Design of a terahertz metamaterial sensor based on split ring resonator nested square ring resonator

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Abstract
A terahertz (THz) sensor based on the metamaterial structure, split ring resonator with four-gaps relied on centro symmetric nested square ring resonator, is presented. The two resonant elements of the metamaterial structure generate a corresponding resonant valley on the transmission spectrum curve in the frequency range from 0.1 to 1.9 THz respectively, and both of these resonant valleys show different redshifts when the surface permittivity of the structure changes. This feature is very suitable for THz sensing, especially the quantum interference effect between the two resonant elements, which results in the formation of an electromagnetically induced transparency (EIT)-like resonance peak on the transmission spectrum curve. The sensing performances are simulated by using commercialized full-wave electromagnetic simulation software. The results demonstrated that the proposed sensor is polarization-insensitive and has a highly boosted sensitivity, which has a promising application prospect in the fields of biomedical science and drug industry.

1. Introduction
Since terahertz (THz) wave exhibits the advantages of low phonon energy, good penetration and fingerprint spectrum properties, THz technology has been widely used in the aspect of THz nondestructive testing [1], especially when the THz metamaterial sensors are applied to this field [2]. Metamaterial is a new type of artificial electromagnetic material composed of sub-wavelength units of periodic array, which are designed as tunable modulators [3, 4], active filter [3] and ultra-sensitive biosensor [6] owing to the fascinating electromagnetic properties negative refractive index [7], negative permittivity [8] and inverse Doppler effects [9]. In particular, resonant metamaterials possesses microsized gaps, that means it can enhance the intensity of the local electromagnetic field [10, 11]. Therefore, the resonance metamaterials can be widely employed in THz sensing due to the sensitivity to the change of dielectric properties [12, 13].

Since the concept of metamaterials was first proposed by Pendry in 1999 [14], split ring resonator (SRR) has been a hot topic and gradually applied to THz band. In recent years, a lot of sensors based on SRR has been studied and developed. This kind of sensor has gained extensive applications which includes biological and chemical sensing. The ability of sensing is thank to excellent sensing performance for the sensor and the superiority of simpleness, swiftness, non-destruction and label-free for THz spectroscopic analysis [15]. In 2018, Yang et al [16] presented a THz metamaterial biosensor to discriminate between the wild-type and transgenic genome DNA. In 2019, Xu et al [17] proposed a graphene-metamaterial sensor, which shows the ability of ultrahigh sensitivity to detect trace amount of chlopyrifos. In 2020, Zhao et al [18] proposed a metamaterial-based terahertz biosensor that comprises of a planar array of three-split ring resonators, which has the potential for high-sensitivity, quantitative identification of aflatoxin B1 and B2 in extremely small amounts. However, the THz metamaterial sensors based on SRR have some limitations in the current work. For example: (1) the high quality (Q) factor is an important index for sensing performance, while the Q factor of single-gap SRR is less than...
although the Fano effect makes the $Q$ factor of asymmetric SRR (ASR) better than others, the intensity of this high $Q$ resonant peak is extremely low, so it is not suitable for THz sensing [19, 20].

Electromagnetically induced transparency (EIT) is a quantum interference effect that results in a distinguished transparent window inside a broad absorption spectrum [21]. The EIT-like effect of planar metamaterials is generated by the interaction among two resonant modes (bright mode and dark mode) or two modes with different $Q$ factors. Due to the excitation of the local aggregated electromagnetic field, the effect can form the high $Q$ resonance peak, and effectively improve the detection accuracy of the sensor. Sun et al [22] designed a kind of THz metamaterial with EIT-Like resonance, but the sensitivity of the EIT-like resonance of the metamaterial sensor is not high, and it is also sensitive to the polarization of THz wave.

In this study, we designed a novel metamaterial structure with EIT-Like resonance. The structure is composed of a split ring resonator with four-gaps relied on centro-symmetric nested square ring resonator. Through adjusting the geometry size and considering the substrate substitution, the structure can obtain preferable resonance peak. Consequently, we can get a high-performance THz metamaterial sensor. The sensing performances are theoretically investigated by using full-wave electromagnetic simulation software. The results illustrate that the metamaterial sensor has the characteristics of polarization-insensitive and high sensitivity, which make it be very helpful for desirable biorecognition in biomedical science and drug industry.

