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High-Efficiency Flexible Terahertz Metamaterial

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***Abstract*—A high-efficiency flexible terahertz (THz) metamaterial is presented, which is composed of parabolic-shape configuration. The device exhibits the larger tunabilities of single-band and dual-band resonances with ultra-narrow bandwidth. It possesses the multifunctionalities of single-band and dual-band switch and polarization switch for the realization of programmable metamaterials.**

Keywords—flexible metamaterial, terahertz, multifunctional switch, modulator

I. Introduction

Terahertz (THz) wave becomes an emerging science and technology owing to the characteristics of THz wave. They are nonionizing and safe to biological tissue, high transmission to be transparent for common plastics and fibers, and shorter wavelength than millimeter waves. It provides a higher spatial resolution for optics and imaging system applications [1-3]. However, THz optics in-between the source and detector become a bottleneck to many dielectric, semiconductor, and metallic components. The integration of THz optics constituted by optical miniaturized components is expected to express higher signal transmission or reflection. It allows for more compact systems and enables the integration with other systems for increasing flexibility and applicability [3]. Such miniaturized THz optical components require new approaches and techniques, especially for devices related to actively THz-wave manipulation and have multifunctionalities.

Here, we demonstrate a high-efficiency flexible THz metamaterial by using polydimethylsiloxane (PDMS) based parabolic-shape configuration. By stretching flexible THz device along different direction, it exhibits ultra-narrowband, polarization-dependent and switchable characterizations. The resonant tunabilities of device are 0.55 THz and 0.32 THz at TM and TE modes, respectively. The integration of proposed device on mechanically flexible and deformable PDMS substrate offers significant promise in flexible electronics and sensors applications.

II. Materials and Methods

Fig. 1(a) shows the photograph and the schematic illustrations of proposed flexible THz device. The pattern of metamaterial is according to the quadratic function complied with the equation of $y = \pm ax^2 \pm b$ to form the parabolic-shape configuration, where a and b are coefficients of quadratic function. It is composed of Au thin-film with 100 nm in thickness fabricated on PDMS elastic substrate. The geometrical deformations of device by applying a stretched force along x-axis and y-axis directions are presented in Fig. 1(b). It is regarding to the direction of stretchable force applied on flexible THz device, resulting in different geometric deformations. The stretchable force along different direction, the deformation of device can be expressed as $\varepsilon_x = \sigma_x/E$ and $\varepsilon_y = \sigma_y/E$, where ε_x and ε_y are the ratio of length changes to initial lengths, σ_x and σ_y are the strains of PDMS along x- and y-axis, respectively, and E is Young's modulus of PDMS. According to the theory of Drude-Lorentz model [4,5], the resonance of flexible THz device is a function of the effective refraction index of THz wave.

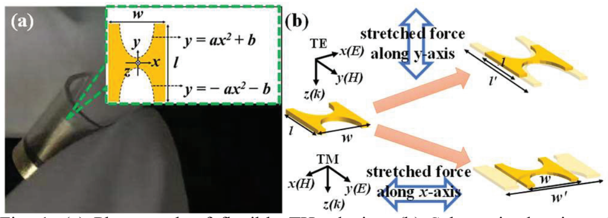

Fig. 1. (a) Photograph of flexible THz device. (b) Schematic drawing of flexible THz device and illustrations for applying a stretched force along x-axis and y-axis directions.

III. Results and Discussions

The transmittance of flexible THz device with different width (w) at TE and TM modes are shown in Fig. 2. The variable of w value is caused from the stretching flexible THz device along x-axis direction while the length (l) of flexible THz device can be kept as constant as 30 μm. At initial state, i.e. w = 30 μm and l = 30 μm, the resonance shift of transmittance is 0.07 THz by stretching w value from 30 μm to 90 μm at TE mode as shown in Fig. 2(a). At TM mode, there are two resonances generated by dipole and inductive-capacitive (LC) resonances denoted as ω_1 and ω_2, respectively, which are 0.30 THz and 1.35 THz at initial state, respectively as shown in Fig. 2(b). By stretching the flexible THz device, i.e. increasing the w value, two resonances are red-shift with a tuning range of 0.07 THz (ω_1) and 0.45 THz (ω_2) from w = 30 μm to w = 90 μm. This large tuning range of LC resonance is caused from the stretching geometrical dimension, which resulted in the period changed along x-axis direction. The corresponding E-field and H-field distributions are shown in the inserted images of Fig. 2(a) and Fig. 2(b). At TE mode, E-field energy is mainly distributed on the four apexes of flexible THz device, while H-field energy is mainly concentrated on both sides of the H-shape of flexible THz device. At TM mode, the E-field energy is distributed on the four corners of flexible THz device and most of energy is concentrated on the center of flexible THz device.

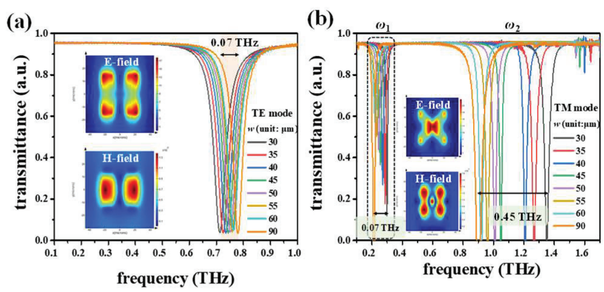

Fig. 2. Transmittance of flexible THz device with different w value at (a) TE mode and (b) TM mode.

