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Article

Dual-Frequency Terahertz Amplitude Modulator Based on the Coupling Effect of Cross-Shaped Structure and U-Shaped Metal Patches

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Abstract: This letter presents a dual-frequency terahertz amplitude modulator based on a cross-shaped structure and U-shaped metal patches. Its structural unit is a typical metal-substrate structure. The top metal consists of a cross-shaped structure and U-shaped metal patches, and the bottom substrate layer is made of quartz. Amplitude modulation is achieved by adjusting the temperature of the vanadium dioxide (VO₂) patches. The modulation depth can be approximately 75%. The mechanism of the resonance frequency is explained by the equivalent circuit model. The proposed structure shows good amplitude modulation capability at different incidence and azimuth angles by changing the location of the VO₂ patches. The dual-frequency terahertz amplitude modulator can be used in terahertz communication, imaging, etc.

Keywords: terahertz waves; metamaterial; amplitude modulator

1. Introduction

Terahertz waves are electromagnetic waves with frequencies from 0.1 to 10 THz [1]. The high-frequency portion of terahertz waves overlaps with infrared waves, while the low-frequency portion overlaps with millimeter waves. Terahertz waves offer several advantages, such as low photon energy [2], which ensures high safety in imaging compared to X-rays. Their high penetration ability [3] enables the non-destructive detection of material structures. Terahertz waves have diverse spectral properties and are applicable in materials characterization and terahertz communication, making communication one of the critical applications of this technology.

A standard terahertz communication system [4] includes various components, including a terahertz radiation source [5] that uses a photoconductive antenna or electronic generation, a terahertz modulator [6], a terahertz mixer [7], a terahertz power divider [8], and a terahertz coupler [9]. Terahertz communication systems utilize various functional devices, with the terahertz modulator playing a crucial role in the system by significantly affecting its overall performance. The specifications of a terahertz modulator typically include parameters such as terahertz modulation depth [10], modulation rate [11] and dynamic modulation characteristics [12].

A temperature-controlled terahertz modulator modulates incident terahertz waves by changing the temperature, which changes the conductivity or dielectric constant of the controllable semiconductor, resulting in a change in the resonant frequency or intensity of the metamaterial structure. In 2009, T. Driscoll *et al.* [13] designed a terahertz modulator using VO₂ patches and a metamaterial structure to change the resonant frequency for modulation. In 2011, R. Singh *et al.* [14] developed a terahertz modulator using strontium titanate, which showed a frequency redshift of 43% when the temperature changed from 409 K to 150 K. In the same year, J. Zhu *et al.* [15] integrated

indium antimonide materials into the metamaterial SRR structure, which opened to modulate terahertz wave frequencies. Li Chun's team also achieved a modulation range of 65% by incorporating indium antimonide material into the SRR structure opening of the metamaterial with a temperature variation of 160 K to 350 K. In 2021, C. Li *et al.* [16] developed an electrically controlled superconducting terahertz modulator using niobium nitride materials and achieved a modulation depth of 82.7% at 0.33 THz. While research on temperature-controlled terahertz modulators has progressed, challenges remain in their practical application. Developing innovative structures for these modulators can increase progress in their implementation.

The study initially focuses on the design of a dual-frequency terahertz amplitude modulator using a cross-shaped structure and U-shaped metal patches based on VO₂ patches. Then, the resonance frequency of the amplitude modulator is analyzed with VO₂ patches. Then, the amplitude modulation mechanism is explained by an equivalent circuit model. In addition, the influence of different structural parameters on the resonant characteristics of the modulator in the On-Off state is also studied. The proposed dual-frequency terahertz amplitude modulator is helpful for the field of terahertz communication, imaging, etc.

2. Structure Design and Mechanism

The objective of our study is to design a dual-frequency terahertz amplitude modulator based on a cross-shaped structure and U-shaped metal patches. This coupling effect between structures is enhanced by the integration of vanadium dioxide patches between the U-shaped metal patches and the cross-shaped structure. Temperature variations are used to adjust the coupling between these two structures. The study also examines the dimensions of the U-shaped structure and the distance from the cross-shaped structure to analyze the resonance frequency of the dual-frequency terahertz amplitude modulator. The resonance frequency generation is examined using an equivalent circuit model. In addition, the study investigates the stability at different incidence and azimuth angles for the cross-shaped structure and U-shaped metal patches.

