High-Sensitivity Multiband Detection Based on the Local Enhancement Effect of an Electric Field at Terahertz Frequency

Zhonggang Xiong, Liping Shang, Hu Deng, Liang Xiong, Linyu Chen, Jin Guo, and Guilin Li

1School of Information Engineering, Southwest University of Science and Technology, Mianyang 621010, China
2School of Mechanical Engineering, Guilin University of Aerospace Technology, Guilin 541004, China
3Tianfu College of Southwestern University of Finance and Economics, Mianyang 621000, China

Correspondence should be addressed to Liping Shang; shangliping@swust.edu.cn

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The terahertz detection sensitivity interaction with other substances has received extensive attention and remains challenging due to the loss of terahertz waves. Herein, a terahertz, multiband sensor with high sensitivity based on the local enhancement effect of an electric field at terahertz frequency is proposed. The designed terahertz sensor is based on a common metamaterial sandwich absorber of electromagnetic energy that only employs an asymmetric metallic strip, which produces three resonance peaks with an absorption coefficient of greater than 95% in the 0.2-1.5 THz range and a maximum \( Q \)-factor of 46 at 1.397. Based on the principle of impedance matching, the high absorption of electromagnetic wave energy is reasonably analyzed. Furthermore, the influence of the top metal structure on the absorptivity and resonance frequency is analyzed by simulation optimization, and the optimum structural parameters are obtained. In addition, the influence of the refractive index (RI) change of the sample and dielectric layer on the resonance characteristics of the sensor is analyzed. When the thickness of the surface sample of the terahertz sensor metamaterial-based absorber is changed so that the RI changes in 1-2, the RI sensitivity increases up to 208 GHz/RIU, which can be used as an RI sensor. Furthermore, the influence of the sensor sensitivity and reflection coefficient on the thickness parameters of the sample covered by the sensor surface is analyzed, and the optimal sample thickness is 6 \( \mu m \). The influence of the incident angle of the THz wave on the detection performance in the TM polarization mode is analyzed, and it is determined that the change in the incident angle in the range of 0-40 degrees has minimal influence on the resonance peak and absorption rate of multiband detection. Therefore, we suggest that our proposed sensor has considerable potential in biomedicine and trace detection applications.

1. Introduction

A terahertz (THz) wave is a kind of electromagnetic wave that has many unique characteristics between microwaves and infrared waves that has a frequency range from 0.1 to 10 THz, including low energy, high permeability, and fingerprint spectrum characteristics [1, 2], and that has been widely employed in biomedicine and trace detection [3–7]. Recently, terahertz sensors based on metamaterial-based absorbers (MMAs) have been extensively utilized in terahertz detection fields. Simultaneously, due to the properties of the negative RI and permittivity [8–11], metamaterials also have considerable potential applications in areas such as invisible [12], biosensing [13], absorbing materials [14], and antennas [15]. A terahertz sensor based on a metamaterial absorber can significantly enhance the local electric field, thus effectively improving the detection sensitivity of the sensor.

For example, Liu et al. [16] reported a metamaterial-based absorber for the identification of waste oil and edible oil, and the frequency offset of the sensor reached 130 GHz when detecting waste oil. Wang et al. [17] simulated a terahertz sensor with a nearly perfect absorption, ultranarrow resonance peak based on a metamaterial-based absorber by
using a square resonator, which achieved an absorption rate of 98.86% with a resonant narrow-band absorption peak at 2.8913 THz. With the bandwidth of only 0.0067 THz, the resonance peak can be obtained under a certain thickness of the dielectric layer. High sensitivity (2.58 THz/RIU) and simultaneous ultranarrow bandwidth are responsible for a high FOM (385.07), which is proven to be very promising for THz detection and sensing optical devices. Tan et al. [18] designed and simulated an ultrasensitive sensor from a three-dimensional, terahertz metamaterial absorber, which could work as a terahertz RI sensor. The results showed that the proposed MMA exhibited a quality factor of 60.09 and a maximum sensitivity of approximately 5.96 GHz/μm at 1.731 THz. Saadeldin et al. [19] designed a terahertz sensor metamaterial-based absorber, which achieved a maximum sensitivity of approximately 300 GHz/RIU and a Q value of approximately 22.05. Banerjee et al. [20] demonstrated a one-band perfect MMA for an RI sensor based on CRRs with an absorptivity of 99.5% at 2.64 THz, which could work as an RI sensor in the terahertz region. The RI sensor achieved a sensitivity of approximately 1500 GHz/RIU and an FOM of 25 at narrow resonance peaks. Appasani [21] designed an MMA based on a concentric hexagonal ring resonator (CHRR) for temperature sensors. The sensitivity reached 3.71 GHz/K, and the maximum absorption was approximately 99.93% at 1.93 THz. Chen et al. [22] simulated a narrow-band, terahertz, RI sensor that is based on a metasurface-based absorber with InSb microcylinder arrays. The designed RI sensor obtained a nearly perfect absorption of approximately 99.9% at 1.8985 THz and a Q value of approximately 120.9.