### 2. Structure and simulation

The unit cell of the proposed sensor is shown in figure 1. Figure 1(a) shows the oblique view of a unit cell of the sensor, and it consists of a metal film with the thickness of 0.2 $\mu$m and a silicon substrate with the altitude of 65 $\mu$m. Figure 1(b) shows the top view of a unit cell of the sensor, and the unit cell consists of a multi-gap split ring resonator with four-gaps and a square ring resonator on the substrate. The split ring resonator is a centro-symmetric structure, and the distance of the starting place of split off the axisymmetric center is about 10 $\mu$m. By repeatedly optimizing the scanning parameters, the appropriate parameters can be obtained. The finally optimised geometries of the sensor are listed in table 1.

The spectral characteristic of the proposed sensor is further explored by using the frequency domain solver which come from the commercial CST Microwave Studio 2015 simulation software and relied on finite element method (FEM) [23]. For the unit cell of the sensor, the open boundary condition is set in the $z$-direction and the periodic boundary conditions are defined in the $x$-direction and $y$-direction, respectively. In order to improve the accuracy of the results, all simulation use adaptive fine mesh settings. The transverse electric (TE) polarized

| a | b | c | d | e | f | g | h |
|---|---|---|---|---|---|---|---|
| 94 | 84 | 56 | 9 | 7 | 6 | 10 | 65 |
THz wave is normally incident to the top surface of the sensor. The material of the metallic layer is gold (Au) which is a lossy metal with conductivity $\sigma = 4.09 \times 10^{-7}$ S m$^{-1}$ and the substrate is moulded as lossy polymer with a dielectric constant of 2.9 and a loss tangent of 0.000 69. Figure 2 shows the THz transmission spectra of the sensor. As can be seen from the figure 2, the resonant frequencies are located at 1.312 THz and 1.538 THz, respectively. Moreover, the EIT-like resonance peak is produced due to the destructive interferences at the frequency of 1.335 THz.

2.1. High Q of EIT-like resonance peak

The high performance of the EIT-like resonance peak can be firstly verified according to the THz transmission spectra of the sensor. The high Q factor is an important index for sensing performance when we design the sensor. The Q value about the EIT-like resonance peak of the sensor is 30.5, which is much better than 6.6 calculated from the resonance dip at 1.538 THz. Likewise, it is also slightly better than 30.4 calculated from the resonance dip at 1.312 THz.

2.2. Polarization insensitive

2.2.1. Transmission spectra of different polarization angles

Polarization insensitive is another important index in the design of the sensor. The speciality can ignore the effect of experimental errors, such as the unfixed placement of the sensor in the case of multiple measurements. The polarization-insensitive property is generated by a symmetrical structure. Through repeated experiments, we found that the performance of the centrosymmetric sensor is superior to that of the axisymmetric sensor. In order to verify the polarization-insensitive property of the sensor, the polarization angle is set as 0°, 30°, 45°, 60° and 90°, respectively. The simulated transmission spectra at different polarization angles (φ = 0°, 30°, 45°, 60° and 90°) are shown in figure 3. As can be seen from the figure 3, the corresponding transmission spectra are completely overlapped, which indicates that the proposed sensor is insensitive to the polarization of THz wave.

2.2.2. Mechanism of polarization insensitive

In order to reveal the mechanism of polarization insensitive for the sensor, the surface current distributions of top metal layer at the resonance frequency are analyzed under different polarization angles. Due to the transverse magnetic (TM) mode has an identical conclusion as the transverse electric (TE) mode, the following analysis uses only the TE mode as an example. Figures 4(a)–(e) show the surface current distributions at 1.335 THz for different incident angles, respectively. It is obvious from the figure 4 that the resonance mode of each ring is electric dipole resonance. The corresponding resonance peak is produced by the destructive interference between two rings. Moreover, the resonance modes about these five angles are identical. Also the strength of surface current distributions is almost similar.

3. Sensing performance

To explore the sensing performance of the THz metamaterials sensor, the surface of the sensor is covered with different thickness and permittivities of the analyte. Then, the sensor are simulated using the CST Microwave
Studio 2015. The perturbation theory and the equivalent medium theory are introduced to analyse the sensing mechanism. In the perturbation theory, the relationship of the relative change of the resonant angular frequency $\Delta \omega / \omega_0$ is described by the following formula [24]:

$$\frac{\Delta \omega}{\omega_0} = -\int_{v_0}^{v} (\Delta \varepsilon |E_0|^2 + \Delta \mu |H_0|^2) \, dv \approx -\int_{v_0}^{v} (\Delta \varepsilon |E_0|^2) \, dv$$

(1)

where $E_0$ and $H_0$ are the electric field and magnetic field in the sensor under without any analyte, respectively. $\Delta \varepsilon$ is the change of dielectric constant in the sensor. For the sensor based on the metamaterials, $\Delta \mu$ is the change of permeability and is not considered. In the equivalent medium theory, the total dielectric constant ($\varepsilon_{\text{eff}}$) of the THz biosensor under covering the thin analytes can be defined as [25]:

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{sub}} + \alpha \varepsilon_{\text{air}} + (1 - \alpha) \varepsilon_r$$

(2)

where $\alpha$ is correlation coefficient between air and sensor, which is related to the thickness of the analyte. $\varepsilon_r$, $\varepsilon_{\text{air}}$ and $\varepsilon_{\text{eff}}$ are the dielectric constants of the substrate, air and analyte, respectively.

