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Ultra-Thin Metamaterial Absorber based Sensor in Optical Regime for Polarization-Independent Biomedical Diagnostics

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Abstract: In this paper, metamaterial absorber (MTM-A) for terahertz (THz)-based biomedical sensing is presented. The proposed assembly involves a symmetrically spotted metallic resonator, a SiO_2 dielectric base and a continuous metallic ground plane to achieve solid electromagnetic confinement and efficient absorption. Numerical analysis shows a maximum absorption of 99.95% at 4.52 THz, and a minimum reflection coefficient of 0.015. The symmetric unit-cell configuration retains a consistent resonant response for different polarization orientations. Sensing performance is investigated by changing the refractive index of a 1.5-um-thick analyte layer from 1.35 to 1.41. The resulting resonance shift from 4.55 to 4.42 THz confirms the structure capability to sense minor variations in dielectric characteristics of biological samples. The sensor exhibits a sensitivity of ~0.55 THz/RIU, Q-factor ~10.5 and figure of merit (FOM) of 1.55 RIU^{-1}. Besides, numerical simulations show distinct spectral characteristics for healthy and diseased biological specimens such as cancer-cell types. These results demonstrate the promise of the presented absorber as a compact, label-free THz sensing platform for biomedical analysis.

Keywords: Metamaterial absorber, THz sensing, Polarization Insensitivity, Biomedical sensing, Cancer detection

1. Introduction

The increasing demand for miniaturized and sensitive biomedical sensing technologies has resulted in the creation of electromagnetic sensors that can detect fluctuations in the dielectric assets of biotic models. Terahertz (THz) sensing has been paid considerable attention since it

enables the investigation of material properties through electromagnetic interactions with biological substances. Reliable detection, however, demands sensor structures which strongly confine the field, possess well-defined resonances and react stably to changes in the surrounding medium [1], [2].

Metamaterial absorbers (MTM-As) are a promising solution to this challenge owing to their tunable electromagnetic responses with carefully designed subwavelength metallic patterns. Such structures can achieve high absorption at selected frequencies by minimizing reflection and suppressing transmission. Their resonant response is also sensitive to refractive index changes of an analyte and thus can be used for label-free sensing without the need of conventional fluorescent or chemical labels [3-6].

Several THz metamaterial sensors have been investigated for biological sample detection and disease related sensing. Dual-band absorbers for glucose and malaria screening, high-sensitivity structures for cancer-cell detection, and polarization-independent designs for biomedical applications have been investigated [7–10]. Other reported methods, have employed dielectric materials such as zinc selenide for improving absorption and sensing properties [11]. Recent studies have also shown the potential of metasurface-based sensors to distinguish between biological samples by refractive index-dependent resonance shifts [12]. However, it is still important to design a compact structure with nearly unity absorption, polarization independent operation and sufficiently distinguishable spectral response.

An ultra-thin metamaterial absorber (MTM-A) is designed to satisfy the requirements of high absorption and compact terahertz (THz) sensing in the frequency range of 4–5 THz. The unit cell consists of a gold resonant layer with a symmetric distribution of curved metallic elements, diagonal connection strips, rectangular patches, and a square-ring resonator with a narrow gap in the middle, printed on a SiO2 dielectric substrate backed by a continuous gold ground plane. The symmetric arrangement is to enable polarization insensitive operation and the resonating layer, dielectric substrate and metallic ground plane are to help in impedance matching and electromagnetic energy dissipation. The simulated results indicate the maximum absorption of about 99.7% at 4.52 THz where the reflection coefficient is about 0.015 and the effective impedance approaches free-space impedance with a real part of 1.02 and imaginary part of 0.03. The proposed structure is also considered for separating the healthy and diseased biological samples including different cancer-cell types through their THz absorption responses changes. The results indicate that the proposed absorber can be a good candidate for compact THz refractive-index sensing and biomedical detection.

2. Layout of Designed Unit Cell

The proposed metamaterial absorber (MTM-A) consists of three layers: a patterned gold (Au) resonator layer, a silicon dioxide (SiO_2) dielectric substrate and a continuous gold ground plane. It is shown in Fig. 1. The unit cell is 50*50µm^2 with a substrate thickness of 6.0µm and a gold thickness of 0.2 µm. The substrate has a relative permittivity of ε_r =3.9 and a loss tangent of tan δ =0.0004. The resonating layer consists of four curved corner elements, diagonal connection strips, rectangular metallic patches, and a square-ring resonator with a narrow split in the middle. The main geometrical parameters are d=18.0 µm, w=5.5µm, g=2.0 µm, b=3.5 µm and s=1.5 µm. The symmetric geometry leads to polarization-insensitive operation, and the metallic resonators and narrow gaps provide inductive and capacitive effects that support strong electromagnetic resonance. The continuous ground plane suppresses the transmission thus allowing efficient absorption and potential applications in THz refractive-index sensing.

