Dual-band terahertz switch with stretchable Bloch-mode metasurface

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Abstract
A polydimethylsiloxane (PDMS)-based stretchable metadevice for dual-band switching of terahertz radiation is experimentally demonstrated. The metasurface can efficiently excite dipole resonance of the metal structure and the surface Bloch mode generated by the periodic lattice substrate. In the tensile deformation operation, these two resonant modes show significant frequency shift sensitivity characteristics, which provides a feasible solution for the realization of dual-band terahertz switches. A transmittance modulation depth of 90% is achieved by the dipole resonance, with a frequency shift of 0.14 THz. The other transmittance modulation depth of 65% is achieved by the surface Bloch mode, with a frequency shift of 0.4 THz. The broad tuning of 0.4 THz is attributed to the surface mode is period-sensitive. This approach provides a promising method for broad frequency tuning of stretchable metasurfaces.

1. Introduction

Metamaterials, as a kind of integrated artificial subwavelength structures with tailored electromagnetic properties, have been extensively studied for many years since it was first reported \cite{1, 2}. Metamaterials in the form of thin films are usually called metasurfaces. From microwave to ultraviolet, metasurfaces have been designed for application in frequency selection, sensing, modulation, detection, and so on \cite{3, 4}. The terahertz (THz) wave is located between microwave and infrared, the unique spectral position makes THz wave has great potential in the fields of biomedicine, communication and radar \cite{5, 6}. THz wave has been less studied due to the lack of natural response materials and the frequency limitations of electronic methods. Recently, the emerging metasurface technique in THz regime has greatly promoted the development of THz functional devices \cite{7–11}. Tunable THz metasurfaces attracted widespread attention as active device to manipulate the characteristics of THz wave.

A series of researches have been performed to improve THz switching operations \cite{12–19}. Yahiaoui \textit{et al} \cite{20} used shining near-infrared light beam to excite free carriers in the silicon patches to dynamically switch the transparent window of the electromagnetically induced transparent (EIT) effect, achieving a modulation depth of more than 70% at 0.57 THz. Li \textit{et al} \cite{21} demonstrate an electrically tunable EIT-like metasurface that works in the low-temperature environment, a modulation depth of a 79.8% are achieved at 0.34 THz through electrically controlled superconductor. However, these designs are based on the response of function materials to electricity, light or temperature, and often require complex structural processing and external configuration. This limits the application of THz switches in deformable environments \cite{22–26}. In
Figure 1. (a) Schematic of the proposed metasurface design. (b) The optical microscope image of the cross array on the PDMS substrate and (c) the microscope image under applied strain along x-axis direction.

particular, only single-band THz switching operations can be performed for most reported switches and there are few reports about multi-band THz switches.

In this paper, we present experimentally a dual-band THz switch with stretchable Bloch-mode metasurface which is composed of a PDMS wrapped cross-shaped metal array. The resonant frequency and optical characteristic of the metasurface are tuned by stretching the PDMS substrate. Under 38% deformation, we exploit the dipole mode and the surface Bloch mode to experimentally achieve dual-band switching with a modulation depth of 90% and a modulation depth of 65% at 1.23 THz and 2.3 THz, respectively. The switching operation frequency via the surface Bloch mode has a large dynamic range. The frequency can dynamically tuned from 2.3 THz to 1.9 THz with good switching contrast. Since the mechanisms of the electric dipole resonance mode and the periodic lattice resonance mode are independent from each other, the two resonance frequencies can be designed independently, which allows the frequency interval of the dual-band switch to be geometrically adjustable. The mechanical tuning of plasmonic microstructures offers a new pathway towards the development of tunable THz devices such as tunable filters and sensors [27–30].

