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A SIMPLE DESIGN OF WATER-BASED BROADBAND METAMATERIAL ABSORBER FOR THz APPLICATIONS

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Abstract. *We report a simple design of a water-based broadband metamaterial absorber in the terahertz region. The absorption performance of the designed absorber is simulated using numerical method. Due to the large frequency dispersive permittivity and high relative dielectric loss of water, the bandwidth of the proposed absorber can extend. The proposed structure achieves the absorption response over 0.9 in the broadband frequency range from 0.6 THz to 10 THz under normal incidence. Moreover, the absorbance maintains above 0.8 for a wide incident angle up to 60° for transverse electronic (TE) mode and above 0.9 for a wide incident angle up to 70° for transverse magnetic (TM) mode in the entire operating frequency range. Therefore, the designed absorber is a potential candidate for broadband THz applications.*

Keywords: water-based metamaterial absorber; THz; broadband.

Classification numbers: 81.05.Xj; 78.67.Pt.

I. INTRODUCTION

The metamaterial absorber has extensively been studied since Landy et al. reported a perfect metamaterial absorber (PMA) in 2008 [1]. After that, PMAs with a narrow band, multiband, and broadband have proposed for many practice applications from the microwave to the optical frequency range such as sensing [2,3], solar energy [4,5] and imaging device [6,7], etc. Among these, the broadband PMA has attracted a lot of interest because numerous applications require the broadband feature as photodetection [8–10], stealth technology [11]. However, designing the broadband absorber remains a challenging issue, especially in the THz region [12]. Therefore, many different methods have proposed to broaden the bandwidth of absorbers, such as using multi-resonators in a unit cell [4], vertical stacking metal-dielectric multi-layers [13, 14], and lumped elements [15, 16] or using graphene [17–19], or vanadium dioxide [20–22], and MoS_2 [23].

However, the mentioned designs are complex in fabrication [4, 13–16] or need to be controlled by outside elements such as temperature and voltage [17–23]. Recently, metamaterials with high dielectric loss have been demonstrated as a potential method to extend the absorption bandwidth [24–33].

The water with high dielectric loss is available in abundance in nature at a low cost. In addition, the water exhibits a large and frequency dispersive permittivity [34]. Thus, its loss is relatively high in a wide frequency range. Because of the above advantages, water has been suggested in designing antennas [35, 36]. Since the first report on the water-base absorber in 2015 [24], water becomes a potential candidate for designing near-perfect absorbers. Then, numerous water-based absorbers have been reported [24–31], but most of them operate in the GHz range. Recently, water-base absorbers worked the THz frequency range get more research interest [29, 32, 33, 37–40]. However, in the range from 0.1-10 THz, which is the hotspot of research today [41], the number of proposed water-based absorbers is still limited.

In this paper, we report a simple design water-based absorber for the THz frequency range. The proposed structure achieves the absorption performance of over 90% in the ultra-wideband from 0.6 to 10 THz. Moreover, the absorption performance obtains over 80% for the incident angle within 60° for transverse electronic (TE) and over 90% within 70° transverse magnetic (TM) modes in the entire frequency range. In comparison with the newest water-based absorber [38], which investigates in the same frequency range from 1 to 10 THz, our proposed design has wider bandwidth and less insensitive incident angle.

II. STRUCTURE DESIGN

Figure 1 shows the water-based absorber structure. The designed absorber is formed by arranging these unit cells in the x- and y-directions with a period of P. The unit cell is a cylindrical water resonator that is encapsulated in a cuboid container and backed with a copper plate. The cuboid container is made of Teflon with an edge (P). The Teflon substrate has a permittivity of 2.1 and a loss tangent of 0.002. Meanwhile, the cylindrical water resonator has a diameter (d) and height (h2). The dispersive permittivity of water depends on both frequency and temperature as described by the Debye formula [30, 33]:

$$\varepsilon(\omega) = \varepsilon_\infty(T) + \frac{\varepsilon_S(T) - \varepsilon_\infty(T)}{1 - i\omega\tau(T)}, \tag{1}$$

where $\varepsilon_S(T)$ and $\varepsilon_\infty(T)$ are the static permittivity and optical permittivity, respectively. While τ is the rotational relaxation time and T is the temperature of the water. It is noticeable that the below investigations are realized at the room temperature in corresponding to with $\varepsilon_\infty(T) = 3.1$ and $\varepsilon_S(T) = 78.4$ and $\tau = 8.27 \times 10^{-12} s$

The electromagnetic performance of proposed absorber is investigated by commercial computer simulation technology (CST) software Microwave Studio 2013. In setup of the simulation, the boundaries of the unit cell are applied in the x- and y-directions while open boundary condition is assigned in the z-direction.

