Highly Sensitive Terahertz Electromagnetically Induced Transparency-like Metasurface for Refractive Index Biosensing

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***Abstract*—In this research, we presented an electromagnetically induced transparency-like (EIT-like) metasurface. The structure is composed of pairs of L-shaped resonators, and by increasing the asymmetry between the coupled resonators, the dark mode has been excited with a transparency peak at 2.84 THz. The transmission spectra based on various asymmetry degree shows the intensifying trend of EIT-like resonance. The distribution of the electromagnetic field and the surface current were also examined to demonstrate the dark mode excitation. The sensing performance of the biosensor was studied based on various refractive index and thicknesses of the sample, and a total theoretical sensitivity of 800 GHZ/RIU based on a narrow line width of 230 GHz was achieved. The results also were compared with similar research works and proved a massive enhancement in sensitivity and Q-factor. The proposed structure can be served as an ultra-sensitive, inexpensive, and label-free biosensor for applications including biological sensing.**

***Index Terms*—THz Metasurface, Biosensor, Electromagnetically Induced Transparency.**

I. Introduction

Terahertz (THz) radiation has been widely adopted for biosensing applications due to its non-ionizing nature and non-label and high-resolution characteristics. This enables the possibility of acquiring spectral measurements without perturbation of the biological sample. Metasurfaces are two-dimensional versions of metamaterials, defined as artificial structures whose size scale is significantly smaller than the wavelength of the incident electromagnetic wave. In THz metasurfaces, light-matter interaction is enhanced due to the excitation of higher-order surface plasmon-like modes. This, in turn, provides excellent field confinement, which boosts the interaction between the metasurface sensor and the biological sample, thus increasing its sensitivity. Classical plasmonic metamaterial sensors rely on split ring resonators manufactured on a dielectric/semiconductor substrate.

Various metasurface types exhibit higher-order plasmonic resonances utilized for thin film sensing. Nanoparticle-enhanced metasurfaces can enhance strong fields by triggering the localized surface plasmons [1]. THz metasurfaces based on graphene also has been widely used for biosensors. When the analyte is present, it shifts the fermi energy level of the graphene, giving a shift in the electromagnetic response due to the change in conductivity compared to the empty structure [2]. Another alternative would be devices based on nano-hole arrays in which subwavelength hole dimensions in a metallic material achieve what is known as extraordinary transmission at specific frequencies. The presence of analyte shifts the transmission frequency giving rise to detection capabilities compared to the empty structure [3].

In order to have a sharp resonance and high sensitivity in a biosensor system, we need to design high-Q factor structures. Exciting dark mode and higher order plasmonic electromagnetically induced transparency (EIT-like) resonance in the metasurfaces suppresses more radiation losses of the system and leads to forming a transparency window with a narrow line width. This phenomenon raises the interaction of the electromagnetic wave and the sample under test, which shows a shift in the transparency resonance frequency. Most of the methods to excite dark mode rely on asymmetry in the design. Due to the atomic system's similarities, the photonic structure must be composed of two resonance elements: "bright," which exhibits strong radiative coupling to the incident light and has a short lifetime, and "dark," which exhibits weak radiative coupling to the incident wave and has a long lifetime. The Fano resonance, in this instance, is known as an EIT-like resonance because the bright mode's resonance frequency is the same as the dark mode's resonance frequency, and their Q-factors substantially contrast. The bright resonator disperses the incident wave's energy into the open space without coupling. The EM response of the system significantly improves when the bright and dark resonators are coupled, and energy received through the bright mode is transferred to the dark mode at the resonance frequency. This results in a transparent window and a significant suppression of the absorption or scattering losses. Asymmetric and symmetric resonators are two groups of methods for inducing Fano and EIT-like resonance in metasurfaces.