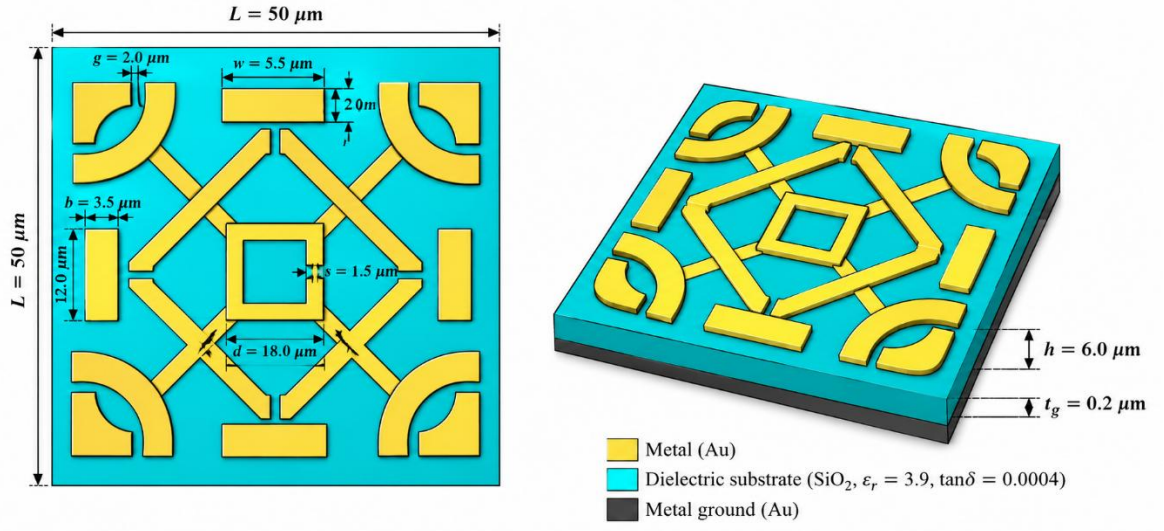


Fig.1 Physical design of projected metamaterial absorber unit cell

3. Metamaterial Absorber Analysis

The absorption performance of the proposed metamaterial absorber (MTM-A) is studied in the frequency range of 4–5 THz by using full-wave electromagnetic simulation. The absorption coefficient is calculated from the reflection and transmission coefficients by the following expression [13], [14]:

$$A(f) = 1 - |S_{11}(f)|^2 - |S_{21}(f)|^2 \qquad (1)$$

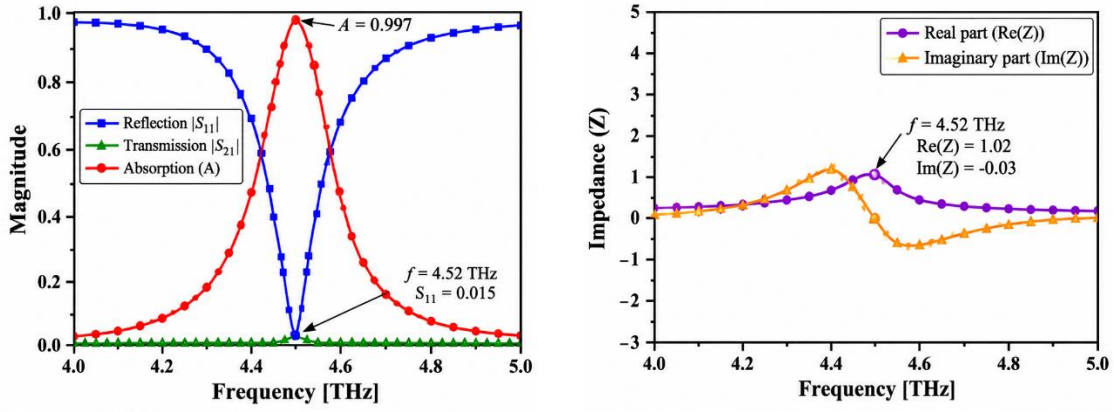
where S_{11} and S_{21} are the reflection and transmission coefficients, respectively. The proposed absorber has a continuous metallic ground plane, and hence the transmission is expected to be negligible. So, the absorption coefficient can be approximated by

$$A(f) \approx 1 - |S_{11}(f)|^2 \qquad (2)$$

The proposed structure exhibits strong resonant response with the reported peak absorption about 99.7% at 4.52 THz as shown in Fig. 2(a). The high absorption is due to the interaction between the incident electromagnetic wave and the patterned metallic resonators, which generate localized electromagnetic fields and dissipate energy in the metallic and dielectric layers. The small gaps and the interconnected metallic elements induce capacitive and inductive couplings which allow to control the resonant response by the geometrical arrangement of the unit cell. The effective normalized impedance is obtained from the simulated S-parameters using the standard retrieval expression [13]:

$$Z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \qquad (3)$$

where $Z\,(f)$ is the effective impedance normalized to the impedance of free space. As shown in Fig. 2(b), the real and imaginary parts of the normalized impedance at 4.52 THz are approximately 1.02 and −0.03, respectively. The real part of effective impedance is near to unity and imaginary part is near to zero, which implies that the effective impedance matches with free space, so the reflection is minimum at resonance. The combined results of absorption and impedance show the potential of the proposed MTM-A for efficient THz absorption and refractive-index sensing. Further, the resonant response can be used for the detection of changes of the dielectric properties of an analyte by measuring spectral shifts. Similar absorption and impedance-retrieval approaches have been reported for metamaterial absorbers and refractive-index based sensing applications [13], [14].

