

High-sensitivity terahertz sensor based on four-nested ring metasurface absorber

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Abstract: Terahertz (THz) waves exhibit distinctive advantages for biomedical sensing, while metasurface technology offers an effective route toward high-performance THz sensors. A high-sensitivity THz metasurface absorber sensor for biological sample detection is proposed and numerically investigated. The sensor adopts a metal-insulator-metal (MIM) configuration, in which four centrosymmetrically arranged split metal rings form a multimode resonator. Copper is employed as the metallic layer, and PTFE is selected as the dielectric spacer. The electromagnetic response of the sensor is analyzed using CST Microwave Studio based on the FIT. Simulation results demonstrate that the proposed sensor supports two independent near-perfect absorption resonances at 3.1564 THz and 3.724 THz, with peak absorption rates of 99.75% and 99.84%, respectively. Owing to the strong localized field enhancement and multimode coupling effects, the resonant frequencies exhibit pronounced sensitivity to variations in the surrounding refractive index. Within the typical refractive-index range of biomedical samples, the maximum sensitivity reaches 241 GHz/RIU, accompanied by a maximum figure of merit (FOM) of 8.02. In addition, the absorption performance remains above 99% for polarization angles from 0° to 90°, with negligible resonance shift, indicating excellent polarization insensitivity. Benefiting from the use of low-dielectric-constant materials, the proposed sensor showed good material compatibility and portability. These results suggested that the designed metasurface absorber provided a promising platform for high-sensitivity terahertz biosensing applications.

Key words: metal-insulator-metal (MIM) configuration; dual-band resonance; refractive index sensing; polarization insensitivity; biomedical detection; equivalent circuit model

0 Introduction

Terahertz (THz) waves^[1] exhibit irreplaceable application potential in biomedical detection^[2], environmental monitoring^[3], security inspection, and imaging^[4], and other fields by virtue of their unique non-destructive penetrability and molecular structural sensitivity. Terahertz time-domain spectroscopy (THz-TDS) technology^[5] has achieved remarkable results in material classification and identification scenarios^[6], including the identification of Chinese herbal medicines^[7], pesticide residue detection^[8], and additive analysis^[9-11], yet it suffers from inherent drawbacks such as susceptibility to interference, low radiation efficiency of THz waves themselves, insufficient sensitivity for trace sample detection, and limited recognition accuracy^[12-13].

Metasurfaces^[14], a class of two-dimensional planar

materials composed of subwavelength-scale artificial micro-nano structural units arranged in a specific pattern, enable flexible and efficient manipulation of key parameters of THz waves, including amplitude, phase, and polarization state. Through the refined design of the size, morphology, array period, and dielectric layer parameters of the metasurface unit structure, targeted modulation of the absorption, reflection, or transmission characteristics of electromagnetic waves can be achieved in the target THz frequency band^[15-17]. Compared with traditional THz functional devices, metasurface devices possess the advantages of high manipulation flexibility, compact structure, and easy integration.

Researchers have conducted extensive work on structural optimization and application validation for terahertz metasurface absorber sensors. As the most fundamental device category, single-channel narrowband absorbers have

taken the lead in achieving breakthroughs in high-sensitivity sensing performance by virtue of their advantages of simple structure and facile design, and have completed detection verification in scenarios such as biosensing of small biological molecules^[18-20]. However, the inherent limitation of the single resonant channel makes it unable to meet the requirements of simultaneous multi-component detection and cross-validation of detection results in biological detection, and it is difficult to eliminate detection errors caused by system noise and fluctuations in ambient temperature and humidity.

To address these shortcomings, multi-channel terahertz absorbers have become a research focus. Nevertheless, the reported dual-frequency terahertz absorption sensing devices still have bottlenecks restricting their practical application. For instance, most LSPR resonant devices adopt noble metals such as gold and silver as the resonant structure material, resulting in high fabrication cost. Multi-channel devices generally suffer from the inability to realize synergistic improvement of sensitivity and resolution, with a comprehensive figure of merit (FOM) lower than $5^{[21-22]}$, which cannot meet the dual requirements of high sensitivity and high resolution for ultra-trace biosensing. Some devices are sensitive to the polarization state of incident waves, which reduces the stability and repeatability in the actual detection process. Therefore, it is urgent to develop a dual-channel terahertz metasurface sensor with low fabrication cost, polarization insensitivity, and synergistically enhanced sensitivity and resolution, so as to meet the practical application requirements of high-reliability terahertz biosensing.

Based on the research background, we design a metal-insulator-metal (MIM)-type THz metasurface absorber sensor based on a four-nested split metal ring array. By

adopting the Cu-PTFE low-cost material system, the fabrication cost of the device is significantly reduced. Meanwhile, the synergistic improvement of dual-band perfect absorption and high sensitivity is realized through structural innovation, and the polarization dependence of the device is greatly lowered. This paper will elaborate in detail the structural design, mechanism analysis, parameter optimization, and performance testing processes of the sensor, providing theoretical support and technical solutions for the development of high-sensitivity terahertz biosensing detection technology.