2.1. Design of Terahertz Dynamic Modulator

In this letter, the designed dual-frequency terahertz amplitude modulator is made of metal-dielectric which is a two-layer structure. The metal is made of aluminum and its conductivity is 3.56×10^7 S/m. The dielectric layer is quartz, the real part of its dielectric constant is 3.75, and the tangent of the loss angle is 0.0004. The device performance simulation is carried out in CST Microwave Studio 2018, using a frequency domain solver with periodic boundary conditions in the x and y directions and open boundary conditions in the z -direction.

Figure 1 shows a schematic diagram of a periodic unit for a dual-frequency terahertz amplitude modulator that uses a cross-shaped structure and U-shaped metal patches. The upper diagram in Figure 1 shows the smallest structural units and the lower diagram schematically shows the periodic structural units. The combined structure consists of two parts, the upper layer is made of a cross-shaped structure and U-shaped metal patches and the lower layer is made of quartz. The cross-shaped structure and the U-shaped metal patches are connected using VO₂ patches. The length and width of the cross-shaped structure are $L=100$ μm and $w_1=5$ μm , respectively. The depth of the U-shaped metal patches is $w_2=10$ μm , and the distance between the U-shaped metal patches and the cross-shaped structure in the vertical direction is $a=4$ μm . The distance between the U-shaped metal patches and the cross-structure in the horizontal direction is $d=25$ μm . The values of P_x and P_y are 150 μm . The thickness of the quartz substrate is $t=25$ μm . Four VO₂ patches are positioned between the cross and U-shaped metal structures. By adjusting the temperature, the conductivity of VO₂ patches can be changed, facilitating connection and separation between the cross-shaped structure. This setting can influence the coupling effect between the cross-shaped structure and the U-shaped metal patches.

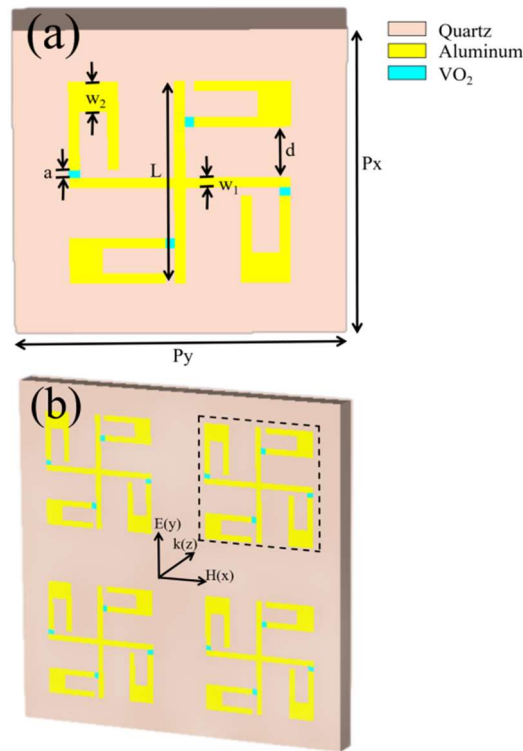


Figure 1. A schematic diagram of a periodic cell structure of the dual-frequency terahertz amplitude modulator based on cross-shaped and U-shaped metal patches.

We simulated the effect of VO₂ patches on the transmission coefficient of the structure under various conductivity states. We analyzed the current distribution of the structure under high (On) and low (Off) conductivity states respectively. Fig.2 shows the variation of the transmission coefficient of the structure as the conductivity of VO₂ patches changes. The current states, on and off, are depicted on the right side of Figure 2. At high conductivity ($g=4 \times 10^7 \text{ S/m}$), the switch is on, and the current loop related to low resonance frequency (On state) is depicted as ①. Conversely, at low conductivity ($g=2 \text{ S/m}$), the switch is open, and the current loop related to high resonance frequency (Off state) is displayed as ② in Figure 2. The intensity of the high-frequency resonance decreases gradually as the conductivity rises. In contrast, the intensity of the low-frequency resonance increases as the conductivity rises. It is observed that the current loop at low-frequency resonance at the on state is longer than that at high-frequency resonance at the off state. According to equivalent circuit theory, the equivalent inductance is governed by the equation $L \propto l$, where l represents the current loop length. The resonant frequency follows the relationship: $f = 1 / 2\pi\sqrt{LC}$, L and C represent the circuit's equivalent inductance and capacitance. Due to the longer length of the current loop associated with resonance frequency, the resonance frequency of the amplitude modulator in the off state is higher than the resonance frequency in the on state.