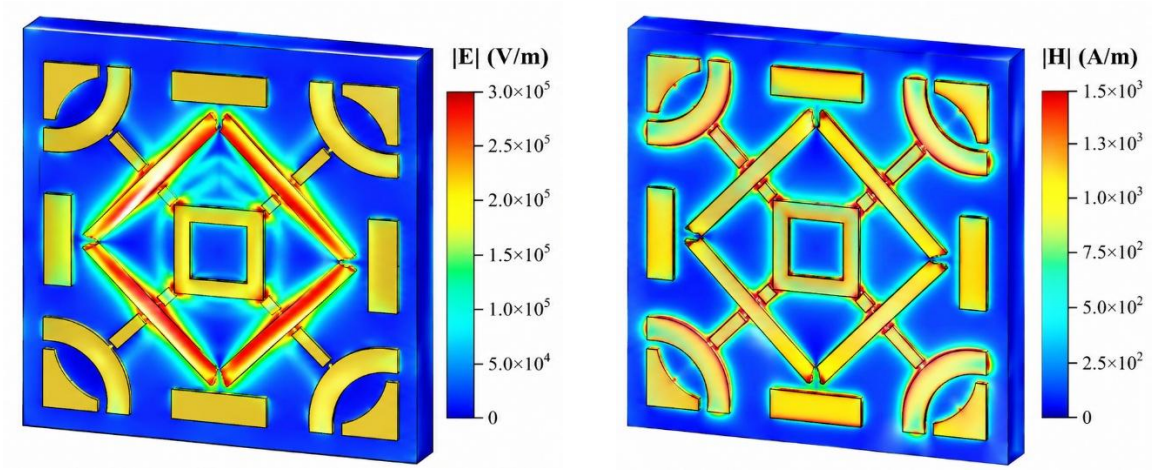


(a) (b)

Fig. 2 (a) Simulated reflection, transmission, and absorption spectra of the proposed MTM-A. (b) Real and imaginary parts of the normalized effective impedance

Fig. 3(a) shows the expected E-field focusing at edges, narrow gaps and sharp corners of the patterned gold resonator, particularly near the central square-ring structure and the adjacent

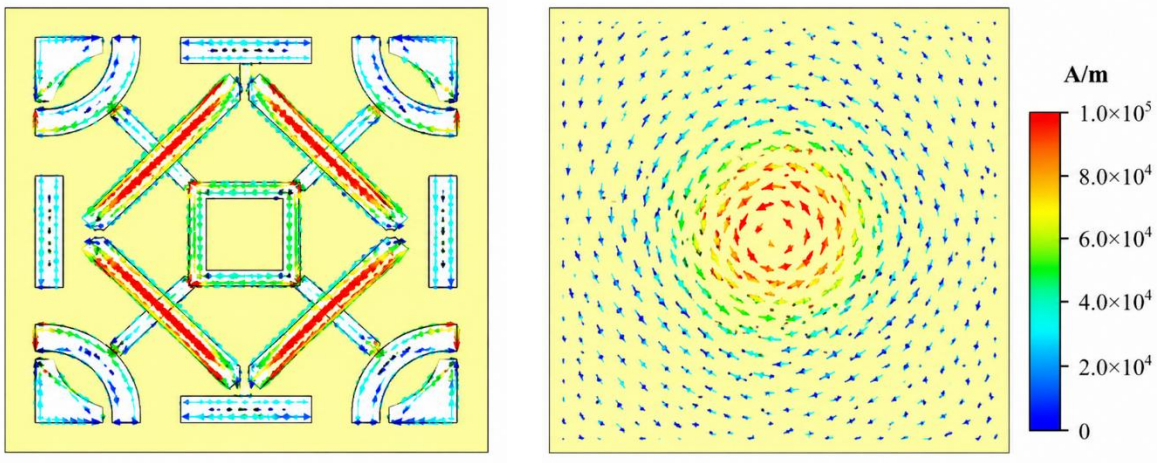
metallic elements. This localization suggests charge accumulation and better capacitive coupling. The H-field distribution is shown in Fig. 3(b) and can give information about the magnetic coupling between the resonating layer and the metallic ground plane. The combined electric and magnetic responses result in the effective LC resonance and enable impedance matching at the operating frequency.



