An ultra-thin multiband terahertz metamaterial absorber and sensing applications

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Abstract
We propose an ultra-thin multiband terahertz metamaterial absorber, whose thickness is only 3.8 μm. Simulation results show that we can get four narrow absorption peaks with near-perfect absorption in the 4.5 THz-6.0 THz frequency range. The resonance absorption mechanism is interpreted by the electromagnetic field energy distributions at resonance frequency. Moreover, we also analyze the sensing performances of the absorber in the refractive index and the thickness of the analyte. The refractive index and thickness sensitivities of the sensor are 0.471 THz/RIU, 0.4 THz/μm and the FOMs are 8.887RIU⁻¹, 8.163 μm⁻¹, respectively. The absorber has potential applications in photodetector, multispectral imaging and biosensors.

Keywords Multiband · Metamaterial absorber · Terahertz · Sensing

1 Introduction

In recent years, with the development of terahertz(THz) radiation, detection technology, and the proposed functional devices, THz technology has presented promising applications in imaging (Theofanopoulos et al. 2019), communication (Nagatsuma et al. 2016), biomedicine (Yang et al. 2016), etc. However, the lack of natural strong absorption material has limited the development of terahertz detector. Researchers found that metamaterials can strongly absorb incident radiations at the resonant frequency (Watts et al. 2012). Thus, the exploration of metamaterial-based absorbers has been becoming a hot topic in THz field.

The first THz metamaterial absorber, having an experimental absorptivity of 70% at 1.3THz, was demonstrated by Tao et al. (2008). Since then, researchers investigated various
metamaterial absorbers at different bandwidth including narrowband (Shi et al. 2020; Wang et al. 2020; Meng et al. 2014), multiband (Liu et al. 2020a; Failed 2018; Zhang and Guo 2013; Ma et al. 2011), broadband (Xiao et al. 2017; Torabi et al. 2017; Bai et al. 2019; Zhang et al. 2018) and ultra-broadband (Zhu et al. 2014; Liu et al. 2020b; Fardoost et al. 2017; Zhang et al. 2019; Guo et al. 2020). The absorption bandwidth is one of the most important factors in the applications of the devices. Broadband absorbers are mainly used to solar cells (Li et al. 2020) and photodetectors (Liao and Zhao 2016; Mittendorff et al. 2013). Narrowband absorbers are mostly applied in sensing (Liu et al. 2010) and thermal emitter (Diem et al. 2009). And absorbers with multiple absorption peaks are required in some applications, such as multispectral imaging (Zhou et al. 2018; Grant et al. 2014) and sensing (Wang et al. 2015a; Xie et al. 2018; Yahiaoui et al. 2015). The resonant structure with multiband absorption may be formed by single resonant cell (Liu et al. 2020a; Zhang and Guo 2013; Nielsen et al. 2012), transverse nested multiple resonant cells (Ma et al. 2011; Wang et al. 2015b; Shen et al. 2011) and longitudinal stacked multiple resonant cells (Dayal and Ramakrishna 2013; Bhattacharyya et al. 2015; Liu et al. 2015). However, these absorbers have the disadvantages of being complicated, too thick, and difficult to integrate.

In this paper, we propose an ultra-thin multiband terahertz metamaterial absorber of only 3.8 μm thickness. The absorber consists of a gold substrate layer and a subwavelength silicon disk. Using finite-difference time-domain (FDTD) method, the designed absorber has four perfect absorption peaks in the 4.5–6.0 THz frequency range. In addition, we also analyze the performances of the absorber in refractive index and thickness sensing. The refractive index and thickness sensitivities of the sensor are 0.471 THz/RIU, 0.4 THz/μm and the FOMs are 8.887 RIU⁻¹, 8.163 μm⁻¹,respectively.

2 Results and discussion

Figure 1a shows the periodic structure of the absorber, it is composed of a gold substrate layer, a dielectric layer (Polyimide), a silicon disk. The period of the structure is \( P = 80 \) μm. The gold has the thickness of \( t_1 = 0.2 \) μm, and its conductivity is \( 4.09 \times 10^7 \) S/m. The

![Fig. 1](image_url)

**Fig. 1** a The periodic structure schematic diagram of a tri-layer terahertz absorber. The top-down for a silicon disk (gray), polyimide (blue) and gold (yellow). b The periodic structure schematic diagram of a bi-layer terahertz absorber. (Color figure online)
thickness and dielectric constant of polyimide are set as \( t_2 \), and 3.9 + i0.09. The silicon disk has the radius of \( r \), the thickness of \( t_3 \), and the dielectric constant of 11.7. The full-wave simulation was performed by the CST Microwave Studio. Adaptive tetrahedral mesh refinement has been used. The period structures are illuminated by a normally incident plane wave with the electric field parallel to the \( x \)-axis. The unit cell boundary condition is set in the \( x \)-direction and \( y \)-direction. The formula of absorption is as follows (Wang et al. 2016):

\[
A(f) = 1 - R(f) - T(f),
\]

where \( R(f) = |S_{11}|^2 \) and \( T(f) = |S_{21}|^2 \) are reflectivity and transmissivity, respectively. \( S_{11} \) and \( S_{21} \) are reflection coefficient and transmission coefficient, respectively. The thickness of the gold substrate layer (0.2 \( \mu \)m) is larger than skin depth of incident electromagnetic wave, so the transmissivity is close to zero. The \( A(f) \) achieves perfect absorption, which only needs to satisfy the reflectivity \( R(f) = |S_{11}|^2 = 0 \).

