Theoretical Investigation of a Simple Design of Triple-Band Terahertz Metamaterial Absorber for High-Q Sensing

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Abstract: This paper presents a simple metamaterial design to achieve the triple-band near-perfect absorption response that can be used in the area of sensor application. The introduced absorber consists of an array of Au strip and a bulk flat Au film separated by an insulator dielectric layer. Three narrow-band resonance absorption peaks are obtained by superposing three different modes (a fundamental mode resonance and two high-order responses) of the Au strip. These resonance modes (in particular of the last two modes) have large sensitivity to the changes of the surrounding index, overlayer thickness and the refractive index of the overlayer.

Keywords: metamaterials; triple-band absorption; terahertz; sensing

1. Introduction

In recent several years, metamaterial perfect absorbers [1–22] as an important and special branch of the metamaterials have received extensive attention because of their excellent and controllable resonance characteristics that frequently used in the application fields of selective thermal emitters, materials detection, sensing, imaging, and so on. The first metamaterial perfect absorber composed of three function layers (electric ring resonator-insulation dielectric layer-metal strip) was demonstrated at the microwave regime in the year of 2008 [1]. In this three-layer resonance structure, the bottom metal strip can effectively block the transmission of the incident waves, and the proper thickness of dielectric spacer layer can make the impedance of the metamaterial structure matched to that of the air. As a result, a resonance absorption peak with near-perfect absorbance can be obtained [1–8]. In fact, in addition to the perfect absorption of incident electromagnetic waves, there are many technologies to achieve the regulation of electromagnetic waves, such as nano-particles [23], near-zero-index materials [24], metasurfaces [25], graphene [26], metamaterials [27]. Some novel and interesting phenomena (including electric/equivalent magnetic currents [28], displacement currents [29], surface waves [30] etc.) have also been explored and studied in the process of light regulation. Although there are many technologies and ways to achieve the regulation of electromagnetic waves, they are difficult or encounter obstacles in achieving the perfect absorption of light. Not to mention that these technologies can regulate the absorption resonance performance of the suggested devices.

Generally, the resonance frequency of the metamaterial absorber can be effectively tuned or changed from optical to microwave regimes by scaling the structure size of the metallic patterns [18–22,31–33]. For example, total visible band metasurface perfect absorber based on coupled Mie resonance was demonstrated in [18]. Near-perfect absorption at 0.70 THz was presented by using a side length (or width) of 39 µm of an electric split-ring-resonator [32]. Microwave metamaterial
absorber operated at 8.96 GHz was designed by expanding the size of the pattern, such as an array of 1.8 mm dielectric cube material [33]. The absorption bandwidth of these light absorbers is very narrow (typically less than 20% of the resonance frequency), which makes these absorbers has promising in sensing related fields, such as detection of changes in the surrounding environment, determination of refractive index of analytes.

Based on the fact that the multiple-band metamaterial absorbers have the great application prospects in terms of the materials detection and analysis, thermal imaging, and sensing, very recently, the research interest of metamaterial absorbers has been transferred to the multiple-band light absorption. In general, the superposition effect of multiple single-band resonance absorption peaks can obtain the multiple-band metamaterial absorbers. Stacking and super-unit coplanar structures are the two most frequently used construction methods to realize the multiple-band metamaterial absorbers. For instance, triple-band metamaterial absorber can be obtained by cascading three metallic layers [34–36]. The combination of three (or three groups of) different sizes of metallic patterns in a super-unit coplanar structure was designed to achieve the triple-band near-perfect absorption response [37–42]. Nowadays, the device design is mainly focused on the trends of simplicity, miniaturization and compact. However, the methods mentioned above are obviously not meeting the trends. Although some alternative strategies have been demonstrated to achieve multiple-band absorption response, the absorption strength and sensing performance of the multiple-band absorbers are far from satisfying, see Table 1 for detailed performance comparisons. The novelty of this paper demonstrated here is mainly reflected in two aspects. Firstly, it simplifies the structure design of multiple-band metamaterial absorbers. Secondly, it improves the sensing performance of multiple-band metamaterial absorbers, that is, improves the application potential of the designed device.

