Front. Optoelectron. 2015, 8(1): 68–72
DOI 10.1007/s12200-014-0431-5

RESEARCH ARTICLE

A high Q terahertz asymmetrically coupled resonator and its sensing performance

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Abstract A terahertz asymmetrically coupled resonator (ACR) consisting of two different split ring resonators (SRRs) was designed. Using finite difference time domain (FDTD), the transmission of ACR and its refractive-index-based sensing performance were simulated and analyzed. Results show that the ACR possesses a sharp coupled transparent peak or high quality factor (Q), its intensity and bandwidth can be easily adjusted by spacing the two SRRs. Furthermore, the resonator exhibits high sensitivity of 75 GHz/RIU and figure of merit (FOM) of 4.4, much higher than the individual SRR sensors. The ACR were fabricated by using laser-induced and chemical non-electrolytic plating with copper on polyimide substrate, the transmission of which measured by terahertz time-domain spectroscopy system is in good agreement with simulations.

Keywords terahertz, asymmetrically coupled resonator (ACR), refractive index sensing, high quality factor (Q)

1 Introduction

Metamaterials are a new class of artificial materials consisting of sub-wavelength structures, enabling unprecedented electromagnetic properties in nature, and based on which lots of devices with new functionality have been achieved [1–3]. Terahertz wave is referred to electromagnetic radiation with specific frequency of 0.1–10 THz (1 THz = 10^{12} Hz). Chemical and biologic molecules can be identified with terahertz wave by detecting molecular absorption peaks or phonon resonance of molecular components. Nevertheless, there is no characteristic absorption peaks or clear finger-prints experimentally observed for many biologic macromolecules such as proteins or DNA. As a result, their ingredients or concentrations need to be identified and detected by means of analyzing changes in dielectric properties attributed to the interactions between terahertz wave and biomolecules. Therefore, it is requisite to detect dielectric properties of trace amounts of chemical and biologic molecular components flexibly and sensitively [4]. Owing to the localized electromagnetic field enhancement and high quality factor (Q), split ring resonator (SRR) based metamaterial shows potential applications in biochemical sensing [5–7]. A higher Q resonant mode can be obtained through breaking geometrical symmetry of the metamaterial structure [8]. Hence, asymmetric SRR has turned to be effective way to gain higher sensitivity for these sensors [9–11]. Chen et al. [12] proposed two SRRs based asymmetrically coupled resonator (ACR) in optical range, the simulation showed that high quality factor could be achieved which is highly required for label-free bio-sensors. In this paper, we designed and fabricated a terahertz resonator based on asymmetrically coupled resonance. The results show that both the intensity and Q value of the transparent resonant peak can be adjusted by spacing the two SRRs, then performance of its refractive index sensing is further demonstrated.

Received March 26, 2014; accepted May 7, 2014

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2 Design and simulation of ACR

The unit cell of the designed ACR is shown in Fig. 1, and the microscopic picture of one fabricated sample is depicted in Fig. 2. This structure consists of two different SRRs, named narrow SRR (SRRn) and wide SRR (SRRw), which are arranged in the vertical direction asymmetrically. The dimensions of the unit cell are chosen as L_1 = 50 μm, L_2 = 70 μm, L_3 = 140 μm, L_4 = 40 μm, g = 8 μm, g_1 = 110 μm, and W = 8 μm. The distance between the two SRRs is d, and the lattice constant p is 180 μm both in x and y directions. When terahertz wave propagates along perpendicular to the sample, the coupling resonance will emerge if the two SRRs with similar resonant frequency