According to the theory of transmission line, the reflection and transmission coefficients depends on the input impedance \( Z(f) = \sqrt{\mu(f) + \varepsilon(f)} = z_1 + iz_2 \). When the input impedance matches the free space impedance, i.e. \( z_1 = 1, z_2 = 0 \), the reflection coefficient equals zero. The normalized input impedance \( Z \) can be expressed as (Smith et al. 2005):

\[
Z(f) = \sqrt{\frac{(1 + S_{11})^2 + S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} = \frac{1 + S_{11}}{1 - S_{11}}
\]

(1)

In order to make sure the input impedance matches the free space impedance at every absorption frequency, the parameters of unit cell are optimized as shown in Fig. 2. There exist multiple resonant absorption peaks in tri-layer absorber from Fig. 2a, and the first four absorption peaks (A, B, C and D) due to the higher absorption are mainly focused on. With decreasing the thickness of the dielectric layer \( t_2 \), the absorption bandwidth is increasingly narrow and each of the absorption peaks has a blue shift. When \( t_2 = 0 \), the structure of the absorber is simplified in Fig. 1b, and peaks A, B, C and D are close to perfect absorbing. Next, the dependences of the radius \( r \) and the thickness \( t_3 \) of the silicon disk on the absorption spectra are shown in Fig. 2b and c, respectively. When the radius \( r \) and the thickness \( t_3 \) gradually reduce, each of the resonant peaks also shows a blue shift. In these two figures, the absorptions of peaks A and D remain nearly constant. While the absorption of peak B is increasing followed with a decrease in \( r \) and \( t_3 \) the maximum absorption of peak C appears at \( t_3 = 3.6 \mu \text{m} \). Based on the above analyses, the optimized values are chosen as follows: \( t_2 = 0, t_3 = 3.6 \mu \text{m}, r = 35 \mu \text{m} \).

Figure 2d presents the absorption spectra for the TE and TM polarizations. It is observed that the two curves are absolutely identical due to the rotational symmetry of the structure. This illustrates that the absorber has a polarization insensitive. Four absorption peaks are located at center frequencies of 4.682THz, 5.150THz, 5.310THz, 5.814 THz with absorptions 99.11%, 99.85%, 99.70%, 99.93% respectively. Their full width at half maximum (FWHM) are 0.049THz, 0.039THz, 0.053THz, 0.078THz, respectively. Figure 2e shows the normalized input impedance \( Z \) of the absorber calculated by formula (1). The \( Z \) at four absorption peaks A, B, C and D read 0.7990 + i0.0408, 1.0758 - i0.0565, 0.9437 - i0.1139 and 0.9215 + i0.0740, respectively. The real part of the \( Z \) is approximately equal to unity, and the imaginary part tends to zero. Therefore, the impedance of the device is fairly matched with the free-space impedance at four absorption peaks.

To understand the physical mechanism of the absorber, the electric and magnetic field distributions at the frequencies corresponding to four absorption peaks are calculated, respectively. Figure 3a–d represent the electric field distributions in the plane of \( z = 3.8 \mu \text{m} \). And Fig. 3e–h illustrate the magnetic field distributions in the plane of \( x = 0 \mu \text{m} \). It can
Fig. 2 Absorption spectra with different thicknesses of the dielectric layer $t_2$ (a), the thickness $t_3$ (b) and the radius $r$ (c) of the silicon disk. d Absorption spectra for the TE and TM polarizations. e The normalized input impedance of the absorber.
be concluded from Fig. 3a that the accumulation of the charges in the silicon disk center leads to the excitation of the fundamental dipole. The opposite currents located between the silicon disk and gold layer excite the magnetic dipole (Guddala et al. 2015) as shown in Fig. 3(e). The simultaneous excitation of the electric and magnetic dipole resonances of the silicon disk forms the fundamental absorption peak A. The appearance of higher order modes is due to the fact that the disk diameter is larger than a multiple of the half-wavelength of the resonant mode. The electric field distribution in Fig. 3b shows the excitation of multiple half wavelength charge oscillations in the silicon disk. This is the first higher order mode corresponding to the absorption peak B. Meanwhile, the charge distribution causes a multiple current circuits between the disk and gold layer, which gives rise to the excitation of multiple magnetic dipoles in the disk. The magnetic field is localized in the silicon disk (Dayal and Ramakrishna 2014) as shown in Fig. 3f. The higher order electromagnetic resonance will result in absorption peaks in higher frequencies. Therefore, the structure has a absorption peak C at 5.31THz because of the second higher order mode and the corresponding electric and magnetic field distributions are shown in Fig. 3c and Fig. 3g, respectively. Similarly, Fig. 3d corresponds to the third higher order mode with a absorption peak D, and the silicon gives rise to excitation of three magnetic dipoles as shown in Fig. 3h.

