A novel terahertz device with multi-function of polarization and switch based on phase transition of VO_2*

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A terahertz (THz) polarizer and switch structure is proposed based on the phase transition of vanadium dioxide (VO_2). When VO_2 is in the insulation phase, the resonance frequencies of the proposed structure are 1.49 THz and 1.22 THz for the *x*- and *y*-polarization, respectively. It can perform as a THz polarizer with extinction ratios of 52.5 dB and 17 dB for the *y*- and *x*-polarization, respectively; When VO_2 transforms into metallic phase, the resonance frequency for *x*-polarization wave shifts from 1.49 THz to 1.22 THz, while that remains still for the *y*-polarization component. It means that the structure can work as a polarization-dependent THz switch with a high extinction ratio of 32 dB.
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Nowadays, terahertz (THz) technology and its applications have made great progress in many fields, such as sensing, spectroscopy, imaging and communication[1-4]. For these applications, the functional devices, including polarizers, switches, filters, isolators and modulators, are indispensable. Wu et al[5] reported a broadband polarizer using bilayer sub-wavelength metal wire grid structure on both sides of polyimide film and the extinction ratio is over 45 dB in 0.2—1.6 THz range. Li et al[6] reported an electrically controlled THz photonic crystal switch with the extinction ratio of 29.9 dB and the response time of 100 μs. Liu et al[7] proposed a metamaterial THz switch based on split-ring resonator embedded with photoconductive silicon, and the rapid response time is less than 1 ps. However, a common disadvantage of these designs is that they only provided a single function. Zhang et al[8] designed a novel magnetically controlled multi-functional THz switch and continuously tunable bandpass filter based on a liquid-crystal filled photonic crystal waveguide, however, its switching time is only in a magnitude of milliseconds. Therefore, to achieve high-speed and multi-function THz devices, it is essential to develop new materials and design novel structures.

Vanadium dioxide (VO_2) can undergo insulator-metal transition (IMT) induced by thermal[9], electrical[10] as well as optical fields[11]. Some experiments have proved that the response time is less than 1 ps for optically induced IMT process, which makes VO_2 as a good choice for optical switch[12]. This phase transition is caused by a structural transition from a monoclinic insulated phase to a tetragonal metallic phase[13], and the conductivity of VO_2 will be exponentially changed, leading to abrupt several-orders-of-magnitude changes in electrical and optical properties. Therefore, we can take the advantage of VO_2 to further realize the switch function. In this work, we propose a novel structure by hybridizing VO_2 pads with the asymmetric metallic cross-shaped metasurface to perform terahertz polarizer and switch. Simulation results indicate that the proposed structure controlled by optical field can serve as a THz polarizer with high extinction ratio, and also a polarization-dependent THz switch.

Fig.1 shows the schematic structure of the proposed multi-functional THz device, which consists of cross-shaped metallic arrays and VO_2 pads deposited on the silica-glass substrate. The length of the cross-shaped metallic array is L=80 μm and a=60 μm, respectively. The length of VO_2 pads is b=10 μm, and width is w=10 μm. Lattice constant P of the structure illustrated in Fig.1(b) is 100 μm. The thicknesses of the metasurface and substrate are 1 μm and 500 μm, respectively. The silica-glass substrate has very low loss for THz waves and no free carrier can be excited by optical pumping.

Within THz frequency range, the dielectric function of VO_2 could be described by Drude model[14,15]:

$$\varepsilon_{\mathrm{m}}(\omega)=\varepsilon_{\infty}-\mathrm{i}\frac{\omega_{\mathrm{p}}^{2}}{\omega(\omega+\mathrm{i}/\tau)}, \tag{1}$$

$$\omega_{\mathrm{p}}^{2}=\sigma/\varepsilon_{0}\tau, \tag{2}$$

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where τ=2.27 fs is the relaxation time, ω_p is plasma frequency and σ refers to conductivity. From Eqs.(1) and (2), it is obvious that the property of VO_2 is determined by its conductivity, which would dramatically change during the IMT process. Several experiments have proved that we can numerically simulate the IMT process of VO_2 by taking different conductivities, and the experimental data agree well with the numerical simulation results[11,16]. In this paper, we describe the phase transition effect of VO_2 pads by using variable conductivity.