Wang et al. [23] designed a triple-band, terahertz, RI sensor metamaterial-based absorber: the realized multiband resonance peaks were 1.23 THz, 2.39 THz, and 3.19 THz; and the nearly perfect absorption values were approximately 99.07%, 99.84%, and 99.01%, respectively; maximum sensitivity values of approximately 0.2 THz/RIU, 0.3 THz/RIU, and 1.6 THz/RIU, respectively, were obtained. Wang et al. [24] also designed a triple-band, terahertz MMA based on three concentric, square ring metallic resonators, which could work as an RI sensor in the terahertz band. The simulation shows three narrowband resonance peaks. The nearly perfect absorption values are approximately 99.5%, 86.4%, and 98.4% at 0.337, 0.496, and 0.718 THz, and sensitivity values of approximately 72, 103.5, and 139.5 GHz/RIU, respectively, are obtained. Li et al. [25] proposed a polarization-insensitive, nearly perfect absorption, triple-band metamaterial-based absorber with a high RI sensor based on a flexible Dirac semimetal. The sensitivity reaches 57.5 GHz/RIU, 152.5 GHz/RIU, and 51.4 GHz/RIU at 1.258 THz, 1.85 THz, and 2.12, respectively, in the range of 1 to 2.4 THz, and three perfect absorptivity values at all three resonance frequencies exceed 95%.

In our work, we propose a terahertz RI sensor from a metamaterial-based absorber for electromagnetic energy, and simulations are performed to investigate its resonance characteristics. In the horizontal TM modes, the influence of the top metal structure on the absorptivity and resonance frequency is analyzed by simulation optimization, and the optimum structural parameters are obtained. By designing the metal structure of the top layer metamaterial-based absorber, three resonance peaks with an absorption coefficient greater than 95% are detected in the 0.2-1.5 THz frequency band. In addition, the influence of the refractive index (RI) change of the sample and dielectric layer on the resonance characteristics of the sensor is analyzed. The distribution of the surface current and terahertz electric field at the resonance frequency is employed to further explain the resonance absorption principle of the designed multiband terahertz sensor. The reflectance...
spectrum of samples at different refractive indices and incident angles was also analyzed. Moreover, the influences of the geometric parameters of the metamaterial absorber and the sample thickness on the detection sensitivity on the resonance characteristics are also investigated, and the best combination of parameters is obtained. The investigation of the RI sensor characteristics will provide considerable potential in biomedicine and trace detection.

2. Structural Design

The design of our proposed terahertz sensor of the metamaterial-based absorber is shown in Figure 1. The top three different microstrip line metal structure, intermediate dielectric layer and metallic reflector layer, as well as the bottom substrate, constitute the MMA. The metal parts of the three-wire structure on the top and the bottom reflector layer on the substrate are composed of aluminum with an electrical conductivity of $3.56 \times 10^7$ S/m, and the thickness is $h = 200$ nm. Polyethylene is selected as the dielectric layer between them with a relative permittivity of $2.1 + j0.01$ [26] and thickness $t = 10 \mu m$. Silicon with high resistivity is used on the bottom layer substrate with a thickness of $500 \mu m$.

The geometric parameters of the structure are $l_1 = 60 \mu m$, $l_2 = 80 \mu m$, $l_3 = 100 \mu m$, $w_1 = 6 \mu m$, $w_2 = 4 \mu m$, $w_3 = 2 \mu m$, $s_1 = 2 \mu m$, $s_2 = 25 \mu m$, and $P = 120 \mu m$.

