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A Broadband Polarization Insensitive Metamaterial Absorber Using Petal-Shaped Structure

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Abstract

A novel terahertz metamaterial absorber design with broadband and polarization insensitive absorption characteristics is presented in this paper. This proposed unit cell structure consists of a single layer dielectric with a petal-shaped metallic patch on the top plane. It is found that the absorber offers a broadband absorption of more than 90% over a frequency ranging from 2.6 to 3.5 THz. The absorption mechanism, electric field distribution and parametric analysis for the observed broadband response are also investigated in this paper. The strong coupling effect in the petal-shaped structure contributes to the broadening of the absorption spectrum. Thus, the proposed single-layer absorber can have effective application in terahertz broadband applications.

Keywords Metamaterials · Terahertz · Absorber · Broadband · Absorption

Introduction

The recent growth of terahertz (THz) technology has opened up new opportunities in applications such as sensing, imaging and spectroscopy. The combination of metamaterials (MMs) with THz gained more popularity mainly due to their exotic properties [1] and effects such as negative refractive index [2], invisibility cloaking [3], inverse Doppler effect [4] and perfect lensing [5]. These properties help in creating materials having negative permittivity and permeability which is unseen in conventional materials. MMs can be employed to design perfect electromagnetic absorbers displaying near unity absorbance for a small or broad frequency band [6–10]. The first metamaterial perfect absorber was demonstrated by Landy et al. [11] yielding near unity absorption due to simultaneous excitation of electric and magnetic resonances. Since the first demonstration, extensive research and alternate designs have been spawned with applications in terahertz imaging, filtering, biological sensing, etc. [12–21]. Different types of THz MMAs were proposed which can be classified based on the number of absorption bands and on the absorption bandwidth. Some of the researchers focussed on developing multi-band absorbers while the others on improving the bandwidth. At present, THz MMAs with eight absorption bands have been developed [22]. However, these MMAs suffer from a drawback of narrow bandwidth [19] and so researchers attempted to design broadband absorbers [23–32].

In order to broaden the bandwidth, the most common methods used are stacking the absorbers and to use multiple metallic patch structures. These two most common methods are also known as planar arrangement and vertical arrangement. The planar arrangement is composed of multiple metallic patterns on the top of a dielectric substrate. Due to the multiple resonances, these MMAs are able to achieve perfect absorptivity over a broad spectrum. Then comes the vertical arrangement in which multiple top layers are stacked in vertical direction yielding broadband absorption. If simple fabrication and low cost are taken into consideration, then single-layer unit cell structure with single metallic pattern on top is more attractive than the above-mentioned methods. Some of the broadband absorbers that have been demonstrated in the literature are shown in Table 1.

It can be observed from Table 1 that the existing works on broadband THz MMAs use either the vertical arrangement or the horizontal arrangement for achieving broadband

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Table 1 Different types of broadband absorbers reported in the literature

Metamaterial absorbers	Unit cell structure	Dielectric thickness	Range of broadband response	% of Absorption
[23]	I-shaped resonators	Polyimide, 8.5 μm	0.905 to 0.956 THz	> 90%
[24]	Cross-shaped ERR	1.8 + 0.06i, 2 μm	4.08 to 5.94 THz	> 80%
[25]	Circular and rhombus	Polyimide, 90 μm	0.22–0.33 THz	> 80%
[26]	Two circular split rings	Polyimide, 26 μm	0.85 to 1.926 THz	> 90%
[27]	Compact resonator	PDMS, 15 μm	1.19 THz and 1.64–2.47 THz	> 90%
[28]	Fishnet layers	Polyimide, 20 μm	0.58 THz	> 75%
[29]	Pyramid structure	Dielectric polymer, 4 μm	0.7 to 2.3 THz	> 80%
[30]	Multi-ring structures	PEN, 50 μm	0.63 to 1.34 THz	88%
[31]	Square-stacked structure	Polyimide, 2.8 + 0.09i	2.6 to 5.7 THz	> 90%
[32]	Rectangular-shaped resonator	1.73 + i0.1, 14 μm	1.24 to 2.58 THz	79.02%
Proposed metamaterial absorber	Petal-shaped broadband absorber	2.8 + 0.009i	2.6 to 3.5 THz	> 90%

absorption. From fabrication perspective, such designs are complicated and so single-layer structures with a single metallic pattern are the current requirement.