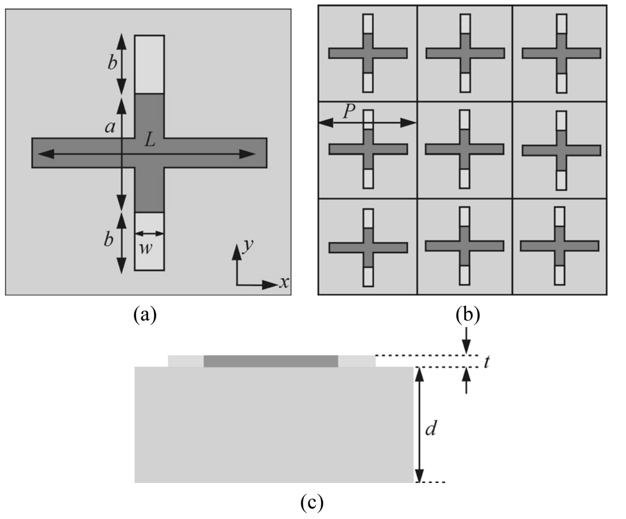


Fig.1 Schematic structure of the proposed device (*L*=80 μm, *a*=60 μm, *b*=10 μm, *w*=10 μm, *P*=100 μm, *t*=1 μm, *d*=500 μm): (a) Geometry of the unit cell; (b) The period structure; (c) Side view of a single unit cell

A normal THz wave is incident on the metasurface and the transmission characteristics of this structure are simulated by the commercial software of CST Microwave Studio. In our simulation, the silica-glass substrate is considered as a lossless dielectric with the dielectric constant of 3.84, and the metallic copper array is treated as lossy metal with the conductivity of σ=5.8×10^7 S/m. As shown in Fig.2, when there is no optical pumping, VO_2 is in insulation phase, and the resonance frequencies for the *x*- and *y*-polarization locate at 1.49 THz and 1.22 THz, respectively. In this case, the proposed structure can perform as a THz polarizer. For the *y*-polarization wave, the extinction ratio defined as $I=\left|T_x-T_y\right|$ is 52.5 dB, and the 10 dB bandwidth is 140 GHz. For the *x*-polarization wave, the extinction ratio is 17 dB and the 10 dB bandwidth is 60 GHz. This polarizer property is attributed to the fact that VO_2 can be regarded as a dielectric when it is in insulation phase, and it has no impact on the transmission of THz waves[17,18]. In this case, the proposed structure behaves like an asymmetrical cross-shaped metal array with different lengths. As a result, the resonance frequencies for *x*- and *y*-polarization are different, which agrees well with the experimental results reported previously[19]. Actually, the transmission spectra are almost the same as those of the structure without VO_2 pads as shown in the inset of Fig.2.

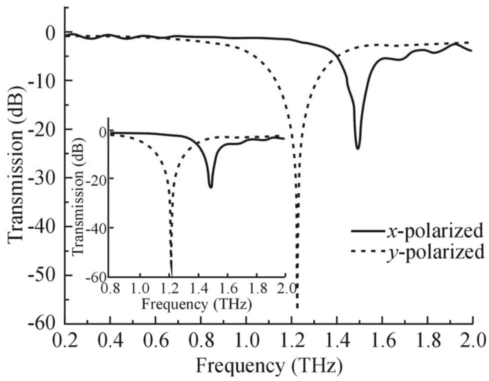
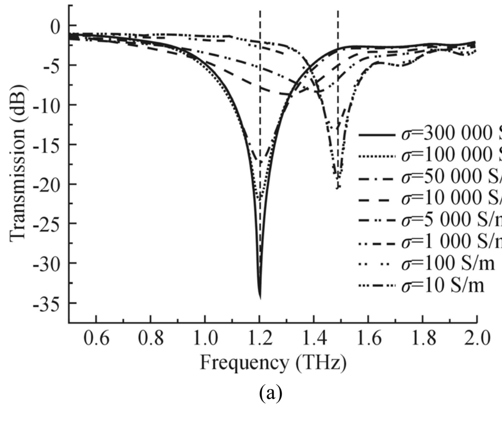
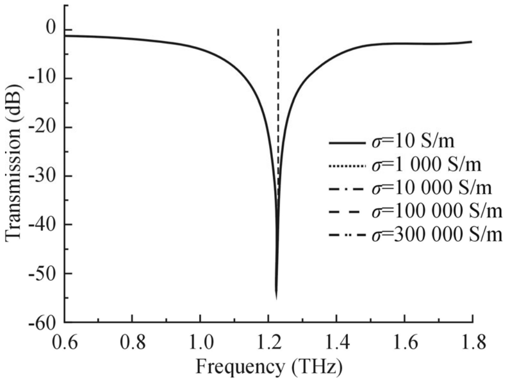


Fig.2 Transmission spectra corresponding to different polarization waves at the insulation phase of VO_2 (The inset shows the case without VO_2 pads)