![Figure 2](image-url)

**Figure 2:** (a) Reflectance spectra of the metamaterial-based absorber; (b–d) diagrams of the relative impedance at $f_a = 0.871$ THz, $f_b = 1.075$ THz, and $f_c = 1.397$ THz, respectively.
The structure was performed with a CST Microwave studio for numerical modeling and simulations. The periodic boundary conditions of the X-Y plane are kept constant, while those of the Z plane are kept as an open boundary. Along the $y$-axis and $z$-axis, electromagnetic waves are polarized and incident, respectively, from the top layer. In the simulation, the unit-cell structure of MMA was irradiated vertically along the $z$-axis with a Gauss pulse as the excitation source. In the $z$ direction, the infinite periodic array structure is simulated by a perfect matching layer with an absorbing boundary condition. The incident terahertz wave is excited with the Floquet port mode set along the $z$-axis. In addition, along the $x$- and $y$-axis, the periodic boundary conditions in the simulation are set to replicate the infinite array of the microstrip line metal structures. Using the Floquet port mode and absorbing periodic boundary conditions, the simulation of the terahertz sensor metamaterial-based absorber is performed.

### 3. Results and Discussion

The reflection spectra of the metamaterial absorber are observed in Figure 2, where the absorber has three resonance peaks at $f_a = 0.871$ THz, $f_b = 1.075$ THz, and $f_c = 1.397$ THz. The frequency-dependent absorption value is defined as follows [27]:

$$ A = 1 - |S_{11}|^2 - |S_{21}|^2, $$

where the reflection coefficient and transmission coefficient are $S_{11}$ and $S_{21}$, respectively, at a certain frequency range. Since the bottom metal layer thickness of the metamaterial absorber is 200 nm, which is greater than the metal skin depth, no transmission was observed ($S_{21} = 0$). Since the designed structure is not completely symmetric and no phenomenon occurs under the polarization of TE, the reflection spectrum obtained by the above expression is shown in Figure 2(a) under TM polarization. Therefore, the maximum absorption rates are observed to be approximately 96%, 99%, and 95% at frequencies of 0.871 THz, 1.075 THz, and 1.397, respectively. To better reflect the resonance characteristics of the sensor, we need to explain $Q = f_0/FWHM$ ($f_0$ is the center frequency of resonance absorption, full width at half maxima, FWHM). By calculation, the $Q$ values of the sensor at 0.871, 1.075, and 1.397 THz are 29, 35, and 46, respectively. In addition, the mechanism of high absorption of mode A, mode B, and mode C was also analyzed. According to impedance matching theory [28, 29], the incident terahertz wave can be absorbed with a nearly perfect absorber when the relative impedance $Z$ of the designed terahertz sensor metamaterial-based absorber is similar to that of the free-space material, and the strongest local enhancement effect for the terahertz electric field is obtained. The relative impedance $Z$ can be expressed as follows [30]:

$$ Z = \pm \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}, $$

where $Z$ is the relative impedance. It is deduced that $Z$ is initially near the space impedance $Z_0 = 1$, and then, it is near each resonance absorption mode, where dissimilation occurs [26]. Around mode A, mode B, and mode C, diagrams of the
Figure 4: Continued.
real and imaginary parts of the relative impedance are obtained to effectively verify the above conjecture by using Equation (2). The results are shown in Figures 2(b)–2(d), where the real part and imaginary part of the relative impedance are shown as black solid lines and red solid lines, respectively.

It can be determined that in the vicinity of the above three resonance modes, the relative impedance of the terahertz sensor metamaterial-based absorber experiences a process of approaching the free-space impedance near each resonance absorption mode from Figures 2(b)–2(d) and then gradually moves away from the free-space impedance.

To further clarify the principle of resonance absorption of the designed multiband, terahertz sensor, the distribution of the surface current and terahertz electric field at each...
resonance frequency, when the electromagnetic wave under the polarization of TM is vertically incident, is investigated in Figure 3. The distribution of the surface current and terahertz electric field of the terahertz sensor metamaterial-based absorber at every resonance frequency is shown in Figure 3. The absolute value distribution of the real part of the local terahertz electric field and the distribution of the surface current are illustrated in Figures 3(a)–3(c) at each resonant frequency of $f_a = 0.871$ THz, $f_b = 1.075$ THz, and $f_c = 1.397$ THz, respectively.

