Tunable Multiband Terahertz Metamaterial with Bidirectional Polarization-Dependent Characteristic

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***Abstract*—We present a tunable terahertz (THz) metamaterial (TTM) composed of chain-link split-ring resonators (SRRs), which is the composition of a tailored Au layer on Si substrate. TTM exhibits bidirectional multi-band polarization-dependent characteristic by applying a direct-current (dc) bias voltage on device. The chain-link SRRs of TTM can be heated up the surrounding temperature to tune the corresponding resonance. The tuning range is 0.027 THz from 0.318 THz to 0.291 THz on the bias of 0.60 V to 1.32 V. By reconfiguring the gap between chain-link SRRs of TTM, there are single-resonance with red-shift at TE mode, and multi-resonance with blue-shift and red-shift at TM mode, respectively. These characterizations of TTM are polarization-dependence and bidirectional tunability. These results show the electromagnetic responses of proposed TTM device is suitable for the uses for resonator, filter, switch, and sensor in the THz frequency range.**

Keywords—tunable metamaterial, MEMS, resonator, polarization-dependence

I. INTRODUCTION

Terahertz (THz) metamaterial is an emerging field for electro-optics applications. It is an artificial material can be designed to many kinds of configurations, such as split-ring resonators (SRRs), arrays of subwavelength wires, fishnet structures, etc. Among of these structures, SRRs possess many unique electromagnetic properties which are widely reported to be used in filter, resonator, polarizer, antenna, and sensor [1].

Recently, reconfigurable metamaterials become feasible in many applications by reconfiguring the dimension of metamaterial unit cell, which are other than the uses of thermal control, liquid crystal, phase transition material, and semiconductor diode are highly dependent on the nonlinear properties of the natural materials [1-4]. These methods suffer from a limited tuning range. The variations in geometrical dimensions of metamaterial structures are often resulted from mechanical movement or metamaterial deformation. However, the resonant frequencies of these designs are unaltered, which can only filter or absorb certain electromagnetic spectrum passively [4]. In addition, the reported THz resonators based on SRRs can be only tuned the corresponding resonance with single-directional shift and polarization-independence. To develop unique bidirectional polarization-dependent characteristics, it is indispensable to have the abilities of active tunability with large tuning range of resonance.

In this study, we propose an active tuning mechanism to manipulate THz wave by using electrothermal force to modify the surrounding temperature and electrostatic force to perform the reconfigurable metamaterial based on microelectromechanical system (MEMS) technique. The proposed device is a tunable THz metamaterial (TTM) composed of chain-link SRRs. TTM can be tuned to realize bidirectional tunability and tunable single-band at transverse electric (TE) and transverse magnetic (TM) modes for THz filter and THz polarizer applications. By using electrothermal actuation mechanism, the applied direct-current (dc) bias voltage can heat up the near-field temperature to generate the Fano-resonance within TTM. Such change of near-field temperature is accompanied with the refraction index change of surrounding environment. We discuss the relationship of influence for bias voltage and corresponding refraction index of surrounding TTM. It can be potentially used in real-world applications such as active sensors, biomedical imaging, modulators and so on.

II. MATERIALS AND METHODS

Fig. 1 (a) shows the schematic drawing of TTM device composed of a tailored Au layer with 300 nm in thickness on Si substrate. The optical microscopy image of TTM device is showed in Fig. 1. (b), and the corresponding denotations of geometrical parameters are indicated in the inserted image of Fig. 1(b). The denotations are length of T-shape (*l*), length of SRRs (*a*) and inner distance between T-shape and SRRs (*g*). The period size of TTM is $Px \times Py$ = 100 μm × 50 μm. The coordinates of incident electromagnetic wave are shown in Fig. 1 (a), where *E*, *H*, and *k* are the electric field, magnetic field, and Poynting vector of electromagnetic wave, respectively.

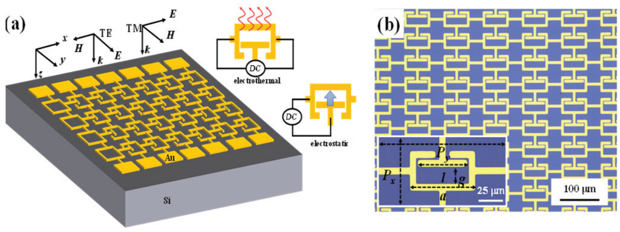

Fig. 1. (a) Schematic drawing and (b) optical microscopy image of TTM device. The corresponding denotations of geometrical parameters are indicated in the inserted image of (b).

III. RESULTS AND DISCUSSIONS

The transmission spectra of model with different *a* value at TE and TM modes are shown in Fig. 2 (a) and (b), respectively. While *l* value is varied along with *a* value simultaneously. The *g* value is kept as constant as 20 μm. At the initial state, resonances of model with *a* = 30 μm are 0.19 THz and 0.32 THz at TE mode and TM mode, respectively. By increasing *a* value from 30 μm to 110 μm, the resonance is blue-shift 0.04 THz first from *a* = 30 μm to *a* = 80 μm, and then red-shift 0.03 THz from *a* = 80 μm to *a* = 110 μm. It is clearly observed that TTM exhibits a bidirectional characterization at TE mode. At TM mode, there is single resonance linearly shifted 0.15 THz from 0.32 THz to 0.17 THz by changing *a* value from 30 μm to 110 μm.

