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A Tunable Hybrid Metamaterial Reflective Polarization Converter Based on Vanadium Oxide Film

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Abstract A metamaterial reflective converter with vanadium oxide (VO_2) film is investigated in this paper. The results indicate that a broadband polarization conversion ratio (PCR) above 90% is achieved from 4.95 to 9.39 THz and the PCR above 98.9% can be obtained at the three peaks. And the hybrid metamaterial converter is demonstrated for realizing temperature tuned electromagnetic properties. The different temperatures across the insulator-to-metal phase transition of the VO_2 film can change the conductivity. Furthermore, the broadband and high-efficiency polarization conversion changes obviously with the temperature changing. In addition, this study demonstrates the application of different temperatures on the performance of the sensor. Moreover, surface current distributions at the resonant frequency are also discussed.

Keywords Metamaterial · Converter · Sensor

Introduction

Terahertz (THz) waves, typically defined between 0.1 and 10 THz, have many novel applications such as security, imaging, communications, and sensing [1–4]. These applications have obvious need for a lot of functional devices such as absorbers [5], polarizer [6], and filters [7] and for manipulating and controlling propagating electromagnetic (EM) waves. One of the remarkable devices is the polarization converter, which could convert the incident EM waves. To date, a large variety of the efficient polarization converters in the THz range depend on the metamaterials [8, 9]. In the THz band, dual-band [10] and multiple-band [11] polarization converters have been researched generally. However, the bandwidth of these polarization converters is still limited. Recently, various polarization converters based on metamaterials to realize the broadband polarization conversion have been demonstrated. For example, Xia et al. [12] present a broadband linear polarization converter with the polarization conversion ratio (PCR) more than 95% between 0.73 and 1.41 THz. What is more, the THz polarization converter can also be used to realize THz thermal modulation according to the vanadium dioxide (VO_2). Lv et al. [13] theoretically study a novel metamaterial for achieving thermal controlled metamaterial using phase change material VO_2 film. At present, few works about temperature-controlled metamaterials have been investigated [13, 14]. With regard to the thermal controlled material, VO_2 film possesses the ability of an insulator-to-metal phase transition [15–18]. Through the phase transition, the conductivity of VO_2 changes depending on the various temperatures [19, 20]. In other words, VO_2-based metamaterials possess the advantage of strong tunability in the THz band. Hence, utilizing the tunable characteristics of VO_2 for polarization converter has attracted considerable attention when considering that VO_2 film has properties of the insulator-to-metal phase transition.

In this work, a new polarization converter is put forward in the THz regime, which consists of the hybrid metamaterial. The hybrid metamaterial is composed of doubled E-shaped embedded into the VO_2 film. This novel design can achieve high PCR for both y and x polarized waves. In addition, to study the PCR of the polarization converter under different

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temperatures, we investigate the various conductivities. Furthermore, the surface current distribution depended on different conductivity is also studied. The proposed converter provides an alternative platform to promote potential applications in the areas of THz polarization devices and sensing.

Table 1 All dimensional parameters of the metamaterial converter (see Fig. 1)

Parameter	p	d	t	L_1	L_2	w	g_1	g_2
Value (μm)	20	4.02	0.2	10.5	4.75	2	1	0.5

Metamaterial Design and Simulation

The compound structure is sketched in Fig. 1, and each unit cell consists of three layers: a hybrid layer, a dielectric spacer, and a metal sheet. The dimensional parameters of the metamaterial converter are shown in Table 1. The hybrid layer is VO_2 film and double E-shaped structures are deposited on the dielectric spacer which is selected the FR-4 with the relative permittivity of 4.3 and loss tangent of 0.025. The E-shaped and the metal sheet are the gold (Au) with the conductivity of $\sigma_{Au} = 4.561 \times 10^7$ S/m. The properties of the VO_2 are described by the simple Bruggeman effective theory [13]:

$$\varepsilon(\mathrm{VO_2}) = \frac{1}{4}\left\{\varepsilon_\mathrm{d}(2-3V) + \varepsilon_\mathrm{m}(3V-1) + \sqrt{\left[\varepsilon_\mathrm{d}(2-3V) + \varepsilon_\mathrm{m}(3V-1)^2 + 8\varepsilon_\mathrm{d}\varepsilon_\mathrm{m}\right]}\right\}$$