Breaking the symmetry of paired resonators is one method frequently used to create Fano and EIT resonance in metasurfaces. It was first introduced in a metasurface with a periodic array of asymmetrically SRRs on the microwave regime [4], and then in the THz regime [5]. Consequently, a model with a similar idea of mirror symmetry breaking of a bilayer was given by [5]. In order to demonstrate a reverse link between the Q-factor and intensity of the Fano resonance response, the same analysis was later performed in ref [6] for a THz metasurface built of asymmetric SRR (split ring resonators).

To examine the EIT-like Fano resonance, we have designed a structure in this work comprising two asymmetric double L-shaped resonators. Interference between two modes results from the coexistence of a magnetic dipole and a circulating surface current. At the frequency of 2.84 THz, a transparency window manifests itself due to the suppression of radiation damping. The distribution of the magnetic fields and surface current demonstrate how the bright and dark modes appear to be coupled, as well as the mechanism of an EIT-like Fano resonance. Furthermore, the sensing performance of the structure was analyzed using various refractive index shifting and different thicknesses of the sample and compared with the literature.

II. Metasurface Design

The proposed terahertz metasurface design includes two pairs of L-shape resonators. Their dimensions can be seen in Fig. 1. A 200nm gold layer was used for the L-shape resonators. A 5μm polyimide was used with a dielectric constant of 2.9 and tangent delta of 0.02. Parametric analysis was performed on the metasurface structure to determine the best dual L-shape pairs configuration. Parameter a was defined as the vertical downward translation of the right L-shape resonator of the left pair. This parameter has been used to make an asymmetry in the design in order to excite an EIT-like resonance. The incident THz waves transfer from the metal where the sample was placed to the dielectric layer. The dimensions of the unit cell geometries is mentioned in the caption of Fig. 1. The metasurface unit cell is simulated and optimized by the CST microwave studio based on a finite difference time domain (FDTD) solver. The electric, magnetic and open (add space) boundary conditions are considered along x, y, and z directions, respectively.

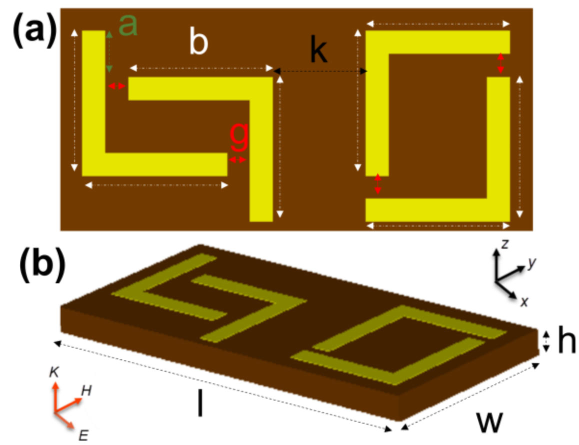

Fig. 1. (a)-(b) Top and side view of the unit cell of the proposed metamaterial and below geometrical parameters : a=8 μm , b=25 μm (white arrows) , k=6 μm, g=4 μm (red arrows), l=82 μm, w=51 μm and h=5 μm. The height of the gold layer is 200 nm.

III. Results and discussion

The simulated transmission spectra of the structure with different asymmetry degrees of a are presented in Fig. 2.

The coupling of the bright and dark modes causes the transparency windows to peak at 2.84 THz at a equal to 8 μm. As can be seen, the coupling strength between the resonators gradually increases as the degree of asymmetry a grows from 0 to 8 μm. As a result, the transparency window intensifies and becomes increasingly obvious as the degree of asymmetry increases.