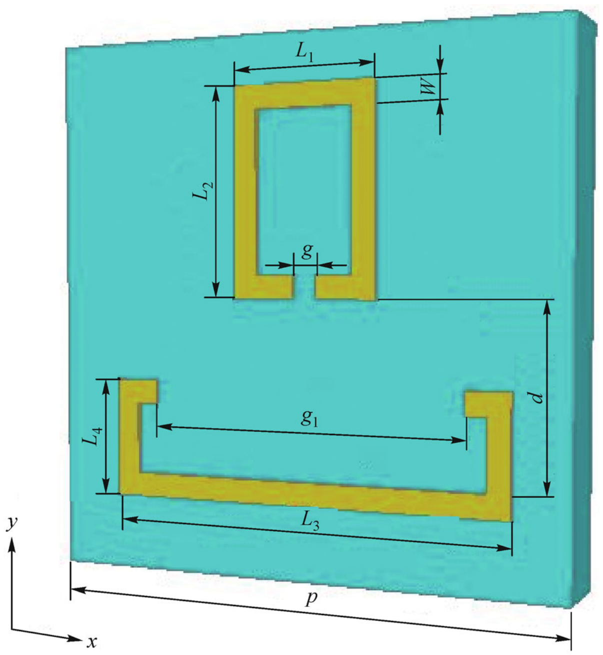

Fig. 1 Schematic view of the proposed ACR

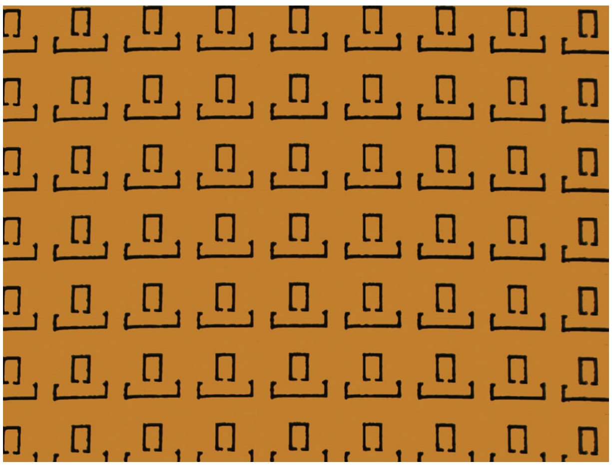

Fig. 2 Microscopic picture of the fabricated ACR

get closed, which is named asymmetrically coupled resonance.

The resonator is simulated using finite difference at time domain (FDTD). The boundary conditions are set to electric field and magnetic field along x and y directions, respectively. The substrate of polyimide (PI) with dielectric constant of 3.5 is assumed, and the conductivity of copper is 5.8×10^7 S/m. The distance d is 30 μm. The simulated transmittance of ACR is shown in Fig. 3, and results for SRRn and SRRw alone are also given. The resonant peaks for SRRn and SRRw alone are quite close to be centered at 0.554 and 0.552 THz, but the width of the resonant peaks

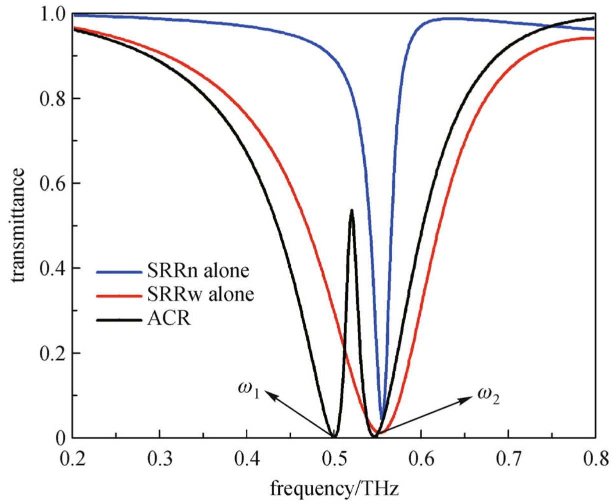

Fig. 3 Transmittance of ACR and SRRs when d = 30 μm

or quality factor value (Q-value) are quite different. The excited resonant mode in the SRRn with large Q-value behaves a less damped resonant type to serve as a subradiant mode, while the resonance in the SRRw is comparably lossy due to the low Q-value to be regarded as a superradiant mode. When the subradiant and superradiant modes coupled with each other in ACR, there emerges an extraordinary electromagnetic response of a sharp transparent resonant peak or two transmission dips at ω_1 and ω_2 (shown in Fig. 3), which can be explained by the plasmonic hybridization mode [12].

We further analyzed the distribution of induced currents at resonant frequency ω_1 and ω_2. As shown in Fig. 4, the low-energy mode (ω_1) presents the opposite direction of induced currents in the two SRRs, which is analogous to bonding mode in hybridized molecule system. But the high-energy mode (ω_2) possesses the same direction of induced currents, which is similar to antibonding mode in hybridized molecule system. Different from those recently reported of electromagnetic induced transparency (EIT) phenomenon generated by interaction between bright mode (radiative) and dark mode (non-radiative), the asymmetrically coupled resonance is excited by the coupling between the two radiative plasmonic modes.

Thus, both the resonant intensity and Q-value can be easily adjusted by the distance between two SRRs, which is shown in Fig. 5. It is easy to see that the intensity of resonant peak decreases when the distance d increases from 30 to 70 μm, and its corresponding bandwidth gets narrower at same time, this means that the Q-value of the resonator gets larger, instead. As a result, the Q-value of transparent peak rises up to 62 while d increases to 70 μm. However, in case of the distance exceeds 90 μm, the sharp transparent peak will disappear because of the decreased coupling effect.