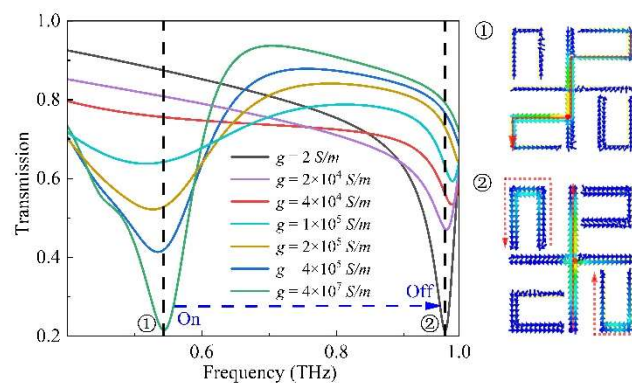


Figure 2. Transmission coefficients of the dual-frequency terahertz amplitude modulator at different conductivities. ① and ② indicate the current distribution in the on and off states.

To further investigate the formation mechanism of the high-frequency resonance peak f_0 , we analyze the transmission coefficients of the cross-shaped structure and the U-shaped metal spots separately. We also examine the combined structure without the VO₂ patches, as shown in Figure 3. The black solid line in Figure 3 represents the transmission coefficients of the combined structure. In contrast, the red dashed line represents of the cross-shaped structure and the blue dashed line highlights the U-shaped metal patches. In resonance mode, a light-dark coupling effect is observed at high-frequency resonance. The incident electromagnetic wave with y -polarization does not directly stimulate the two U-shaped metal patches with openings up and down. Instead, the resonant field energy is coupled through the vertical structure of the cross-shaped structure, as illustrated in f_0 in Figure 3. As the resonance frequency increases, the coupling effect becomes more pronounced. At the transparent window, the resonant frequency f_0 is reached, and the overall resonant field of the structure decreases. The bright mode (cross structure) generates a dark mode (U-shaped structure with an opening downwards) while simultaneously suppressing each other, thereby reducing the total resonant field and weakening the structure's ability to localize the incident electromagnetic wave, increasing in the transmission coefficient. At the resonance frequency of f_0 , the electromagnetic wave directly induces the resonance effect within the two U-shaped metal patches with horizontal openings, creating a new resonance field.

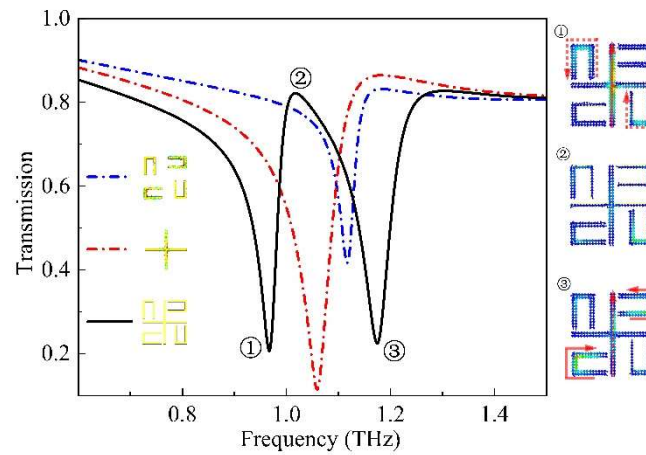


Figure 3. Transmission coefficients and current distributions for the combined structure, cross-shaped structure and four U-shaped metal patches.

2.2. Equivalent Circuit Modelling in the On and Off States

The equivalent circuit of the terahertz dual-frequency terahertz amplitude modulator is shown in Figure 4, where the incident wave is vertically polarized. The VO₂ patches act as a temperature control switch, connecting the cross-shaped structure in the middle to the U-shaped metal patches. When the switch is conducting (on), the oscillating circuit path is red. When the switch is closed (off), the oscillating circuit path is blue. The resonance intensity of the two circles correlates with the transmission coefficients of the respective peaks. As the switch is gradually turned on, the resonance intensity of the low-frequency resonance increases, while the high-frequency resonance loop is increasingly disturbed, resulting in a decrease in its resonance intensity. Thus, the dual-channel modulation effect is achieved by modulating the temperature with the baseband signal. Based on the formula $M = |V_{on} - V_{off}| / \max(V_{on}, V_{off})$, M is the modulation depth and V represents the amplitude of the modulated envelope signal. The modulation depth is 75.4% for the low-frequency component and 73.5% for the high-frequency component.