| References | Working Bands | FOM |
|------------|---------------|-----|
| [43]       | terahertz     | 2.3 |
| [44]       | terahertz     | 1.2 |
| [45]       | terahertz     | 3.0 |
| [46]       | terahertz     | 7.5 |
| [47]       | terahertz     | 3.0 |
| [48]       | terahertz     | 1.5 |
| [49]       | terahertz     | 2.3 |
| [50]       | terahertz     | 1.5 |
| This work  | terahertz     | 40.7|

Herein, a triple-band near-perfect terahertz metamaterial absorber is demonstrated by using a pattern array of Au strip and an insulator dielectric spacer backed with a bulk continuous Au film. Three separated and narrow-band absorption peaks are realized, and the maximum absorbance of the device can reach 99.89%. The physical origin of the triple-band absorption originates from the combined effect of the fundamental mode resonance and two high-order (3-order) responses of the Au strip resonator, which is entirely different from previous multiple-band light absorbers. Sensing performance of triple-band absorber (in terms of the surrounding refractive index, thickness and refractive index changes of the overlayer) is also analyzed. The results demonstrate that the FOM (figure of merit) of the third resonance peak can be up to 40.67, which is much larger than previously reported works [43–50], see Table 1. More importantly, we found that besides the frequency shifts with the change of the refractive indexes of the surrounding, the absorbance of the third resonance peak has an apparent change. The absorbance sensitivity of the third peak can reach 646.3% per refractive index. To the best of our knowledge, this is the highest degree of sensitivity in the absorbance change. These resonance characteristics prove that the designed triple-band absorber has promise in many areas, in particular of sensors.
2. Materials and Methods

Due to the periodic nature of the triple-band light absorber, we only provide one unit cell with \( P_x = 70 \, \mu m \) and \( P_y = 68 \, \mu m \), see Figure 1a. As shown in Figure 1a, three layers (two metallic layers as the first and third layers and an insulation dielectric layer as the second layer) are used in this absorber structure. We chose the high conductivity \((\sigma = 4.09 \times 10^7 \, S/m)\) Au as the first and the third layers of the absorber. The first layer is a pattern Au strip, while the third layer is a bulk flat Au film, which can block the transmission of the light wave. The length and width of the Au strip are respective \( l = 60 \, \mu m \) and \( w = 15 \, \mu m \). The second layer is an insulation dielectric film with the thickness of \( t = 9.6 \, \mu m \), which is sandwiched by the two Au layers. The dielectric constant of the second layer (polyimide) is \( 3(1 + i0.06) \) \[15,16\]. The reason why we chose a single metallic strip array as the research object is that it has the ability of simple structure design and easy construction. Finite-difference time-domain methods based on (FDTD Solutions, Lumerical Canada) are used to investigate and analyze the electromagnetic properties of the presented absorber structure. The limitations of the proposed are mainly reflected not only study the fundamental mode resonance absorption peak but also the high-order responses. As a common sense that large Q value has potential application in the field of sensing.

3. Results and Discussion

Figure 1b is the absorption spectra of the triple-band light absorber. As observed, three discrete and narrow-band peaks are obtained in this metamaterial structure. The absorbances of the three peaks at frequencies of 1.316, 3.474 and 4.245 THz are respective 98.38%, 99.89%, and 85.92%. Of particular note here is the bandwidth (we choose the FWHM as its resonance bandwidth) of the triple-band light absorber, the bandwidth of the third absorption peak is only 0.075 THz, which is only 3/10 of the first absorption peak (0.245 THz). If converted into the quality factor \( Q \) (defined as the ratio of the resonance frequency and resonance bandwidth), the \( Q \) value of the third absorption peak can reach 56,600, which is 10.537 times as much as the first absorption peak. That is to say, the \( Q \) value of the absorption at 4.245 THz is an order of magnitude larger than the absorption at 1.316 THz. It is a common sense that large \( Q \) value has potential application in the field of sensing.