2. Design and experiment

The proposed THz stretchable metasurface comprises a silver cross array that is embedded in a PDMS film as indicated schematically in figure 1(a). The unit cell is zoomed to indicate the detailed structural parameters. The dimensions of the metasurface involve the periods \( P_x = P_y = 110 \mu m \), the length of the cross \( l = 80 \mu m \), the width \( w = 10 \mu m \), the thickness of cover \( t_1 = 5 \mu m \) and the thickness of substrate \( t_2 = 22 \mu m \). Since the silver cross is polarization independent, the response characteristics of the metasurface are controlled by the relationship between the stretching direction and the polarization direction. We define TM (TE) wave as incident wave with polarization perpendicular (parallel) to the stretching direction.

The stretchable metasurface is fabricated by traditional photolithography and wet etching techniques. The fabrication process is illustrated as follows. First, a clean glass slide was spin-coated with a sacrificial negative photoresist layer and exposed to ultraviolet light. Second, the monomer (Sylgard 184 Silicone Elastomer) and curing agent for PDMS were mixed in a weight ratio of 10:1 and then placed in a vacuum desiccator to degas for 20 min. Third, the liquid PDMS was spin-coated onto the prepared slide at 1500 rpm for 1 min and baked at 70 °C for 180 min to form a 22 \( \mu m \) layer. Fourth, a 200 nm layer of silver was deposited onto the PDMS surface by magnetron sputtering. Fifth, a positive photoresist was coated on the silver surface and was patterned by using a photolithography technique. Sixth, the patterning of the stretchable metasurface was realized by using a wet etching process (Fe(NO₃)₃ solution). Seventh, a 5 \( \mu m \) thick PDMS was overlaid on the silver pattern to prevent the metal from falling off. Finally, the PDMS film with the silver cross pattern is peeled off from the glass slide.

The optical microscope image of the prepared sample is given in figure 1(b). Under applied stretching force, the geometric change of the unit cells is shown in figure 1(c) with the sample micrograph in the
Figure 2. The measured THz transmission spectra of the stretchable device for (a) TM and (b) TE wave at different levels of stretching.

deformed state. The images indicate that the period in the stretching direction is significantly increased with the effect of stress, while the period in vertical direction is slightly decreased. It is worth noting that since the Young’s modulus of the 200 nm silver film is $10^4$ times that of the PDMS film [29, 31], the deformation of the silver film can be ignored compared to the PDMS film when the sample is stretched. The disproportionate change between silver cross pattern and PDMS film results in a larger pattern pitch. The mechanical strain can be accurately described by stretching ratio $S$, which is defined as the proportion of the length change with respect to the initial lengths of the sample,

$$S = \frac{L - L_0}{L_0}$$

where $L$ is the stretched length and $L_0$ is the initial length of the sample.

The effect of deformation on the resonant frequency of the stretchable metasurface was experimentally investigated by applying a stretched force to deform the metasurface along the $x$- and $y$-axis directions, respectively. The tested metasurface is mounted on a custom sample holder, which is fixed on one side and movable on the other. The transmission spectra of the stretchable metasurface were measured by using a commercial THz time-domain spectroscopy system (BATOP THz-TDS 1008). In the experiment, a beam of THz radiation was collimated for normal incidence on the sample.

3. Results and discussion

Figure 2 shows the experimentally measured transmission spectra of the TM and TE waves under various applied strains. The macroscopic deformation of PDMS leads to the change of metasurface response, which is manifested as the modulation of THz transmission spectra. It is observed from figure 2 that the metasurface has the same response to the TM and the TE waves when no deformation is applied to the metasurface ($S = 0\%$). Two resonance modes are excited at 1.23 THz ($\omega_1$ mode) and 2.3 THz ($\omega_2$ mode), respectively. For TM incident wave, figure 2(a) indicates that both the $\omega_1$ and $\omega_2$ modes have a significant frequency red shift with the increase of the stretching deformation. Particularly under a stretching ratio of 38%, the amount of frequency shift of $\omega_1$ mode is 0.14 THz, crossing the spectra from 1.23 THz to 1.09 THz. The amount of frequency shift of $\omega_2$ mode is 0.4 THz, crossing the spectra from 2.3 THz to 1.9 THz. Such broad tunable spectra support the promising potential of stretchable metasurface beyond the dynamic tunability of electrical or thermal control manners. In contrast to TM wave, the TE incidence exhibits different behavior in frequency shift induced by stretching deformation. As shown in figure 2(b), as the stretching deformation increases, the frequency of $\omega_1$ mode has a blue shift. The change trends of the transmission spectra under stretching are plotted with a gray dotted line.