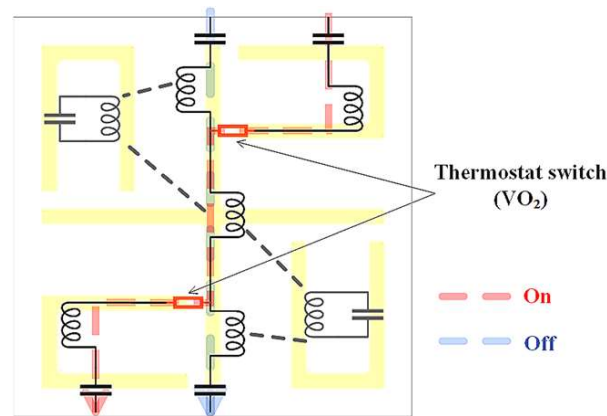


Figure 4. Equivalent circuit model of the dual-frequency terahertz amplitude modulator when VO₂ patches are in the on and off states.

2.3. Transmission Coefficients for Different Coupling Effects

To investigate the coupling effect between the structures, transmission coefficients were explored at varying distances d from 15 to 30 μm , as depicted in Figure 5. To improve clarity regarding the location of resonance peaks in transmission coefficients, two vertical dashed lines are utilized to mark the low and high-frequency peaks. The coupling effect between the U-shaped metal patch and the cross-shaped structure is manifested in the intensity and bandwidth of the electromagnetically induced transparent peaks. An increase in the parameter d results in a rise in the intensity and bandwidth of the transparent resonance peaks, indicating a strengthened coupling between the structures. At $g=1.2 \times 10^7 \text{ s/m}$, the frequency of the low-frequency resonance peak remains nearly constant, but the intensity slightly decreases. However, when $g=40 \text{ s/m}$, the intensity of frequency $f_I=0.46 \text{ THz}$ in the transmission coefficients remains relatively constant with increasing d values. Regarding high-frequency resonance peaks, the frequency of $f_{II}=0.85 \text{ THz}$ is blue-shifted with increasing d values at $g=40 \text{ s/m}$. Conversely, at $g=1.2 \times 10^7 \text{ s/m}$, the high-frequency resonance frequency experiences a blueshift as d increases. Notably, at $d=25 \mu\text{m}$, the terahertz modulation effect is relatively effective, leading to dual-state switching at f_{II} . This finding suggests that achieving a terahertz modulation effect with dual frequencies at $d=25 \mu\text{m}$ is feasible by controlling the temperature of VO₂ patches.

We conduct a detailed analysis of the factors influencing resonance frequencies at various distances. The resonance frequencies are associated with two terahertz communication bands, specifically 0.46 THz and 0.85 THz. Increasing the parameter d shortens the current loop of the U-shaped structure, causing the resonance peak to shift to a higher frequency (blue dashed line in Figure 3). The position of the resonance peak generated by the excitation of the cross-shaped structure remains stable, resulting in a larger frequency separation between the two resonance peaks. Furthermore, the higher value of d increases the physical separation between the cross-shaped and U-shaped metal patches, resulting in a reduction in the coupling effect. The high-frequency modulation peak increasingly approaches the resonance frequency induced by the cross-shaped structure (red dashed line in Figure 3), with the transition from the black solid line to the red dashed line in Figure 3. So, the frequency, bandwidth and resonance intensity increase, as indicated by the green solid line in Figure 5.

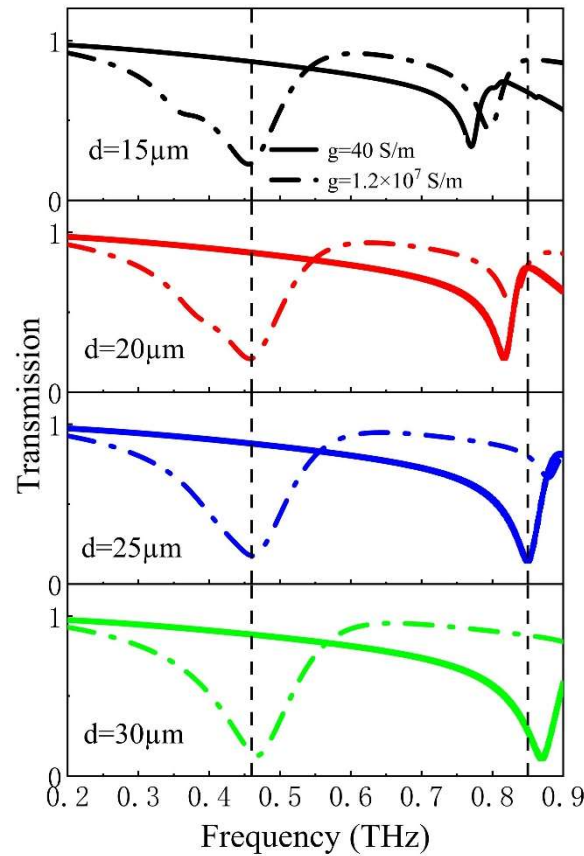


Figure 5. Transmission coefficients at different distances d .

