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Design, fabrication and characterization of a perfect absorber using simple cut-wire metamaterials

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Abstract
Using an irreducible design we experimentally and numerically study a perfect metamaterial absorber, providing excellent absorption at microwave frequencies. The impact of geometric parameters on the absorption is also investigated. The experimental and the simulated results are in good agreement. Finally, we propose a polarization-insensitive absorber for the improvement.

Keywords: perfect metamaterial absorber, cut-wire pair structure, cross-shaped structure

Classification numbers: 3.02, 5.17

1. Introduction

Since the first demonstration of metamaterial in 2000 [1], its exotic properties have been exploited in various applications, namely, small metamaterial antenna [2–4], negative-index superlens [5, 6] and electromagnetic cloaking [7, 8]. Recently, as an expansion, the so-called perfect metamaterial absorber has attracted interest because of its achieving unity absorptance [9–13].

One of the oldest absorbent bodies is the Salisbury screen [14]. It consists of a 377 Ω resistive sheet placed at integer multiple of a quarter-wavelength ($\lambda_0/4$) apart from a metal plate at working frequency (λ_0). A reflection dip or the resonant absorption can be observed by using this configuration because the incident wave interferes destructively with the reflected one from the metallic screen. However, this configuration makes them considerably heavy, thick and cumbersome for the microwave region. Although other proposed techniques such as frequency-selective [15] and high impedance surfaces [16] indeed have better dimensions than the Salisbury screen, their structures are still comparable to wavelength. Hence, scaling down of the structure size is continued.

Through the endeavor to overcome these obstacles, the pioneering works of metamaterial absorber were first proposed by Bilotti *et al* [9] in the microwave region. This absorber is composed of a resistive sheet and an array of split-ring resonators (SRRs) to produce a strong magnetic resonance. Unlike the conventional absorbers, the required dimensions of each unit cell of metamaterial absorber are much smaller than the wavelength of the resonance. Therefore, the thickness of metamaterial absorber is reduced approximately by an order of magnitude compared to the conventional ones. Recently, Landy *et al* [10] have demonstrated a perfect absorption using a double ring resonator and a metallic bar separated by a dielectric spacer. It was shown that by rigorously controlling the electric and the magnetic responses of metamaterial structure, the incident electromagnetic wave can be completely absorbed. Afterwards, the perfect absorption of metamaterials has been

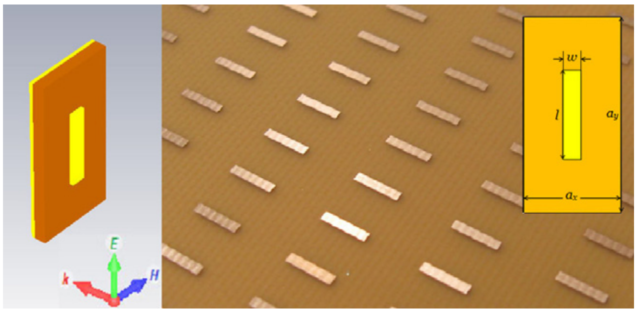

Figure 1. (Left) A unit cell of CW-based absorber with electromagnetic polarization and (right) an actual absorber sample. The width and the length of CW are w and l, respectively. The periods of the unit cell in the **H**–**E** plane are a_x and a_y.

confirmed both numerically and experimentally using many other structures [11]. However, the quest for a simple but effective design for optical frequencies is still a challenging topic for scientists so far.

In this paper we propose a perfect metamaterial absorber using a very simple cut-wire (CW) structure. By microwave measurements and numerical simulations, we elucidate the absorption mechanism based on the coupling between magnetic and electric resonances. The influence of geometric parameters is also investigated. Finally, the polarization-insensitive cross-shaped (CS) structure is studied to compare with the behaviour of the CW structure.

2. Simulation and experiment

Numerical simulations of the design are performed by using the commercial CST Microwave Studio. The boundary conditions are selected appropriately as shown in figure 1. The incident wave **k** propagates along the z direction, while the **E** field is polarized along the y direction and the **H** field along the x direction. A unit cell of proposed metamaterial absorbers is made up of a dielectric layer sandwiched between a copper CW and a copper film. The dielectric layer is lossy FR-4 with the thickness of $t_{\mathrm{d}} = 0.4$ mm and a defined dielectric constant of $\varepsilon_{\mathrm{r}} = 4.2 + 0.09i$. The thickness of the copper strips in FR-4 board is $t_{\mathrm{s}} = 0.035$ mm. The period of each unit cell in the x direction, a_x, and the y direction, a_y, are 5.5 and 11.0 mm, respectively. We use TEM plane wave to stimulate the single unit cell, which provides S-parameters in order to calculate the absorptance. The absorption power $A(\omega)$ is calculated through $A(\omega) = 1 - R(\omega) - T(\omega) = |S_{11}|^2 - |S_{21}|^2$, where the reflection power $R(\omega) = |S_{11}|^2$, and the transmission power $T(\omega) = |S_{21}|^2$.