(a) (b)

Fig. 3 Field distributions of planned MTM-A at 4.52 THz: (a) E-field (b) H-field

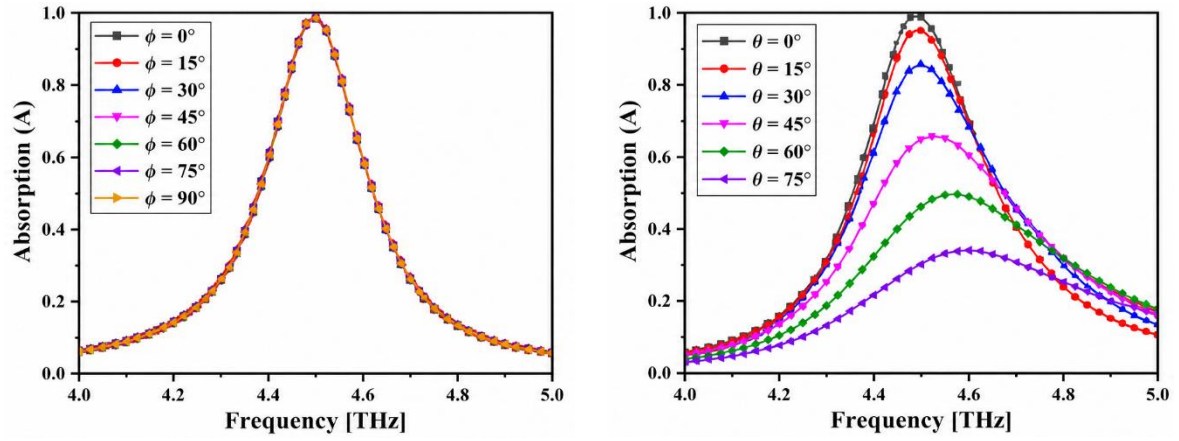
Fig. 4(a) shows the surface current distribution on the top resonating layer and Fig. 4(b) shows the induced current on the bottom ground plane. The geometry controls the effective inductance and capacitance and hence the current concentration is expected along the metallic edges, connecting strips and central resonator. It is found that the presence of antiparallel currents in the resonator and ground plane is a signature of a magnetic-dipole response, which contributes to the resonance and absorption.



(a) (b)

Fig. 4 Surface current of planned MTM-A at 4.52 THz (a) top layer and (b) bottom layer

The polarization stability is evaluated for polarization angle varied from $\emptyset = 0^0\ to\ 90^0$at normal incidence $\theta = 0^0$ as shown in Fig. 5(a). A polarization-insensitive response is expected from the symmetric resonator geometry. The result shows that the absorber has stable performance for the different orientations of the incident electric field, if the resonance frequency and absorption level are nearly unchanged in this range. Such behaviour can be explained by the geometrical symmetry of the unit cell which helps to keep similar electromagnetic coupling under different polarization conditions. The angular response is studied by varying the incidence angle (θ) as shown in Fig. 5(b). The absorption spectra are compared to study the change in resonant frequency, peak absorption and bandwidth at different incidence angles. A small variation in these parameters implies that the absorber maintains effective electromagnetic coupling at oblique incidence. However, the change of the incidence angle can also change the electric- and magnetic-field components interacting with the resonator, which may affect the absorption response.



(a) (b)

Fig. 5. Absorptivity response of planned MTM-A (a) polarization angle '$\emptyset'$ (b) incidence angle 'θ'

4. Use of Planned Unit Cell in Sensing Applications

3D structure of the proposed MTM-A is shown in Fig. 6. The MTM-A is composed of a sensing layer, metallic resonating layer, dielectric substrate, and metallic ground plane. The resonating layer interacts with incident THz waves and the ground plane suppresses transmission. The sensing layer alters the effective dielectric environment of the resonator, causing a shift in the resonance frequency that enables refractive index-based sensing. The resonance frequency is shifted by

$$f_r = \frac{1}{2\pi\sqrt{LC_{eff}}} \qquad (4)$$

Where, 'L' is the effective inductance and 'C_{eff}' the effective capacitance. The increase of the effective capacitance is usually accompanied by a change of the resonance frequency to a lower value. This frequency shift can be exploited to detect changes in the refractive index of the analyte, enabling potential biomedical sensing applications.

As seen in Fig. 7(a), $|S_{11}|$ shows a clear dip once the sensing layer is applied, reaching approximately −30 dB at around 4.43 THz. Without the sensing layer, the minimum value is about −24 dB at around 4.55 THz. The shift toward lower frequency in the presence of the sensing layer indicates a change in the effective dielectric properties of the resonator.

The corresponding absorption spectra are shown in Fig. 7(b). The maximal absorption is approximately 0.98 with the sensing layer and 0.88 without it. The shifting of the absorption peak to a lower frequency reflects the sensitivity of the MTM-A to the change of its surrounding dielectric environment.