In this formula, ε_d represents dielectric constants of the insulating, ε_m denotes dielectric constants of the metallic phase VO_2 films, and V is the volume fraction of the metallic regions. Generally, the tuning conductivities of σ_{VO2} are obtained by the changing temperature and the properties of VO_2 film undergo alternatively dynamic insulator-to-metal phase transition [16–18]. The relative permittivity of 9 of VO_2 film is applied [21], while the conductivity in the insulating state is smaller than 200 S/m and as high as an order of 10^5 S/m in the metallic state [13]. All the designs are carried out using the CST Microwave Studio with frequency domain solver. The periodic boundaries are applied along the x and y directions and open boundary condition is utilized along z direction, respectively.

In order to understand the polarization conversion, the reflection matrix r can be defined in terms of the incident E_{yi} (E_{xi}) and reflected E_{yr} (E_{xr}), where y and x represent the y and x polarized incident waves, respectively. The reflection ratio $r_{yy} = E_{yr}/E_{yi}$, $r_{xy} = E_{xr}/E_{yi}$, $r_{xx} = E_{xr}/E_{xi}$, and $r_{yx} = E_{yr}/E_{xi}$ are also defined, respectively [22]. The polarization conversion ratio (PCR) can be defined as PCR = $|r_{xy}|^2/(|r_{yy}|^2 + |r_{xy}|^2)$ (PCR = $|r_{yx}|^2/(|r_{xx}|^2 + |r_{yx}|^2)$). And to study the polarized state, the $\triangle\varphi_{xy} = \arg(r_{xy}) - \arg(r_{yy})$ ($\triangle\varphi_{xy} = \arg(r_{yx}) - \arg(r_{xx})$) is defined, which reveals the phase difference between the x(y) and y(x) components of the reflected EM wave. The value range of $\triangle\varphi_{xy}$ is −180°, 180° depending on the frequency [23, 24].

The Results and Discussion

The results are presented in Fig. 2, which shows that the reflectance and the polarization conversion ratio (PCR). From Fig. 2a, it can be seen clearly that the reflection coefficients r_{xy}, r_{yx} are above 0.5 in the broad frequency from 4.95 to 9.39 THz, while the reflection coefficients are no more than 0.25 for both x and y polarizations under normal incidence. The results show that the proposed converter possesses the property of the polarization insensitive. In Fig. 2b, it is worth noting that the PCR is above 90% from 4.95 to 9.39 THz. Especially, around the resonant frequencies of 5.22, 6.95, and 9.19 THz, the distinct peaks are observed with large PCR efficiency of 98.9, 99.8, and 99.9% due to the existence of the resonances, respectively. It indicates

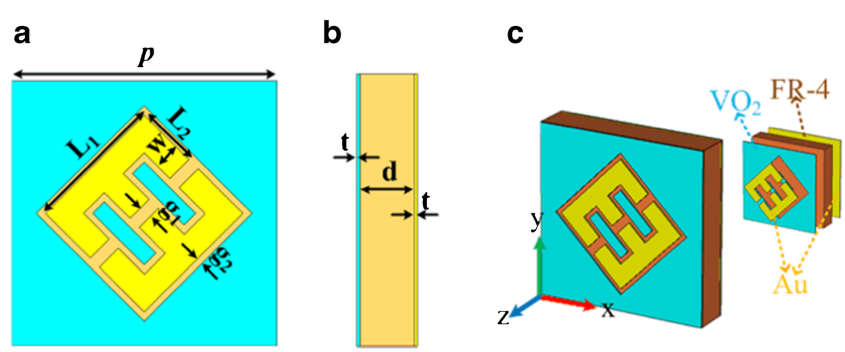

Fig. 1 Schematic of the hybrid metamaterial **a** front view, **b** right view, and **c** perspective view

