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Terahertz Electromagnetic (EM) Wave Absorber Based Biological Sensor for Cancer Detection Application

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Abstract

This work presents a terahertz metasurface absorber-based biomedical sensor for cancer cell detection applications. The proposed metasurface structure is designed using the metallic split annular ring on GaAs substrate, which offers more than 97% absorption at 3.77 THz with the FWHM absorption bandwidth and Q factor of 110 GHz and 34.27, respectively. The absorption mechanism inside the THEMWA is exploited with the help of a normalized input impedance (Z_{eff}) plot and electric and magnetic coupling. Four-fold symmetry inside the resonator makes this structure's polarization insensitive. This study further uses this proposed structure as a sensor where cancer cells are detected by the shift of resonance frequency caused by variations (changes) in the refractive index of biological samples placed on top of the absorbers. The simulation's output demonstrates that the proposed structure's resonance frequency shifts from 3.608 THz to 3.59 THz with a change in refractive index from 1.35 to 1.40. This TEMWA-based sensor offered high sensitivity and FOM of 360 GHz/RIU and 3.273, respectively, which make this proposed structure a good candidate for refractive index-based biomedical sensors for cancer detection applications.

1. Introduction

Metasurfaces are artificially designed resonating structures that can be employed for transmission or reflection-based polarization conversion [1], wavefront control and gain enhancement of planar antennas [2], 1 D and 2- D leaky wave antenna design [3] and absorption of electromagnetic (EM) waves [4]. Metasurface or FSS-based EM absorbers generally consist of three layers: a metasurface pattern (resonating pattern), a dielectric substrate (spacer), and a complete metal [4]. These absorbers can be potentially used for RF imaging (mainly in THz and Infrared), stealth/RCS reduction application and radiative cooling [5]. Terahertz (THz) radiation [5] is the frequency range between the microwave and infrared bands, spanning from 0.1 to 10 THz. THz waves do not usually interact with natural materials, but artificial designed metasurfaces structures have given us a new way to do so. THz technology offers significant application possibilities in a variety of sectors, including broadband communications, the medical field, chemistry, and detection. Among these applications, terahertz sensing is expected to play a significant role in the identification of materials and due to this, In the past few years, metasurface-based absorbers have been getting a lot of attention.

The first planar metamaterial absorber was created by Landy et al. in 2008, and it had an absorption of approximately 100% in the microwave band [6]. In the latter part of the same year, Hu Tao et al. [7] suggested an absorber consisting of a branch line and a ring resonator separated by a dielectric. Based on Landy's observations, the first THz metamaterial absorber was presented in 2009 by scaling down the unit cell dimensions at the micron level. This absorber is designed using an electrically coupled ring resonator (ECL) on the grounded substrate, which achieves the absorption of nearly 95% at 1.13 THz [8]. After that, this suggested absorber opened up a new avenue for studying metamaterial absorbers. Following this, other metasurface-based perfect absorption techniques with working ranges in the microwave to visible light wavelength band have been developed [5]. In recent years, metamaterial/metasurface based absorbers have introduced a new sensing technique that has found widespread use in fields as diverse as medical diagnostics, environmental analysis, and food quality control. In 2014, Cong et al. [9] developed TEMWA-based sensors with a sensitivity of 163 GHz/RIU ((refractive index unit)), a Q-factor of 7, and a FOM of 2.63. After that, another THz metamaterial-based sensor with a sensitivity of 4.05 x 10^-2 GHz/nm is presented in [10]. This sensor makes use of a metamaterial structure on a thin substrate for sensing purpose. Similarly, for DNA detection application, [11] presents a biosensor based on a metasurface that has a frequency shift of 3.6 GHz. Thereafter, Wang et al., [12] presented a polarization insensitive metasurface based THz biosensor with the sensitivity of 95 GHz/(mmol/L). Most of the sensors mentioned above have complex structure and low sensitivity. However, the absorber for sensing application required high sensitivity and FOM.

In this work, a terahertz metasurface absorber (THEMWA)-based biomedical sensor for cancer cell detection applications is presented. In this work, study of this absorber as a sensor for cancer detection application is also presented. The proposed metasurface structure resonating at 3.77 THz frequency and offers than 97% absorption with the Q-factor and of 34.27 and full width half maximum (FWHM) bandwidth of 0.11 THz.