1 Structural design and mechanism analysis

1.1 Structural design and simulation

The schematic diagram of the periodic array structure of the sensor designed in this paper is shown in Fig.1 (a). It consists of a periodic array of four split-ring resonators (SRRs) arranged in a centrosymmetric manner. At specific terahertz frequencies, a strong field enhancement effect occurs at the edges of the split-ring resonators, thereby strengthening the interaction between the analyte and terahertz waves. As shown in Fig.1 (b), the proposed metasurface structure adopts an MIM sandwich configuration^[23], in which the top and bottom are Cu metal layers separated by a polytetrafluoroethylene (PTFE) dielectric layer. The upper surface is a resonator composed of four centrosymmetrically arranged metal rings, and the lower surface is a continuous copper layer that can totally reflect THz waves. The schematic diagram of the metasurface unit cell structure is shown in Fig.1 (c), where L , D , and W denote the outer diameter, ring width, and split width of the metal split ring, respectively.

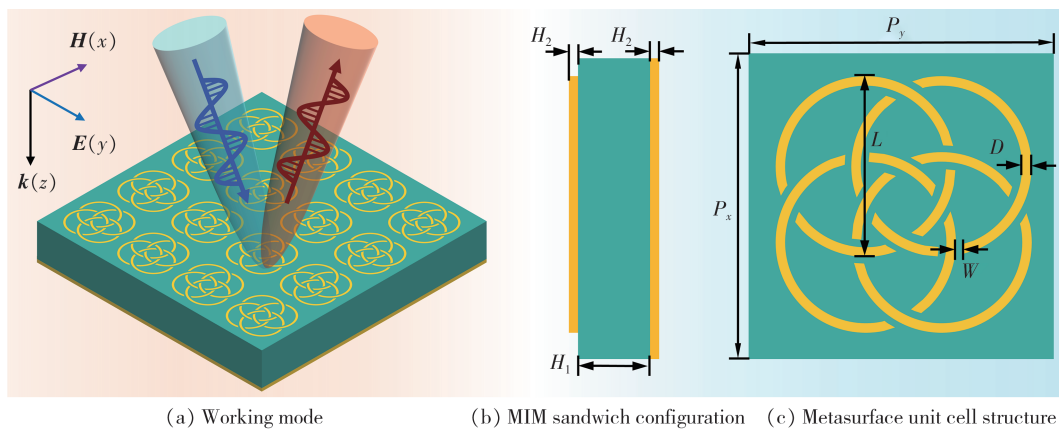


Fig. 1 Schematic diagram of four-nested ring metasurface structure

The distance from the outer edge of the outermost metal split ring to the boundary of the unit cell is $17\text{ }\mu\text{m}$. Strong mutual coupling is realized between adjacent split

rings, forming a nested structure visually analogous to the traditional Chinese knot. The unit cell side lengths satisfy $P_x=P_y=P$, and the optimized parameters of the

unit structure are listed in Table 1.

Table 1 Geometric parameters of unit structure

Parameter	Value/ μm
Unit cell side length P	90
Outer diameter of split ring L	56
Ring width D	4
Split width W	3
Thickness of dielectric PTFE layer H_1	30
Thickness of bottom copper layer H_2	0.2

To investigate the electromagnetic response of the designed metasurface, we performed simulation analysis of the sensor structure using the 3D electromagnetic field simulation software CST MWS 2025, and calculated the absorption characteristic curves, electric field and current distributions, and other parameters of the sensor using a frequency-domain solver based on the finite integration technique (FIT). The THz wave was incident normally on the upper surface of the sensor with the polarization direction along the x -axis, i. e., the electric field E was oriented along the y -direction and the magnetic field H along the x -direction. In addition, periodic boundary conditions were applied in the x and y directions, and open boundary conditions were set in the z direction. In the simulation, the relative permittivity of PTFE was set to 2.1, the loss tangent to 0.000 2, and the electrical conductivity of copper to 5.8×10^7 S/m.

After the simulation, the absorption rate was obtained through numerical post-processing. As the most fundamental performance metric of a metasurface absorber, the absorption rate is defined as the proportion of the incident electromagnetic wave absorbed by the device^[24], and is expressed by

$$A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2, \quad (1)$$

where $A(\omega)$ is the absorption rate of the device, $R(\omega)$ is the reflectance, $T(\omega)$ is the transmittance, $S_{11}(\omega)$ is the reflection coefficient, and $S_{21}(\omega)$ is the transmission coefficient.