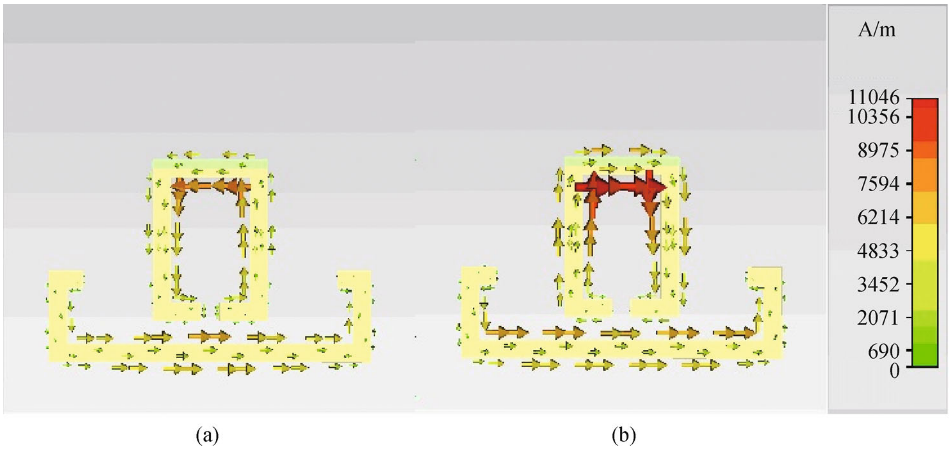

Fig. 4 Distribution of induced currents at resonances ω_1 (a) and ω_2 (b)

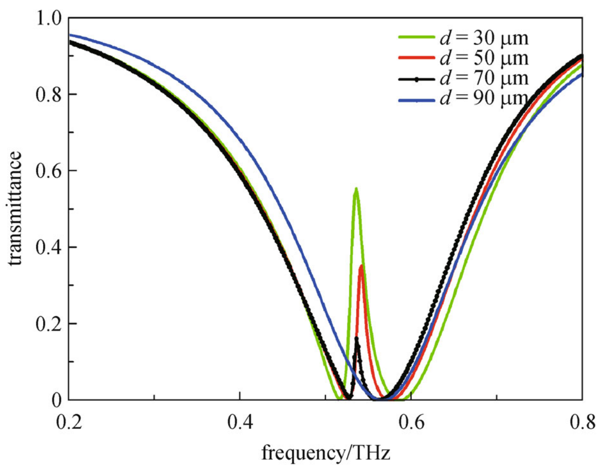

Fig. 5 Simulated transmission of ACR with different distances d

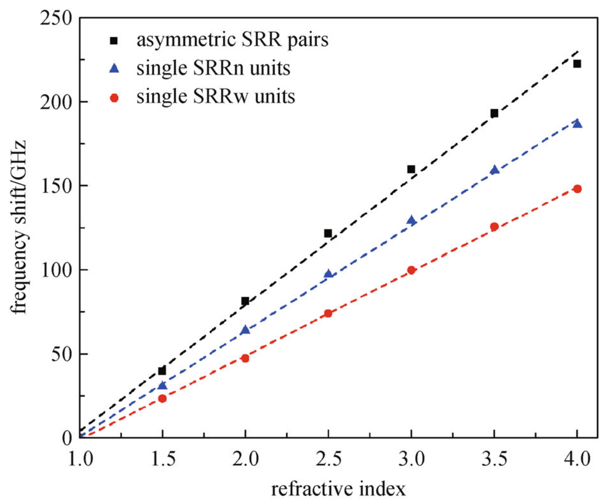

Fig. 6 Frequency shift of the resonant peak *vs* refractive index of analyte

3 Sensing performance of resonator

According to the above interpretation, the excitation of ACR is caused by the interaction between superradiant and subradiant modes. Intensive localization of electromagnetic energy will happen when the two resonant modes are strongly coupled, which is substantially similar to nano-cavities with high Q [13]. Therefore, it can be used as a refractive index sensor since its resonant spectral position depends on surrounding dielectric medium. Here we analyzed and simulated the sensing properties of the three resonators (ACR, SRRn and SRRw), respectively, which were coated by analyte with different refractive index. In simulation, the thickness of the analyte film assumes to be 3 μm, the refractive index of which varies from 1.0 to 4.0. An apparent linear relationship between frequency shift of the resonant peak and refractive index is demonstrated in Fig. 6. The refractive index sensitivities of the three resonators (ACR, SRRn and SRRw) are 75.1, 62.8, and 50.1 GHz/RIU, respectively. It is clear that the sensitivity of ACR is higher than other two individual SRRs.

In addition, figure of merit (FOM) [14] is used in further for evaluating the refractive index sensing performance of the resonator, which is defined as

$$\mathrm{FOM} = \frac{m(\mathrm{nm/RIU})}{\mathrm{FWHM(nm)}},$$

where m is the wavelength shift of resonant peak caused by unit refractive index change of the analyte, FWHM (full width at half maximum) refers to 3 dB bandwidth of resonant peak.