Additionally, this unit cell possesses a fourfold symmetry, making it insensitive to the polarization of incidence EM wave. Along with these, the proposed structure has of low value of co and cross reflection at 3.77 THz which leads to maximum absorption and low value polarization conversion. Here, Electric coupling (with the help of E-field distribution), magnetic coupling and input impedance of the proposed unit cell is utilized to explain the absorption mechanism inside the structure. For the analysis of sensor application, a 5-micrometer thin biomedical analyte (sample) is placed on the top of the absorber. Here, this absorber is simulated for different value of refractive indices (1.35-1.4) for biomedical analytes and offers the sensitivity (S) of 0.36 THz/ RIU with quality (Q)-factor and FOM of 34.27 and 3.273, respectively.

2. Design of Proposed Absorber Unit Cell: The proposed THEMA is designed using three layers: the top layer is a metasurface pattern (metallic split annular ring), the bottom layer is complete gold metal, and these both the layers are separated by a Gallium Arsenide (GaAs) substrate with the thickness, dielectric constant, and loss tangent of 10 micrometers, 12.94 and 0.006, respectively. Here, Simulia's CST microwave studio software is used to simulate the proposed THEMWA unit cell in the frequency domain solver. To simulate this structure, the unit cell boundary conditions are taken in the XY direction, and the free-space boundary condition in the Z direction is taken. Fig. 1 depicts the front and side views of the proposed unit cell with the unit cell's dimensions and full absorber grid.

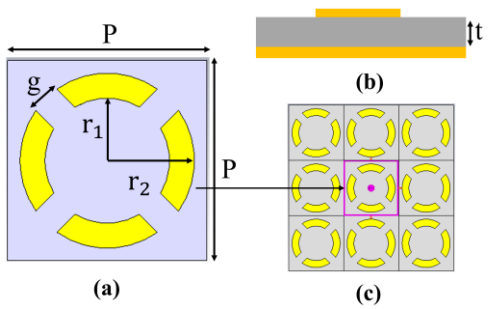


Fig. 1 **(a)** Front view **(b)** side view of proposed unit cell **(c)** complete absorber grid design by repetition of unit cell in X and Y direction (P = 80, g = 12, r_1 = 25, r_2 = 35, and t = 6; all dimension in micrometer)

It is visible from Fig.1 (b) that the THEMA unit cell has complete metal on the bottom side, and due to this, there is no transmission through the structure. However, the combination first, the second and third layer of the proposed unit cell at its resonance frequency provides the matching condition. This matching condition further reduces reflection, which leads to maximum absorption at the resonance frequencies. The absorption of this presented metasurface structure can be calculated using the absorption's equation given in [13]. The proposed THEMA unit cell's simulated reflection coefficient and absorption are depicted in Fig.2 (a) and (b), respectively. It is observed from Fig. 2 (a) that the proposed unit cell resonates at 3.77 THz frequency and offers the low value of co and cross reflection at the same frequency, which leads to nearly 100 % of absorption at 3.77 THz frequency with the FWHM bandwidth and Q- factor of 110 GHz and 34.27, respectively.

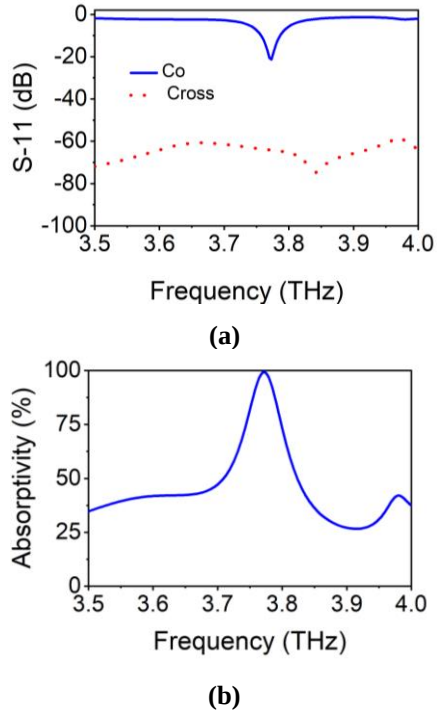


Fig. 2 Simulated **(a)** co/cross reflection coefficient and **(b)** absorptivity of the proposed unit cell under normal angle of incident

The slot gap (g) and inner radius (r_1) are the two most important design parameters, which change can bring a significant change in the resonance (absorption) frequency of the proposed unit cell. Therefore, to analyze the effect change of 'g' and 'r_1' on the absorption/reflection coefficient frequency, the reflection coefficient is calculated for different values of 'r_1' and 'g' and shown in Fig. 3 (a) and (b), respectively. Fig. 3 (a) shows that the resonance frequency of the proposed metasurface shifted from higher to lower as 'r_1' increased from 15 to 30 µm. As the 'r_1' increases, the inductance offered by the metasurface pattern increases. Hence, resonance frequency shifted from the higher to the lower side.