3 Analysis of the sensing performance

The quality factor $Q$ (which is defined as $Q = f_0 / \text{FWHW}$, where $f_0$ is the center frequency of the absorption peak) is an important factor to estimate resonant modes, directly reflecting whether a resonant mode is applicable to sensing filed (Wang et al. 2015b). The higher the $Q$ value, the better the sensing performance. The $Q$ values of the resonant peaks A, B, C and D are 95.55, 132.05, 100.19, 74.54, respectively. Thus, the device is suitable for terahertz sensor. In general, the sensitivity $S$ and the FOM (figure of merit) are used to estimate the sensor quality and defined as (Liu et al. 2010; Lu et al. 2015):
\[ S = \frac{\Delta f}{\Delta n} \]  

(2)

\[ FOM = \frac{S}{FWHM} \]  

(3)

where \( \Delta f \) is a frequency shift as the refractive index \( \Delta n \) unit changes.

First, the influences of refractive index (RI) of the analyte on four absorption peaks are analyzed. With the RI changing from 1.00 to 1.10 and a fixed thickness \( (d = 1 \ \mu m) \), the frequency shifts (FS) of four peaks are calculated in Fig. 4a. Data fitting discovers a linear relationship between the RI of the analyte and the FS. The slope of the linear fitting equation is the sensitivity \( S \) (Cong et al. 2015). The sensitivities of peaks A, B, C and D are \( S_A = 0.323 \text{THz/RIU}, \ S_B = 0.178 \text{THz/RIU}, \ S_C = 0.471 \text{THz/RIU}, \ S_D = 0.462 \text{THz/RIU}, \) respectively. The FOMs are 6.532RIU\(^{-1}\), 4.564RIU\(^{-1}\), 8.887RIU\(^{-1}\), 5.923RIU\(^{-1}\), respectively. Therefore, considering the highest values of \( S \) and \( FOM \), peak C is most applicable for the RI sensor. Figure 4b shows the absorption spectrum shifts of peak C under different RI. It is observed that the increase of the RI can result in strongly red shift of the absorption spectra.

Next, the influences of the analyte thickness on four absorption peaks are investigated in detail. The RI of analyte keeps \( n = 1.04 \). It is shown from Fig. 5a that with the increase of the thickness \( d \), peak C will gradually disappear and the red shift of peak D is far smaller than those of peaks A and B. Therefore, peaks C and D are not suitable for the thickness sensor. Furthermore, the FSs of peaks A and B are calculated in Fig. 5b, with the fitting functions \( FS_A = 1.201 - 1.798 \times \exp(-d/11.896) \) and \( FS_B = 1.464 - 1.466 \times \exp(-d/15.346) \), respectively. Apparently, the relationship between the analyte thickness and the FS filed the exponential function. Our aim is to detect only thickness variations, so the sensitivity in the context of thin-film sensing can be defined as (Jauregui-Lopez et al. 2018) \( S = \Delta f/d \), where \( \Delta f \) is a frequency shift as the analyte thickness \( d \) unit changes. The highest sensitivities of peaks A and B are 0.4 THz/\( \mu m \) and 0.235 THz/\( \mu m \), as shown in Fig. 5c. The FOMs are 8.163 \( \mu m^{-1} \) and 6.026 \( \mu m^{-1} \), respectively. By combining the above analysis results, peak A is ideal for the thickness sensor.

![Fig. 4](image-url)

**Fig. 4**  
\( \text{a} \) The FSs of four peaks with the RI of analyte varying from 1.00 to 1.10. \( \text{b} \) The absorption spectrum of peak C with different refractive index
In conclusion, a novel multiband bi-layer ultra-thin terahertz metamaterial absorber with total thickness of 3.8 μm is proposed. Simulation results show that the absorber has four resonant peaks with the absorption of each resonant peak over 99% in the 4.5 THz-6.0 THz frequency range. Due to the higher Q of four resonant peaks, the application of the proposed absorber in sensing fields is explored. It is found that the refractive index and thickness sensitivities of the device are 0.471THz/RIU, 0.4THz/μm and the FOMs are 8.887RIU⁻¹, 8.163 μm⁻¹, respectively. The proposed absorber has multiband prefect absorption and higher sensitivities of the refractive index and thickness, making great applications in multi-spectral imaging, photodetector and biosensors.

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Authors Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Jinjun Bai, Wei Shen, Shasha Wang, Meilan Ge, Tingting Chen, Pengyan Shen and Shengjiang Chang. The first draft of the manuscript was written by Wei Shen and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors have no financial or proprietary interests in any material discussed in this article.

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