Aim of this study is achieving absorption performance over 90% in wide THz frequency range. Thereby, simulation method is chosen to optimize the structure parameters. The geometric parameters of the proposed absorber are optimized at $P = 56\ \mu$m, $h_1 = h_3 = 15\ \mu$m, $h_2 = 300\ \mu$m, $d = 46\ \mu$m, and $t = 0.02\ \mu$m. It shoud be noted that the well-known photolithography technique can be used to fabricate the desiged absorber structure because the size of the proposed structure is in the micromet range.

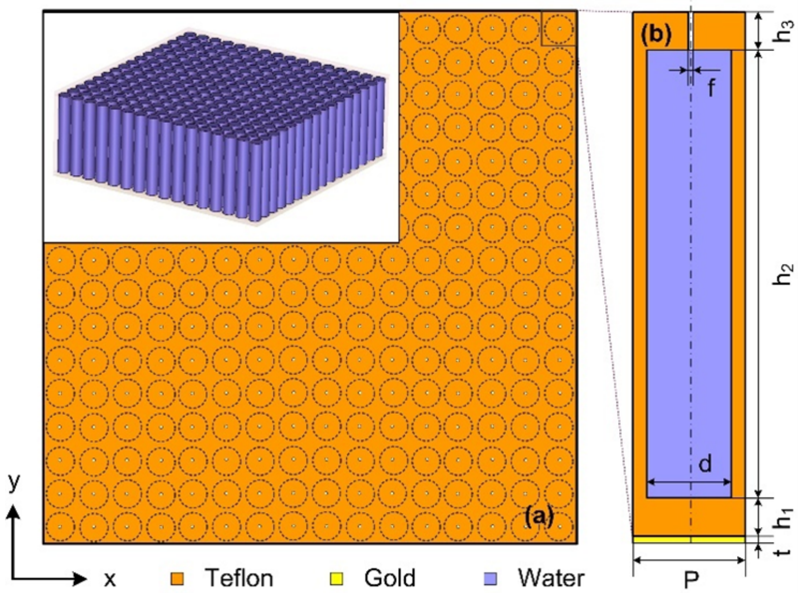

Fig. 1. Schematic of the designed water-based absorber: (a) the top-view and (b) the enlarge cross-section-view of a unit cell. The inset is the 3D-view of the absorber.

III. RESULTS AND DISCUSSION

The absorptivity of the proposed absorber is calculated from the reflection coefficient (S11) as the equation (2) due to the transmission coefficient is blocked by copper plate [30, 33].

$$A(\omega) = 1 - S_{11}^2(\omega). \tag{2}$$

Figure 2 shows the absorptivity under normal incidence for both TE and TM modes. As seen in Fig. 2, the absorption performance is higher than 0.9 in the frequency range from 0.6 THz to 10 THz in both TE and TM modes. Furthermore, the absorption spectra of TE and TM modes are coincident, indicating the proposed absorber is polarization insensitivity.

The absorption mechanism can be explained by the impedance matching between the proposed absorber and the free space. The normalized impedance is calculated by equation (3) from the scattering parameters of the reflection coefficient $(S_{11}(\omega))$ [33] and the absorption is evaluated

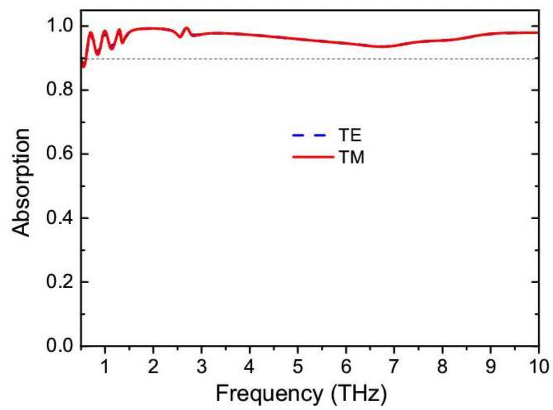

Fig. 2. The performance of the proposed absorber at normal incidence for TE and TM modes.

using the normalized impedance which is given by equation (4) [42].

$$Z(\omega) = \frac{1 + S_{11}(\omega)}{1 - S_{11}(\omega)}, \tag{3}$$

$$A(\omega) = 1 - \left| \frac{Z-1}{Z+1} \right|. \tag{4}$$

From equations (3) and (4), when $Z = 1$, the perfect matching can be obtained and the absorbance reaches the maximum. Fig. 3 shows the normalized impedance of the designed absorber. As shown in Fig. 3, the real-part of the impedance is approximately unit while the imaginary part of the impedance is close to zero, covering a broad frequency range from 0.6 THz to 10 THz. It indicates that the near impedance matching is obtained in this frequency range, and the near-perfect broadband absorption is achieved in our designed absorber.