Figure 1 shows designed unit cell (left picture) with the proper electromagnetic polarization and a photo of our fabricated absorber sample (right picture). The components of metamaterial absorbers were fabricated by standard optical lithography. We verified the behaviour of absorbers by performing reflection and transmission measurements using the Hewlett-Packard E8326B Vector Network Analyzer. We measured reflection coefficient S_{11} with the incidence angle of 20° and transmission coefficient S_{21} with the normal incidence. It is noteworthy that S_{21} is zero for our all measurements, as expected since the metallic ground plane plays the role of an electromagnetic screen.

3. Results and discussion

3.1. Perfect absorber based on CW

It is well known that the metamaterial absorbers are commonly composed of a dielectric layer sandwiched between an electric ring resonator (ERR) and a thin metallic background plane [11, 17, 18]. However, the main drawback of these structures is their complexity of geometry, which might be difficult to be accurately fabricated, especially in the optical region. Recently, an irreducible electric resonator, the so-called CW structure, has been studied extensively owing to its geometric simplicity [19–23].

In the present work, we systematically investigate the electromagnetic characterizations and the geometric dependence of a perfect absorber based on simple CW metamaterials.

In general, the absorptance was calculated by $A(\omega) = 1 - R(\omega) - T(\omega) = |S_{11}|^2 - |S_{21}|^2$. Hence, the unity absorptance can be possibly achieved at a certain frequency by reducing the reflection and the transmission to zero simultaneously. While the zero reflection can be achieved by the impedance-matching technique [24], the minimum transmission is usually obtained by the high imaginary part of refractive index due to the coupling between the electric resonator and the plasma behavior of the metallic film. This argument is clearly demonstrated in figure 2, where the CW, the cut-wire pair (CWP) and the cut-wire-based absorber (CWA) are simulated for comparison. It is commonly understood that the individual CW can be considered as an electric dipole antenna, yielding an electric resonance, while the induced anti-parallel currents of CWP structure responds for a magnetic resonance. At the microwave frequency, the metallic film acts like a perfect reflector. Our simulations and measurements indicate that the perfect absorptance of CWA always occurs exactly at the magnetic resonance of CWP structure. This finding suggests that the loss via magnetic resonance is likely the main channel of the power dissipation. To confirm this point, the simulated current distributions of CW, CWP and CWA at resonant frequency are presented in figure 3. Obviously, at the absorbing frequency, the CW structure is strongly coupled with the metallic film behind, behaving completely differently to the single CW structure only. In particular, it is shown that the CWA induces the anti-parallel currents as those in the magnetic resonance of the CWP structure.

Further simulations allow us to give a conclusive comment on the mechanism of absorption in the proposed structure. As shown in figure 4, where the loss powers at CW, metallic film and dielectric spacer are calculated, the loss is principally dissipated in the dielectric spacer. Moreover, the loss is not equally distributed in the spacer. It locates mainly at the edges of CW, where the effective capacitances are formed. This definitely implies that the dielectric loss plays the key role in the absorbing mechanism.

3.2. Influence of geometry parameters and electromagnetic polarization

The CWP structure was first studied by Zhou *et al* [25]. It was proved that the magnetic resonance frequency is