It can be shown that every single resonance peak is mainly caused by the dipole resonance of the corresponding metal strip in Figure 3. Among them, the electric field at $f_b$ is relatively strong and that at $f_c$ is relatively weak, which is reflected in Figure 2, where the absorption rate is the highest at $f_b$ and at $f_c$ is the lowest. Therefore, more resonance peaks can be obtained by the addition of more metal strips of different lengths.

In addition, the effect of the metal structure parameters of the terahertz sensor metamaterial-based absorber on the
performance of the three narrow-band resonance peaks is also explored. The lengths $l_1, l_2$, and $l_3$ of the three metal strips were calculated from $20\,\mu\text{m}$ to $120\,\mu\text{m}$ with a step length of $20\,\mu\text{m}$ at one time, as shown in Figures 4(a)–4(c), respectively. The widths $w_1, w_2$, and $w_3$ of the three metal strips were also calculated from $2\,\mu\text{m}$ to $10\,\mu\text{m}$ with a step length of $2\,\mu\text{m}$ at one time, as shown in Figures 4(d)–4(f), respectively.

Figure 4(a) shows that the frequencies of resonance mode A and mode B shifted from $0.841$ to $0.877$ THz and from $1.078$ to $1.062$ THz and that the absorption improved obviously from $60\%$ to $98\%$ and from $61\%$ to $98\%$, respectively. However, mode C has a resonant frequency of approximately $1.361$ THz, and the absorption reaches $98\%$ at only $l_1 = 60\,\mu\text{m}$ when $l_1$ changes from $20\,\mu\text{m}$ to $120\,\mu\text{m}$ with a $20\,\mu\text{m}$ step length. Figure 4(b) shows that the frequencies of resonance mode A and resonance mode C shifted from $0.848$ to $0.877$ THz and from $1.316$ to $1.361$ THz and that the absorption improved obviously from $70\%$ to $98\%$ and from $58\%$ to $98\%$, respectively. However, mode B has a resonance frequency of approximately $1.062$ THz, and the absorption rate reaches $98\%$ at only $l_2 = 80\,\mu\text{m}$. Figure 4(c) shows that the frequencies of resonance mode B and mode C shifted from $1.044$ to
Figure 9: Continued.
1.062 THz and from 1.413 to 1.361 THz and that the absorption improved obviously from 62% to 98% and from 63% to 98%, respectively. However, mode A has a resonance frequency of 0.877 THz and the absorption reaches 98% at only \( l_3 = 100 \mu m \).

In Figure 4(d), as \( w_1 \) increases from 2 \( \mu m \) to 10 \( \mu m \) with a 2 \( \mu m \) step length, the maximum absorption rate is observed to be approximately 98.8% for \( w_1 = 8 \mu m \) in modes A and B, while mode C reaches nearly perfect absorption of approximately 99% at \( w_1 = 4 \mu m \). Mode A and mode B have almost no frequency shift, while mode C is obviously redshifted.

As shown in Figure 4(e), the maximum absorption rate is observed to be approximately 98% in modes A, B, and C. Modes A, B, and C are redshifted. In Figure 4(f), the maximum absorption rate is obtained at approximately 98% for modes A and B, and the nearly perfect absorption reaches 99% for mode C. Moreover, the resonance peak frequency at mode A is redshifted, while the resonance peak frequency at modes B and C is obviously redshifted.

Figure 5(a) shows that the resonance peak frequency at modes A and B underwent a blueshift of different degrees as the distance \( s_1 \) between the metals increased, while the resonance peak frequency at mode C was redshifted. The
resonance absorption showed a decreasing trend in modes A and B and a trend of initially increasing and then decreasing in mode C. The results of adjusted distance $s_2$ are shown in Figure 5(b).

Generally, the three resonance modes are minimally affected by distance $s_2$. The frequency of the resonance peak and the absorption change slightly in the range of $10\, \mu m$ to $30\, \mu m$ with a step length of $5\, \mu m$, as shown in Figure 5(b).