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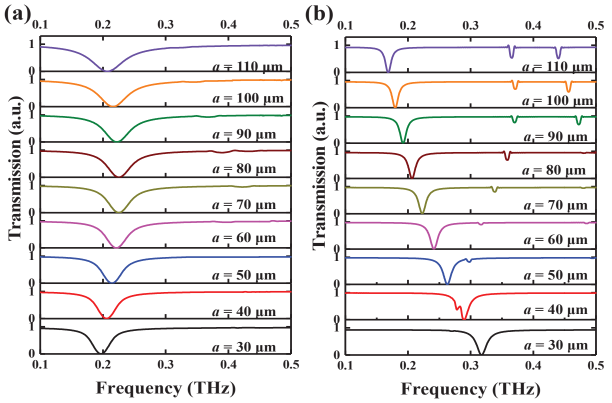

Fig. 2. Transmission spectra of TTM with different a value at (a) TE mode and (b) TM mode.

By applying a dc bias voltage on TTM, the surrounding temperature can be heating up. Fig. 3 shows the experimental results of TTM applied different bias voltage at TM mode. The resonances of TTM are red-shift with a tuning range of 0.027 THz from 0.318 THz to 0.291 THz. The driving voltage is 0.60 V to 1.32 V. The parameters of TTM device are kept as constant as a = 30 μm, l = 20 μm, g = 20 μm at TM mode applied different dc bias voltage. The resonance is quite linear with a correlation coefficient of 0.98097. These results provide that the proposed TTM device can be used in tunable sensor with single-band resonance characteristic.

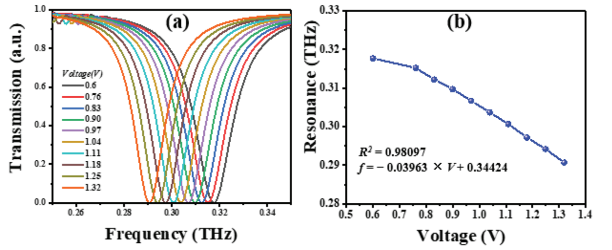

Fig. 3. (a) Transmission spectra of TTM with a = 30 μm applied different dc bias voltage (V) at TM mode. (b) is the corresponding relationship of resonance and V.

To further investigate the active tunabilties of TTM device, the gaps between chain-link SRRs and T-shape metamaterials are tuned by using electrostatic force to shorten the gaps from 20 μm to 0 μm. Fig. 4 (a) shows the optical microscopy image of TTM device after released chain-link SRRs. The transmission spectra of TTM device with different g value at TE and TM modes are shown in Fig. 4 (b) and Fig. 4 (c), respectively. The geometrical parameters are kept as constant as a = 65 μm and l = 55 μm. At TE mode, the tuning range of resonance is red-shift 0.11 THz from 0.29 THz to 0.18 THz for g = 20 μm to g = 0 μm as shown in Fig. 4 (b). It exhibits tunable single-band resonance. At TM mode, the initial resonances are 0.18 THz (first resonance) and 0.32 THz (second resonance) under the condition of g = 20 μm. By tuning g value to 10 μm, the first resonance is kept as constant and second resonance is blue-shift to 0.34 THz, while there is generated third resonance around 0.46 THz. By shortening g value to 0 μm, the first resonance becomes two resonances, which are 0.19 THz and 0.23 THz while the second and third resonances will merge together at 0.40 THz as shown in Fig. 4 (c). Thus, TTM exhibits multi-band with bidirectional polarization-dependent characteristic.

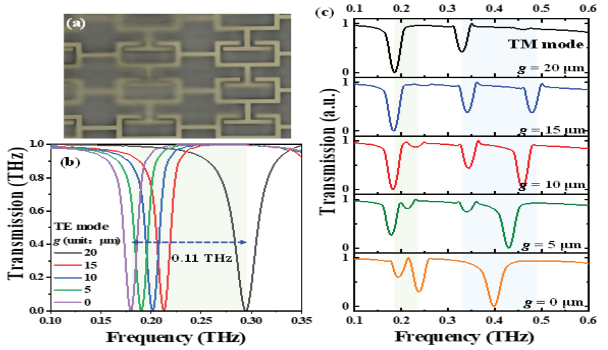

Fig. 4. (a) Optical microscopy image of released TTM. Transmission spectra of TTM with different g value at (b) TE mode and (c) TM mode.

IV. Conclusion

In conclusion, an actively tunable TTM is presented, which is composed of chain-link SRRs and T-shape metamaterials on Si substrate. By applying a dc bias voltage on TTM without released chain-link SRRs, the tuning range is 0.027 THz with a correlation coefficient of 0.98097. For TTM with released chain-link SRRs, the dc bias voltage is applied to change the gap between chain-link SRRs and T-shape metamaterials that could be modified and then reconfigured TTM microstructures. The electromagnetic responses exhibit bidirectional polarization-dependence. It can be not only used for THz filter and polarizer applications, but also for single-band to multi-band THz switches. TTM can be actuated by using electrothermal actuation mechanism to heat up the near-field temperature and then make the Fano-resonance of TTM shifting. Such electromagnetic response of Fano-resonance is artificially created by the induced anisotropic near-field coupling. It can be observed in the resonance tuning by applying varying voltage on TTM, which creates the possibility to be used in high-efficiency environmental sensor application.

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