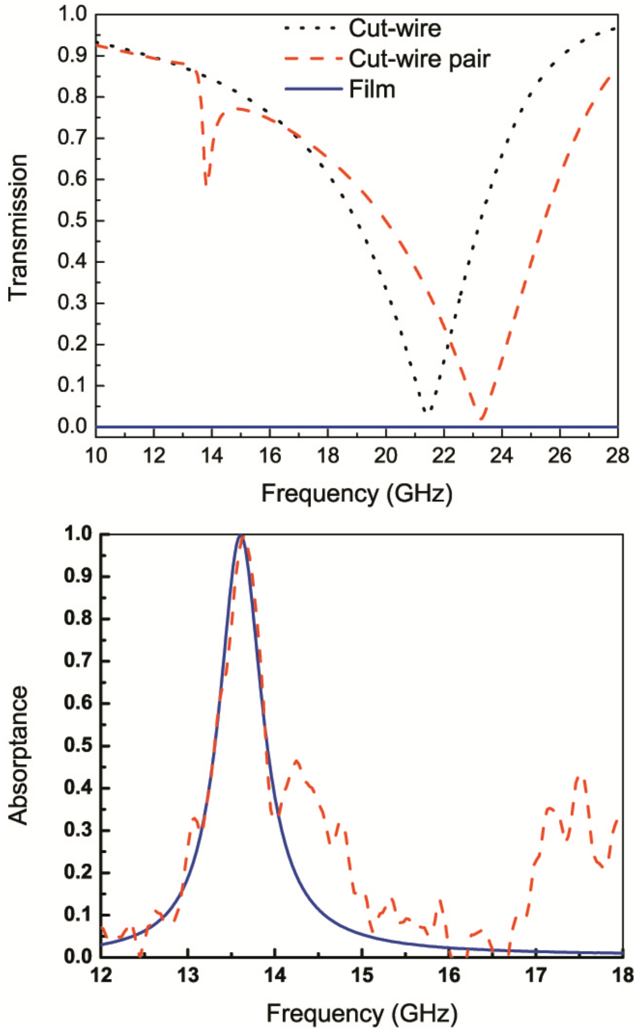

Figure 2. (Top) Simulated transmission of one-side CW, cut-wire pair and metallic film. (Bottom) Simulated (solid) and experimental (dashed) absorptance of the CW-based absorber. $l = 5.5$ mm and $w = 1.0$ mm are used for the simulations and the experiments to minimize the reflection at resonant frequency.

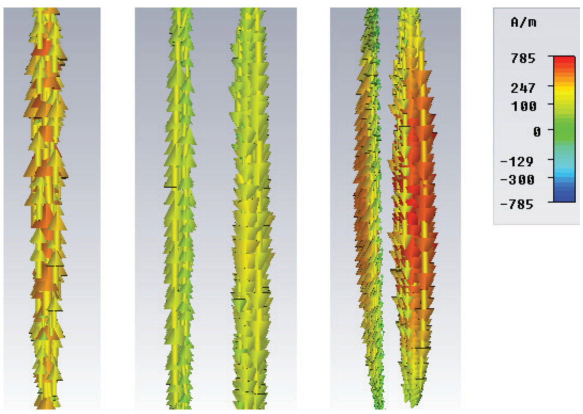

Figure 3. (From the left to the right) Simulated surface currents of CW, CWP and CWA, respectively, at 13.6 GHz.

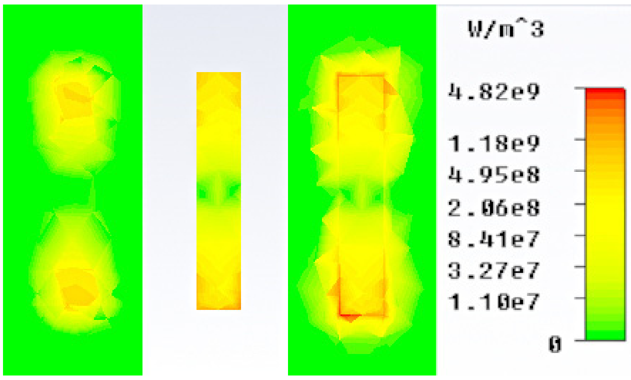

Figure 4. (From the left to the right) Simulated power loss density of copper film, copper CW and dielectric substrate, respectively, at absorption frequency.