In Fig. 3, the structure's magnetic field and current distribution is shown at the transparency peak frequency of f_2 and the two resonance dips of f_1 and f_3. It shows that at f_1, a weak magnetic field is produced on each side of the resonator pairs due to an incomplete semi-circulating current. Then a magnetic dipole, as well as a complete circulating current, is produced between the resonators at frequency f_2, causing destructive interference and a suppressed condition in the bright resonator. As a result, a transparency window was created at this frequency, and radiative losses were reduced and the structure's EIT-like Fano resonance relies entirely on non-radiative dampings, such as the loss of the metal components. Due to the fact that any change in the lineshape deviation can only be explained by a change in the external

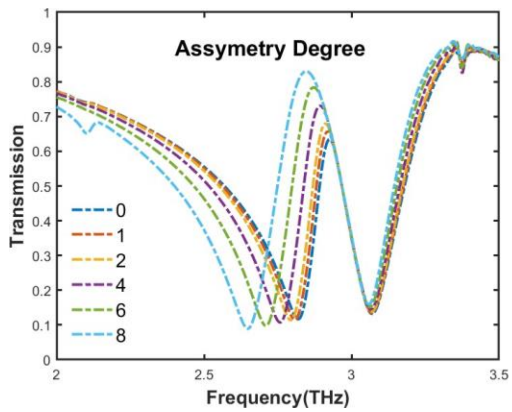

Fig. 2. Simulated transmission spectra of the EIT-like resonance for different asymmetry degrees of a

dielectric environment, this exceptional feature encourages the development of ultra-sensing behavior [20]. At the frequency of f_3, the transmission transparency disappeared, and radiation losses took over. This resulted in the reformation of a weaker out-of-phase current distribution [7].

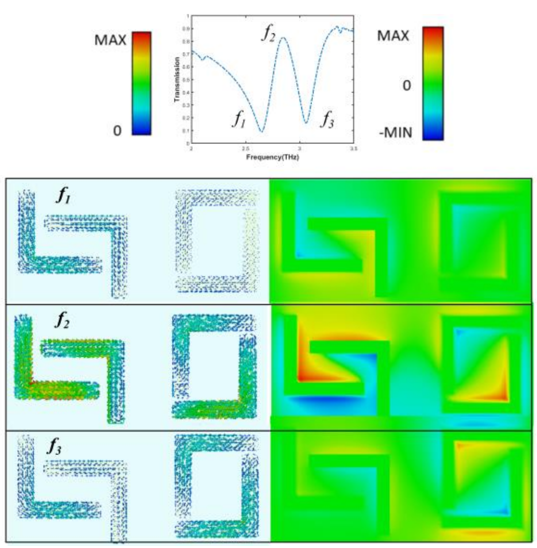

Fig. 3. Simulated transmission spectra for asymmetry degree of 8μ m, and related magnetic fields distribution, and surface currents of the designed biosensor associated with f_1 = 2.64 THz, f_2 = 2.84 THz and f_3 = 3.05 THz

The theoretical sensitivity based on refractive index variations has been calculated to study the suggested metasurface's sensing capabilities further. The ratio of the frequency shift of the pick frequency to the change in refractive index determines theoretical sensitivity. We simulated an analyte with a thin thickness of 15 μm and altered its refractive index from 1 to 1.6, which corresponds to the permittivity range of skin [12], to demonstrate the bio-sensing capacity of the suggested structure. Fig. 4 illustrates the linear shift in the transmission spectra's peak toward the lower range. The transmission peak frequency varies from 2.84 THz to 2.36 THz with a refractive index change from 1 to 1.6, resulting in a characteristic theoretical sensitivity ($S = \Delta f/\Delta n$) of 800 GHz/RIU (RIU is the unit of refractive index). Moreover, we have analyzed the sensitivity of the biosensor to the sample thickness. Therefore, we simulated the sample with a fixed refractive index of 1.6 and varied the thickness from 1 to 15 μm. It can be seen in Fig. 5 that increasing the thickness makes the EIT-like resonance shift to a lower frequency. It can be observed that this change gets smaller after 9 μm and nearly unchanged after 15 μm. The concentrated electromagnetic fields restricted to the surface area cause this saturation.

