Terahertz metamaterial absorber with sensing capabilities

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We have designed a terahertz highly sensitive plasmonic sensing device. According to the concept of the sensing phenomena, we have chosen the cylindrical metal structure which is independent to the polarization of the incident wave. To analyse its sensing functionality we employ the magnetic resonance. The amplitude modulation and a shift in the resonant frequency of the terahertz transmission have been done by depositing a thin film overlayer on the surface of the metallic apertures. Refractive index and the thickness of the overlayer is the main reason to investigate the frequency shift and the amplitude modulation for deciding the sensing capability of the proposed structure. From this analysis, we obtained that the proposed absorber provided the better sensing which is used for biological applications.

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1. Introduction

Metamaterials, on the sub-wavelength scale, have attracted intense attention because of their unique properties that are not available in nature, like cut wire pairs [1], perfect lensing [2], invisibility cloaking [3], fishnet structures, negative index of refraction [4] and Split ring resonators [5]. The first perfect metamaterial absorber is proposed by Landy et al., with the absorptivity of about 88%, which consists of a cut wire and a metallic split ring separated by a dielectric substrate [6].In most designs, the absorption loss of the metamaterials absorbers leads to degrading their performance but in the artificial absorber, the absorption loss becomes important and it can be increased by proper design of the structure. Unfortunately, these all have the same shortcomings of single-band absorption, which are not enough for their practical applications [7]. In many applications such as THz imagers and detectors, an absorber with tri-band or multi-band is required, because the detector based multi-band absorber can be used to increase imaging resolution and the detection sensitivity also decrease the environmental disturbance and realize the frequency selective detection. Initially, most theoretical and modelling explanations only came from many researchers then the applications-oriented research is increased such as sensor [8], super lenses, energy harvesting, perfect absorbers [9], thermal emitter, antireflection Coating, and high refractive index materials, solar cells. To make the metamaterials absorbers resonate at some discrete frequencies then only we will get a number of absorption peaks. According to this strategy, microwave [9], infrared [10], optical [11] also Terahertz triple-band [12] or multiple-band [13] and broadband metamaterial absorbers [14] have been demonstrated also the stacked structure provides the multiband operation. By measuring the resonance of the metamaterials we will analyse the sensing of the metamaterials, such as the depth of the position and shift of the resonance position done by the analyte approaching them. Resonant responses are varied so it created the alteration in transmission and reflection signals when the analyte is established on top of the metamaterial absorber [15]. These changes can be easily detected and determined the attributes of the analyte effectively like the concentration of mass in a bio-chemical compound. Terahertz sensing application is difficult because of a terahertz wave-matter interaction, and terahertz source resolution limitations. To identify the amount of bio-chemical and chemical substances can be done by using Terahertz metamaterials sensor [16].

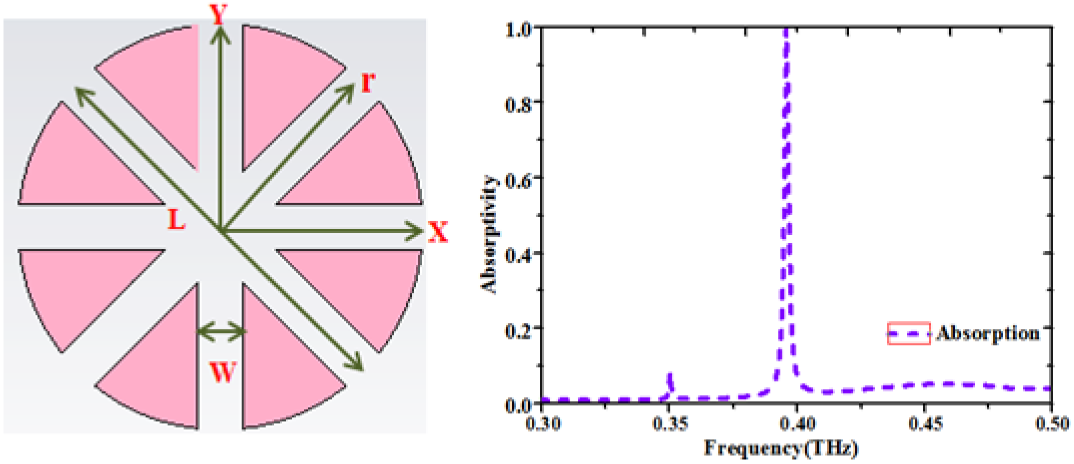

Fig.1. (a).Geometrical parameters of the metamaterial unit cell (r=0.16mm, l=0.32mm, w=0.036mm), 1(b) Absorption curve for the proposed absorber (color online)

In this paper, we have designed a highly sensitive plasmonic sensing device in the terahertz regime that provides more advantages. This structure removes the fabrication difficulty. We numerically explained the performance of the device in terms of sensing technology. To add a dielectric material with an original structure the absorptivity of the structure is varied according to the changes in the refractive index and the thickness of the analyte.