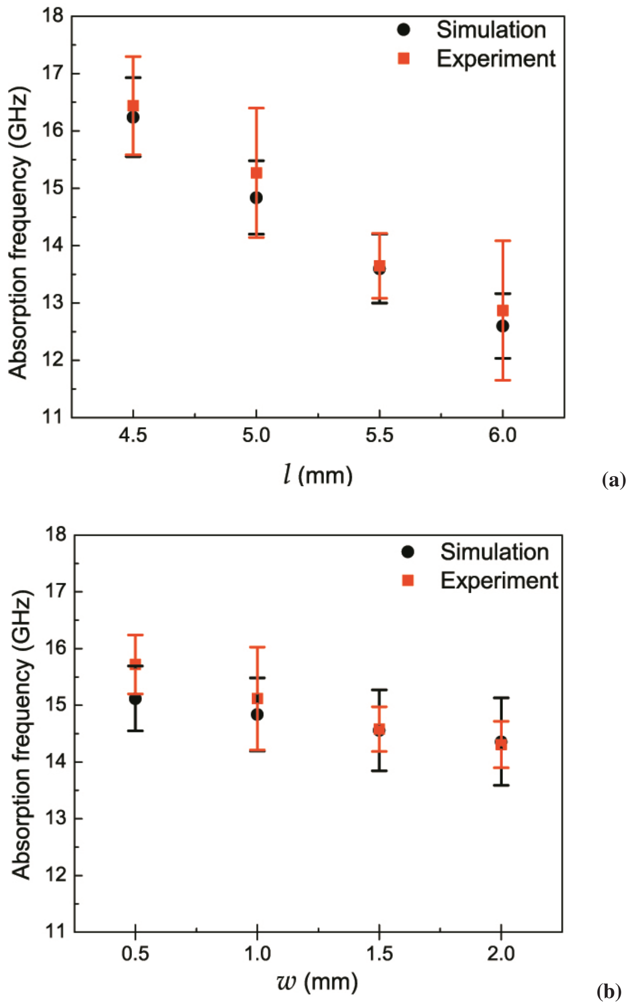

Figure 5. (a) Dependence of absorption frequency on the length (l) of CW and (b) the width (w) of CW. The error bar indicates the FWHM of the absorption peak.

strongly dependent on structural parameters. As mentioned above, our proposed absorber can have magnetic behaviour like the CWP structure. Besides, the perfect absorptance frequency is close to the magnetic resonance frequency as shown in figure 2. Those confirm that the magnetic resonance is the background resonance when coupling to the electric resonance. For these reasons, we also investigate the influence of structural parameters on the CWA.

In figure 5(a) there is a pronounced shift towards the lower frequency of the absorption peak, and its full-width at half-maximum (FWHM) also decreases when the length of the CW increases. In case of the width (figure 5(b)), the absorption peak shows the red-shift behaviour too, while the

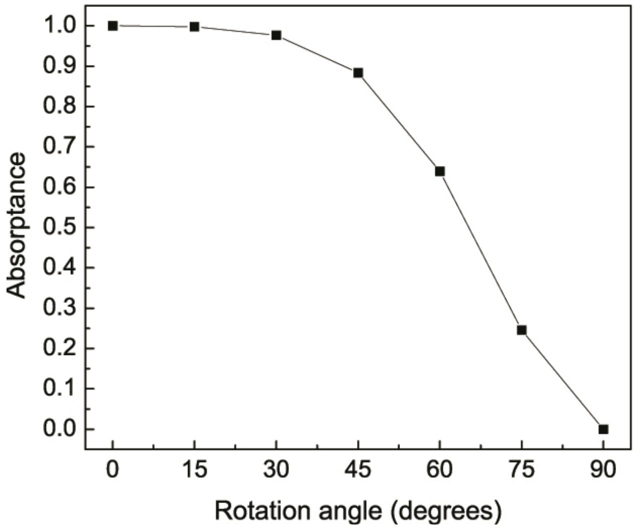

Figure 6. Influence of the transformation from TE to TM mode on the absorptance in CWA.

FWHM of the peak exhibits the trend to increase. In addition, the shift in the case of the length is larger than in the case of the width. This can be accounted for the fact that the capacitance increases by either shortening the separation of two neighboring CWs or widening the width of the CW. The influence of geometry parameters on the absorption frequency is totally consistent with the model of Zhou *et al* for the CWP structure. The mismatch between simulated and experiment results may be explained due to the imperfectness of the fabrication condition. Interestingly, the nearly perfect absorptance still maintains in both cases. These results also prove that the electric resonance and magnetic resonance are simultaneously displaced when a structural parameter of the CW is changed. That makes the CWA become flexible and dimensionless, especially down-scalable to the THz region.

The CWA is as polarization dependent as the CWP structure. Figure 6 describes the dependence of the absorptance on the rotation angle of the incident electromagnetic wave, where the rotation axis is the propagation direction **k**. The absorptance declines to zero from near unity as the rotation angle increases to 90°. This phenomenon is expected since the CW is sensitive to the polarization. When the rotation angle equals 90°, there is no electric and magnetic resonance at all due to the orientation of the electromagnetic field at this moment. Consequently, the impedance of the sample highly mismatches to that of air, which causes the total reflection.