Since the designed metasurface is equipped with a copper reflective layer at the bottom, the transmittance of the device $T(\omega) = 0$, so Eq. (1) can be simplified to

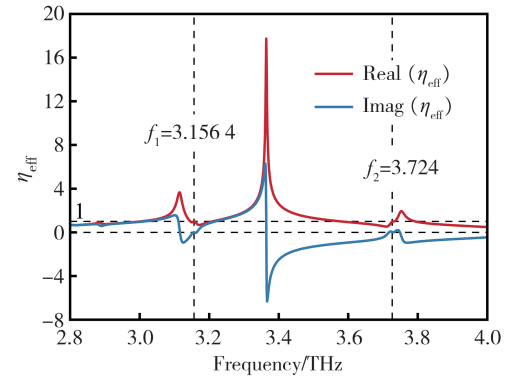
$$A(\omega) = 1 - |S_{11}(\omega)|^2. \quad (2)$$

According to the effective medium theory proposed by Smith et al.^[25], the effective impedance η_{eff} of the metasurface can be calculated from the S -parameters by

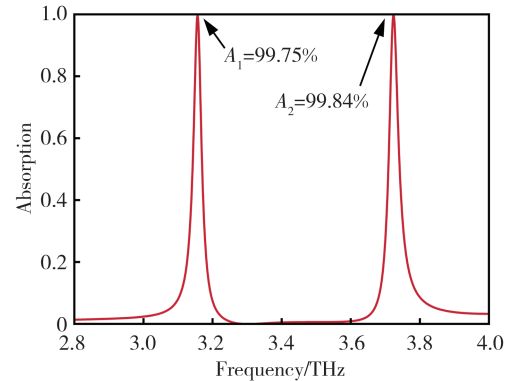
$$\eta_{\text{eff}} = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}. \quad (3)$$

The numerically simulated normalized equivalent

impedance, as well as the reflection and absorption spectra of the proposed device, are presented in Fig.2. As can be observed from Fig.2(a), at the two resonant frequencies of $f_1 = 3.1564$ THz and $f_2 = 3.724$ THz, the normalized equivalent impedance of the device satisfies the ideal impedance matching condition, i.e., the real part is 1 and the imaginary part is 0. Accordingly, two distinct absorption peaks are generated at the two frequencies, as depicted in Fig.2(b), with the corresponding peak absorptivity reaching as high as 99.75% and 99.84%, respectively. Both resonant peaks (hereinafter referred to as f_1 and f_2 for brevity) achieve near-perfect absorption of terahertz waves, which fully validates the excellent impedance matching characteristics and electromagnetic wave absorption performance of the designed structure.



(a) Normalized equivalent absorption impedance



(b) Absorption characteristic curves

Fig. 2 Frequency domain simulation results for sensor without cover

To quantify the resolution of the absorption peaks, we use the quality factor Q to describe the sharpness of the resonant peaks^[26], which is defined as

$$Q = \frac{f_0}{\text{FWHM}}, \quad (4)$$

where f_0 is the central frequency of the resonant peak, and FWHM denotes the full width at half maximum of the resonant peak. A high Q value indicates a sharp resonant peak, which is more sensitive to tiny frequency shifts.

Sensitivity is a core metric for evaluating the sensing

performance of metasurface sensors. In this work, we use environmental refractive index sensitivity to quantify the sensor's ability to respond to small variations in the refractive index of the surrounding medium. Its physical essence lies in the change of the sensor's optical resonance characteristics caused by the variation of the environmental refractive index (Δn), which is expressed as

$$S = \frac{\Delta f}{\Delta n}, \quad (5)$$

where Δf represents the frequency shift of the resonant peak induced by the change in the refractive index of the surrounding medium.

When evaluating the comprehensive performance of the device, it is necessary to jointly consider sensitivity and the Q factor, thus introducing the FOM.

$$\text{FOM} = \frac{S}{\text{FWHM}}. \quad (6)$$

FOM reflects the sensitivity per unit bandwidth, and a higher value indicates a stronger ability of the sensor to resolve small refractive index changes.

1.2 Resonance mechanism analysis

To further investigate the resonance mechanism of the device at the two frequencies, we extracted the electric field and current distributions of the unit cell at each frequency, respectively, and analyzed its resonance modes based on the multipole scattering theory^[27].

From the electric field distribution of the device shown in Fig.3 (a), the electric field at f_1 is highly concentrated at the split edges and inter-ring gaps of the upper-left and lower-right metal rings, exhibiting a strong local field enhancement effect. This effect originates from the capacitive coupling of the metal structure and the excitation of localized surface plasmons (LSPs), thereby enhancing the interaction intensity between the incident terahertz wave and the device. As shown in Fig.3 (d), the electric field distribution at f_2 extends to the split edges and inter-ring gaps of all metal ring structures with a higher electric field intensity, which is a typical characteristic of high-order resonant modes.