FOM is more effective than sensitivity used for evaluating a sensor because it takes the bandwidth of resonant peak into consideration, which is crucial for determining the resolution or precision of the measurement. For the same sensitivity of sensors, narrower bandwidth (or higher Q) means larger FOM, thus higher resolution or precision can be achieved. We figure out the FOM values for ACR, SRRn, SRRw as 4.42, 3.01 and

0.43, respectively. As resonant peak of ACR has a narrower bandwidth, its FOM value shows significantly higher than other two individual SRRs.

4 Fabrication and measurement of ACR

To verify the effectiveness of asymmetrically coupled resonance, two ACRs with distances of 40 and 90 μm respectively have been fabricated on 25 μm-thickness PI film using laser-induced and chemical non-electrolytic plating with copper [15,16]. The microscopic pictures of resonators are shown in Fig. 2 (d = 40 μm) and inset of Fig. 7. The whole size of resonator is 1 cm × 1 cm and the thickness of copper is about 2 μm measured by step profiler Dektek150.

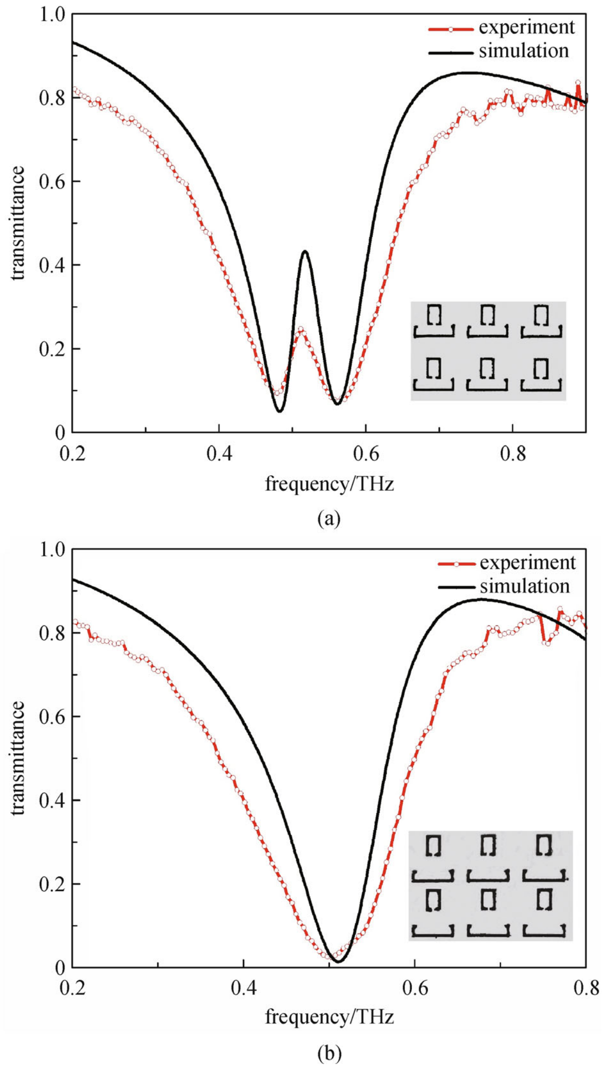

Fig. 7 Comparison of transmittance spectra between simulation (black line) and experiment (red line), the distance d is 40 μm (a) and 90 μm (b)

The transmission spectra of two ACRs were measured by terahertz time-domain spectroscopy (THz-TDs, shown in Fig. 7). To reduce the terahertz absorption of moisture in air in the measurement, the optical path of THz-TDS is sealed in a box filled with dry nitrogen to assure that relative humidity is less than 1%. The simulation results are also shown in Fig. 7. The coupled resonant peak is observed when spacing the two SRRs closely (d = 40 μm), though its intensity measured is weaker than simulated, mainly due to the lossy substrate and geometry error in fabrication. But it does not appear at d = 90 μm, due to weak coupling effect as simulation predicted. The experimental results are in good agreement with simulations.

5 Conclusions

A terahertz resonator based on asymmetrically coupled resonance has been designed. Using FDTD method, sensing performance of the resonator as well as transmission characteristics were simulated. Results show that the intensity and bandwidth of its resonant peak can be easily adjusted by spacing the two SRRs. Furthermore, the resonator exhibits high refractive-index sensitivity of 75 GHz/RIU and FOM of 4.4, much higher than the individual SRR sensors. The experimental results characterized by THz-TDS is in good agreement with simulations, which suggest that the ACR type resonators may have potential applications in refractive-index-based biochemical sensing.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 61377108).

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