As shown in Figure 6, the transmission coefficients for different values of w_2 are shown. The VO₂ patches in Figure 6 have a conductivity of 40 S/m in the solid line and a conductivity of 1.2×10^7 S/m in the dashed line. When $g = 40$ S/m, the frequency and intensity of the low-frequency resonance in the transmission coefficients remain essentially constant as w_2 increases. Figure 6 shows that the high-frequency resonance gradually shifts to higher frequencies as the internal depth w_2 of the U-shaped metal patch increases. This is mainly because as the depth w_2 of the U-shaped metal patches increases, the effective length of the current flowing through the cross-shaped structure and the U-shaped metal patches gradually decreases as the U-shaped metal patches and the cross-shaped structure are connected. The equivalent inductance connecting the U-shaped structure and the cross-shaped structure decreases and the frequency of the high-frequency resonance peak tends to shift at high frequencies. In contrast, the equivalent capacitance remains approximately the same.

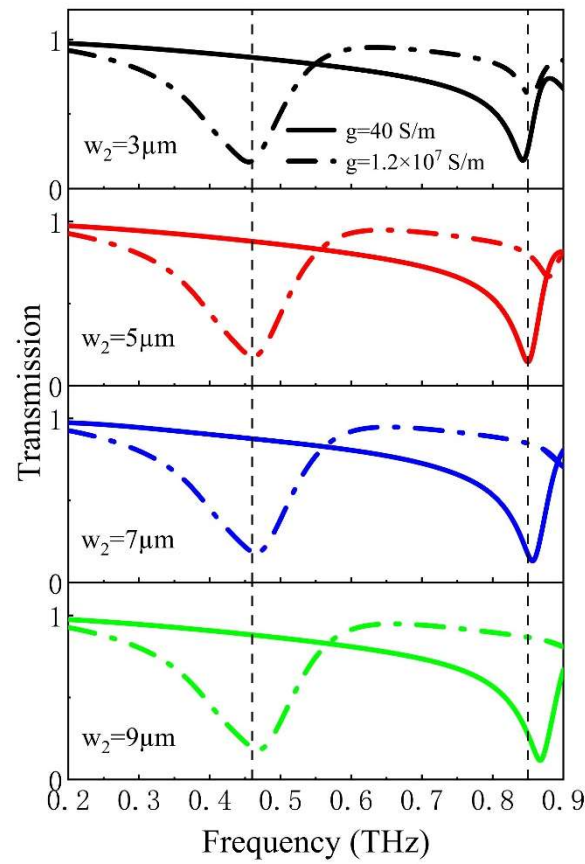


Figure 6. Transmission coefficients for different w_2 . The conductivity of VO₂ patches in the solid line is 40 S/m and the conductivity of VO₂ patches in the dashed line is 1.2×10^7 S/m.

2.4. Incidence Angle and Polarization Properties of Combined Structures

The transmission coefficients at different angles of incidence of terahertz waves for conductivities $g=40$ S/m and $g=1.2 \times 10^7$ S/m are shown in Figure 7. The angles of incidence of the terahertz waves range from 0° to 75° . At a conductivity of $g=1.2 \times 10^7$ S/m, the low-frequency resonance remains stable as the angle of incidence of the terahertz waves increases. In contrast, the intensity of the low-frequency resonance gradually decreases. In addition, the high-frequency resonance exhibits a red shift with increasing angle of incidence of the terahertz waves. The dual-frequency terahertz amplitude modulator demonstrated angular stability from 0° to 30° .