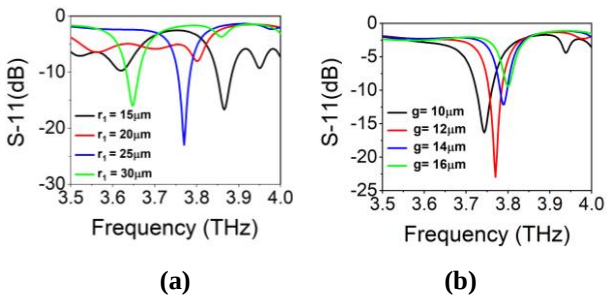


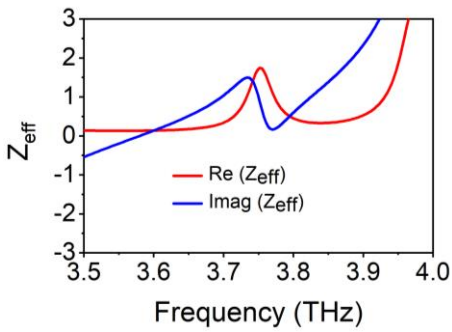
Fig. 3 Effect of change of dimensional parameters **(a)** 'r_1' and **(b)** 'g' on the resonance frequency

Similarly, it can be noted from Fig. 3 (b) that when 'g' increases from 10 to 16 µm, the resonance frequency shifts lower to the higher side. This shift in resonance frequency

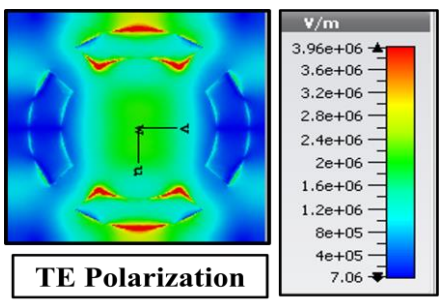
happened due to a reduction in capacitance with respect to an increment in the slot gap 'g'.

3. Absorption Mechanism in the Proposed structure and Its Application as a Sensor

3.1 Absorption mechanism inside the absorber: Here, the absorption mechanism of the proposed THEMWA unit cell is explained (exploited) with E-field, surface current distribution (J_s) and effective impedance (Z_{eff}) plot. Here, Z_{eff} (ω) is the normalized input impedance (Z_{in}) of the proposed structure at air-absorber interface (Here, free space impedance Z_0 = 377 Ω is used as a normalization factor). Fig.4 (a), (b), and (c) show the Z_{eff}, E-field distribution (on top of the unit cell @ 3.77 THz), and surface current distribution of the proposed THEMWA unit cell. It can be noted from the Z_{eff} plot shown in Fig. 4 (a) that the value real (Re (Zeff)) and imaginary (Imag (Z_{eff})) parts of the Zeff are 1 and 0, respectively. This confirms the matching conditions that leads to minimal reflection and maximum absorption. The E-field distribution the proposed THEMWA unit cell shown in Fig. 4 (b) demonstrates that, in the case of TE Polarization, the E-field is mostly stimulated on the upper and lower arms of the resonator, which indicate the electric coupling at 3.77 THz. This can be seen in Fig. 4(c) that the excited surface current at the top and bottom surfaces of the proposed THEMWA unit cell are flowing antiparallel to one another at 3.77 GHz, forming a closed loop that denotes the magnetic coupling. The simultaneous electric (E) and magnetic (H) coupling at the resonance frequency signifies (implies) the electromagnetic coupling or absorption of the electromagnetic wave at 3.77 THz frequency.



(a)



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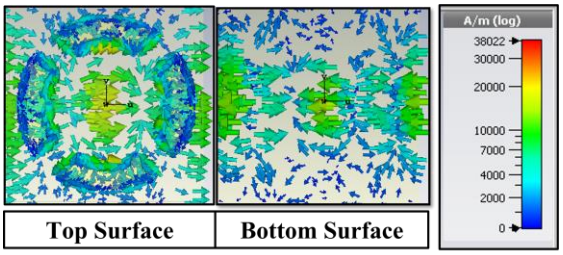