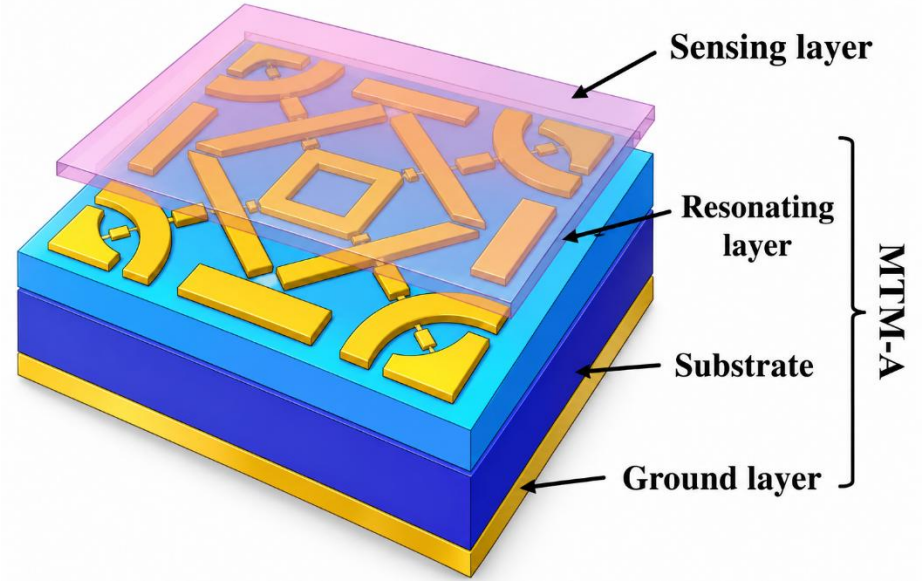
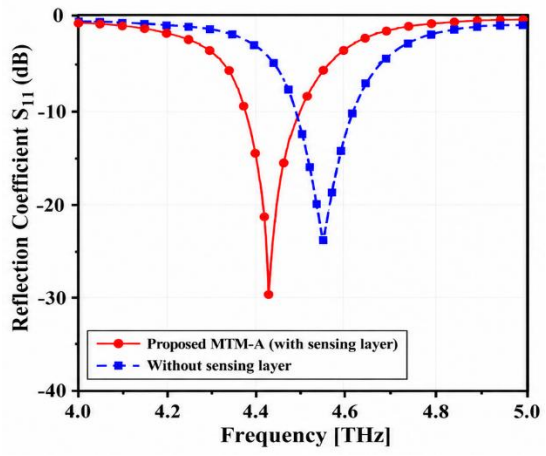
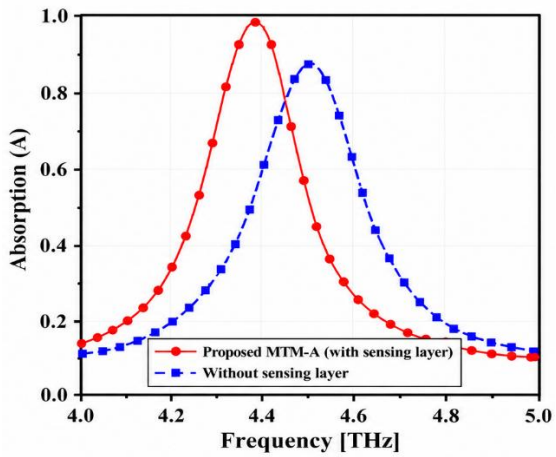


Fig. 6 3D structure of planned MTM-A with a sensing layer



(a)



(b)

Fig. 7 Comparison of planned MTM-A with and without the sensing layer: (a) S_{11} and (b) absorption

The sensing capability of the proposed structure is evaluated using two prominent performance indicators, sensitivity and figure of merit (FOM). Sensitivity is defined as the change in resonant frequency due to the change in the parameter of the material under study. It is mathematically written as follows [10]:

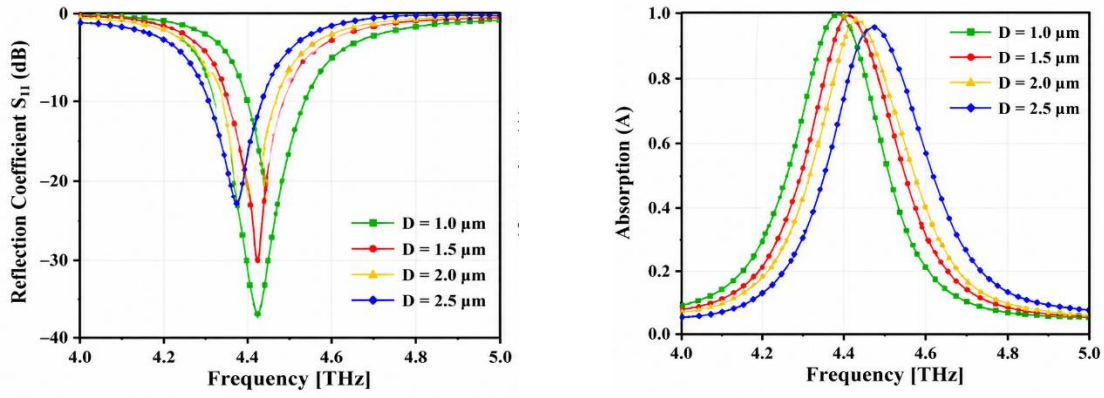
$$S = \frac{\Delta f}{\Delta P} \tag{5}$$