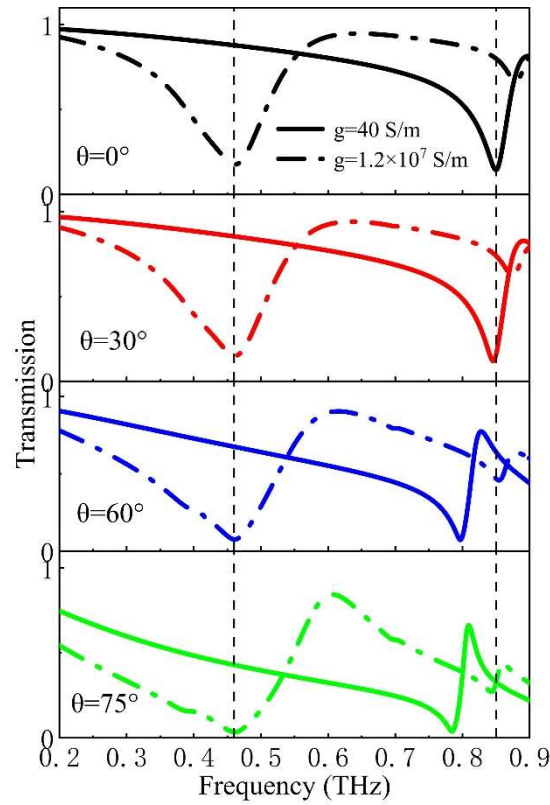


Figure 7. Transmission coefficients of the structure with VO₂ in the on or off states at different incidence angles.

To investigate the polarization-insensitive properties of the structure, four VO₂ patches were inserted on the outside between the U-shaped metal patches and the cross-shaped structures. Figure 8(a) shows the schematic of the symmetrical structure. Figure 8(b) shows the transmission coefficients of VO₂ patches in both on and off states at different azimuth angles. The azimuth angle of terahertz waves is between 0° and 90°. In Figure 8(b), the transmission coefficients remain constant when the azimuth angles vary between 0° and 90°, regardless of whether the VO₂ patches are turned on or off. This observation suggests that the structure exhibits polarization insensitivity.

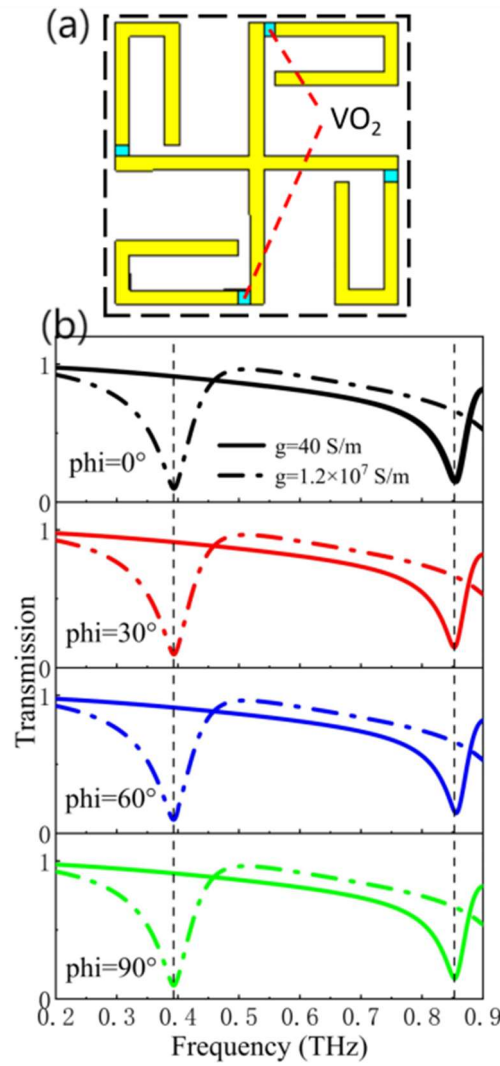


Figure 8. Terahertz polarization properties based on symmetric structures.

3. Conclusion

This letter proposes a terahertz dual-frequency amplitude modulator achieved by coupling a cross structure with U-shaped metal patches. We examined the modulation depth of the dual-frequency modulator by varying the temperature to modulate the conductivity of the VO₂ patches, the size of the U-shaped metal patches, and the distance between the cross-shaped structure. An equivalent circuit model is used to investigate the physical mechanisms underlying the formation of resonance frequencies at lower and higher frequencies. The modulation depth of the dual-frequency terahertz amplitude modulator can reach about 75%. By symmetrically positioning the VO₂ patches, we examined the incidence angles and polarization insensitivity properties with both the U-shaped metal patches and the cross-shaped combination structure. The results show that the dual-frequency terahertz amplitude modulator has good angle of incidence and polarization insensitivity (by changing the location of the VO₂ patches) characteristics. In summary, the proposed dual-frequency terahertz amplitude modulator is useful for applications in terahertz communication, imaging, etc.

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DATA AVAILABILITY: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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