Fig. 3 shows the transmittance of flexible THz device with different length (l) at TE and TM modes, which is caused from the stretching flexible THz device along y-axis direction while the width (w) of flexible THz device is kept as constant as 30

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μm. At TE mode, the resonance is red-shift 0.32 THz from 0.72 THz to 0.40 THz by stretching l value in the range of 30 μm to 90 μm, while the resonant intensities of transmittance could be kept as high as 80%. This is caused from the stretching geometrical dimension resulted in the period changed along y-axis direction. At TM mode, there are two resonances generated by dipole (ω_1) and LC (ω_2) resonances, which are 0.30 THz and 1.35 THz at initial state, respectively as shown in Fig. 3(b). By stretching the flexible THz device, i.e. increasing the l value, two resonances are red-shift with a tuning range of 0.08 THz (ω_1) and 0.06 THz (ω_2) from l = 30 μm to l = 90 μm, respectively. Although these tuning ranges are quite small, but the resonant intensities of transmittance could be kept as high as 80%. That can be explained by the E-field and H-field distributions of flexible THz device at TE and TM modes as shown in Fig. 3(c). At TE mode, the E-field energy is distributed on the four apexes of flexible THz device, and the H-field energy is mainly concentrated on the center region of flexible THz device. At TM mode, the E-field energy of ω_1 is distributed on the surface of device to form X-shape electromagnetic response, and the H-field is concentrated on the center region on device surface. While the E-field and H-field energies of ω_2 are complementary with those of ω_1.

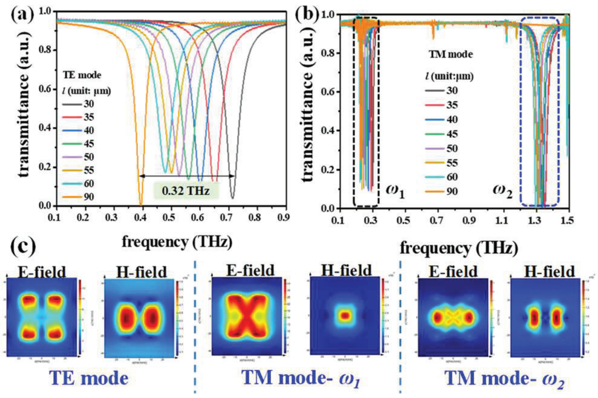

Fig. 3. Transmittance of flexible THz device with different l parameter at (a) TE mode and (b) TM mode. (c) The corresponding E- and H-field distributions of flexible THz device with l = 45 μm at TE mode and TM mode for ω_1 and ω_2 resonances.

The summaries of experimental results for the relationships of TE and TM resonances to the deformation of flexible THz device with different w and l values are plotted in Fig. 4. By stretching w value along x-axis direction, the resonance is blue-shit 0.06 THz at TE mode and red-shift 0.55 THz at TM mode as shown in Fig. 4(a). By stretching l value along y-axis direction, the resonances are red-shifts 0.32 THz and 0.06 THz for operating at TE and TM modes, respectively as shown in Fig. 4(b). Fig. 4(c) and Fig. 4(d) are optical microscopy images of flexible THz device stretched along x-axis and y-axis directions to deform double elongations from initial state (w = 30 μm), respectively. These results indicate the proposed flexible THz device possess active tuning, larger tuning range, and ultra-narrow bandwidth. It shows good agreements with preliminary simulation results. It paves a way to use this proposed flexible THz device in flexible THz wave applications.

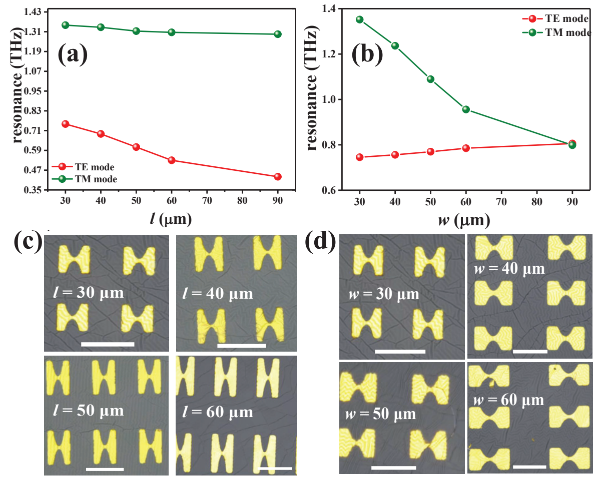

Fig. 4. (a) and (b) are summaries of resonances of flexible THz device with different (a) l and (b) w at TE mode and TM mode. (c) and (d) are optical microscopy images of flexible THz device with different l and w values.

IV. Conclusion

In summary, we demonstrate a flexible THz device with actively high-efficiency tunability and large tuning range. The proposed device exhibits the tunabilities of single-band and dual-band resonances with an ultra-narrow THz spectrum bandwidth. The resonance could be tuned by using mechanical force to deform the geometrical period of flexible THz device. The tuning ranges of resonances could be spanned from 0.20 to 1.40 THz to be a THz switch function. It can be not only realized an ultra-narrowband THz filter but also a THz switch and polarization switch. With the investigation of geometrical relationships of flexible THz device being fully understood, the design of flexible THz device opens an avenue to a new direction for future designs of optical applications and offers significant promise in flexible electronics applications.

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