The transmittance and frequency data with error bars at different stretch ratio for TM wave are measured as shown in figure 3. Adequate experiments were carried out for the error analysis. At $\omega_1$ mode, the experimental results are given in figure 3(a). Under 38% stretching ratio, the frequency of $\omega_1$ mode shifts from 1.23 THz to 1.09 THz. This corresponds to the frequency sensitivity of 0.37 THz/USR in unit stretching ratio (USR, $S = 100\%$). By use of the stretch-induced spectra shift, one can control the transmission modulation of THz wave. At the initial resonance frequency of 1.23 THz, the transmittance can increase from 0.05 to 0.59 with a maximum difference of 0.54. This achieves large intensity modulation depth of up to 90%. The near-linear relationship between transmittance and stretching ratio exhibits. Figure 3(b) gives the experimental results at $\omega_2$ mode. Under 38% stretching ratio, the amount of frequency shift can reach 0.4 THz, which has the frequency sensitivity of 1.05 THz/USR. The available maximum deformation of 38% is limited by the elasticity of PDMS. Similarly as shown in figure 3(a) for $\omega_1$ mode, the transmittance increases from 0.27 to 0.77 at the initial frequency 2.3 THz, under the applied stretching...
deformation. The transmittance difference of 0.5 can achieve an intensity modulation depth of 65%. Unlike the $\omega_1$ mode, the intensity modulation of the $\omega_2$ mode at 2.3 THz exhibits saturation effect over 15% of stretch ratio. The large modulation depths suggest that the stretchable metasurface is favorable to achieve dual-band switching effect.

The switching effect of metasurface comes from the broadband frequency shift. To get a better understanding of the frequency shifts of $\omega_1$ mode and $\omega_2$ mode, the simulations were determined by using the commercial finite element method software package COMSOL multiphysics. In simulations, perfectly matched layer conditions are applied along the $z$ direction and periodic boundary conditions are applied in the $x$ and $y$ directions. The perfect electrical conductor boundary is used to replace silver cross due to the large imaginary part of the complex permittivity in metallic materials at THz regime. The complex refractive index of the PDMS substrate was taken as $n = 1.57 - 10.02$. The macroscopic stretching is simulated by proportionally increasing the period of the metasurface in the stretching direction, while the sizes of the metal patterns and the period in the vertical stretching direction remain unchanged.

The simulated transmission spectra at different levels of stretching for TM wave and TE wave are drawn in figures 4(a) and (b), respectively. The frequency shifts of the experimental and simulation results are in good consistency. The acceptable deviations in resonance frequency and transmittance values come from fabrication and testing process. The electric field intensity distribution of $\omega_1$ mode is given in the inset of figure 4(a). The electric field is localized at both ends of the silver cross structure, which indicates that the $\omega_1$ mode is at a dipole resonance. The incident THz wave excites the induced current on the arm of the cross metal in the polarization direction to form an oscillating electric dipole. The red shift of the TM wave and the blue shift of the TE wave in the $\omega_1$ mode can be explained by the coupling effects. The laterally coupled symmetric dipoles lead to a higher resonance frequency, and the longitudinally coupled symmetric dipoles lead to a lowering of the resonance frequency. For TM waves, the lateral coupling weakens as the stretching increases, which causing the frequency of $\omega_1$ mode to decrease. For TE waves, the longitudinal coupling weakens as the stretching increases, which causing the frequency of $\omega_1$ mode to increase.