In fact, the absorption peak at 1.316 THz is the fundamental mode resonance of triple-band absorber, and this resonance mode is most researchers concern. In this manuscript, however, we not only study the fundamental mode resonance absorption peak but also the high-order responses.
As the high-order absorption peak usually has narrow resonance bandwidth (i.e., the large \( Q \) value), its sensing sensitivity is typically much greater than that of the fundamental mode resonance absorption peak. In addition, the absorbances of the three peaks are very low when the imaginary part of the insulation dielectric layer is zero (i.e., Loss-free), see the blue line in Figure 1b.

In order to investigate the underlying mechanism of the triple-band light absorber, the field distributions of the three different resonance modes are given in Figure 2. The \( |Hy| \) distributions of the three modes in Figure 2(a1,b1,c1) are all mainly distributed in the insulation dielectric layer of the absorber, which indicates that the three absorption peaks are the localized resonance modes of the pattern Au strip array. Furthermore, for resonance at 1.316 THz, see Figure 2(a3), only a strong field distribution region is found in the insulation dielectric layer, while for resonances at 3.474 THz and 4.245 THz, three strong trapped regions in the dielectric layer are observed, see Figure 2(b3,c3). These \( |Hy| \) distribution features prove that the first resonance mode at 1.316 THz is caused by the 1-order fundamental mode resonance of the Au strip resonator, while the last two resonance modes are due to the high-order (i.e., the 3-order) responses of the pattern Au array [4].

![Figure 2](image-url)

Figure 2. Field distributions of \( |E| \) (a1), real \( Ez \) (a2), and \( |Hy| \) (a3) for resonance at 1.316 THz; Field distributions of \( |E| \) (b1), real \( Ez \) (b2), and \( |Hy| \) (b3) for resonance at 3.474 THz; Field distributions of \( |E| \) (c1), real \( Ez \) (c2), and \( |Hy| \) (c3) for resonance at 4.245 THz.

Although at first glance the \( |Hy| \) distributions of the absorption peaks at 3.474 THz and 4.245 THz are the same, the effective lengths and intensity distribution of them are different. As shown in Figure 2(b3,c3), the effective length and field intensity distribution of the second mode (3.474 THz) are larger than that of the third mode at 4.245 THz. Generally, the frequency of metamaterial absorber is proportional to the reciprocal of structure size (or effective length) of the metallic array, and thus, the frequency of the third peak is greater than that of the second peak because the effective length of the third mode is smaller than that of the second mode. Besides the differences in effective length and intensity distribution, the real \( Ez \) distributions of the last two modes are also different. The real \( Ez \) in Figure 2(b2) is mainly distributed in the surface (or edge) of the metallic array, while the real \( Ez \) shown in Figure 2(c2) not only distributed in the surface (or edge) of the metallic array but also the four corners of the unit cell. The real \( Ez \) distribution of the third mode demonstrates that its absorption performance could be tuned by changing the period of the triple-band light absorber, while
the performance changes of the first two resonance modes should be neglected because their real $E_z$ values are mainly focused on the surface (or edge) of the metallic array.

Generally, the sensing performance is a very important index for evaluating the narrow-band absorber. Here we first analyze the dependence of the absorption spectra on the refractive index change of the surrounding. As shown in Figure 3a, we observed that frequency and absorbance changes of the first resonance peak can be neglected, while the absorption performance of the last two modes has a large dependence on the change of the surrounding index. Different from the second peak having only frequency change, the third peak not only has the characteristics of frequency shift but also absorbance decrease.