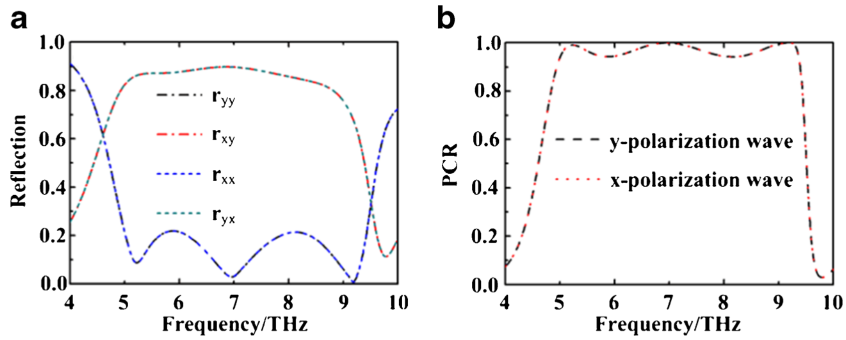

Fig. 2 **a** Simulated reflection spectra. **b** PCR

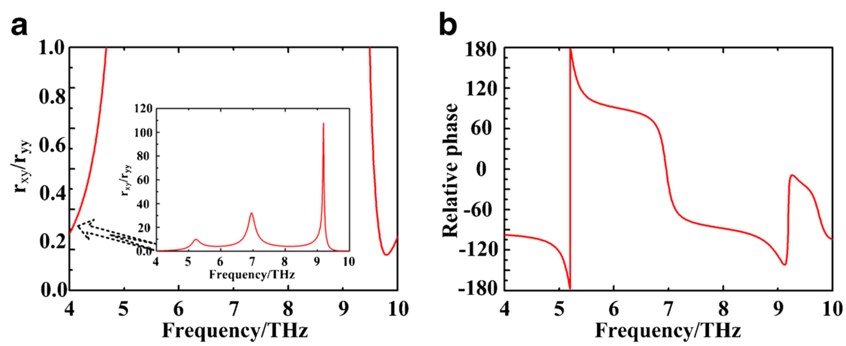

Fig. 3 **a** The ratio of r_{xy}/r_{yy}. **b** The relative phase $\triangle\varphi_{xy}$

that nearly total linearly polarized wave is converted to its cross-polarization wave.

Because the polarization is insensitive, the y-polarized wave is studied in-depth. From Fig. 3b, we also observe that $\triangle\varphi_{xy}$ becomes zero or ±180° in the vicinity of the resonance frequencies, respectively. It also means that the linearly polarized wave is converted to its cross-polarization wave. At other frequencies, $r_{xy}/r_{yy} \neq 1$ indicates that elliptically polarized waves are expected.

In fact, the perfect conversion can be enhanced by the hybrid material. From Fig. 4, the bandwidth of the PCR over 90% can be achieved by metal-FR-4-metal structure (red line) from 5.07 to 9.01 THz, while the VO_2-FR-4-metal structure (blue line) shows that the conversion is close to zero in the broad frequency band. It is also observed that the PCR of VO_2-FR-4-metal structure is below 0.001% in Fig. 4b. And the broadband polarization converter can be obtained by the hybrid metamaterials. So, the bandwidth of perfect conversion can be enhanced by using the hybrid material.