Figures 4(a) and (b) show the $\omega_2$ mode of the simulation results in the initial state ($S = 0\%$) appearing as a plasmon-induced transparency (PIT) effect, which is different from the experiment results. When stretching is applied, the PIT effect disappears and the simulation results are consistent with the experimental results. Figures 4(a) and (b) reveal that change of period in the direction of the magnetic field or electric field ($P_x \neq P_y$) can lead to the PIT effect disappear. The disappearance is manifested as the separation of two resonances which constitute the PIT effect, one of the resonances is red shifted and the other remains unchanged. Figures 4(c) and (d) show the transmission spectra of the metasurface with different geometric parameters. It is worth noting that as the length of the silver cross increases, the frequency of dipole resonance is expectable red-shifted, while $\omega_2$ mode is not affected. It turns out that the $\omega_2$ mode is independent from the metal pattern. As the periods in electric and magnetic directions gradually increase ($P_x = P_y$), the $\omega_2$ mode still exhibits the PIT effect and the frequency is red-shifted. Comparing the results of figures 4(a), (b) and (d), a natural conclusion is that these two resonances of PIT effect relate to the periods in the electric and magnetic directions, respectively. We define the resonance related to the period of the magnetic field direction as the magnetic mode (MM), and the resonance related to the period of the electric field direction as the electric mode (EM). The resonance frequency is inversely proportional to the period and can be expressed as,

$$f_\alpha = c / (n_{\text{eff}} \cdot P_\alpha)$$

where $c$ is the vacuum speed of light, $n_{\text{eff}}$ is the effective refractive index $n_{\text{eff}} \approx 1.1$, and $P_\alpha$ is the period in the electric or magnetic direction.
Figure 4. The simulated THz transmission spectra of the stretchable device at different levels of stretching ratio for (a) TM wave and (b) TE wave; (c) the transmission spectra with different lengths of the silver cross; (d) the transmission spectra with different periods ($P_x = P_y$).

Figure 5. (a) The distribution of electric field $E_z$ at 2.48 THz (EM) and (b) the distribution of magnetic field $H_z$ at 2.28 THz (MM) for TM wave when $S = 12\%$; (c) and (d) are the electric and magnetic field strength distribution of the eigenmode of the latticed substrate, respectively. (e) The resonance frequency of MM of TM wave at different stretch ratio and the characteristic frequencies of the latticed substrate with corresponding size.

Figures 5(a) and (b) show the electric field $E_z$ distribution of the EM and magnetic field $H_z$ distribution of the MM. In the simulation, the polarization of the incident wave is along the $x$ direction and the stretching is along the $y$ direction. The frequency positions of EM and MM are marked with green (2.48 THz) and purple (2.28 THz) dotted lines in figure 4(a), respectively. The field distributions of the EM and MM indicate that they are the surface modes, similar to waves propagating along the surface of the substrate. Equation (2) shows that momentum of surface wave satisfied Bloch wave momentum conservation from the coupler equation.

$$\vec{k}_{sw} = \vec{k} + \frac{i}{\epsilon} \vec{G}_x + \frac{j}{\mu} \vec{G}_y$$

where $\vec{k}$ is the in-plane momentum of the incident light at the metal-dielectric interface, $\vec{G}_x = \frac{2\pi}{P_x} \hat{x}$ and $\vec{G}_y = \frac{2\pi}{P_y} \hat{y}$ are the reciprocal lattice vectors for the periods $P_x$ and $P_y$. Therefore, the surface wave is in the form of Bloch mode. The surface Bloch mode is closely related to the substrate and period of metasurface [33].