In this paper, a novel broadband metamaterial absorber in terahertz frequency is proposed using a petal-shaped structure on a single-layer absorber design. In order to study the absorption properties of the MMA, numerical simulations have been performed. From the simulated results, it is seen that the metamaterial absorber exhibited a broadband spectrum along with polarization-insensitive characteristics displaying perfect absorption above 90% and the bandwidth of about ~ 1 THz ranging from 2.56 to 3.5 THz. In addition, parametric study has been performed in order to justify the parameters of the design. This broadband metamaterial absorber can find potential applications in THz spectrum [33–37].

Unit Cell Structure

The proposed terahertz metamaterial absorber is composed of a petal-shaped structure. The top and side view of the novel MMA is given in Fig. 1. The unit cell structure consists of three layers in which top layer is a metallic gold patch in the shape of a petal, where radius of the circle $r = 3$ μm, major radius of the ellipse $c = 30$ μm and thickness is set to $t = 0.4$ μm. Then, the bottom layer named as metallic ground plane also consisted of gold having conductivity given by $\sigma = 4.07 \times 10^7$ S/m and thickness $b = 0.5$ μm. Next, the middle layer is the dielectric layer or dielectric spacer with a permittivity of 2.8 + 0.09i [38, 39] and thickness $h = 42$ μm. The thicknesses of the top and bottom metallic layer are set to such values that it is more than the gold layer coating depth in order to negligibly reduce the transmission coefficient (T). Thus, the absorptivity (A) depends only on the reflectance (R) shown by the equation (1).

$$A = 1 - R = 1 - |s_{11}|^2 \quad (1)$$

So, by using the commercially available High Frequency Electromagnetic Field Simulator (HFSS) software, this metamaterial absorber is designed for terahertz frequency regime. While designing the MMA, periodic boundary conditions along the z-plane are assigned to the four side walls of the unit cell. Then for the excitation, ports are assigned in the z-direction [40].

Results and Analysis

The novel metamaterial absorber is simulated using finite element method to obtain the absorption spectrum. In Fig. 2, the absorption plot (TE polarization) is shown.

From Fig. 2, it can be observed that the metamaterial absorber structure is displaying broadband response over a frequency range of 2.6 to 3.5 THz with an absorption greater than 90%. This broad absorption is due to the coupling between the four symmetrical petals. These are designed so close to each other that the strong coupling between them results in widening of the bandwidth. There are five absorption peaks within 2.6 to 3.5 THz broadband width given by different mode of frequencies f_1, f_2, f_3, f_4 and f_5. The absorptivity tends to be 99.16%, 91.42%, 95.44%, 92.17% and 97.49% for frequencies 2.66, 2.9, 3.1, 3.3 and 3.5 THz, respectively. Furthermore, the physical origin of the broadband mechanism is interpreted by electric field distributions corresponding to five absorption frequencies 2.66 THz, 2.90 THz, 3.10 THz, 3.3 THz and 3.5 THz for TE polarization and normal incidence is depicted in Fig. 3. The images indicate the electric field strength in the petal-shaped structure. The excitation of strong electric fields in the four petals gives rise to strong coupling leading to broadband performance.