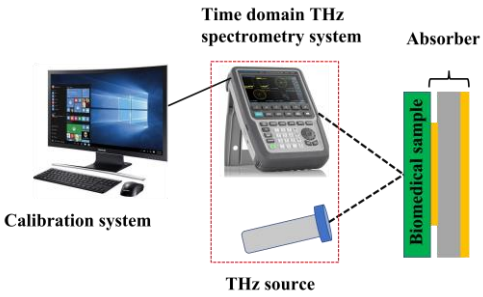
(c)

Fig. 4 **(a)** Calculated normalize effective input impedance over 3.5 – 4.0 THz frequency band **(b)** E-field distribution and **(c)** surface current distribution of THEMWA unit cell at 3.75 THz

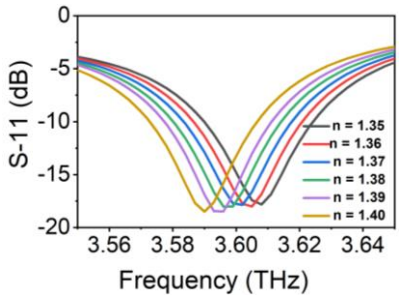
3.2 Application of THEMWA as a sensor for detection of cancers cell: For sensing applications, the shift of the absorption peak (resonance frequency) due to a change in the medium's index of refraction has been exploited here. Fig 5 (a) depicts the schematic for THEMWA sensors for cancer detection (which consist of absorber with biomedical sample placed on the top of the absorber). It can be noted from the Fig.5 (a) that the if the refractive index (n) of the biomedical sample (analyte) is change, the effective refractive index of the medium will also change which vary (change) the frequency of absorption/resonance. Fig. 5 (b) depicts the change in the resonance frequency due to changes in 'n' of biological sample placed just above the proposed absorber structure. This proposed sensor system (absorber + biomedical analyte) is a good refractive index sensor since the absorption peaks vary significantly for a little change in the 'n'. The majority of biological samples have a value of 'n' is around 1.35 [14]. For example, healthy human blood has a value of 'n' (refractive index) is 1.35, whereas the value of a refractive index of T-type leukemia-infected blood has 1.39 [14]. As a result, the reflection coefficient of the absorber is determined for various value of refractive index ('n') ranging from 1.35 to 1.40 in the interval of 0.01 and is shown in Fig. 5. (b). Fig. 5 (b) shows that increasing the refractive index of the medium decreases the resonance frequency and vice versa. Therefore, the cancer and its type can be detected with the help of the proper calibration of the shift of the absorber's resonance frequency [5]. The resonance frequency plot of absorber-based sensor over the refractive index is depicted in Fig. 5(c). The sensitivity (S) is one of the important design parameters of the sensors and it can be calculated using the Eq. No-1.

$$S = \frac{\Delta f}{\Delta n} \qquad (1)$$

Here, the sensitivity of the proposed sensor can be calculated with the help of above formula by differentiating the plot given in Fig.5 (c) and the calculated value of sensitivity (S) of this proposed sensor is 360 GHz/RIU.



(a)



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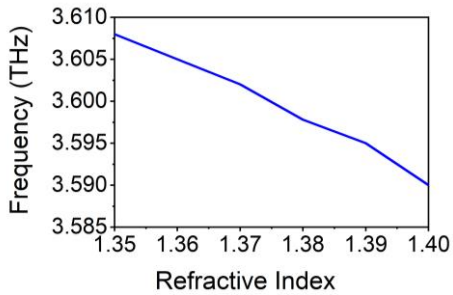

(c)

Fig. 5 **(a)** Schematic for cancer cell detection using THEMW Absorber **(b)** reflection coefficient of proposed sensor for different value of refractive indices, and **(c)** sensitivity plot of proposed unit cell

4. Conclusion: In this work, THEMWA based biological sensor is presented. The simulation results show that the proposed structure resonates at the Frequency of 3.77 THz with the absorption of 100%. The proposed absorber has FWHM bandwidth and Q-factor of 110 GHz and 34.27, respectively. Here, the absorption mechanism inside the proposed THz metasurface absorber is illustrated with the help of Z_{eff} plot, and electric (E) and Magnetic (H) coupling. In this study, cancer cells were detected using the shift in resonance frequency caused by variations (changes) in the refractive index of biological samples placed on top of absorbers. Based on the simulation, it is determined that a change in refractive index from 1.35 to 1.40 results in a shift in the resonance frequency of the proposed structure from 3.608 THz to 3.59 THz. Simulation results also confirm that the proposed structure offered high FOM and sensitivity of 3.27 and 360 GHz/RIU, respectively which make this sensor a good candidate for refractive index based biomedical sensors for cancer detection applications.

5. References

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