Asymmetrically Polarization-Dependent Terahertz Metamaterial Resonator

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***Abstract*—A design of asymmetrically polarization-dependent Terahertz (THz) metamaterial resonator is presented. There are three designs with different length of F-shape metamaterial, which are 60 μm, 65 μm, and 70 μm kept other parameters as constant. The electromagnetic response of THz resonator exhibits the switch function for single-band resonance at transverse magnetic (TM) mode and dual-band resonance at transverse electric (TE) mode by changing the gap between F-shape metamaterials. These characterizations of device can be used for a THz filter at TM mode and a THz switch at TE mode. To compare the proposed device with and without a gap, that can be switched in the range of 0.20 THz to 0.40 THz for single-band switching resonance at TM mode and dual-band switching resonance at TE mode, respectively. These resonances have ultra-narrow bandwidths with a highest Q-factor of 41 at TE mode and 20 at TM mode. Such results are very suitable to be used for an environmental sensor. To enhance the flexibility of device, it is exposed on different surrounding environment with different refraction index. It shows the correlation coefficient is 0.9999 for high-efficiency environmental sensor application. This study paves a way to the possibility of high-sensitivity of tunable THz metamaterial in filter, switch, polarizer, and other applications.**

Keywords—metamaterial, terahertz, switch, polarizer, modulator, resonator

I. INTRODUCTION

Transformation optics is one of the key theories to describe the propagation path of electromagnetic wave [1]. Recently, terahertz (THz) metamaterial becomes a feasible material for electro-optics applications due to their unique optical properties that cannot be found in natural materials. There are many literatures reported THz metamaterials by using symmetrical or asymmetrical split-ring resonator (SRR) to perform THz filter, THz polarizer, and THz switch [2]. However, the resonant frequencies of these designs are unaltered, which can only filter or absorb certain electromagnetic spectra passively. To improve the flexibility of THz metamaterial, researches have been proposed and demonstrated many tuning mechanisms, including optical, electrical, magnetic, and thermal approaches [3]. These reported tuning mechanisms are limited to a single application caused from the symmetric or asymmetric SRR configurations. Therefore, the desire to achieve a multifunctional THz device with active tunability has been a research topic of interest for scientists.

In this study, we propose a polarization-dependent THz resonator by using asymmetrical F-shape metamaterial. This design exhibits multi-functionalities and ultrahigh Q-factor. It can be not only tuned from single-band to dual-band resonance at TE mode for filter and switch, but also tuned between TE and TM modes for polarizer. This design of asymmetrically polarization-dependent THz metamaterial resonator opens an avenue to the possibility of THz wave manipulations for the uses in filter, resonator, switch, and other THz applications.

II. MATERIALS AND METHODS

Fig. 1 shows the schematic drawing of asymmetrically polarization-dependent THz metamaterial resonator composed of an Au layer with 300 nm in thickness on silicon-on-insulator (SOI) substrate. The corresponding geometrical denotations of unit cell are illustrated, where P_x = 125 μm, P_y = 60 μm, a = 40 μm, c = 5 μm, d = 10 μm are kept as constant in this study. Three designs of proposed device are b = 60 μm, b = 65 μm, and b = 70 μm, respectively, while x parameter is changed from 0 μm to 40 μm. The resonant frequency can be tuned by using MEMS-based actuation force to change x parameter, e.g. electrothermal or electrostatic force. Asymmetrically polarization-dependent THz resonator with gaps, i.e. x parameters between double F-shape metamaterials can be considered as an inductive-capacitive (LC) resonator from the view of equivalent circuit. The inductance and capacitance are related to the contour and gap of F-shape metamaterial, respectively. The electromagnetic resonance is a function of refraction index of THz wave, according to the quasi-static formulas for a parallel plate capacitor and a solenoid. The inductance and capacitance in the formula can be expressed as $C = \varepsilon_0\varepsilon_c ct/x$ and $L = \mu_0 b^2/t$, where ε_0 is the free space permittivity, and ε_c is the relative permittivity of the materials within gap, t is the metallic thickness. Therefore, the resonant frequency of proposed device can be actively tuned to blue-shift by increasing x value.

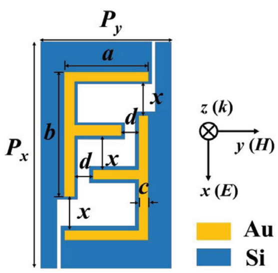

Fig. 1. Schematic drawing of asymmetrically polarization-dependent THz metamaterial resonator.