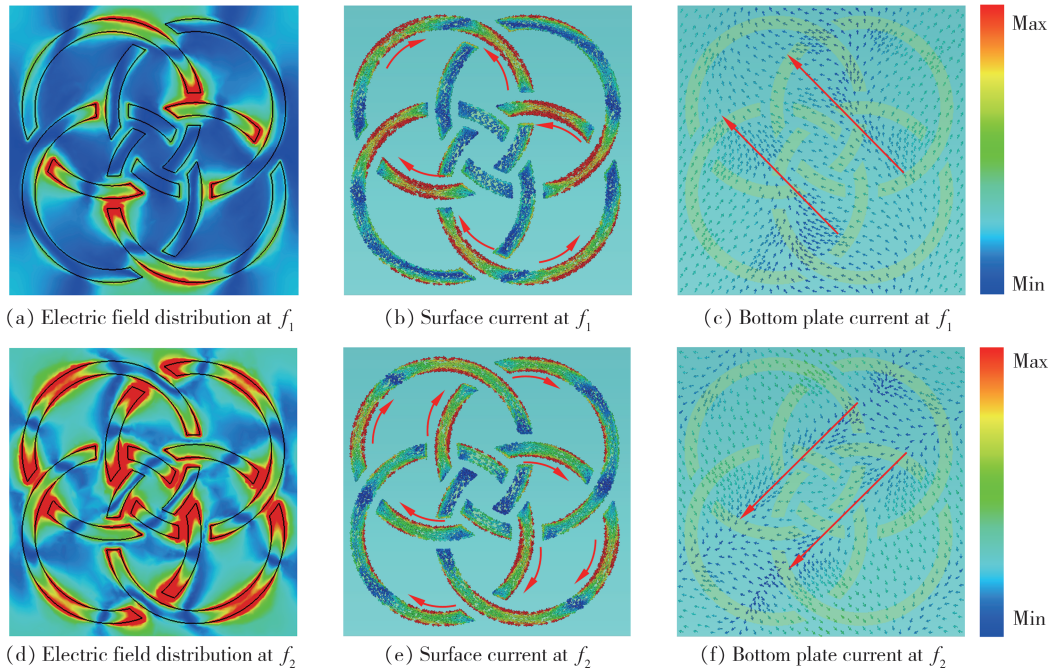


Fig. 3 Electromagnetic field simulation results of metasurface

Fig. 3(b), 3(c), 3(e), and 3(f) shows the current distributions of the sensor at the two resonant frequencies, where the current intensity is characterized by a color gradient, and the vector arrows reflect the flow direction, including the surface current of the structural layer and the current of the bottom copper layer.

As shown in Fig.3 (b), at $f_1 = 3.1564$ THz, the surface of the structural layer exhibits a localized current distribution. The surface current is mainly concentrated on the two diagonal metal split rings at the upper-left and

lower-right, forming directional annular flow along the direction indicated by the arrows. According to the equivalent circuit theory, a single metal ring can be equivalent to an inductor L , and a capacitor C is formed at its split due to charge accumulation. The induced charges excited by the incident terahertz wave accumulate at the split and drive the directional movement of charges, forming a typical LC resonant current. Therefore, the resonance at this frequency is essentially a coupled resonance effect of dual LC units. Corresponding to the

current distribution of the bottom copper layer in Fig.3(c), it can be seen that the current coverage area has a clear spatial correspondence with the local high-current-density area of the structural layer, and the direction of the current vector is in-phase correlation with the current in the same area of the structural layer. Meanwhile, the overall current density of the bottom copper layer is lower than that of the structural layer, and its distribution range is strictly limited to the vertical projection area of the local high-density current area of the structural layer. This phenomenon is a direct result of local in-phase inductive coupling mediated by the alternating electric field generated by the local LC resonance of the structural layer.

As shown in Fig. 3(e), the surface current of the structural layer at $f_2=3.724$ THz exhibits a global distribution characteristic, uniformly covering all four centrosymmetric arranged metal split rings and forming a synchronized annular flow mode. The current directions among the metal rings are consistent, and the density distribution is uniform, reflecting the characteristic of high-order multi-unit cooperative resonance. From the perspective of the equivalent circuit, each of the four metal rings constitutes an independent LC resonant unit, and synchronized current oscillation is achieved through strong capacitive coupling between rings. Compared with the dual-unit resonance at f_1 , its coupling effect is stronger and the coverage range is wider. Corresponding to the current distribution of the bottom copper layer in Fig.3(f), the bottom current is no longer limited to a local area, but forms an annular current array corresponding to the four metal rings of the structural layer. This distribution characteristic is an inevitable result of the high-order resonant mode. The synchronized current of the four metal rings in the structural layer generates a stronger and more uniform alternating magnetic field, which induces globally distributed eddy currents in the bottom plate. This ensures that each LC unit can form an effective resonance loop with the bottom plate through magnetic coupling, thereby enhancing the local electric field enhancement effect.