In our work, RI $n$ for the terahertz sensor metamaterial-based absorber is considered an important factor that can directly reflect the transmission characteristics. The reflection spectra of the absorber surface are simulated, which is covered with various refractive index samples that have different thicknesses; part of the curve is shown in Figure 6(a). When the thickness of the sample is fixed to $6\, \mu m$ and the refractive index is varied from 1-2 in steps of 0.2, the resonance peak of the absorber is redshifted. Therefore, the absorber moves to low frequency, and the reflection coefficient of the terahertz sensor metamaterial-based absorber gradually increases. The reason behind this trend is the change in the refractive index of the sample, which covers the surface of the terahertz sensor metamaterial-based absorber and causes the surrounding dielectric environment to change, which consequently changes the absorber spectrum. The relationship between the resonant frequency shift of the terahertz sensor metamaterial-based absorber and the refractive index of the sample is analyzed, where the refractive index sensitivity is calculated with $S = \Delta f / \Delta n$. As shown in Figure 6(b), the sensitivity of the sensor is $S_n = 131 \, \text{GHz/RIU}$, $S_p = 150 \, \text{GHz/RIU}$, and $S_s = 208 \, \text{GHz/RIU}$.

The effect of the sample thickness variation on the reflection coefficient and resonance frequency is investigated. As shown in Figure 7, the RI of the sample remains constant, and the sample thickness changes in steps of 2 within the range of $0-10\, \mu m$.

When the thickness of the sample increases from 0 to $2\, \mu m$, the resonance frequency of the sensor shifts. Moreover, the resonance frequency does not change significantly as the sample thickness further increases. Therefore, it is found that when the thickness of the sample is greater than $2\, \mu m$, no significant effect on the frequency shift of the terahertz sensor resonant frequency is observed. Moreover, as the sample thickness increases, the reflection coefficient at the absorber ($f_a$) is the smallest, and the sample thickness is $4\, \mu m$ when $f_b$ is at $6\, \mu m$, and $f_c$ is the smallest at $10\, \mu m$. A comprehensive analysis of the above results and discussion led us to conclude that the thickness of the samples should be $6\, \mu m$.

The influence of the dielectric layer thickness on the resonant frequency and absorption coefficient of the terahertz sensor is further investigated in this section. The thickness of the terahertz sensor dielectric layer varies from 5 to $20\, \mu m$ in steps of $5\, \mu m$. The result is shown in Figure 8.

Figure 8 shows that the resonant frequency of the terahertz sensor slightly shifts as the dielectric layer thickness increases. The reflection coefficient of the terahertz sensor initially decreases and then increases as the dielectric layer thickness increases. The smallest reflection coefficient and largest absorption coefficient are observed when $t = 10\, \mu m$. Therefore, the terahertz sensor has the optimal performance as the dielectric layer thickness increases to $10\, \mu m$.

Furthermore, the influence of geometric parameters $w$ and $s$ of the metal structure on the resonance characteristics of the terahertz sensor is investigated. The simulated results are shown in Figure 9. The effect of line width $w$ on the resonance characteristics of the terahertz sensor is depicted in Figures 9(a) and 9(b). When $s_1 = s_2 = 10\, \mu m$, $w_1$, $w_2$, and $w_3$ each change from 2 to $10\, \mu m$ in steps of 2. We did not observe any significant shift in the resonance frequency of the terahertz sensor, while the reflection coefficient of the terahertz sensor is significantly changed. Among them, $w_1 = 6\, \mu m$, $w_2 = 4\, \mu m$, and $w_3 = 2\, \mu m$, and the reflection coefficient of the terahertz sensor resonance peak is the lowest. We also investigated the influence of distance $s$ along the $y$ direction on the resonance characteristics of the terahertz sensor.