It is worth mentioning that the VO_2 film conductivities change with the transition temperature. At the temperature of 25 °C, the VO_2 film is the insulating state with conductivity of 200 S/m. When the temperature is increased to 85 °C, the VO_2 film becomes metallic with conductivity of 10^5 S/m [13]. Figure 5 shows simulated PCR for the polarization converter for different conductivities. It is more intuitive that the PCR efficiency changes greatly with the various conductivities. When the VO_2 film behaves as the insulator state with $\sigma_{VO2} = 200$ S/m, almost all of the incident waves can go through the top hybrid metamaterials. The linearly polarized wave can be converted to its cross-polarization wave. So, the hybrid metamaterial reveals that the PCR is above 90% from 4.95 to 9.39 THz. When the temperatures increases, VO_2 film undergoes an insulator-metal phase transition coupling with an

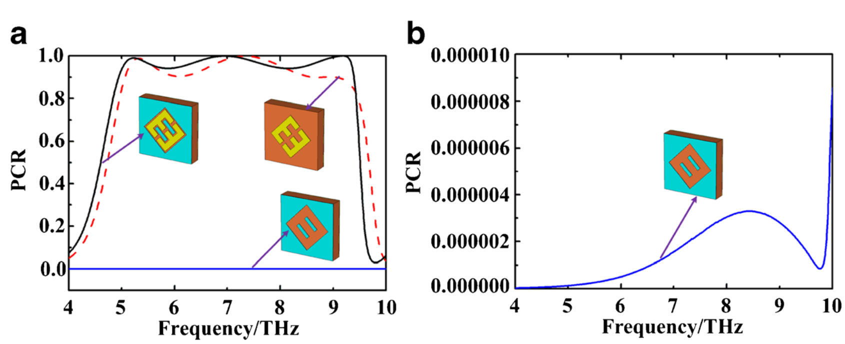

Fig. 4 **a** The PCR of the different converter under normal incidence. **b** The PCR of VO_2-FR-4-metal converter

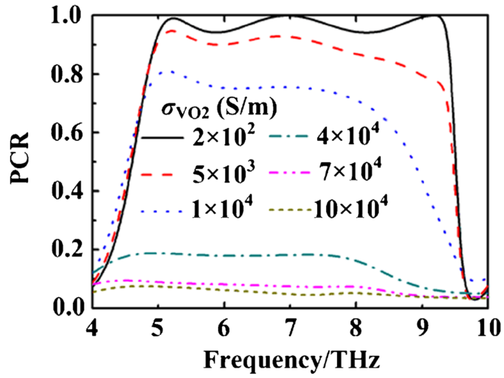

Fig. 5 The PCR of the proposed converter under different conductivities

increasing conductivity. As the conductivity is swept from 200 to 10^5 S/m, the PCR efficiency of the converter decreases obviously. When the VO_2 film is the metal state with $\sigma_{VO2} = 10^5$ S/m, almost all of the incident waves are reflected by the top hybrid metamaterials. Thus, the PCR is zero in the vicinity. In other words, the hybrid metamaterial makes the y-to-x cross-polarization conversion into the "off" state. As a result, the state-transition process of the VO_2 is accompanied by remarkable changes in various conductivities [21]. And the various states of the hybrid layer leads to different state resonators. The different state resonators result in the obvious changes of the PCR efficiency. Therefore, the hybrid metamaterial embedded with VO_2 film can alternatively realize a thermal switching effect of the cross-polarization conversion.

To understand the physical mechanism, the surface current distributions for the top layer and the bottom metal at 5.22 THz are presented in Fig. 6. The results verify that the strong anti-parallel current pairs between the top layer and the bottom layer as shown in Fig. 6a, b. Without thermal excitation, the VO_2 film is insulating state and the resonator is double E-shaped for the case of $\sigma_{VO2} = 200$ S/m. The strong anti-parallel current pairs excited by the incident wave can lead to magnetic dipole which induces magnetic resonance [23]. The cross-coupling exists between the incident electric field $\mathbf{E}_i$ and the component $\mathbf{H}_y$ because the component $\mathbf{H}_y$ parallels to the incident electric field $\mathbf{E}_i$. Thus, the component $\mathbf{H}_y$ can include an electric field $\mathbf{E}_x$ which is vertical to the incident electric field. As a result, the polarization conversion exists. The $\mathbf{H}_x$ is vertical to the incident electric field $\mathbf{E}_i$, so that the linearly polarized wave cannot be converted to its orthogonal direction, due to the same direction of the incident magnetic field [23]. While the $\sigma_{VO2} = 5 \times 10^3$ S/m, the anti-parallel current pairs are excited between the top layer and the bottom layer as shown in Fig. 6c, d. However, compared with the case of