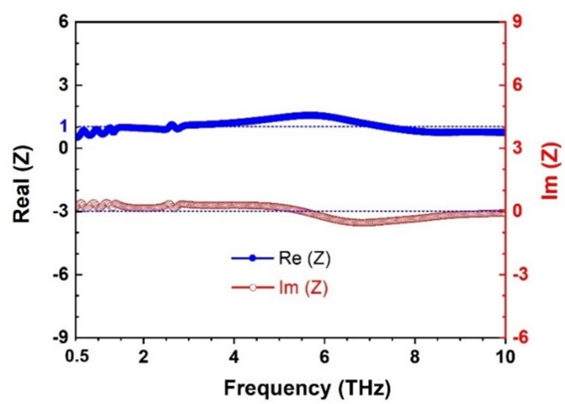

Fig. 3. The normalized impedance of the absorber.

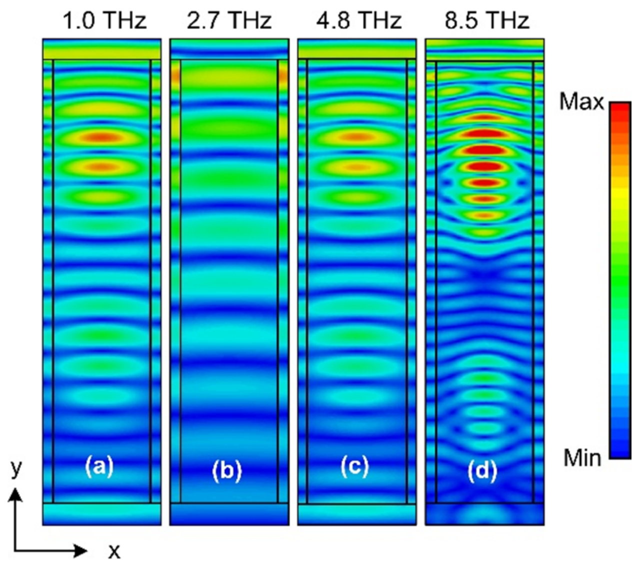

Fig. 4. The distribution of electric field at various frequencies (a), 1.0 THz, (b), 2.7 THz, (c), 4.8 THz and (d) 8.5 THz.

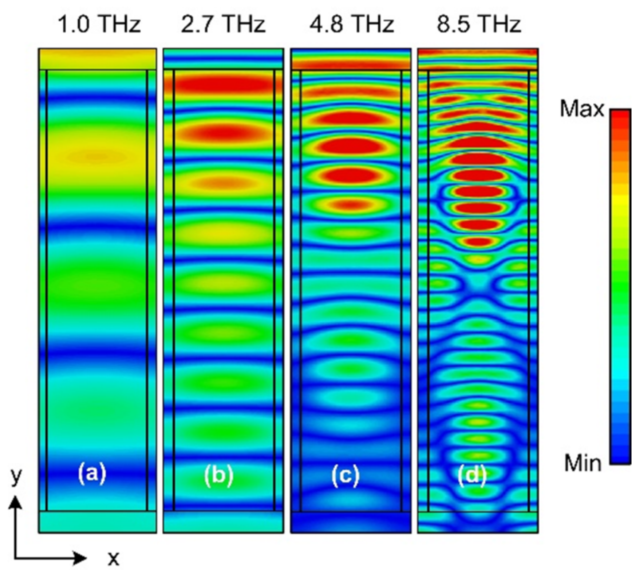

Fig. 5. The distribution of magnetic field at various frequencies (a), 1.0 THz, (b), 2.7 THz, (c), 4.8 THz and (d) 8.5 THz.

To gain insight into the physical mechanism of the absorption, we have investigated the distribution of electric and magnetic fields in a unit cell of the proposed absorber in the XOY plane at various frequencies 1 THz, 2.7 THz, 4.8 THz, and 8.5 THz and the results are shown in Figs. 4 and 5, respectively. As seen in Figs. 4 and 5, at the frequencies of 1 THz, 4.8 THz and 8.5 THz, the distribution of electric and magnetic fields mainly concentrates at the upper half of the cylindrical water resonator and on the top border between the water and the adjacent Teflon shell. At the frequency of 2.7 THz, the electric field locates mostly at the upper border of water and Teflon shell and it is very weak at the bottom, while the magnetic field concentrates at the upper half of the cylindrical water resonator and the upper border of water and Teflon shell. Based on this observation, it can be summarized that the chemical interaction between water and the Teflon substrate generates the electromagnetic resonator [39]. Furthermore, the electric and magnetic resonance are both contributed to these absorption peaks. It was reported that the magnetic resonance is major contribution to broadband absorption [33, 39] in the water-based absorbers. It is due to the coupling of water and PTFE at the top border [33].