When VO_2 transforms from insulation to metallic phase with optical pumping, its conductivity increases dramatically and the VO_2 pads can work as metal, which has been proved in experiments[11,17,18]. This leads to the elongation of *y*-axis metal arm length from 60 μm to 80 μm. For the transmission of *x*-polarization wave shown in Fig.3(a), it is seen that as the conductivity increases, the resonance at 1.49 THz initially weakens and becomes broader with no frequency shift. When conductivity continues increasing larger than 1 000 S/m, the resonance frequency shows a significant shift towards the lower frequency region. At the conductivity level of 300 000 S/m, the resonance frequency locates finally at 1.22 THz, we achieve a dual-channel switch at 1.22 THz and 1.49 THz with the IMT process of VO_2, and the extinction ratios are 32 dB and 17 dB, respectively. However, for the *y*-polarization wave, the resonance frequency does not shift during the transition process, as shown in Fig.3(b). This is because the arm length perpendicular to the polarization direction of incident wave affects the resonance frequency, while the arm length parallel to the polarization direction of the incident wave not. Therefore, the proposed structure can also serve as a polarization-dependent THz switch.

The influence of structural parameters on resonance frequencies has been investigated. Fig.4 shows the transmission spectra of the proposed device with different *y*-axis arm lengths. With the increment of arm length,





(b)

Fig.3 Simulated transmission spectra for different conductivities of VO_2: (a) *x*-polarization THz wave; (b) *y*-polarization THz wave

the resonance frequency gradually shifts from 1.49 THz to 1.22 THz, and the extinction ratio increases from 23 dB to 46 dB. The resonance originates from the dipole localized surface plasmons, and the charge accumulation at the edges of the cross-arm is shown in the inset of Fig.4. It can be found that stronger resonance could be acquired as the arm length increases, so the extinction ratio is larger. Meanwhile, the resonant cavity becomes longer with the increment of arm length, as a result, the resonance frequency shows red shift.

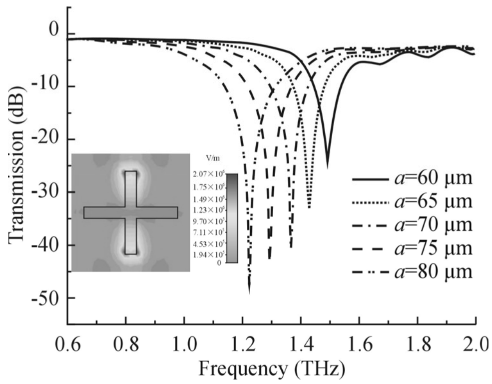


Fig.4 Transmission spectra of *x*-polarization THz wave for different *y*-axis arm lengths (The inset shows the charge accumulation at the edges of the cross-arm.)

Next, we further investigate the influence of asymmetric factor defined as a_1/a_2 on the resonance frequency as shown in Fig.5. We keep the total *y*-axis arm length of a_1+a_2+w as 60 μm. As the asymmetry factor changes, the resonance frequency of *x*-polarization wave exhibits red shift. The smaller the asymmetry factor is, the larger the red shift would be. Specifically, when the metal array is symmetric, namely $a_1=a_2$, the resonance frequency locates at 1.49 THz, and it gradually moves to 1.39 THz for an asymmetry factor of 0.67. When the asymmetry factor further decreases to 0.25, the resonance frequency shifts to 1.17 THz with a large red shift of about 320 GHz. This indicates that the resonance frequency is sensitive to the asymmetry factor for the direction perpendicular to the incident wave polarization. Therefore, according to the practical needs, we can choose the proper structural parameters to realize different applications.

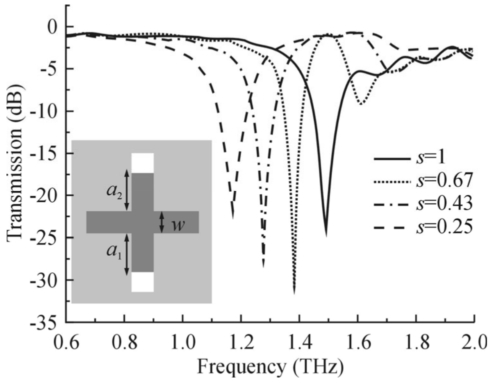


Fig.5 Transmission spectra of *x*-polarization THz wave for different asymmetric factors

In conclusion, a novel terahertz device with multi-function of polarization and switch based on phase transition of VO_2 has been proposed. When VO_2 is in the insulation phase, the structure can serve as a THz polarizer with high extinction ratios of 52.5 dB and 17 dB for the *y*- and *x*-polarization, respectively. When VO_2 transforms from insulation to metallic phase with optical pumping, the structure can work as a polarization-dependent THz switch with a high extinction ratio of 32 dB. Furthermore, the switch frequency is sensitive to the length and asymmetry factor of the metal arm. The multi-functional device has a broad potential in THz application systems.

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