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# Design of a five-band terahertz perfect metamaterial absorber using two resonators

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ABSTRACT

We present a polarization-insensitive five-band terahertz perfect metamaterial absorber composed of two metallic circular rings and a metallic ground film separated by a dielectric layer. The calculated results show that the absorber has five distinctive absorption bands whose peaks are greater than 99% on average. The physical origin of the absorber originates from the combination of dipolar, hexapolar, and surface plasmon resonance of the patterned metallic structure, which is different from the work mechanism of previously reported absorbers. In addition, the influence of the structural parameters on the absorption spectra is analyzed to further confirm the origin of the five-band absorption peaks. The proposed absorber has potential applications in terahertz imaging, refractive index sensing, and material detecting.

## 1. Introduction

The first perfect metamaterial absorber (PMA) was experimentally demonstrated by Landy et al. [1], research into the topic has grown rapidly. Of late, metamaterial absorbers have been developed from microwave to terahertz, infrared, and visible regions [2–4]. In fact, the study of metamaterial absorber is especially important for terahertz frequencies, because it is very difficult to find natural materials with high absorption. Unfortunately, owing to strong electromagnetic response of metamaterials, these absorbers often have one narrow absorption band [5–12], which is not beneficial to practical applications at terahertz frequencies, because in some applications such as terahertz spectroscopic imagers and detectors, multi-band absorbers can achieve frequency-selective detection, reduce the environmental disturbance and thus improve the detection sensitivity and imaging resolution.

To overcome the drawbacks of single narrow-band absorption, there are usually two approaches to realize multiple absorption bands. One is assembling multiple resonator structures with different geometric parameters in a coplanar [13–22], and the other is vertically stacking multilayer subwavelength metallic structures to obtain multiband absorbers [23–26]. The first approach makes the unit cell of the absorber too large, and go against the development of miniaturization absorbers. The second approach is considerably constrained by the fabrication process. Moreover, most of them are dual-band and triple-band absorbers, the multi-band (especially the five-band) absorbers are little investigated.

To add a new design strategy in the field of multiband PMA, we present a novel design of a polarization-insensitive five-band terahertz PMA using two concentric metallic circular rings to form a compact single particle. The absorber shows five distinctive absorption peaks at frequencies of 0.90 THz, 1.83 THz, 2.55 THz, 2.92 THz, and 3.71 THz with absorption rates of 99.83%, 98.92%, 99.96%, 99.35%, and 99.00%, respectively. We also investigate the physical insight of the proposed PMA using electric and magnetic fields distributions. Compared with previously reported multiband absorbers [12–26], the proposed absorber has at least two advantages: Firstly, the structure of the proposed PMA is simple, perfectly symmetric and is compact, which is useful for terahertz spectroscopic applications. Secondly and most importantly, the physical origin of the five-band PMA originates from the combination of dipolar, hexapolar, and surface plasmon resonance of the patterned metallic structure. Such a simple and compact PMA has many potential applications in the area of optoelectronics, such as terahertz imaging, refractive index sensing, and material detecting.

## 2. Structure and design method

The proposed five-band PMA consists of a dielectric layer sandwiched between two nested metallic circular ring resonators and a continuous metallic film, which is stacked on a 500−μm-thickness silicon wafer ($n_{si} = 3.31$) [27]. The silicon wafer only provides mechanical

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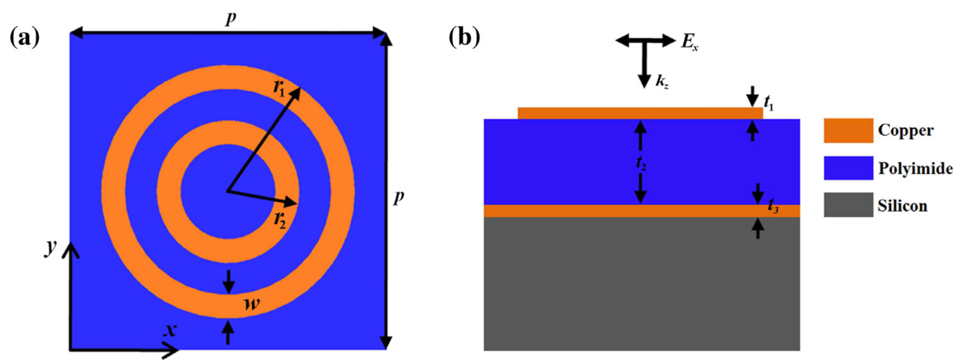


**Fig. 1.** (a) Schematic of the circular ring resonators of the proposed PMA and (b) cross section of the complete PMA.

support and does not affect the performance of the proposed absorber due to the presence of the ground metal film. The single unit cell is depicted in Fig. 1. The optimized structural parameters of the unit cell in simulation are as follows: $r_1 = 32$, $r_2 = 18$, $w = 6$, $t_1 = 0.5$, $t_2 = 18$, $t_3 = 0.5$, and $p = 80$ (units:μm). The circular metallic rings are made of copper with frequency independent conductivity of $5.8 \times 10^7$ S/m [28]. The dielectric layer is a polyimide with refractive index of $1.8 + 0.06i$ [29]. The underside of the dielectric polyimide layer is made of copper without pattern, so that the transmitted wave can be completely suppressed. The calculated results are gained by using finite-difference time-domain (FDTD) software package [30], where a unit cell is illuminated by a normally incident terahertz plane wave with electric field parallel to the $x$-axis. Periodic boundary conditions are used in the $x$ and $y$ directions, and perfectly matched layers are employed in the $z$ direction.