In summary, the resonant essence of the sensor can be attributed to the superposition and coupling effects of multiple LC resonant units. When analytes are coated on the sensor surface, a new equivalent capacitance C_{sensor} is formed on the surface of the metal rings. With variations in the permittivity of the surrounding medium and the thickness of the analytes, the value of C_{sensor} changes regularly, which in turn leads to the reconstruction of the overall equivalent capacitance of the metasurface sensor.

According to the LC resonant frequency formula $f=1/(2\pi\sqrt{LC})$, the resonant frequency exhibits a predictable frequency shift law with the variation of equivalent capacitance. The physical properties of analytes can be inverted by detecting this frequency shift signal.

1.3 Equivalent circuit mode

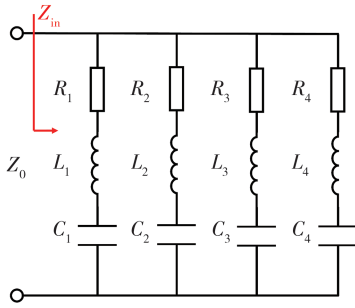
To analyze the broadband absorption mechanism of the proposed structure from the perspective of circuit theory, an equivalent circuit model of the structure is established in this paper. The bottom Cu metal layer can achieve total reflection of incident THz waves in the THz frequency band, which is equivalent to an ideal short-circuit boundary in the equivalent circuit model. The intermediate PTFE dielectric layer, a THz low-loss dielectric, can be equivalent to a transmission line and simultaneously provide a subwavelength confinement space for the resonant electromagnetic field. The top patterned Cu structure serves as the resonant core of the metasurface. The ohmic loss caused by the skin effect of the conduction current in the metal structure is equivalent to a lumped resistor R. The magnetic effect generated by the current flowing along the metal strips is equivalent to a lumped inductor L. The fringing capacitance between adjacent metal structures and the parallel plate capacitance between the top and bottom metal layers are jointly equivalent to a lumped capacitor C. Accordingly, a single independent resonant structure can be equivalent to a RLC series resonant branch.

The metasurface unit cell contains four groups of mutually coupled symmetric resonant structures, corresponding to an equivalent circuit topology with four groups of RLC series branches connected in parallel. Incident THz waves can be synchronously coupled to each parallel resonant branch, thus the equivalent circuit of the proposed metasurface is shown in Fig.4(a). The lumped parameter values of each branch in the equivalent circuit are listed in Table 2, which are obtained by fitting and inversion based on the S-parameters from CST full-wave electromagnetic simulation using the advanced design system (ADS) developed by Keysight technologies. When the operating frequency matches the resonant frequency of the circuit, the input impedance of the equivalent circuit achieves good matching with the free-space wave impedance, the reflection of incident waves is significantly suppressed, and the electromagnetic energy is efficiently absorbed via the ohmic loss of the metal. As shown in Fig. 4(b), the calculated S-parameter results of the equivalent circuit are in excellent agreement with the CST full-wave electromagnetic simulation results, which

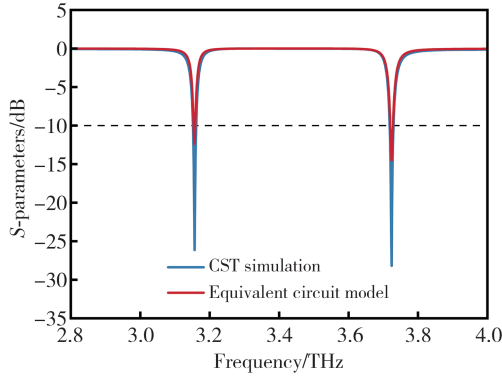
verifies the accuracy and rationality of the proposed equivalent model.

Table 2 Lumped parameters of each branch in equivalent circuit

Parameter	Value
R_1/Ω	0.717 11
L_1/pH	2.975 00
C_1/fF	0.510 82
R_2/Ω	0.066 16
L_2/pH	1.801 00
C_2/fF	0.373 64
R_3/Ω	0.519 41
L_3/pH	4.668 00
C_3/fF	0.621 64
R_4/Ω	0.000 02
L_4/pH	4.990 00
C_4/fF	0.426 79



