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Design of High Q Fano Resonance Sensor in THz range

Amit Chandra Das

Abstract

A sharp Fano resonance in planar terahertz metamaterial is achieved by introducing a cut-wire resonator asymmetrically inside an annular ring resonator. The interference between the resonances arising from the cut-wire and annular ring gives rise to the high quality factor (Q=59) Fano type resonance enabling sensitive sensing (at 2.14 THz) in between 0.1 to 3 THz. Full wave EM simulations show frequency sensitivity of 0.08 THz per refractive index unit (RIU). Tuning of this Fano resonance has done by minute structural variations. The Fano peak can be efficiently modulated because of strong coupling between the incident THz wave and asymmetric ring resonator. Such sharp resonances could be exploited for chemical and biological sensing and detectors in Terahertz regime.

Keywords:

Asymmetric ring resonator;
Fano resonance;
High quality factor(Q);
Terahertz metamaterial.

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1. Introduction

Research on Metamaterials (MMs) has attracted a great interest in the past two decades. The interest is mainly due to the scope of achieving new electromagnetic properties unachievable in natural materials. Negative refraction [1], cloaking device [2], asymmetric transmission [3], magnetic mirror [4] etc. are few examples of the application of MMs. It is found that MMs exhibit Fano-type resonance phenomenon when there is coherent coupling or interference between discrete and continuous states [5]. Fano resonances have many potential applications in biochemical sensors[6], electrical switching of infrared light [7], slow light field [8] and Electromagnetic induced transmission (EIT) [9] etc. Among these, sensing becomes the most critical application of Fano resonances at THz. Narrow linewidth and high Q, are highly desirable for increasing the sensitivity of a sensor [10]. Hence, it is promising to incorporate Fano resonances into traditional MMs to enhance their sensing performances [11]. In this work, we have numerically studied a THz sensor with Fano type resonance using periodic array of unit cells consisting of gold ring and cut wire resonator within 0.1 to 3 THz.This range of THz radiation is mostly available for doing spectroscopy (ZnTe and antenna based THz spectroscope). A Fano resonance with a narrow line-width and high Q at 2.14 THz is excited.Under certain conditions the Q-factor of our resonator can be as high as 59. Our designed resonator exhibit different sensing sensitivities (frequency sensitivity 0.08 THz per RIU) in the 0.1 to 3 THz range when the analytethickness is set to 0.5µm.

2. Structural Design And Numerical Model

The MMsunit cell structure is shown in Fig. 1,which is constructed by an annular ring resonator and a cut wire resonator of gold on silicon substrate. The size of substrate is 64 x 128 μm^2 and thickness is 1 µm. The outer and inner diameters of the ring are R_2=30 µm and R_1= 27 µm respectively. The length of the cut wire is c=23 µm and width is 2 µm. The thickness of gold is 0.1 µm. Numerical simulations have been carried out using CST Microwave Studio. The simulation conditions were set as follow: periodic boundary conditions were applied to the side walls parallel to z direction. A plane y polarized electromagnetic wave was chosen to excite the MMs, as shown in Figure 1, the electromagnetic wave normally incident on the MMs along the –z direction. And a probe was placed far behind of the silicon plate to detect the transmitted signals. The simulated transmission spectrum is shown in Figure 2(b). There is a very high Q Fano resonance peak in the curve at 2.19 THz with Q value 59 (marked as C).

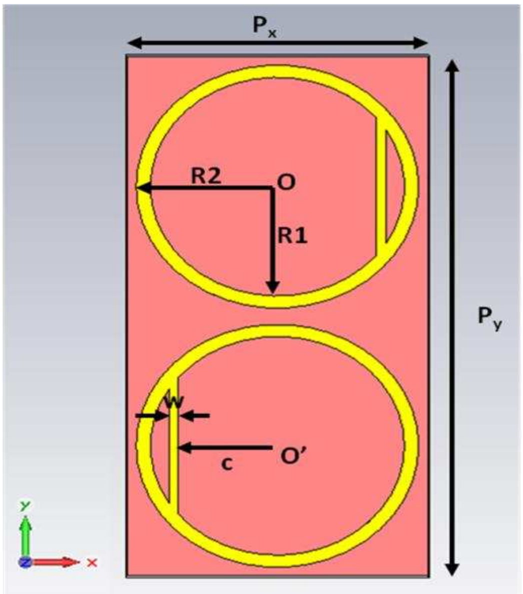

Figure 1. *Top view of the unit cell with the dimension R_2= 30 µm, R_1= 27 µm, w = 2 µm, periodicity P_x= 64 µm and P_y=128 µm.*

The value of the Q-factor can be calculated from (1), given as

$$Q = \frac{f_{res}}{FWHM} \qquad (1)$$

Where, FWHM is the full width at a half maximum bandwidth and(f_{res}) is the resonantfrequency.

3. Result And Discussion

The reflection, transmission andabsorption resonance spectral curves of the asymmetric ring resonator structure are shown in figures 2(a)-(c).