2. Structure and sensor design

Fig. 1 presents the proposed plasmonic metamaterial sensor configuration and the single unit cell used in the simulation at terahertz regime. The electromagnetic characteristic of the sensor design is characterized by using CST Microwave Studio software in the frequency domain. The polyimide of thickness 0.125mm is placed in-between the ground metallic plane and a metamaterial absorber structure. The Terahertz plasmonic sensor device chosen in this work is a cylindrical metal structure. The etched shape from the cylindrical structure is indicated at L, W from the Fig. 1 (a).The radius of the circular ring is 0.16mm also the width and length of the etched shape is 0.036mm and 0.32mm respectively, X and Y represents the axis direction of the proposed absorber. Fig. 1 (b) represents the absorptivity of the proposed terahertz absorber is about 99.5% at the 0.3956THz frequency. This structure is a resonance at the 0.3956THz frequency according to the geometrical parameters. A loss in materials and fabrication difficulties only limits the scalability of the structure. The proposed terahertz absorber is rotational symmetry so that the polarization direction is insensitive to the incident wave direction. In order to see the proposed terahertz absorber ability, we continuously change the dielectric properties in the surrounded medium [17]. According to the changes in the analyte refractive index (RI) and thickness (t) the corresponding outputs are monitored to analyse the sensing capability of the absorber [18]. This creates the amplitude modulation and frequency shift in the resonance conditions and transmission curves.

The incident electromagnetic response of the structure is identified by using finite element method based numerical analysis. The electric and magnetic field of the sensor structure was illuminated by x and y-axis respectively which is parallel to the fields. Periodic boundary conditions are applied in a correct manner in order to simulate the structure. In order to identify the sensing behaviour, the electric field, magnetic field and surface current distributions in the structures are simulated.

3. Performance evaluation of the plasmonic sensor

Polyimide is a commercially available substrate which is placed over the top surface of the proposed terahertz plasmonic sensor structure in order to identify the sensing characteristics. Corresponding to the refractive index value (RI=1.41) the thickness of the substrate is 50µm and the dielectric constant value is 2.Here particularly this value is chosen according to the biological applications. For example, the refractive index of the biomolecules in RNA varies from 1.6 to 2and in the DNA varies from 1.4 to 1.6 [19-20]. Fig. 2. shows the metamaterial frequency response of coated (green dotted line) and uncoated (pink dotted line) metamaterial terahertz sensor.

The original structure is a resonance at the 0.3956THz frequency. If we add the analyte for the thickness of 0.05mm to the top surface of the structure we got the resonance at a 0.3876THz frequency. So the simulated resonance frequency is green shifted from 0.3956 down to 0.3876 in the simulation. The performance of the sensor is analysed by the refractive index value. 0.05mm thick analyte layer RI value is chosen from one to two with a step size of 0.2. Each analysis for RI (1-2) the absorption rate and frequency value is continuously monitored and saved. The sensing mechanism using analyte is quantified by an amplitude modulation and frequency shifting of the resonance mode. If we increase the refractive index value gradually the frequency is shifted to a lower value because the optical thickness of the substrate is increased. The amount of frequency shifting is calculated by the difference between the resonant frequencies with the analyte refractive index and frequency without analyte. If the refractive index of the analyte increases linearly with the frequency shift of the resonant mode decreases linearly this is shown in Fig.3 (a).