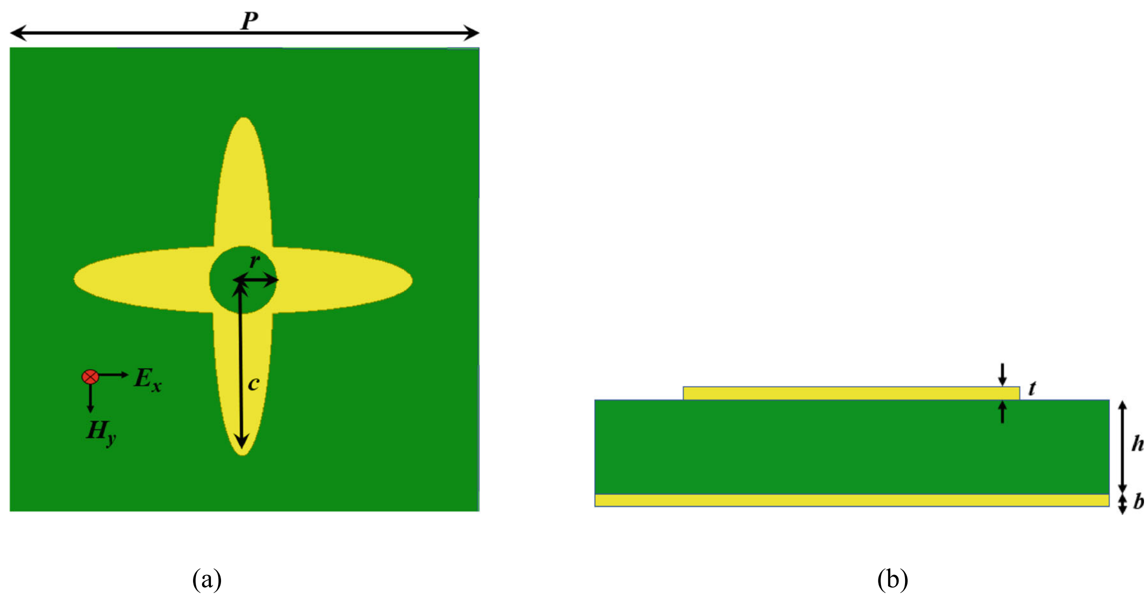


Fig. 1 Proposed broadband metamaterial absorber structure. **a** Top view. **b** Side view

In order to investigate the influence of different parameters on the design, a parametric analysis is done which is shown in Figs. 4 and 5. The first parametric analysis is done by varying the radius (r) of the circle. From the simulated result, it can be observed that at 3 μm, the MMA is yielding a broadband absorption of about 1 THz bandwidth with an absorption greater than 90%. Similarly, when radius is reduced to 2 μm, the absorption bandwidth as well as absorptivity is getting decreased. With the increase in radius to 4 μm, the bandwidth is further diminishing.

The next parametric study is shown in Fig. 5 with respect to major radius of the ellipse forming the petals. So, from the obtained absorption spectra, it can be seen that a proper broadband response is seen for $c = 30$ μm, and by increasing and decreasing the values, there is a fluctuation in the absorptivity and bandwidth giving undesirable output.

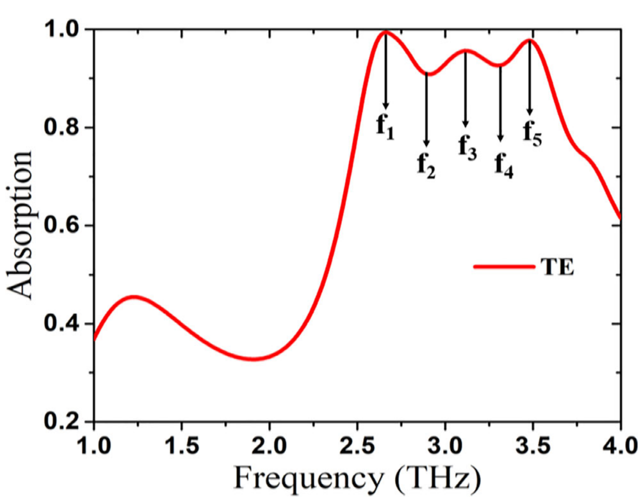


Fig. 2 Proposed MMA absorption plot for TE polarization

From the results of the parametric investigation, it is precisely indicated that the radiuses of the design were optimally selected to obtain large broadband absorption with a bandwidth greater than 90%. Increasing or decreasing the radius of the circle and ellipse results in degradation of absorption characteristics.

As the absorption spectra for TE is already shown in Fig. 2, so it is important to carry out further simulation to verify the influence of various incident and polarization angles on the proposed MMA structure. The simulated output plots are shown in Fig. 6 in which (a) gives the absorption for different polarization angle and (b) shows the plot for different angle of incidence.

Figure 6 a shows the absorption spectra for different polarization angles in which angle is changed from 0° to 90° with the step size of 15°. For various polarization angles, the absorption remains almost similar. It means the proposed absorber is insensitive to the polarization angle of the incident waves. The structure is a symmetrical design, and thus, it displays characteristics that are insensitive to polarization.

The dependence of absorption on the incident angle is specifically studied for TE polarization as shown in Fig. 6 b. The angle of incidence is varied from 0° to 60° with the step size of 15°. The broad band absorption characteristics were observed even for large incident angles. When the incident angle is increased from 0° to 30°, the absorption characteristics do not change significantly. The absorptivity decreases with the increase in angle of incidence from 45° to 60°. This result demonstrates that the broadband with highly effective absorption is sustained over a wide range of incident angle (up to 45°).