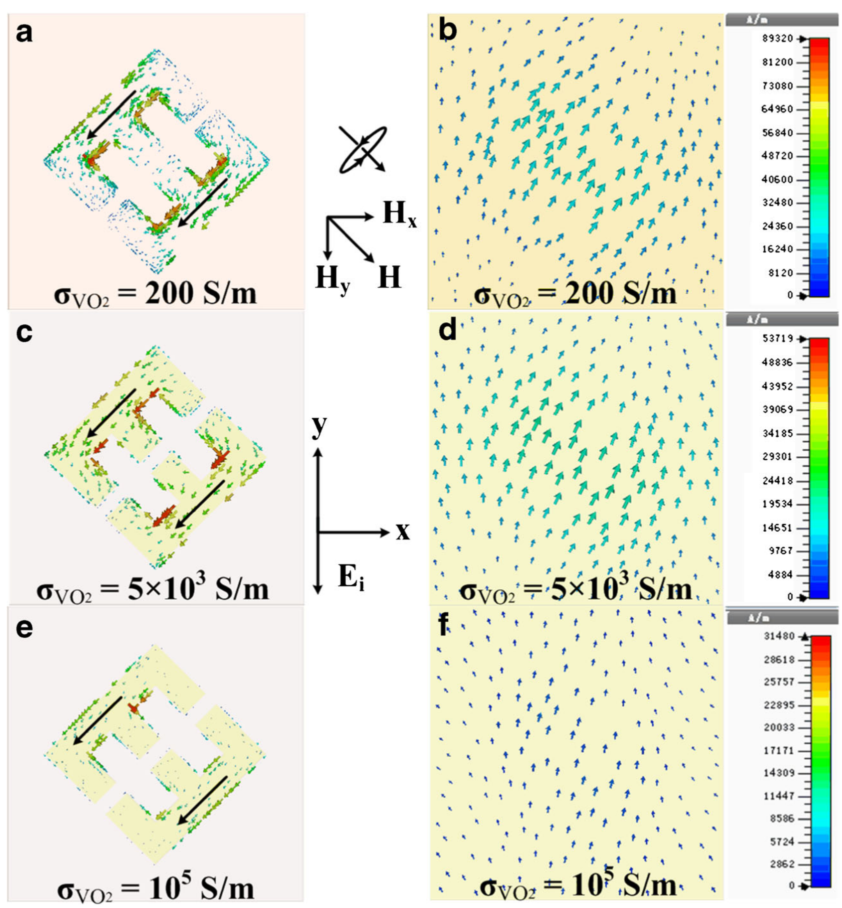

Fig. 6 **a**–**f** Surface current distributions at 5.22 THz

σ_{VO2} = 200 S/m, the current strength is weak when $\sigma_{VO2} = 5 \times 10^3$ S/m. It reveals that a strong magnetic response is not excited. Thus, the polarization conversion is weak. With the $\sigma_{VO2} = 10^5$ S/m, VO_2 film behaves as metal material and the resonator is the metal plate. Consequently, no strong anti-parallel current pairs exist between the top layer and the bottom layer as shown in Fig. 6e, f. Thus, the polarization conversion cannot be observed. This hybrid metamaterial converter provides an alternative platform to promote the THz polarization modulators and thermal sensors.

Conclusion

A novel polarization converter with the embedded VO_2 film on the top layer has been investigated numerically. The PCR is above 90% with the bandwidth of 4.44 THz for both the y and x polarized waves. Simulated results indicated that the broadband polarization conversion is temperature sensitive relating to the various conductivities of the VO_2. To further study, the different conductivity of the proposed converter, the PCR depending on the variation in conductivity is analyzed. Finally, surface current distribution for different conductivity was discussed at the resonant frequency. And the converter can be potentially developed as a temperature sensor and polarization devices.

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