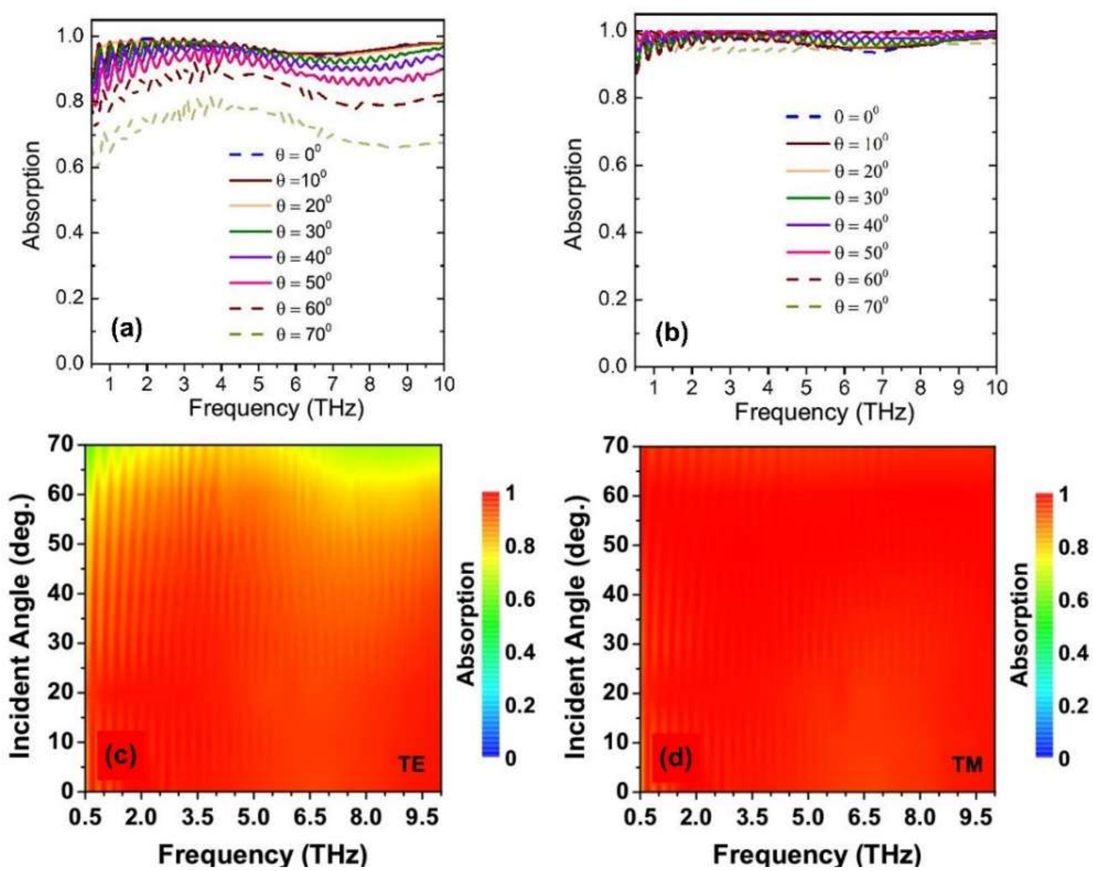

Fig. 6. Absorption spectra of the absorber with different incident angles for (a) and (c) TE mode, and (b) and (d) TM mode.

In practical applications, the electromagnetic waves illuminate the surface of the absorber in various directions. Therefore, the absorption performance of the absorber at different angles is studied. The absorption performance significantly decreases with the incidence angle over 60° for TE mode, as shown in Figs. 6(a) and 6(c). Meanwhile, the absorption performance insignificantly decreases and still maintains the absorptivity over 0.9 in the entire frequency range with the incident angle up to 70° for TM mode, as depicted in Figs. 6(b) and (d). Form obtained results, it can be concluded that the proposed design achieves the high absorption performance with large incident angles for both TE and TM modes.