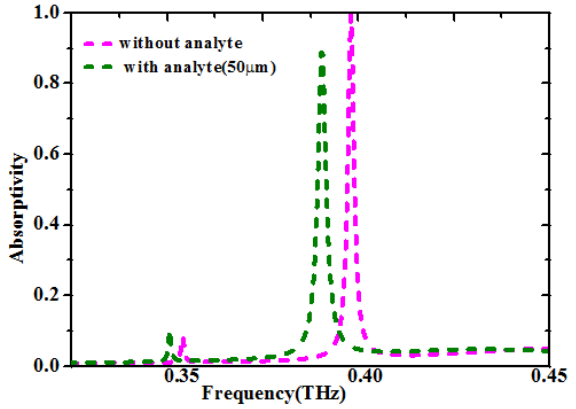

Fig.2. (a) Simulated absorption curves with a 50-μm-thick analyte and without analyte (color online)

Similarly, the amplitude of an absorption curve varies with respect to the analyte refractive index value. This amplitude modulation is defined as the difference between the amplitude of the resonant frequency mode with analyte and the amplitude of the resonant mode without analyte which is shown in Fig. 3 (b).after analysed the performance of the amplitude modulation for the 0.05mm fixed thickness of analyte, we got the better amplitude sensitivity at the refractive index value is below 1.6. So, we clearly investigated the importance of the thickness of analyteon the characteristic of the plasmonic terahertz sensor through detailed simulations using CST Microwave studio software. Now the original structure is loaded with the thin substrate according to the refractive index value of 1.41 with the dielectric constant value of 2.The thickness of the thin analyte is gradually increased from 0.01mm to 0.05mm with a step size of 0.01mm. Each analysis for analyte thickness (0.01mm-0.05mm) the amplitude rate and frequency value is continuously monitored and saved. According to the analyte thickness, the frequency shifting and the amplitude are modulated which is shown in Fig. 3(c) and Fig. 3 (d).

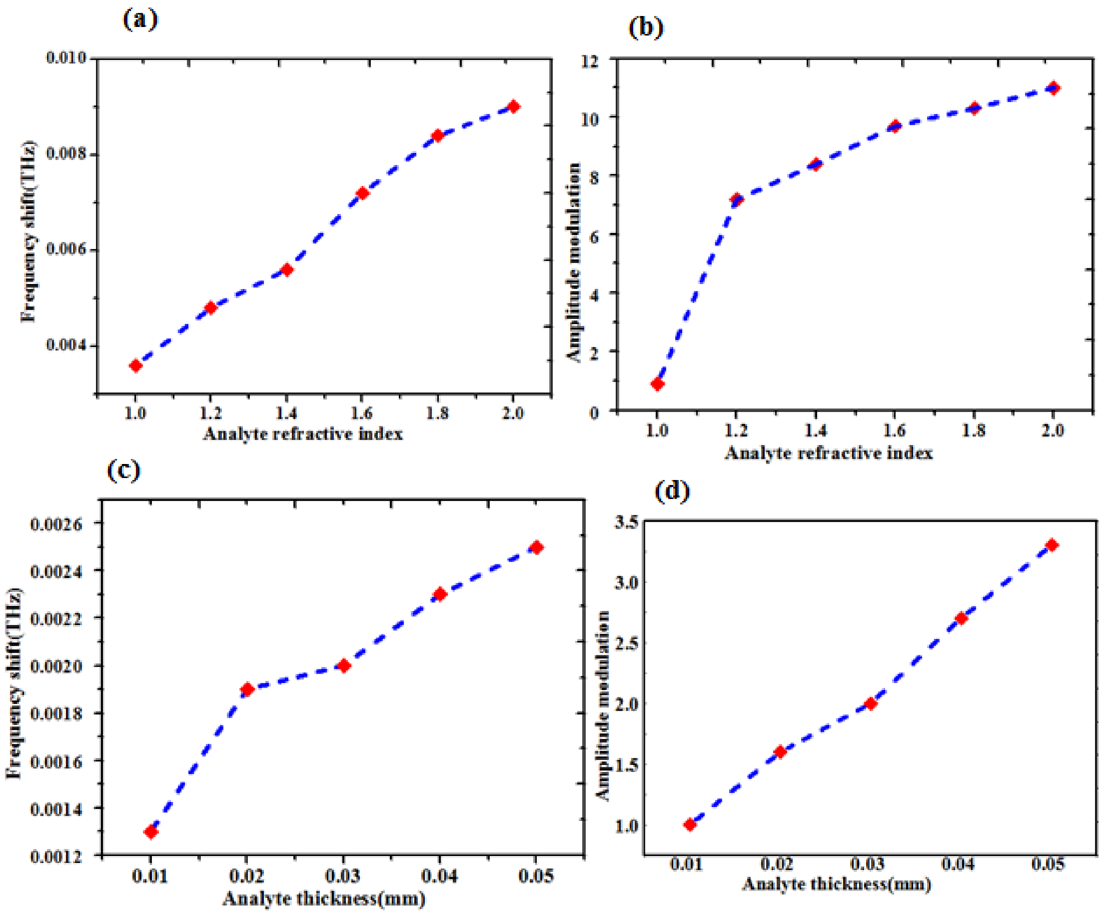

Fig. 3. (a) Frequency shift versus analyte refractive index, (b) Amplitude modulation versus analyte refractive index at a top layer thickness of 50μm, (c) (d) Frequency shift and amplitude modulation versus analyte thickness (color online)