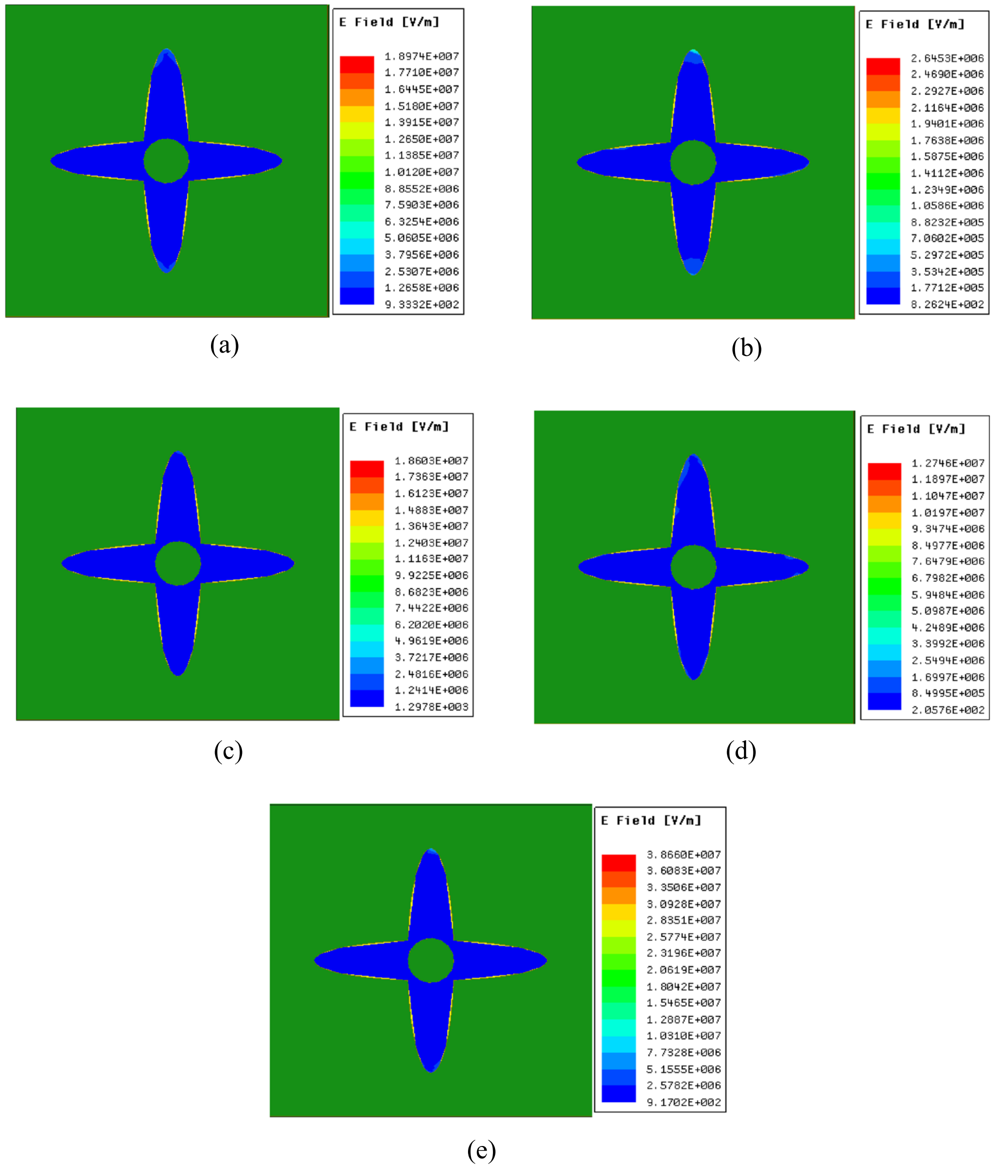


Fig. 3 Electric field distribution plots of the proposed absorber for the interface between the top metal layer and dielectric layer at different mode of frequencies **a** $f_1 = 2.66$ THz, **b** $f_2 = 2.90$ THz, **c** $f_3 = 3.1$ THz, **d** $f_4 = 3.3$ THz and **e** $f_5 = 3.5$ THz