(a) Equivalent circuit



(b) Corresponding S-parameters

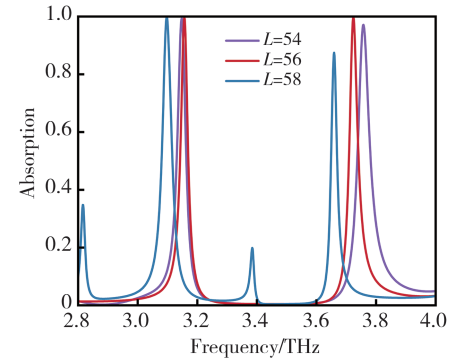
Fig. 4 Equivalent circuit model of metasurface

2 Structural optimization and performance analysis

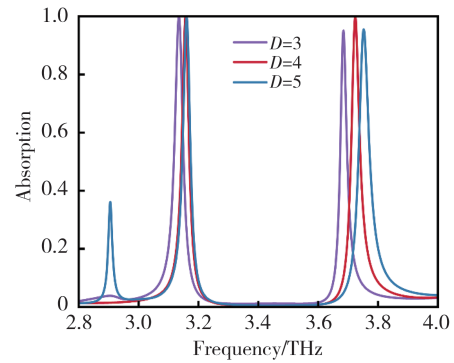
2.1 Structural parameter optimization

To explore the regulation law of core geometric parameters on the absorption characteristics of the sensor and achieve the synergistic optimization goal of multi-band high absorption and high sensitivity, we selected the metal ring outer diameter L , metal ring width D , and inter-ring gap width W as key structural variables. The FIT based on the CST MWS 2025 simulation software is used to systematically investigate their effects on the

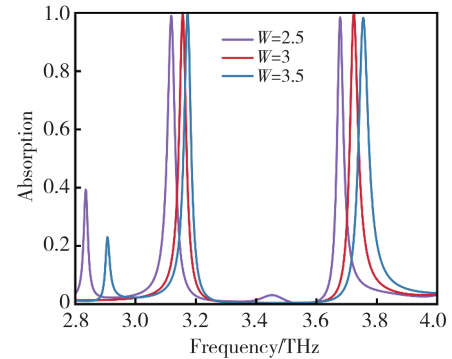
resonant response of the sensor, and the simulation results are shown in Fig.5.



(a) Outer ring outer diameter L parameter sweep



(b) Ring width D parameter sweep



(c) Split width W parameter sweep

Fig. 5 Simulation results of parameter optimization

Fig.5(a) presents the absorption characteristic curves under different metal ring outer diameter L . It can be seen that with the variation of the metal ring outer diameter, the absorption rate at f_1 does not show an obvious attenuation, while the absorption rate at f_2 decreases significantly when $L \neq 56 \mu\text{m}$. The above phenomena indicate that the variation of outer diameter does not damage the high absorption characteristic of f_1 , but has a significant impact on the absorption characteristic of f_2 . Meanwhile, as L increases from $54 \mu\text{m}$ to $58 \mu\text{m}$, both resonant peaks exhibit an obvious red shift trend. This is because the increase in the metal ring outer diameter leads to the rise of the structural

equivalent inductance. According to the LC resonance principle, the resonant frequency decreases with the increase of inductance value, which provides an effective approach for the precise regulation of the sensor's frequency response.

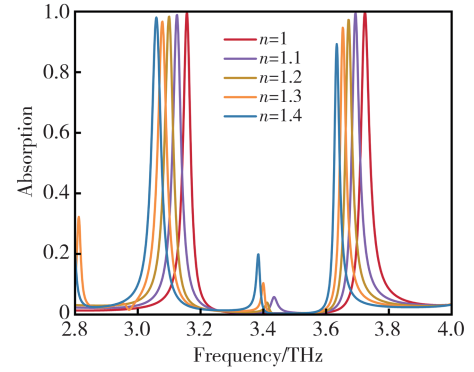
Fig.5(b) illustrates the effect of the metal ring width D on the absorption performance. When $D=4\ \mu\text{m}$, the sharpness of the two absorption peaks is optimal, and the FWHM is the smallest. Combined with the definition of the Q factor, it can be known that the frequency selectivity of the resonant peaks is the strongest under this parameter, which lays a foundation for improving the sensor's response sensitivity to tiny refractive index changes. In contrast, the absorption peaks are slightly broadened when $D=3\ \mu\text{m}$, and the absorption rate of the high-frequency band absorption peak decreases slightly when $D=5\ \mu\text{m}$.

Fig.5(c) demonstrates the regulation law of the inter-ring gap width W on the absorption peaks. The gap width is directly related to the capacitive coupling effect and the degree of local electric field concentration of the metal ring structure. When $W=3\ \mu\text{m}$, the absorption rates of the two absorption peaks both reach the peak value, and the positions of the resonant peaks are more stable. This is because the charge accumulation effect at the split of the metal ring is optimal, and the excitation intensity of localized surface plasmons (LSPs) is the maximum under this gap width, thus strengthening the light-matter interaction. When W deviates from $3\ \mu\text{m}$ (either reduced to $2.5\ \mu\text{m}$ or increased to $3.5\ \mu\text{m}$), the absorption rates of the absorption peaks all attenuate to varying degrees.