### 3.1. Different thicknesses of analyte

When the thicknesses of the analyte is changed from 3 $\mu$m to 9 $\mu$m and the permittivity is fixed to 3, the corresponding transmission spectra are plotted in figure 5. As shown in figure 5, the resonance frequencies show a significant redshift when $t$ increases, which indicates that the sensor is sensitive to the change of analytes. But when $t = 12$, 20 and 30 $\mu$m, the red shifts of the resonance frequencies have little changes, which is in accordance with the literature result [8]. According to the formula (1) and (2), the value of $\varepsilon_{\text{eff}}$ is increase and the value of $\alpha$ is decrease with the thicknesses of the analyte is changed from 3 $\mu$m to 30 $\mu$m. The result lead to a significant redshift the of the resonance frequencies. In order to find the trend of frequency changes, we define the frequencies of these two resonance dips and EIT-like resonance peak as $f_1$, $f_3$ and $f_2$ respectively, and the red shifts of the resonant frequencies with different thicknesses of analyte are presented in table 2.

### 3.2. Different permittivities of analyte

When the surface of the sensor is covered with a layer of analyte with the permittivity $\varepsilon_r$ from 1 to 6 and the thickness is fixed to 9 $\mu$m, the increase of $\varepsilon_r$ results in the value of $\varepsilon_{\text{eff}}$ is increase and the resonance frequencies will go down. The corresponding transmission spectra are plotted in figure 6(a). The situation of $\varepsilon_r = 1$ could be interpreted as air, which means that no analyte is placed on the sensor in the actual experiment. To explore the sensing performance of the THz metamaterials sensor, we define the sensitivity of the sensor as resonance frequency shift with per-refractive index unit. Because magnetic permeability is equal to 1, we could ignore the influence of it. And because $n = \sqrt{\varepsilon_r + \mu_r}$ (where $\mu_r = 1$), refractive index is function of permittivity.
Ultimately, the sensitivity can be defined according to the following formula:

\[ S = \frac{\Delta f}{\Delta n} \propto \frac{\Delta f}{\Delta \varepsilon_r} \]  \hspace{1cm} (3)

where \( S \) is sensitivity, the unit is THz/RIU (RIU, Refractive Index Unit), \( \Delta f \) is resonance frequency shift, \( \Delta n \) is the change of the refractive index; \( \Delta \varepsilon_r \) represents the change of analyte’s permittivity.

Figure 6(b) shows the relationship between the resonance frequency shift and the refractive index at the three frequencies \( f_1, f_3 \) and \( f_2 \). The sensitivity \( S \) of the sensor, which equaled to the slope of the lines in figure 6(b), reached 0.275 THz/RIU, 0.285 THz/RIU and 0.280 THz/RIU at the three resonance frequencies \( f_1, f_3 \) and \( f_2 \), respectively. The figure of merit (FOM) is obtained by multiplying the quality factor by the sensitivity, which is a composite index and used to comprehensively evaluate the sensing performance of a sensor. The FOM is described as:

**Figure 4.** Surface current distributions at 1.335 THz for (a) \( \varphi = 0^\circ \), (b) \( \varphi = 30^\circ \), (c) \( \varphi = 45^\circ \), (d) \( \varphi = 60^\circ \) and (e) \( \varphi = 90^\circ \).
Table 3 shows the values of $Q$, $S$ and FOM of the THz metamaterial sensor at the different resonance frequencies. Seen from table 3, comparing with other resonance dips, the EIT-like resonance peak is better suitable for THz sensing because of it has superior sensing performance. Meanwhile, the dephasing time of the

Table 2. The red shifts of the resonant frequencies with different thicknesses.

| Thicknesses ($\mu m$) | $\Delta f_1$ (THz) | $\Delta f_2$ (THz) | $\Delta f_3$ (THz) |
|-----------------------|--------------------|--------------------|--------------------|
| 3                     | 0.159              | 0.165              | 0.113              |
| 6                     | 0.209              | 0.217              | 0.168              |
| 9                     | 0.226              | 0.234              | 0.188              |
| 12                    | 0.238              | 0.243              | 0.208              |
| 20                    | 0.243              | 0.252              | 0.232              |
| 30                    | 0.246              | 0.252              | 0.246              |