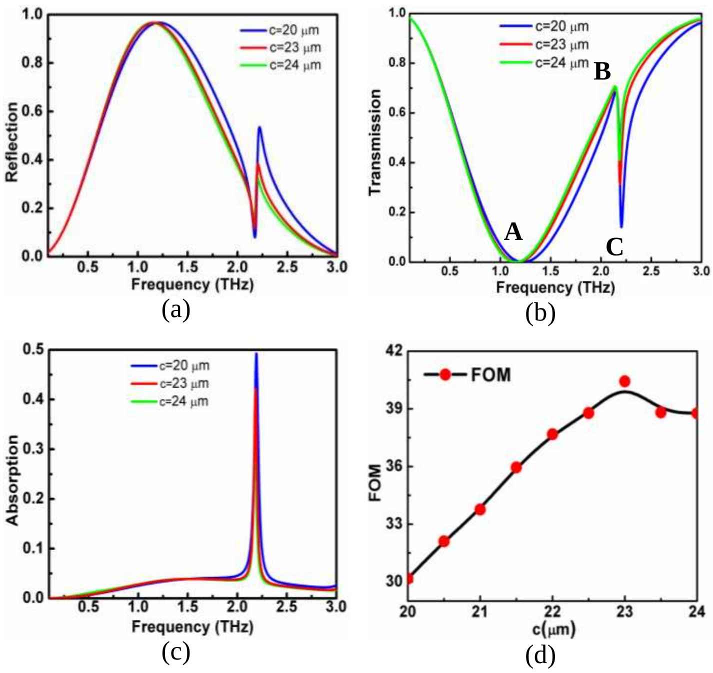

Figure 2. *(a)-(c) the reflection, transmission and absorption of the resonator for different asymmetry. (d) The FOM of the transmission curves.*

It can be found from figure 2 that the influence of cut wire distance (c) from the centre of the ring resonator on the resonant curve is significant. As the valueof c increases, the peak amplitude of the Fano curves decreases, and the resonant peak position manifests a blueshift. The reasons are as follows. As the gap distance between the cut wire and ring centre increases, the asymmetry between the ring resonator and cut wire increases, and the Qvalue of the Fano curves increases.For instance, if the distances are 20 μm, 21 μm, 22 μm, and23 μm, the Q values are 35, 41, 50, and 59 respectively. Thus, when the distance increases, the larger asymmetry of the local field inside the resonator leads to higher coupling. This can alsobe confirmed by the absorption curves given in figure 2(c),demonstrating that the absorption decreases with the increaseof asymmetry. Consequently, the resonant coupling strength improves further, resulting in sharp and deep transmissiondips as shown in figure 2(b). Additionally, figure 2(d) illustrates the figure of merit (FOM) of thetransmission curves. The peak value of the transmission curvedecreases with distance c, but the transmission curves also become sharper, resulting in the Q-factor increasing. In order to quantize the trade-off between the Q-factor and resonant strength, FOM has been defined as: FOM = Q×A, where A is the peak amplitude of the Fano curve. It can be found from figure 2(d) that as the distancec increases, the peak value and FOM of the Fano curve increase. As the values of c increase further, the Q-factor ofthe spectral curve decreases, and FOM reduces at a large value of distance. That is to say, there exists an optimum value of distance, i.e. 23 μm, in which the Fano peak has larger amplitude and relatively low losses simultaneously.

To understand the mechanisms of Fano resonance better,the 2D field plots are shown in figure 3, which displays the surface current density distribution for the asymmetric resonator structure.

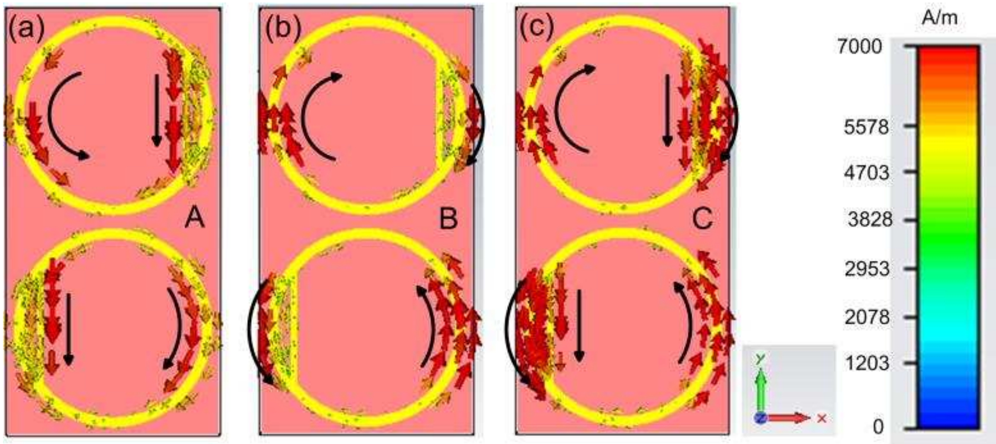

Figure 3. *The surface current density distributions((a), (b) and (c)) for the resonant frequencies 1.17 THz, 2.14 THz and 2.19 THz respectively.*