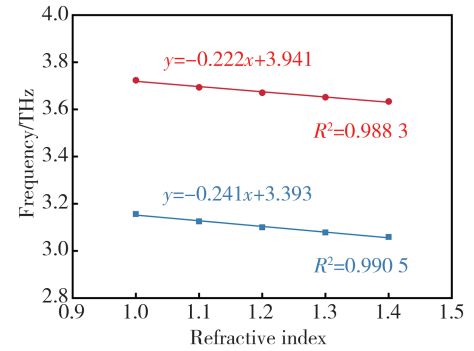
The parameter optimization results indicate that by rationally regulating the outer diameter, width, and inter-ring gap width of the metal rings, flexible modulation of the resonant frequencies and peak sharpness can be achieved on the premise of maintaining the near-perfect absorption characteristics of the sensor. This provides important theoretical basis and simulation support for the comprehensive improvement of subsequent sensor performance and parameter adaptation in practical application scenarios. Calculations based on Eq. (3) show that when $L=56\ \mu\text{m}$, $D=4\ \mu\text{m}$, and $W=3\ \mu\text{m}$, the two absorption peaks achieve their maximum quality factors, with $Q_1=105$ and $Q_2=116$, respectively. By comprehensively considering the quality factor, resonant frequency, absorption intensity, and other key performance factors of the sensor, the geometric parameters of the unit structure are set as listed in Table 1.

2.2 Sensing performance analysis

Fig. 6 presents the absorption characteristics and sensitivity fitting results of the sensor under different refractive index (n) conditions when its surface is coated with analytes of $1\ \mu\text{m}$ thickness. Considering that the refractive index of most biological tissues is approximately 1.4^[28], the maximum refractive index of the analytes is set to 1.4 in this study.



(a) Variation of absorption peak with refractive index of $1\ \mu\text{m}$ thick covering layer



(b) Sensitivity fitting curves

Fig. 6 Sensing performance of metasurface

As shown in Fig.6 (a), when the refractive index of the analytes increases gradually from 1.0 to 1.4, both resonant peaks exhibit an obvious red shift trend. This is because the increase in the refractive index of the analytes directly alters the dielectric environment surrounding the sensor, thereby modulating the equivalent capacitance of the four split metal ring structure.

According to the LC resonance principle, the resonant frequency decreases with the rise of dielectric constant. Throughout the entire refractive index variation range, the absorption rate of the sensor remains above 90%, sustaining the near-perfect absorption characteristic without severe attenuation induced by the change in the dielectric environment. Fig.6 (b) shows the linear fitting curves of the resonant peak frequency shift against the refractive index variation of the analytes, and the fitting results reveal an extremely high linear correlation

between them. Based on these fitting curves, the refractive index sensitivities of the sensor at the two resonant peaks are calculated to be 222 GHz/RIU and 241 GHz/RIU, respectively. Combined with the Q factors obtained from the previous structural optimization, the values of $FOM_1=8.02$ and $FOM_2=7.51$ are further derived, which fully demonstrates the high resolution capability of the sensor for tiny refractive index variations.

To evaluate the accuracy of the fitting formula and verify the refractive index sensing performance of the proposed device, we selected 3 groups of refractive index test points not involved in the fitting process for inversion verification. Under the same refractive index condition, the simulated resonant frequencies were substituted into the fitting formula respectively to obtain an inverted refractive index at each of the two resonant frequencies. The final inverted refractive index was acquired by calculating the average value of the two

results. The actual refractive index compared with the inverted refractive index are listed in Table 3.

Table 3 Inversion results and relative errors of refractive index

Ground-truth refractive index	Inverted refractive index	Relative error/%
1.15	1.179 4	2.60
1.25	1.252 3	0.18
1.35	1.357 8	0.58

For all three groups of validation test points, the relative errors between the inverted refractive index and the true refractive index are at an extremely low level, with a maximum relative error of no more than 2.6% across the entire test range. This fully verifies that the fitting formula established in this paper has extremely high calculation accuracy and generalization ability, and can achieve stable and accurate quantitative inversion even for unknown refractive index samples not involved in the fitting process.

The performance of the proposed structure is compared with that of similar works, as listed in Table 4.