Here, (Δf) is the resonance frequency shift and (ΔP) is the corresponding change in the sensing parameter, for example the sample layer thickness or the refractive index. To more comprehensively evaluate the sensor performance, the figure of merit (FOM) is used to consider both the sensitivity and the resonance sharpness, and is defined as [15]:

$$FOM = \frac{S}{FWHM} \tag{6}$$

$|S_{11}|$ of planned MTM-A for different sensing-layer thicknesses (D=1.0, 1.5, 2.0, and 2.5 μm) is shown in Fig. 8 (a). With increasing thickness, the resonant frequency shifts which implies that the dielectric loading introduced by the sensing layer influences the electromagnetic response of the resonator. The minima of the reflection also change in depth, which points to a change of the impedance matching at resonance. The corresponding absorption spectra are shown in Fig. 8(b). The absorption peak moves to higher frequencies as (D) increases. It is interesting to note that the peak absorption is close to unity for all four thicknesses. This means that the resonant frequency and spectral response are affected by the thickness of the sensing-layer with good absorption. These changes are due to changes in the effective dielectric environment and capacitive coupling between the sensing layer and the resonator.

The results show that the proposed MTM-A is sensitive to the changes of sensing-layer thickness in general. This behaviour is relevant for sensing applications since analyte thickness can affect the resonant response. A sample thickness of 1.5μm is chosen for the refractive-index measurements as a reasonable compromise between sensing efficiency and structural stability.

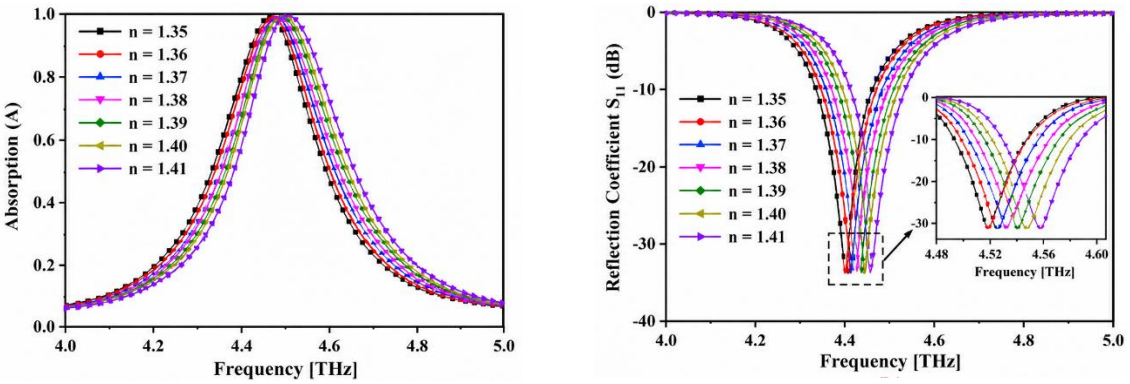


(a) (b)

Fig. 8 Effect of sensing-layer thickness 'D' on planned MTM-A (a) $|S_{11}|$ (b) Abroption

Fig. 9 (a) shows that the absorption spectra exhibit a gradual shift in the resonance peak as the refractive index of the sensing layer is increased from (n=1.35) to (n=1.41). However, the maximum absorption is still close to unity for the curves shown. The absorption peak shifts to higher frequency. This means that the resonator is sensitive to changes of the dielectric properties of the surrounding sample. The corresponding $|S_{11}|$ spectra are shown in Fig. 9 (b). As the refractive index increases, the minima of the reflection are shifted to higher frequencies, which confirms the effect of the sensing layer on the resonant response of the MTM-A. In the inset the resonance region is zoomed in to make the frequency shifts clearly visible.

The sensing mechanism is based on the changes of the effective permittivity and capacitance induced by the analyte. The obtained resonance frequency shift can be used for estimating the refractive index of the sample. The sensitivity can be expressed as ($S=|\Delta f/\Delta n|$), with $'\Delta f'$ being the shift in resonance frequency and 'Δn' the change in refractive index. The results show the feasibility of the proposed MTM-A for refractive-index-based sensing in the 4-5 THz range.