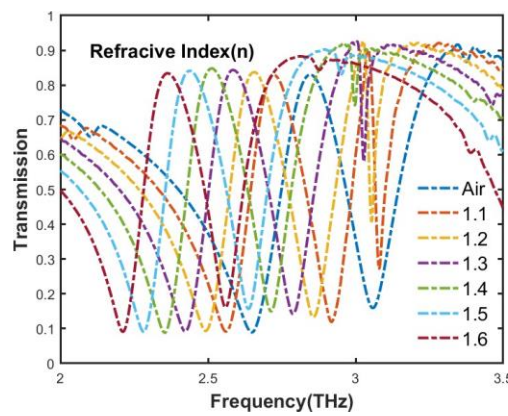

Fig. 4. Sensing performance of the simulated transmission spectra of proposed metasurface based on the different refractive index of the sample

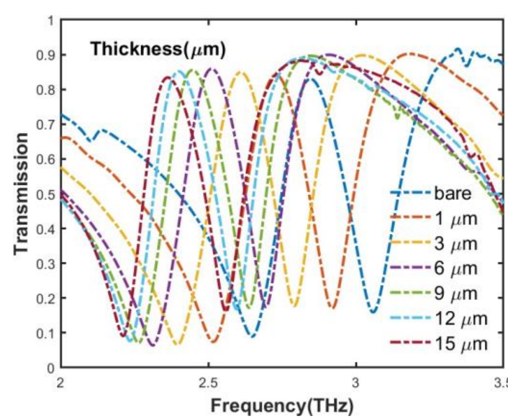

Fig. 5. Sensing performance of the simulated transmission spectra of proposed metasurface based on different thicknesses of sample

The FWHM of the resonance response is calculated to be as narrow as 230 GHz using the Fano resonance and the special design. The comparison of these results with other THz biosensors operating in the frequency range of 1-3 THz (com-patible with the THz-TDS system) is presented in Table 1. It comprises n_a and h_a, which stand for the sample's refractive

TABLE I

COMPARISON OF SENSITIVITY AND FWHM IN DIFFERENT RESEARCH WORKS. n_a AND h_a ARE REFRACTIVE INDEX AND THICKNESS OF THE SAMPLE, f_0 IS THE EIT-LIKE RESONANCE AND THEORETICAL SENSITIVITY CALCULATED AS $S = \Delta f/\Delta n$

Ref-year	n_a	$h_a(\mu m)$	$f_0(THz)$	FWHM(GHz)	Sensitivity (GHz/RIU)
[8]-2018	1.6	-	0.85	-	182
[9]-2019	1.6	11	1.67	400	455.7
[10]-2020	1.8	8	0.81	-	240
[11]-2021	1.6	18	1.94	300	550
This work	1.6	15	2.84	230	800

index and thickness, f_0, which stands for the metamaterial's resonance frequency in the absence of an analyte, as well as FWHM of the corresponding bare biosensor. As can be observed, there has been a notable improvement in theoretical sensitivity in this work. Additionally, the FWHM is smaller and helps to suppress more losses and get a sharp sensitivity. Based on the discussion, the proposed structure can be utilized in thin film biological sensing.

ACKNOWLEDGMENT

This research was supported by the James Watt School of Engineering, University of Glasgow.

IV. CONCLUSION

A metasurface based on the excitation of dark mode and EIT-like resonance is proposed in this work. It proved that when the bright and dark resonators are coupled, a transparency window at 2.84 THz is created, non-radiation damping is reduced, and any fluctuation in the transparency lineshape spectra is attributable to the variation in the surrounding dielectric environment. A parametric investigation of the coupling strength of the resonators was conducted, along with the electromagnetic fields and surface current distribution of the resonators that were developed using an EIT-like system. Additionally, the system's sensitivity performance was confirmed by various refractive index and thicknesses of the sample, and a total theoretical sensitivity of 800 GHz with a narrow FWHM of 230 GHz was achieved. These results were compared with other works, and a significant enhancement in sensitivity parameters was observed.

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