Table 4 Performance comparison with reported terahertz absorber sensors

Reference	Operating frequency/THz	Number of resonance peaks	Peak absorption/%	Sensitivity/(GHz•RIU ⁻¹)	Polarization Insensitivity/(°)
Ref.[18]	1.345	1	>99.90	33.70	
Ref.[29]	3.370	1	≈100	83.33	0–90
Ref.[30]	0.661	1	99.96	161.99	
Ref.[21]	0.985	2	≈100	27.50	0–90
	1.203		≈100	36.25	
Ref.[31]	0.250	2	99.09	0.43	0–90
	1.300		99.72	2.24	
Ref.[32]	7.360	2	98.90		
	11.640		99.70	205	
This work	3.156	2	99.75	222	0–90
	3.724		99.84	241	

Fig. 7 depicts the variation curves of the absorption characteristics of the proposed sensor across the polarization angle range of 0° to 90°. The unit cell features a strictly four-fold centrosymmetric rotationally symmetric structure, endowing its electromagnetic response with 90° rotational invariance. Quantitative results demonstrate that, within the full polarization angle range of 0° to 90°, the absorption rates of both resonance peaks remain above 99%, with the relative offset of the resonant center frequency below 0.2% and no observable attenuation or frequency shift. These results fully validate the excellent polarization insensitivity of the proposed sensor, which can effectively accommodate complex scenarios involving fluctuations in the polarization angle of the incident wave in practical detection applications. This enables the sensor to tolerate minor fluctuations in the polarization angle of incident terahertz waves in practical applications, significantly improving the stability and reliability of the detection system, effectively expanding its applicable scenarios under complex incident

conditions and providing an important guarantee for the operational convenience in subsequent actual sample detection.

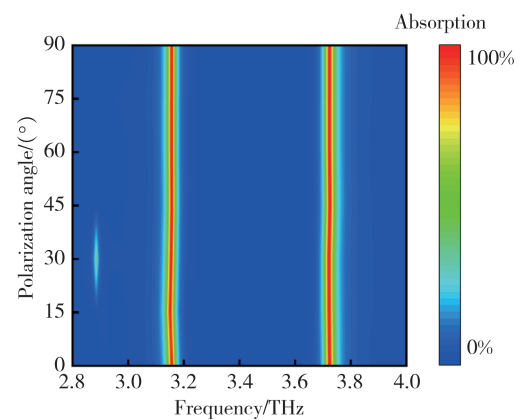


Fig. 7 Absorption of sensor under different polarization angles

3 Conclusions

A dual-band terahertz metasurface absorber sensor

based on an MIM configuration was designed and numerically demonstrated. By employing four centrosymmetrically arranged split metal rings, the proposed sensor supports two independent near-perfect absorption resonances at 3.156 4 THz and 3.724 THz, with absorption rates exceeding 99.7%. Structural parameter optimization leads to high-quality resonances, with quality factors of 105 and 116 for the two absorption peaks, respectively. The sensing performance of the device was systematically evaluated by analyzing its response to variations in the refractive index of the surrounding medium. Within the refractive-index range relevant to common biomedical samples, the resonant frequencies exhibit clear and linear red shifts, yielding sensitivities of 222 GHz/RIU and 241 GHz/RIU and a maximum FOM of 8.02. Furthermore, the absorption characteristics remain stable for polarization angles ranging from 0° to 90°, with negligible attenuation and frequency shift, demonstrating strong polarization-insensitive behavior.

Overall, the proposed metasurface sensor combines dual-band near-perfect absorption, high refractive-index sensitivity, polarization insensitivity, and favorable material compatibility. These features make it a promising candidate for high-resolution terahertz sensing in biological and biomedical detection scenarios.

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Declaration of conflicting interests

The authors have no conflict of interests related to this publication.

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基于四嵌套圆环超表面吸波体的高灵敏度太赫兹传感器

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摘 要: 太赫兹波在生物医学检测领域具有独特优势, 超表面技术则为高性能太赫兹传感器的构建提供了有效途径。本文设计了一种用于生物检测的高灵敏度太赫兹超表面吸波体传感器, 该传感器以金属-绝缘体-金属(MIM)为基础构型, 由四个呈中心对称的开口金属环构成多模谐振器, 金属层选用铜, 介电层采用聚四氟乙烯。借助CST仿真软件, 基于有限积分法对传感器的电磁响应特性展开模拟分析。仿真结果表明, 该传感器在3.156 4 THz与3.724 THz处形成两个独立的谐振峰, 对应吸收率分别为99.75%和99.84%; 传感器对周围介质折射率变化响应显著, 在常见生物医学样品折射率区间内最高折射率灵敏度可达241 GHz/RIU, FOM值最大为8.02; 在0°-90°偏振角范围内传感器吸收率始终稳定在99%以上, 未出现明显衰减与频移。此外, 因采用低介电常数柔性材料, 其具备良好的生物相容性与便携性。该传感器为太赫兹高灵敏生物传感检测提供了可行的技术方案。

关键词: 金属-绝缘体-金属结构; 双频共振; 折射率传感; 极化不敏感; 生物医学检测; 等效电路模型

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