(a) (b)

Fig. 9 Refractive-index sensing performance of the proposed MTM-A (a) Absorption (b) $|S_{11}|$

The performance of the proposed metamaterial absorber (MTM-A) in the refractive index range of 1.35 to 1.41 for the refractive index sensing is summarized in Table-1. As the refractive index increases, the resonance frequency shifts from 4.46 THz to 4.54 THz. This indicates the absorber is sensitive to the change of the dielectric environment of sensing layer. The Q-factor is slightly increased from 10.55 to 10.63, indicating that the resonance characteristics are relatively stable over the investigated range. The sensing sensitivity is calculated in the range of 0.48-0.55 THz/RIU, showing the feasibility of the proposed structure to detect the variation of refractive index. Furthermore, the FOM are within 1.42 to 1.53 RIU^{-1}, which represent the sensing performance in terms of the sharpness of the resonance. Overall, the results indicate that the proposed MTM-A is a promising candidate for refractive-index sensing applications in the 4–5 THz frequency range.

Table-1 Refractive Index Sensing Properties of Planned MTM-A

n (RIU)	f_r (THz)	Q-factor	Sensitivity [THz/RIU]	FOM [RIU^{-1}]
1.35	4.46	10.55	-	-
1.36	4.47	10.56	0.55	1.51
1.37	4.48	10.57	0.54	1.45
1.38	4.49	10.59	0.52	1.42
1.39	4.5	10.6	0.5	1.48
1.4	4.52	10.61	0.49	1.5
1.41	4.54	10.63	0.48	1.53

In addition, the refractive-index sensing results are analysed to assess the capability of the suggested MTM-A to distinguish between healthy and infected biological samples. The method is based on the detection of the effective refractive index changes of biological analytes through the corresponding changes of the resonance frequency. The frequency domain analysis is very useful because the dielectric response of biological materials is affected by the incident electromagnetic waves due to the molecular motions such as stretching, bending and collective vibrational modes [22].

Fig. 10(a)–(d) shows the absorption responses of healthy and cancer-affected cells for basal, cervical, breast, and blood cancer, and compares them with the proposed MTM-A. Variations of the cellular composition and dielectric properties alter the effective refractive index giving rise to detectable shifts of resonance frequency. Magnified views of these shifts are shown in the insets, which show the potential of the absorber for refractive index-based biosensing. But the modified design 4-5 THz requires its own simulation data to confirm the resonance

frequencies and sensitivity values. The ability of the proposed MTM-A to discriminate the healthy and cancerous samples based on their resonance responses that depend on the refractive index is summarized in Table-2. The response of the basal cell varies from 4.56 THz to 4.49 THz and the response of the cervical cell varies from 4.53 THz to 4.498 THz. For breast cells, the resonance frequency changes from 4.55 THz to 4.491 THz and for blood cells, it changes from 4.57 THz to 4.52 THz. These changes indicate that the sample dielectric properties influence the absorber resonant behaviour. The sensitivity is reported to be in the range of 0.49–0.54 THz/RIU and the FOM varies from 1.451 to 1.535 RIU^{-1}. The results demonstrate the potential of the proposed MTM-A for refractive-index-based biosensing in the 4-5 THz range.