![Figure 3](image-url)

**Figure 3.** (a) Absorption spectra of refractive index change of surrounding; (b) frequency and absorbance of the third absorption peak as the function of the refractive index of the surrounding.

Figure 3b gives the resonance frequency and absorbance of the third peak as the function of the refractive index of the surrounding. The results show that the resonance frequency and absorbance of the third peak are both approximately linearly decrease with the increase of surrounding index. When the refractive index of the surrounding is changed from 1.00 to 1.10, the frequency change range of the third absorption peak can reach 0.305 THz, and the linearly fitted bulk sensitivity of the frequency change of the third resonance mode is 3.05 THz per refractive index, which is respective 2.440 and 12.200 times larger than that of the second peak (1.25 THz per refractive index) and the first peak (0.25 THz per refractive index). If converted into the FOM (figure of merit, for the definition of FOM the reader can refer to References [35–40]), the FOM value of the third peak can be up to 40.667, which is 5.205 and 39.853 times as much as the second (7.813) and the first (1.020) peaks, respectively. These results demonstrate that sensing performance of the high-order resonance response is much greater than that of the fundamental mode resonance. In other words, these studies provide us with a new way to design high sensitivity sensors. Moreover, we found that the variation range of the absorbance of the third peak can be as high as 64.63% when the refractive index is changed from 1.00 to 1.10. The linearly fitted sensitivity of the absorbance change of the third mode is 646.6% per refractive index, which is far greater than that of the first two resonance peaks, and even previous works.

We also investigated the dependence of the absorption spectra on the overlayer thickness change of the triple-band absorber. It can be seen from Figure 4a that the frequencies of the three peaks are all blue-shift with the increase of the overlayer. The frequency changes of these peaks are due to the increase of the capacitance of the absorber. Besides the frequency shifts, the absorbances of these peaks are also decreased when the overlayer thickness is increased. For example, the variation ranges of the absorbances of the second and the third peaks are respective 11.45% and 53.19% when the thickness of the overlayer is changed from zero to 8 μm. Furthermore, we found that the refractive index of overlayer also affect the absorption performance of the triple-band absorber, see Figure 4b. These results prove that the designed triple-band absorber can be used for sensor applications by adding thickness (or changing the refractive index) of the overlayer.

The main research focus of this paper is mainly on the three-band absorption and the analysis of its sensing performance. The following work can include how to improve the absorption intensity of the third absorption peak, how to improve the sensing ability of the first resonance absorption peak, how to design absorption peaks with narrow resonance bandwidths to improve the overall sensing
performance of the device, and how to design the resonance absorption performance that is insensitive to incident electromagnetic wave polarization.

![Absorption spectra](image)

**Figure 4.** (a) Absorption spectra of the thickness change of the overlayer; (b) absorption spectra of refractive index change of the overlayer (and here its thickness is 2 µm).

### 4. Conclusions

In conclusion, a simple metamaterial design to realize a triple-band absorption response at the terahertz frequency is demonstrated. Three narrow-band absorption peaks with a maximum absorbance of 99.89% are obtained, and the $Q$ value of the third absorption peak is 56.6, which is an order of magnitude larger than the absorption at first resonance peak. The mechanism of triple-band light absorption is demonstrated (by investigating their field distributions) as being induced by three different modes such as 1-order fundamental mode resonance and two 3-order responses. The sensing performance of absorber is also investigated by analyzing the dependence of the absorption spectra on the parameter changes of the refractive index of the surrounding, the thickness and refractive index of the overlayer. The results show that the bulk fitted sensitivities of the resonance frequency and absorbance of the third absorption are both much larger than that of the first two resonance peaks. The great sensitivity of the third absorption peak has promise in the field of sensing [35–42].

**Author Contributions:** B.-X.W. conceived the research and supervised the whole work. T.C., R.Z. and B.-X.W. conducted the simulations and analyses and wrote the manuscript. T.C. and R.Z. assisted in processing the data and figures. All authors read and approved the final manuscript.

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