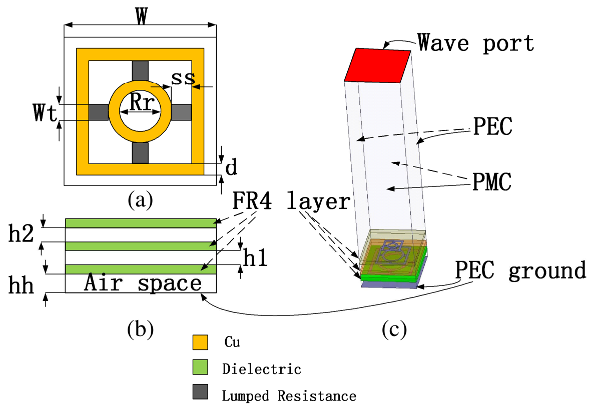


Figure 1: Schematic structure of the metamaterial absorber unit cell.

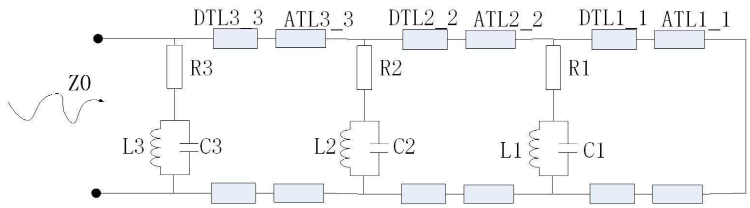


Figure 2: Equivalent circuit model of the proposed metamaterial absorber.

absorber, such as d, R_r, values of resistors, hh, $h1$, $h2$, etc., a good impedance matching over a wide bandwidth to the free space characteristic impedance Z_0 can be achieved, resulting in a wideband metamaterial absorber.

3. SIMULATED RESULTS

The proposed metamaterial absorber is investigated based on the interference theory [4, 5] and the magnetic resonance [1–3]. The model in Fig. 1(c) is used to find the expected reflection or absorption. Parameters d, R_r, values of resistors, hh, $h1$, $h2$ and the size of the unit cell were optimized. Table 1 shows the optimized dimensions of each square-circular rings on each FR4 layer. The height of the air space are $h2 = 3.4\,\text{mm}$, $h1 = 1.6\,\text{mm}$, and $hh = 3.5\,\text{mm}$, as shown in Fig. 1(b).

Table 1: Dimensions of each square-circular rings on FR4 layers (unit: mm).

Location of layer	d	ss	R_r	W_t
Top layer	1.1	1.2	4.2	1.25
Middle layer	1.2	1.2	10.4	1.25
Bottom layer	1.5	2.2	14.8	1.6

In this work, only the reflection needs to be examined, and the absorption is calculated by the equation $A(\omega) = 1 - |S_{11}|^2$. As shown in the Fig. 3, the absorption within the frequency range of 1.96 GHz–7.44 GHz is over 90%, showing a wide bandwidth of up to 116%. The real part of normalized equivalent impedance, which is normalized to wave impedance of free space, 377 Ω, is about one and the imaginary part maintains at around zero at the operating band, demonstrating that the absorber has a good impedance matching to the free space and its reflection is nearly zero.

The reflection coefficients for different incident angles are also investigated. Figs. 4(a) and (b) show the simulated results for TE and TM incident cases. It can be seen that a broadband $S_{11} < -10\,\text{dB}$ reflection is obtained at normal incidence for both TE and TM cases. With the increase of incident angles, the reflection remains unchanged at lower frequency, and has a little changing at the higher band. In summary, the proposed absorber is able to achieve polarization-insensitive performance and good absorption for wide-angle incidence, due to its symmetrical structure.

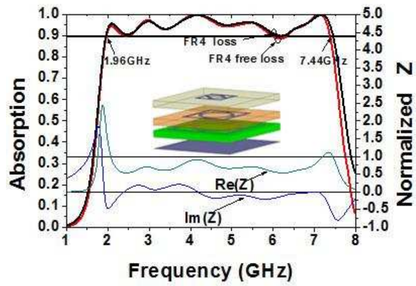
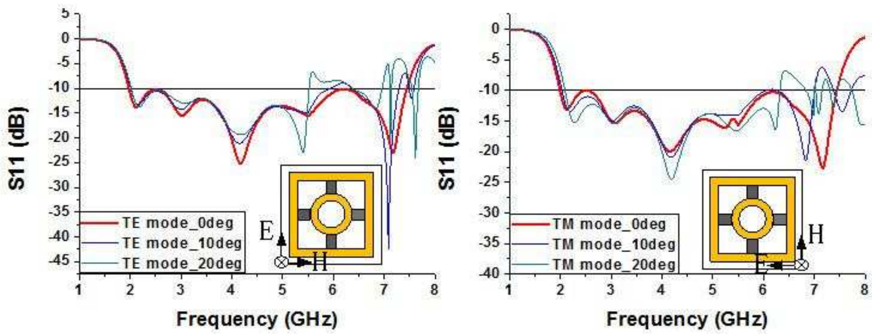


Figure 3: Simulated results of the absorption and the normalized impedance at 377 Ω.



(a) (b)

Figure 4: Reflection coefficients for incident angles 0°, 10° and 20°. (a) TE incidence. (b) TM incidence.

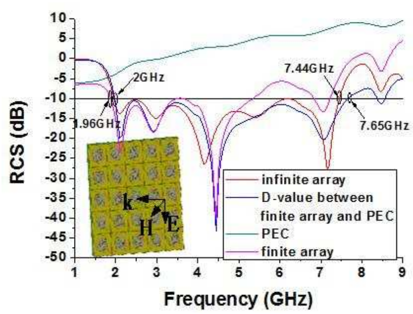


Figure 5: The RCS (Radar Cross-Section) reduction of the metamaterial absorber.

The unit cell of the proposed metamaterial absorber is simulated with the boundary conditions, which means that the absorber is a infinite array and hardly fabricated in reality. To investigate its RCS (Radar Cross-Section) reduction in practice, a model of 5×5 unit cells is applied and its structure is shown in the inset of Fig. 5. The RCS reduction of the model is the death value (D-value) between the finite array of the absorber and the PEC ground with the same dimension of the metamaterial finite array. As shown in Fig. 5, the agreement between RCS (< -10 dB) reductions of the finite and infinite array is excellent, validating the predicted performance of the proposed metamaterial absorber.

4. CONCLUSIONS

We propose a metamaterial absorber that has simultaneous magnetic responses and destructive interference, and has a good impedance matching to free space over a broad frequency band. By adding the lumped resistors, the employed square-circular rings produce a strong magnetic resonance loss. Simulations demonstrate that the proposed low-profile planar absorber has a good absorption ($S_{11} < -10$ dB) in the range of 1.96 GHz to 7.44 GHz, up to a bandwidth of about 116%. The simulated RCS reduction of a 5×5 finite array also validates the wideband absorption performance.

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