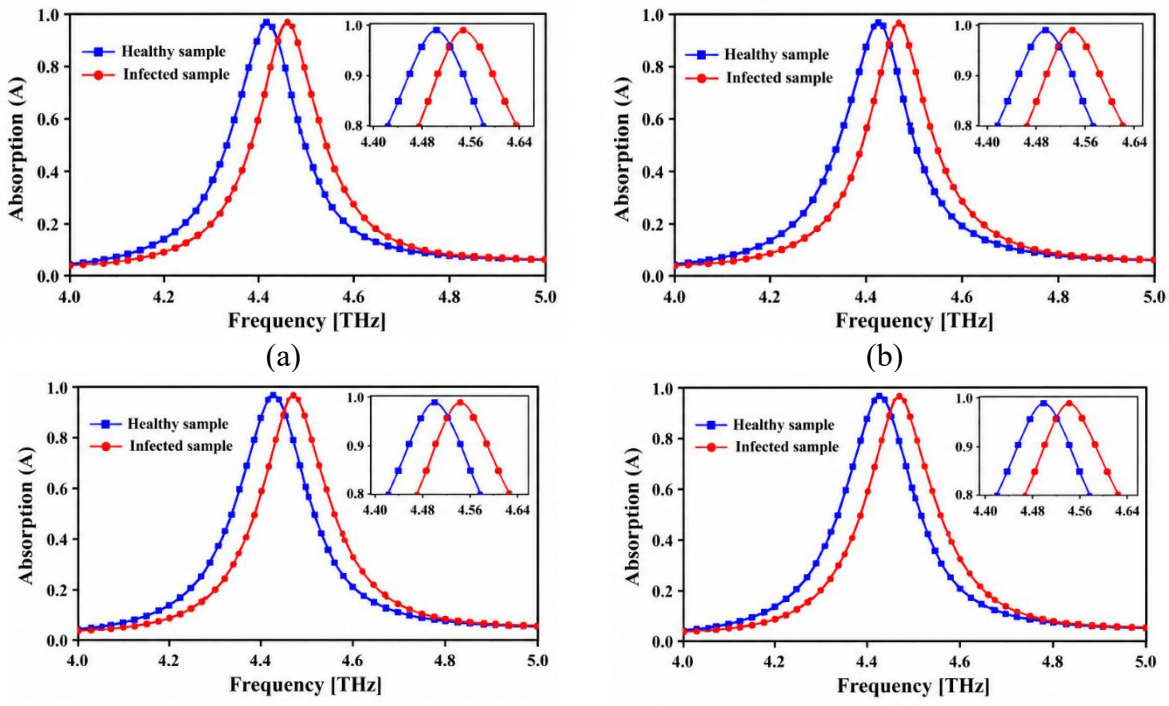


Fig. 10 Absorption spectra comparing healthy and cancer-affected biological samples: (a) basal cell, (b) cervical cell, (c) breast cell, and (d) blood cell

Table-2. Detection metrics for the proposed MTM-A biosensor

Cell type	Sample condition	n (RIU)	fr (THz)	Sensitivity (THz/RIU)	FOM (RIU^{-1})
Basal cell	Healthy	1.36	4.56	0.53	1.53
Basal cell	Cancer-affected	1.38	4.49		
Cervical cell	Healthy	1.368	4.53	0.49	1.451
Cervical cell	Cancer-affected	1.392	4.498		
Breast cell	Healthy	1.385	4.55	0.54	1.535

Breast cell	Cancer-affected	1.399	4.491		
Blood Cell	Healthy	1.351	4.57	0.51	1.482
Blood Cell	Cancer-affected	1.390	4.52		

Table-3 presents the summary of the performance of the proposed metamaterial absorber (MTM-A) with the previously reported metamaterial absorbers in terms of unit-cell dimensions, resonance frequency, absorption efficiency, sensitivity, polarization response and sensing applications. The proposed MTM-A works at about 4.52 THz which is in the terahertz frequency range of biomedical sensing. The absorption level is reported provisionally at about 99.7% pending validation with the final simulation data. The proposed absorber works at a higher resonance frequency than most of the reported structures and is designed for refractive-index-based biosensing in comparison with the listed designs. However, its sensitivity and polarization-insensitivity need to be verified before a definitive performance advantage can be claimed. To conclude, the comparison shows the potential of the proposed MTM-A for terahertz biosensing, while further validation is required to demonstrate its advantages over the existing designs.

Table-3. Comparison of the Proposed MTM-A with Previously Reported Metamaterial Absorbers

Ref.	Unit-cell size (μm³)	Resonance frequency (THz)	Absorption (%)	Sensitivity (THz/RIU)	Polarization-insensitive	Application
[8]	150 × 150 × 100	1.757	99.9	0.104	Not specified	Temperature and refractive-index sensing
[9]	80 × 80 × 50	1.025–1.535	Not reported	0.278	Not specified	Biological sample detection
[10]	94 × 94 × 65	1.312–1.538	Not reported	0.280	Yes	THz metamaterial sensing
[11]	80 × 80 × 9	3.664	86.6	0.214	Yes	Blood cancer detection
[12]	100 × 120 × 3.5	1.672	96	0.374	Yes	Biomedical sensing
Proposed	50 × 50 × 6.0	4.52	99.7	0.51	Yes	Refractive-index-based biosensing

5. Conclusion

This paper proposes an ultra-thin polarization-insensitive metamaterial absorber (MTM-A) for terahertz biomedical sensing at 4–5 THz frequency range. The proposed structure consists of a patterned gold resonator, a dielectric substrate of SiO2, and a continuous gold ground plane. Numerical results show that the peak absorption could reach up to 99.7% at 4.52 THz, which is attributed to the good impedance matching and strong electromagnetic confinement. The sensing analysis shows that changes in the analyte refractive index alter the resonance frequency, permitting the detection of dielectric property changes. Furthermore, the proposed sensor is studied to discriminate between healthy and cancerous biological samples in terms of their absorption responses. The obtained sensitivity, quality factor, and figure of merit suggest the potential for sensing based on refractive index. In general, the proposed MTM-A can be a promising platform for compact label-free THz biosensing.

Declarations

***Ethics approval and consent to participate: Not Applicable**

*** Consent for publication: I, Voruganti Santhosh Kumar, give my consent for the publication of identifiable details, which can include photograph(s) and/or videos and/or figures and/or details within the text ("Material") to be published in the above Journal and Article**

*** Availability of data and materials:** Not Applicable

*** Funding:** No funds, grants, or other support was received.

*** Authors' contributions:** Conceptualization and Methodology [G. Karthik Reddy and Bhukya Shankar]; Writing - revised draft preparation: [A. Dinesh Kumar]; Analysis and Investigation: [Krishna Dharavath and G. Karthik Reddy]; Writing - original draft preparation and Supervision: [Voruganti Santhosh Kumar]

*** Disclosure of potential conflicts of interest:** There are no potential conflicts of interest.

*** Research involving Human Participants and/or Animals: Not Applicable**

*** Acknowledgements: Not Applicable**

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