By optimizing the geometrical parameters of the proposed terahertz sensor also using thin substrates will increase the sensor performance. Refractive index and the thickness of the analyte is the main reason to investigate the frequency shift and the amplitude modulation for deciding the sensing capability of the proposed structure. The proposed absorber provided the better sensing which is used for biological applications.

4. Electromagnetic characteristics of the sensor

In order to know the sensing mechanism and physical sensor characteristics we want to know the electric field, magnetic field and surface current distribution corresponding to the absorptivity of 99.5% at 0.3956THz. Here, analyse its sensing functionality we employ the magnetic resonance. Due to the behaviour of rotational symmetric, the proposed sensor is polarization insensitive.

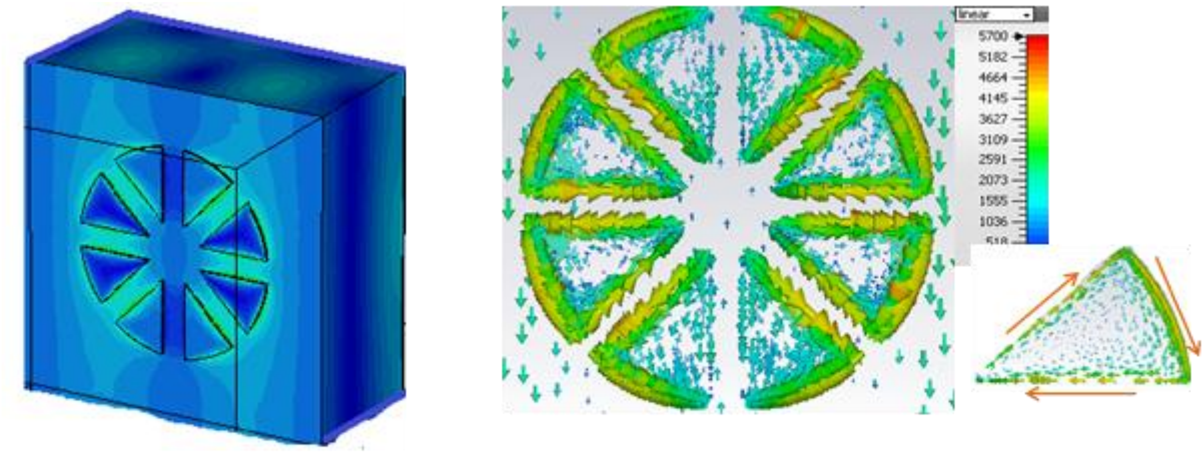

Fig.4. (a).Distributions of the magnetic field for the proposed terahertz sensor at a frequency of 0.3956 THz, (b) Surface current distribution and direction of the current flow (color online)

Fig. 4 clearly shows the modes of magnetic excitation of surface plasmons in the patterned terahertz metallic sensor. Normally, the electric excitation in the surface plasmons created the oscillations in the metallic flow of electrons. But in this metamaterial field, there is also the availability of making magnetic excitations along the surface of a metamaterial. The proposed sensor provides the better magnetic resonance at the frequency of 0.3956THz which is shown in Fig. 4 (a) also the corresponding surface current distribution and the direction of the current flow indicated by arrows which are shown in Fig. 4(b). All the slices from the metallic patterned structure provide the good surface current distribution at the frequency of 0.3956THz.

5. Conclusion

In conclusion, we have designed and simulated a terahertz plasmonic sensor. Numerical Calculations were investigated to characterize the sensing mechanism. The proposed terahertz sensor offers the fabrication simplicity and polarization independence of the incident electromagnetic wave. Refractive index and the thickness of the top layer is used to analyse the frequency shift and the amplitude modulation for deciding the sensing capability of the proposed structure also the electromagnetic characteristics of the sensor is analysed by a magnetic field and surface current distribution mechanisms. From this analysis, we obtained that the proposed terahertz sensor provided the better sensing which is used for biological applications.

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