III. RESULTS AND DISCUSSIONS

Fig. 2 shows the transmission spectra of asymmetrically polarization-dependent THz metamaterial resonator by changing x parameter from 0 μm to 40 μm at TE and TM modes as shown in Fig. 2(a-c) and (d-f), respectively. In the initial state, the gap between F-shape metamaterial is zero, i.e. x = 0 μm, there is single-resonance at TE mode and TM mode. When x value is changed from 4 μm to 40 μm, there are two resonances at TE mode. The first resonance is kept as constant as 0.21 THz and second resonance is blue-shift. It is clearly observed that exhibits a single-band and dual-band switching

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characteristic. At TM mode, there is one resonance shifted from 0.33 THz to 0.44 THz (b = 60 μm), 0.33 THz to 0.45 THz (b = 65 μm), and 0.31 THz to 0.43 THz (b = 70 μm) for x value changing from 0 μm to 40 μm. The trend of tuning resonance is nonlinear. The resonance is blue-shift and then saturated gradually due to the F-shape metamaterial is moved to be farer than another F-shape metamaterial. The Q-factors and x values of proposed device are plotted in Fig. 3. It is clearly observed the relationships of Q-factors and x values of three devices are linear trends. These Q-factors are almost identical and kept as constant as 20 at TM mode. At TE mode, the trends of Q-factors to x values of three devices are increasing gradually. The corresponding slopes are 0.27, 0.30, and 0.42 for b = 60 μm, b = 65 μm, and b = 70 μm, respectively. The average Q-factors are 37, 30, and 32 for the cases of b = 60 μm, b = 65 μm, and b = 70 μm at TE mode, respectively. The highest Q-factor is 41 for the case of b = 60 μm and x = 40 μm. Such electromagnetic characteristic of ultra-high Q-factor is very suitable for the use in sensing application. To further prove the applicability of proposed device, which is designed to be exposed on different environmental medium and then demonstrated the high-efficiency sensor application. Fig. 4(a) shows the transmission spectra of device by changing ambient reflection index (n) from 1.0 to 2.0. The geometrical parameters are kept at x = 4 μm, a = 40 μm, b = 60 μm, c = 5 μm, and d = 10 μm, respectively. The relationship of resonance and reflection index is summarized in Fig. 4(b). The trend is linear with a correlation coefficient of 0.9999. This value is better than those reported in literatures [1-4]. Such design of device can be used as a high-efficiency environmental sensor.

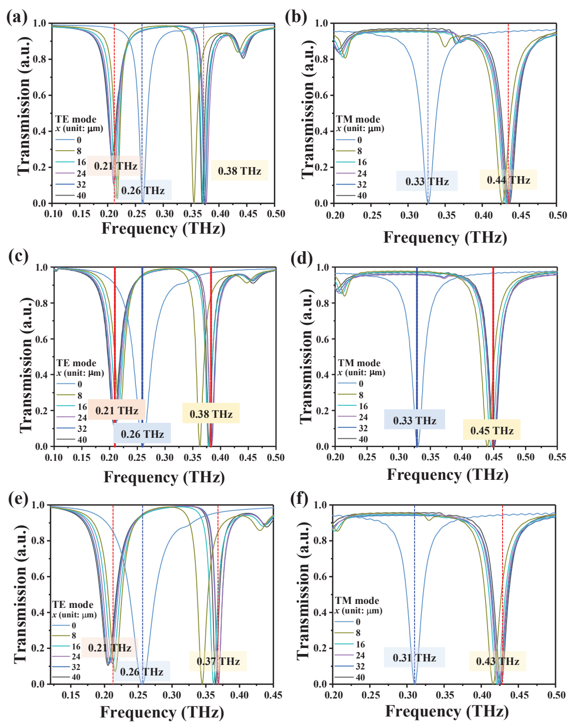

Fig. 2. Transmission spectra of proposed device with (a)(b) b = 60 μm, (c)(d) b = 65 μm, and (e)(f) b = 70 μm at TE mode and TM mode.

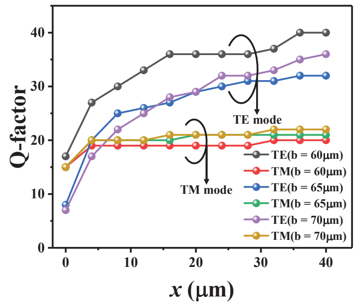

Fig. 3. The summaries of Q-factors for proposed device with different b value.

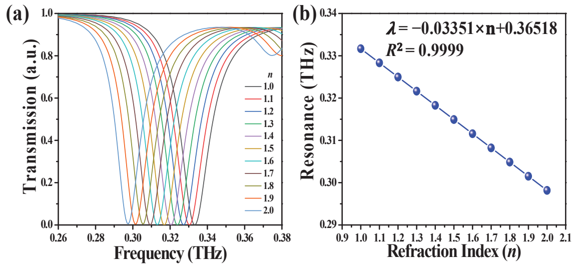

Fig. 4. (a) Transmission spectra of device exposed on different refraction index (n) from 1.0 to 2.0. (b) The relationship of resonance and n.

IV. Conclusion

In conclusion, an actively tunable MEMS-based THz resonator by using F-shape metamaterial is presented. The proposed device exhibits the tunabilities of single-band and dual-band resonances with an ultra-narrow bandwidth. The resonance could be tuned by changing the gap between F-shape metamaterials. The tuning ranges of resonances could be spanned from 0.20 to 0.40 THz to be a THz switch function. The highest Q-factor is 41 for the case of b = 60 at TE mode. At TM mode, Q-factors of three devices are stable and kept as constant as 20. The proposed device can be not only realized an ultra-narrowband resonator but also a THz switch and polarization switch. This work provides the detail investigation of tunable THz resonator by using F-shape metamaterial. With the investigation of geometrical relationships of F-shape metamaterial being fully understood, this design provides a new direction for future THz device applications.

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