## 3. Results and discussion

The calculated absorption spectra of the proposed five-band PMA are shown in Fig. 2(a). It is clear that five obvious absorption bands can be gained at frequencies of $f_1 = 0.90$, $f_2 = 1.83$, $f_3 = 2.55$, $f_4 = 2.92$, and $f_5 = 3.71$ THz, with absorption rates of 99.83%, 98.92%, 99.96%, 99.35%, and 99.00%, respectively. The high absorption of those five resonance peaks originates from the combining of the dipolar resonance, multipole resonance, and surface plasmon resonance of the patterned metallic structure, and the comprehending of such a five-band absorption mechanism is demonstrated by investigating the electromagnetic field distributions at the five resonance frequencies (see Figs. 3–5 below).

In addition, it should be noticed that the proposed absorber does not depend on the polarization state of the incident terahertz wave, as it is a 360° rotational symmetry structure. To prove our point, we investigate the absorption spectra as a function of polarization angle for TM wave, where the incidence angle is fixed at 0°. The polarization angle is defined as the angle between the polarization direction and the $x$-axis of the coordinate, which is equal to rotating the designed absorber structure even as fixing the polarization direction. Fig. 2(b) presents the calculated absorption spectra of the proposed five-band PMA at different polarization angles of the normal incidence. It is obvious from Fig. 2(b) that the calculated absorption spectra of the proposed five-band PMA are polarization-insensitive.

To study the physical origin of the proposed five-band PMA, we investigate the loss mechanisms to understand the contributions of each part of the metamaterial structure. Fig. 2(a) shows the effect of the loss properties (lossy and lossfree) of the dielectric layer on the absorption spectra when the metal layers stay constant. It can be seen from Fig. 2(a) that the positions of the absorption peaks remain unchanged as loss properties of dielectric slab change, which is consistent with previously reported results [31]. Furthermore, we can also see that the majority of the energy is dissipated as dielectric loss in the polyimide layer for the first four absorption peaks and as ohmic loss in the metal layers

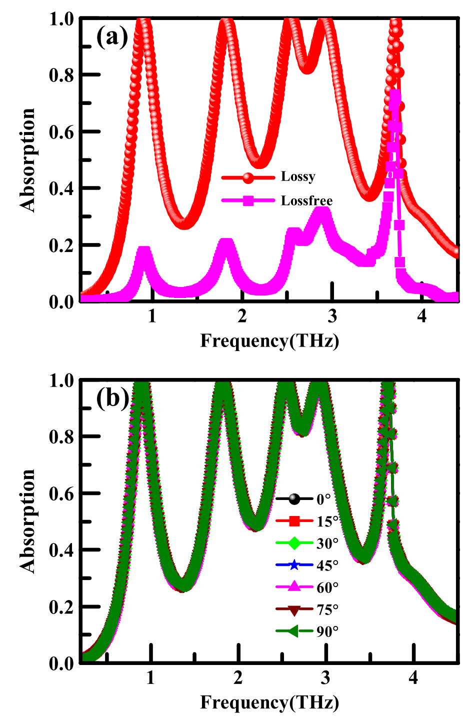


**Fig. 2.** (a) Calculated absorption spectra of the proposed five-band PMA with two different loss properties (lossy and lossfree) of dielectric, respectively. (b) Calculated absorption spectra with different polarization angles of incident terahertz wave.

for the fifth absorption peak ($f_5$). It makes the absorber have extensive application prospects in some areas where the electromagnetic energy needs to be collected by the dielectric layer.

For insight into the underlying physical origin of the five-band absorption peaks, we give the calculated electric field [abs($E$)] distributions in Fig. 3. For modes $f_1$, $f_3$, and $f_4$, the electric fields are localized mainly at both edges of the outer closed ring [see Fig. 3(a), (c), and (d)]. However, the mode $f_2$ induces the enhanced electric fields accumulated mainly at both edges of the inner closed ring [see Fig. 3(b)]. For mode $f_5$, electric fields are focused on both the inner ring and the outer ring. From the distribution characteristics of the electric field, we can find that high-order localized surface plasmons are excited at the outer ring for modes $f_3$, $f_4$, and $f_5$.

To verify that high-order localized surface plasmon can be effectively excited, we present the $z$-component electric field [real($E_z$)] distributions in Fig. 4. From Fig. 4(a) and (b), it can be seen that opposite surface charges are accumulated at both sides of the outer ring, indicating excitation of dipolar resonance. Hexapolar resonances are also excited