In the metasurface, due to the effect of the metal array, the substrate can be regarded as two-dimensional unit cells in the $x$–$y$ plane. In order to explore the causes of surface Bloch mode, COMSOL was used to calculate the eigenmode and characteristic frequency of the latticed substrate. The calculation uses a two-dimensional model with the same geometric and material parameters as metasurface and no metal structure is added. The periodic boundary condition is applied in the horizontal boundary of the model. The electric and magnetic field strength distribution of the eigenmode of the latticed substrate are shown in figures 5(c) and (d). Comparing figures 5(a) and (c), the similar field distribution indicates that the EM is the intrinsic mode of the latticed substrate. Similarly, figures 5(b) and (d) show that the MM is also the intrinsic mode of the latticed substrate. Lattice mode resonances can occur due to a discontinuity in the
Figure 6. The measured THz transmission spectra of the stretchable device at different levels of stretching after 1000 cycles of stretching.

dispersion curves at ambient medium-substrate interfaces at the Rayleigh cutoff wavelengths of an incident field [33–35]. The difference between figures 5(b) and (d) stems from the induced magnetic field generated by the current in the metal cross. In figure 5(e), the characteristic frequencies of the latticed substrate are plotted for comparison to the simulated and measured frequencies of the MM of TM wave at different stretch ratio. The experimental value were obtained by multiple measurements with the error ranges shown in figure 5(e). The results of figure 5(e) indicate that the calculated, the simulated and the measured data are in good consistency. This supports the effectiveness of applying eigenmode theory to interpret the underlying mechanism. Note that due to the fact that the PDMS film in experiment is thicker than the theoretical design, the experimental values at the initial stage are somewhat smaller in comparison with the theoretical values. Under the stretching operation, the film thickness is becoming thinner and thinner, gradually approaching to the design value. Consequently, it can be observed that at high stretching ratios, the experimental curve crosses the simulated and theoretical curves.

Now the phenomena in simulation and experiment can be reasonably explained. The incident THz wave excite surface Bloch mode in the directions of electric and magnetic field, respectively. When there is no stretching effect, the resonance frequency of the MM and EM is the same, which is the reason for the PIT effect in the simulation. As the strain applied on the metasurface, the period in the magnetic field direction increases for TM wave, which causes the red shift of the frequency of the MM; while the period in the electric field direction does not change, so the frequency of EM does not change. In contrast, for the TE wave, the frequency of the EM changes, and the frequency of the MM is basically unchanged. One thing in common for TM wave and TE wave is that EM is significantly weaker than MM, and the EM weakens to almost disappear under tension. In the experiment, because EM is too weak and the equipment precision is limited, only MM can be observed.

The actual THz dual-band switch requires the ability to maintain the THz wave modulation characteristics after repeated stretching operation. We repeatedly stretched the sample metasurface 1000 cycles to evaluate its fatigue performance. Figure 6 shows the relationship between the transmission spectra of the stretched sample and the stretch ratio under fatigue testing. The testing results under repeated stretching operation are consistent with the initial measurement of figure 2(a). This shows that the metasurface sample has good anti-fatigue performance.

It should be mentioned that narrow-band resonance is much desirable in the application of stretchable devices. Devices with high Q factor are more sensitive to deformation and can easily achieve the modulation functions with a smaller stretching ratio. Some metasurface structure can be exploited to perform high-Q resonance depending on the future special applications [30, 36, 37]. It is a meaningful research direction for elastic metasurface to look for structures with narrow-band resonance.

4. Conclusion

In summary, a stretchable metasurfaces composed of a PDMS wrapped cross-shaped metal array is presented for operation in THz region. The metasurfaces can perform dual-band switching effects. The modulation depth over 90% is obtained at 1.23 THz using the frequency shift of dipole resonance. The surface Bloch mode generated from the latticed substrate is revealed and the characteristics of surface Bloch mode is studied. A broad transmittance spectral shift of 0.4 THz and a high modulation depth of 65% at 2.3 THz is experimentally demonstrated by exploiting the period-sensitive surface Bloch mode. The excellent performance makes the dual-band stretchable metasurfaces widely suitable for tunable filters and sensors. The use of surface Bloch mode provides ideas for the design of future metasurface devices.
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