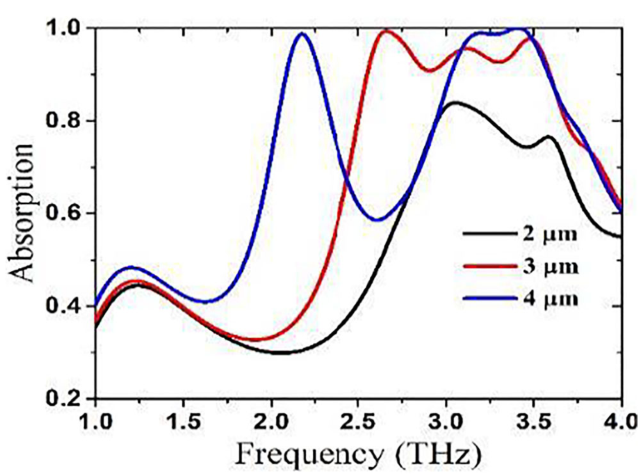


Fig. 4 Parameter analysis with respect to radius (r) of the circle

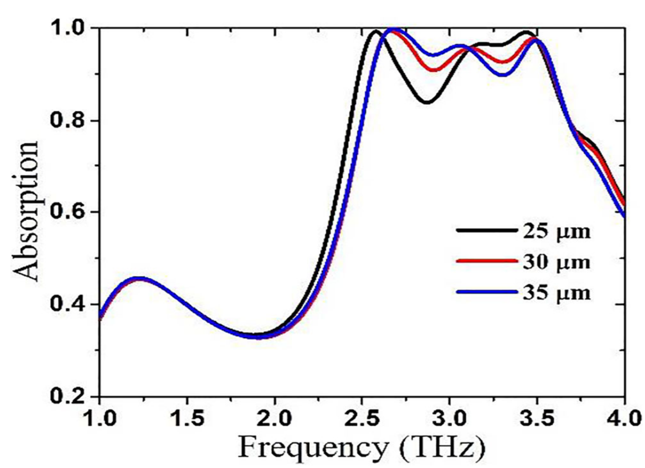
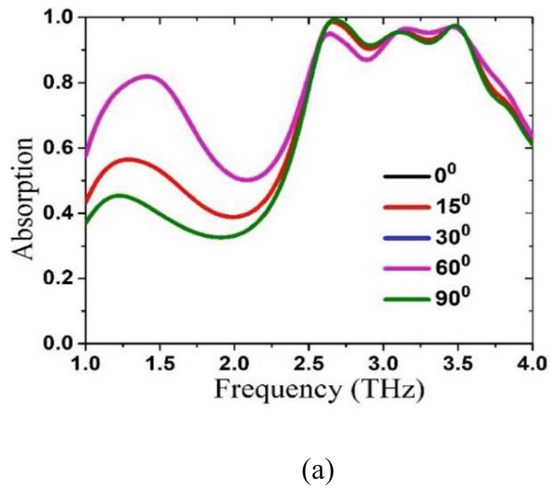


Fig. 5 Absorption spectra with respect to major radius (c) of the ellipse



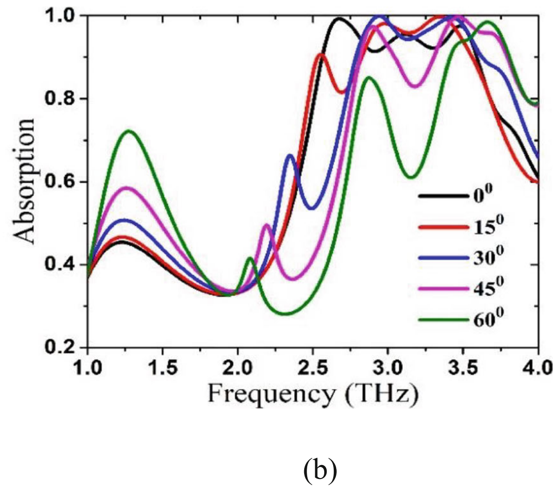


Fig. 6 Absorption spectra of proposed MMA for **a** angle of polarization and **b** angle of incidence

Conclusion

The broadband characteristics of a novel petal-designed MMA in terahertz frequency regime has been presented in this paper. The structure offered a broadband response of nearly 1 THz with an absorption greater than 90%. The absorption mechanism of the structure is investigated by electric field strength plots for frequencies at 2.66 THz, 2.90 THz, 3.1 THz, 3.3 THz and 3.5 THz. Parametric analysis by varying the radius of the circle and ellipse has been performed to validate the selection of design parameters. Then, the absorber was also analysed for its broadband response at different polarization and incidence angles. From the analysis, it is observed that the broadband MMA is polarization insensitive due to its symmetric pattern on top. Thus, the proposed broadband metamaterial absorber can find potential application in terahertz technology.

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