The resonant frequencies are 1.17 THz, 2.14 THz, and 2.19 THz, which are in accordance with the resonant frequencies in figure 2(b), marked as A, B and C respectively. As shown in figure 3(a), at a low frequency of 1.17 THz, left side of the ring resonator and the cut wireare excited and interacts strongly with the incident THz wave.From this surface current distribution, it can be inferred that responses at the A point correspond to the dipolar modes of the ring resonator and cut wire. At frequency of 2.14 THz, only the ring resonator is excited, as shown in figures 3(b). This is LC type resonance as the surface currents in two sides are in anti-phase and form a loop. While for the resonance at 2.19 THz, marked as C in figure 3(c), both dipole and LC resonance is observed. The destructive interference occurs in between the ring resonator and cut wire, which is not a simple summation of the excitation of the ring resonator and cut wire. The possible reasons are as follows. For the asymmetric resonator structure, there exists a bright broadband in-phase mode and a narrowband dark opposite mode. The coupling between them gives rise to the characteristic Fano line shape. The peak positions of the Fano curves are in accordance with the absorption peaks, coming from the fact that energy transfers from the bright mode to the dark mode. But due to the asymmetric structure, the field intensities are different; therefore, the dark mode couples to the bright mode and the Fano resonance can be observed in the transmission spectral curves. The responses of this trapped-mode are extremely sensitive to the dielectric properties of the surrounding media, which means that a small detectable region and a tiny shift of resonant frequency can be detected. It is beneficial for fabricating high sensitivity devices, such as a high sensitivity sensor, modulator and filters.

To investigate the sensitivity of our proposed sensor based onFano resonances, we apply an analyte layer on the top of the device. The thickness and refractive index of the analyte are t_a and n, respectively. The influence of the analyte refractive indiceson the response of the Fano resonator is investigated. For thisset of simulations, we fix the thickness of the analyte at 0.5 μm. We investigate the amplitude transmission spectra versus frequency with different refractive indices of the analyte. The simulated results are shown in Figure 4 for the analyte thickness t_a = 0.5 μm.

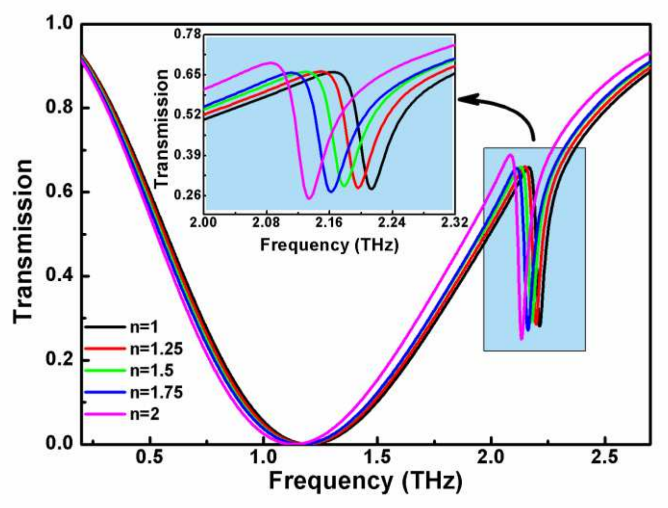

Figure 4. *Simulated amplitude transmission spectra with different refractive indices of the analyte (thickness 0.5 μm) placed on the top ofthe device.*

The resonance frequency of mode C red-shift while the refractive index of the analyte increases from 1.0 to 2 in steps of 0.25. The total shift in resonance frequency of mode C is 0.08 THz. In addition, the amplitude transmission slightly decreases with the increasing refractive index because of the mismatching of indices at the interface. The range of refractive indices represents a set of technologically important materials for terahertz sensing applications. For example, our mid-range of index represents the refractive index of PTFE (n = 1.43), a material frequently used as the binder with many explosives such as TNT (n = 1.76), RDX (n = 1.66), and HMX (n = 1.81). The range also covers biological materials such as air-dried Herring DNA (n ≈ 1.65) and ovalbumin (n ≈ 1.15). The calculated frequency sensitivity of mode C is 0.08 THz per RIU for an analyte thickness of 0.5 μm.

4. Conclusion

In summary, we have demonstrated a tunable ultrasensitiveTHz sensor with Fano resonance, which result from the interference between the ring resonator and the cut-wire. The influence of refractive index of an analyte on the frequency and amplitude sensitivities is studied in detail. Numerical results show that a high frequency sensitivity of 0.08 THz per refractive index unit (RIU) for mode C canbe obtained simultaneously using our proposed structure. The proposed structure can be realized using current micro/nano fabrication facilities, which may open up a new path for sensingin the THz frequencies.

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