The effect of the polarized angle on absorption performance is also investigated, and the results are presented in Fig. 7. Figs. 7 (a) and (c) show the absorption performance of the absorber under normal incidence with the polarized angle changing from 0 to 90° for TE mode. Figs. 7 (b) and (d) present that results in case of TM mode. As seen in Fig. 7, the absorption spectra of the absorber are unchanged in the whole operating frequency range with the polarized angle increases from 0 to 90°, which demonstrates the proposed absorber is insensitive to polarization for both TE and TM modes due to the symmetric structure of the designed absorber.

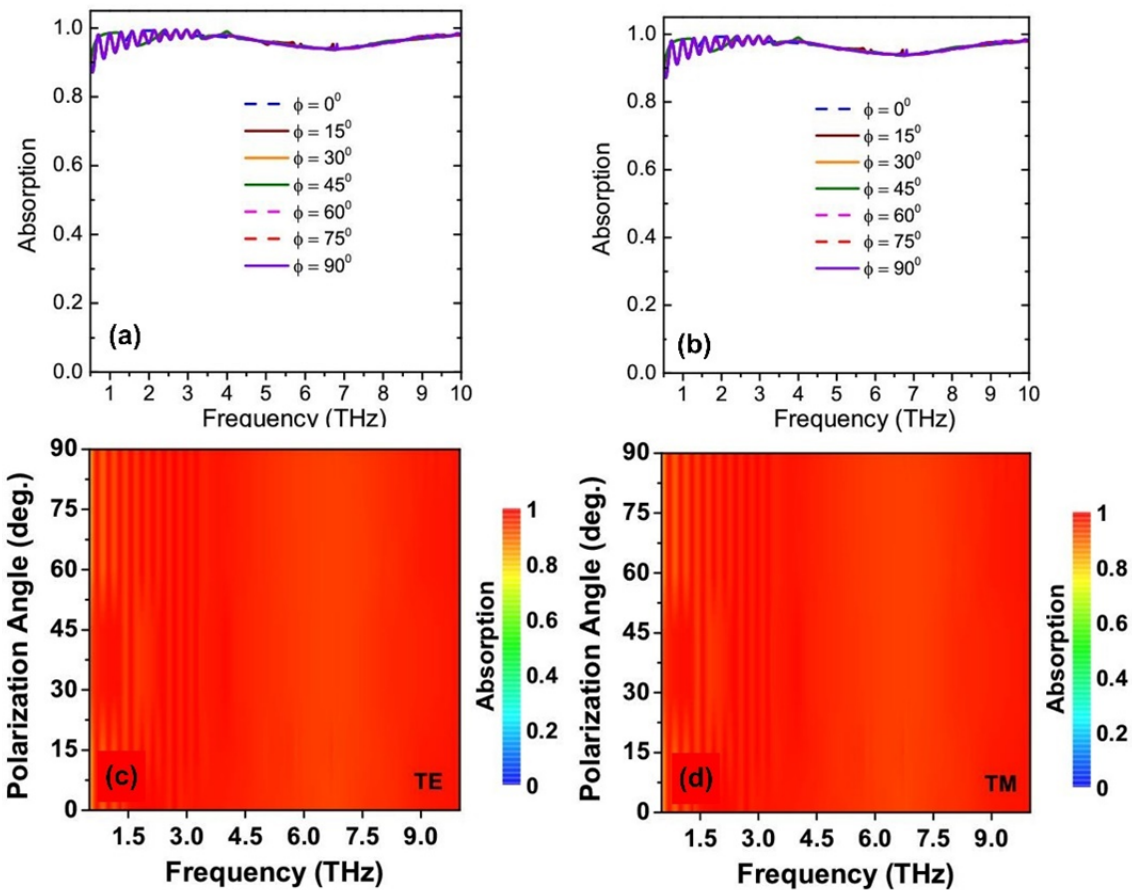

Fig. 7. The absorption spectra of the absorber with different polarization angles for (a),(c) TE mode and (b),(d) TM mode.

IV. CONCLUSIONS

A simple design of the water-based broadband terahertz metamaterial absorber was proposed and numerically studied. The proposed absorber consists of a periodic array of a cylindrical water resonator encapsulated in the cuboid container and backed with a copper plate. The designed absorber structure achieved an absorption efficiency above 0.9 in the wide frequency range from 0.6 to 10 THz. Moreover, the absorber maintained a high absorption performance of over 0.9 with a wide variation of incident angle up to 40o for TE mode and 70o for TM mode. The physical mechanism of the absorber was investigated through the distribution of electric and magnetic fields at different frequencies, indicating that both electric and magnetic resonances contributed to broadband absorption. Due to the obtained excellent absorption performance, the designed absorber is a very promising candidate for THz applications.

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