### Table 1: Comparison with previously reported literature.

| Designed structure/material | RI sensor range | Resonance frequency | Sensitivity | $Q$-factor | Absorptivity |
|-----------------------------|----------------|---------------------|-------------|------------|--------------|
| Two identical circular ring resonators [20] | 1.34 to 1.39 | 2.64 THz | 1500 GHz/RIU | 44 | 99.5% |
| Concentric hexagonal ring resonator [21] | 1.31 to 1.39 | 1.93 THz | 1045 GHz/RIU | 178.7 | 99.93% |
| Microcylinder arrays [22] | 1.0 to 1.05 | 1.8985 THz | 960 GHz/RIU | 120.9 | 99.9% |
| Asymmetric cross [23] | 1.0 to 1.1 | 1.23 THz | 200 GHz/RIU | 7 | 99.07% |
| | 2.39 THz | 300 GHz/RIU | | | |
| Three concentric square ring metallic resonators [24] | 1.0 to 1.6 | 0.337 THz | 72 GHz/RIU | 99.5% |
| | 0.496 THz | 103.5 GHz/RIU | — | 86.4% |
| | 0.718 THz | 139.5 GHz/RIU | | 98.4% |
| | 1.258 THz | 57.5 GHz/RIU | 46.6 | 95.5% |
| Dirac semimetal [25] | 1.0 to 1.8 | 1.85 THz | 152.5 GHz/RIU | 52.86 | 98% |
| | 2.12 THz | 51.4 GHz/RIU | 106 | 98% |
| This work | 1.0 to 2.0 | 0.871 THz | 208 GHz/RIU | 29 | 96% |
| Three asymmetric metallic strips | 1.075 THz | 150 GHz/RIU | 35 | 99% |
| | 1.397 THz | 131 GHz/RIU | 46 | 95% |
sensor. As shown in Figure 9(c), when \( \omega_1 = 6 \mu m, \omega_2 = 4 \mu m \), and \( \omega_3 = 4 \mu m \), \( s_1 \) and \( s_2 \) each change from 10 to 30 \( \mu m \) in 5 \( \mu m \) steps and the resonant frequency of the terahertz sensor has no obvious shift. However, the reflection coefficient of the sensor is significantly changed. Among them, when \( s_1 = 20 \mu m \) and \( s_2 = 25 \mu m \), the reflection coefficient of the terahertz sensor’s resonance peak is the lowest.

The unit structure of the multiband terahertz sensor designed in this paper is not completely symmetric, so only the incident characteristics at different angles in the sensitive TM mode are analyzed. Figure 10 shows the influence of the incident angle of the multiband terahertz sensor in TM polarization mode on the sensor sensing performance.

Figure 10 clearly shows the influence of the incidence angle \( \theta \) on the absorption and resonance frequencies. When the incident angle \( \theta \) reaches 40°, the absorption of mode A and mode B is higher than 95%, the absorption of mode C is higher than 92%, and the frequency shifts of modes A, B, and C are not obvious. The results show that the multiband terahertz sensor is insensitive to the wide incident angle.

Therefore, in this paper, the proposed multiband terahertz sensor has a few qualities different from those reported in the literature, such as a high absorption, high Q value, high sensitivity, and high multiband. and has considerable potential in biomedicine and trace detection applications. Table 1 shows the comparison between the terahertz sensor recommended in this paper and the results reported in the references.

4. Conclusions

In this paper, a terahertz sensor with three asymmetric metallic strips is designed from a metamaterial absorber with high-sensitivity multiband substance detection, which can be employed for terahertz RI sensors. The numerical simulations for our proposed terahertz sensor are performed using a CST Microwave studio. The terahertz sensor metamaterial-based absorber produces three different types of resonance peaks with an absorption coefficient greater than 95% in the 0.2-1.5 THz frequency band, and the maximum Q value is 46. In addition, the sensing ability of the terahertz sensor metamaterial-based absorber is analyzed. When the surface of the terahertz sensor is covered with a certain thickness of samples with a change in the RI of 1.0-2.0, the maximum RI sensitivity of 208 GHz/RIU is achieved. Therefore, the terahertz sensor metamaterial-based absorber can serve as an RI sensor. Through the electric field and surface current distribution of the terahertz sensor, the occurrence of resonance peaks and variations is analyzed. Similarly, the influence of the cover sample thickness on the resonant frequency shift and the reflection coefficient of the terahertz sensor are also analyzed. The final thickness of the sample is selected as 6 \( \mu m \), which is based on the above changes and the amount of sample. We suggest that the designed terahertz sensor metamaterial-based absorber can be employed for various applications, such as trace detection of substances and biomedical sensing.

Data Availability

The data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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