Because of this polarization sensitivity of the CWA, another type of ERR, the so-called cross-shaped (CS) structure, is used to overcome the limitation of the CW structure [26, 27]. In the CS structure, a similar horizontal CW is added in order to constitute a symmetric configuration which compensates for the polarization of the vertical CW. Therefore, the absorptance maintains near unity no matter what the polarization is. In this part, we also numerically studied the influence of geometry parameters on the cross-shaped based absorber (CSA). Figure 7 is the unit cell of the CSA. Most of the geometry parameters are kept as origin apart from a modification: the period of each unit cell

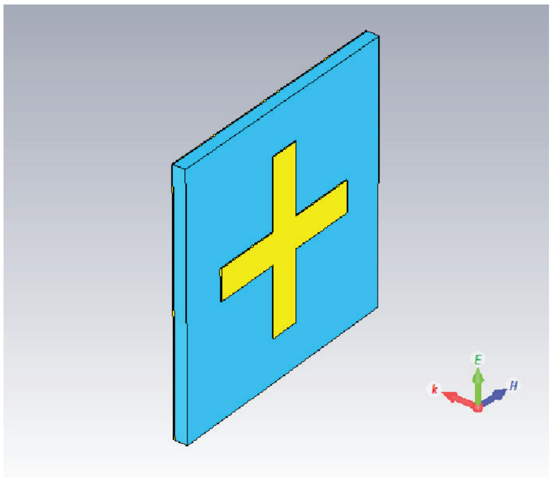

Figure 7. Unit cell of CS structure. The structure parameters are $a_x = a_y = 8.3$ mm, $w = 1.0$ mm, and $l = 5.5$ mm.

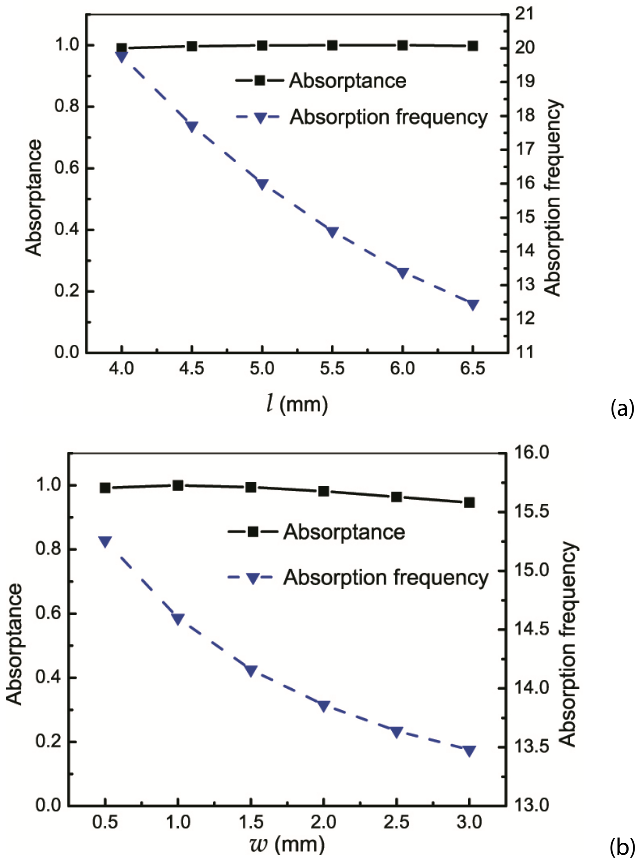

Figure 8. (a) Simulated absorptance and the corresponding frequency of CS structure as the length of CW varies while the width of CW is fixed and (b) vice versa.

in x direction and y direction is 8.3 mm. The simulation proves that the CSA behaves similarly to the CWA.

Figure 8 shows the red-shift of the absorption peak when either the length or the width of the CW increases. The absorptance also maintains above 95% with the different length or width. These results are expected since the underlying physics of the CS structure originates from the CW structure.

4. Conclusion

We proposed a metamaterial absorber, which is simple but efficiently absorptive and down-scalable. The absorption mechanism of the CWA was determined clearly to be the coupling of electric and magnetic resonances and the plasma behaviour of the metal film. The influence of geometry parameters was also investigated. The experiment results are in agreement with the simulations. Finally, the study on the polarization-insensitive CSA shows the inherent advantages of the CWA.

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