FOM = $Q \ast S$  \hspace{1cm} (4)

Table 3 shows the values of $Q$, $S$ and FOM of the THz metamaterial sensor at the different resonance frequencies. Seen from table 3, comparing with other resonance dips, the EIT-like resonance peak is better suitable for THz sensing because of it has superior sensing performance. Meanwhile, the dephasing time of the
EIT-like resonance is a critical parameter that can be defined by the formula [26]: \( T_\text{d} = 2h / \text{FWHM} \), where \( h \) is the reduced Planck’s constant, the FWHM is the linewidth of EIT-like resonance from the resonance dip \( f_1 \) to \( f_3 \). The dephasing time is calculated as \( T_\text{d} = 5.82 \) fs. A comparative analysis of the proposed sensor over the prior presented sensor is carried out and shown in the table 4. The result indicates that the proposed sensor has a higher \( Q \), FOM and sensitivity by comparing with other sensors which are designed in the recent five years. In conclusion, the sensor is more suitable for biological and chemical sensing.

4. Effect factors of sensing performance

4.1. Effect of geometric variation
In order to visualize the effect of each parameter on the sensing performance, we discuss eight different cases. In each case, only one parameter, e.g. the length \( a, b, c, d, e, f, g \) and the thickness \( h \), is changed and the others are kept constant as listed in table 1. The simulated results are shown in figures 7(a)–(h), respectively. Taking the resonance strength and high \( Q \) factor into consideration, the values of the eight parameters listed in table 1 are superior to others.

4.2. Effect of the dielectric losses of the substrate
Both the thickness and the dielectric types of the substrate are vital to sensing performance. The effect of the thickness has been analyzed in figure 7(h). For the sake of uncovering rules, the value of dielectric constant is 2.9 and loss tangent changed as 0.000 0069, 0.000 069, 0.000 69, 0.0069, 0.069 in turn, representing the imaginary part of dielectric constant changed as 0.000 02, 0.0002, 0.002, 0.02, 0.2 in sequence. Figure 8 shows that the simulated results. As we have seen in figure 8, the loss tangent of 0.000 69 is the optimal solution in the five cases. The substrate with low loss speciality has a significant influence on the property of the sensor, but when the loss tangent reaches a certain degree, the property of it will not change.

5. Conclusion
In this paper, a THz metamaterial sensor based on split ring resonator nested square ring resonator is proposed. The sensor generates two resonant valleys on the transmission spectrum curve between 0.1 and 1.9 THz; especially, the EIT-like resonance peak is produced due to the quantum interference effect interferences. The performance of the sensor is analyzed by using the frequency domain solver. The results indicate that the EIT-like resonance peak shows better performance than that of the two resonant valleys, and the value of \( Q \), \( S \) and FOM can reach to 30.5, 0.280 THz/RIU and 8.54, respectively. Moreover, the sensor is insensitive to the polarization direction of the incident THz wave, which makes it can ignore the placement of the sensor and

| References | \( Q \) | \( S \text{ (THz/RIU)} \) | FOM | Year |
|------------|--------|-----------------|-----|------|
| [27]       | 11.6   | 23.7% RIU\(^{-1} \) | 2.3 | 2015 |
| [28]       | —      | 0.128 THz/RIU   | 1.5 | 2016 |
| [29]       | 58     | 0.105 THz/RIU   | 7.5 | 2018 |
| [30]       | 120    | 0.187 THz/RIU   | 7.2 | 2018 |
| [31]       | 92     | 0.061 THz/RIU   | 8.5 | 2018 |
| [32]       | —      | 6.94 GHz/PU*    | 1.5 | 2018 |
| [33]       | 22.05  | 0.3 \text{ THz/RIU} | 2.94 | 2019 |
| This work  | 30.5   | 0.280 THz/RIU   | 8.54| —    |

| Frequency | \( Q \) | \( S \text{ (THz/RIU)} \) | FOM |
|-----------|--------|-----------------|-----|
| \( f_1 \) | 30.4   | 0.275           | 8.36|
| \( f_2 \) | 30.5   | 0.280           | 8.54|
| \( f_3 \) | 6.6    | 0.285           | 1.88|
coverage of analyses during the test. In conclusion, this study provides a highly-sensitive and polarization-insensitive THz metamaterial sensor, which has numerous potential applications in biological and chemical sensing.
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Figure 8. Effect of the dielectric losses of the substrate.
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