Broadband operation of active terahertz quarter-wave plate achieved with vanadium-dioxide-based metasurface switchable by current injection

Toshihiro Nakanishi,1 Yosuke Nakata,2 Yoshiro Urade,3 and Kunio Okimura4
1)Department of Electronic Science and Engineering, Kyoto University, Kyoto 615-8510, Japan
2)Graduate School of Engineering Science, Osaka University, Osaka 560-8531, Japan
3)Center for Emergent Matter Science, RIKEN, Saitama 351-0198, Japan
4)School of Engineering, Tokai University, Kanagawa 259-1292, Japan
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We demonstrate the broadband operation of a switchable terahertz quarter-wave plate achieved with an active metasurface employing vanadium dioxide. For this purpose, we utilize anisotropically deformed checkerboard structures, which present broadband characteristics compatible with deep modulation. Moreover, the metasurface is integrated with a current injection circuit to achieve state switching; this injection circuit can also be employed to monitor the electric state of vanadium dioxide. We estimate the Stokes parameters derived from the experimental transmission spectra of the fabricated metasurface and confirm the helicity switching of circularly polarized waves near a designed frequency of 0.66 THz. The relative bandwidth is evaluated as 0.52, which is 4.2 times broader than that in a previous study.

Terahertz waves have unique properties, such as high transparency to optically opaque materials, and distinct spectral responses to molecules; they have been extensively applied in nondestructive imaging, biomaterial detection, and other areas.1,2 In the development of terahertz technologies, it is quite important to manipulate polarization, which is one of the most fundamental characteristics of electromagnetic waves. In optical regions, a birefringent material is used to realize polarization devices, such as a half- or quarter-wave plate; however, the available terahertz components for polarization control are still limited and inefficient. Furthermore, active control of terahertz polarization is much more difficult.

Recently, artificial materials composed of designed subwavelength structures, called as metamaterials, have gained significant interest for the manipulation of electromagnetic waves.3 Numerous investigations have focused on two-dimensional subwavelength structures, called as metasurfaces, which induce discontinuous phase shifts in transmitted or reflected electromagnetic waves.4,5 Generally, anisotropic and chiral metasurfaces can modify the polarization of electromagnetic waves, owing to the phase difference between orthogonal polarizations, and various types of metasurfaces have been proposed to provide a birefringent response or optical activity.6 In addition, active polarization control can be realized by reconfigurable metasurfaces incorporating dynamic elements, such as microelectromechanical systems (MEMS),7 semiconductors,8,9 and graphene.10 Phase-change materials, such as vanadium dioxide (VO2) (which undergoes an insulator-to-metal transition near 65 °C), have also been utilized to achieve active polarization control11,12,13. Previously, we have also proposed a VO2-integrated metasurface with dipole-embedded checkerboard structures functioning as an active quarter-wave plate, whose fast and slow axes can be interchanged by increasing the temperature using an external heater.14,15 This metasurface can reverse the rotational direction of circularly polarized waves that are generated from linearly polarized incident waves. Generally, the broadband operation of metasurfaces is challenging, because they frequently employ resonances to induce effective electromagnetic responses. The above-mentioned active terahertz quarter-wave plate also suffers from a severely limited bandwidth, owing to its complex spectral response unique to Fano resonances16–19. This is resulting from the interference between the broad resonance of the checkerboard structures and the sharp resonance of the dipole structures that are embedded in the checkerboard structures to induce an anisotropic response.

In this study, we significantly broaden the operation bandwidth of a metasurface functioning as an active quarter-wave plate. For this purpose, we take advantage of the broadband responses inherent to checkerboard structures without the use of dipole structures, which adversely affect these responses. Instead of introducing dipole structures, we anisotropically deform the checkerboard structures and achieve broadband operation of the active quarter-wave plate. In conjunction with bandwidth broadening, we integrate a current injection circuit with the metasurface, to induce a phase transition. The state of the metasurface can be controlled by injecting an electric current into the VO2 sheets incorporated in it, and the electric state of VO2 is identified by monitoring the injecting current and the applied voltage. This integrated design of a metasurface without an external heater is suitable for the miniaturization of a device.

We briefly review the design rules based on Babinet’s principle10 using an actual metasurface, whose top view is shown in Fig. 1(a). The metasurface is composed of metallic sheets and variable resistive sheets whose sheet impedance Z can vary over a wide range. Figures 1(b) and (c) illustrate the states, labeled as off and on states, in the limit of Z → ∞ and Z → 0, respectively. These two states are complementary to each other, for the inversion of the metallic and vacant
parts. The on state can be obtained by rotating the inverted structure of the off state by 90 degrees, and vice versa. From Babinet’s principle applying to the metasurface with the distinct symmetry, the following relations can be derived for the complex amplitude transmission coefficients:

\[
\tilde{t}_x^{(\text{off})} + \tilde{t}_y^{(\text{on})} = 1, \quad \tilde{t}_y^{(\text{off})} + \tilde{t}_y^{(\text{on})} = 1,
\]

where subscripts \(x\) and \(y\) represent the corresponding polarizations of the incident waves, and superscripts (on) and (off) represent the states of the variable resistive sheet.\(^{24,25}\) If the single-layer metasurface with a subwavelength thickness does not have any loss, including the Ohmic dissipation and energy leakage resulting from diffraction and polarization conversion between the \(x\) and \(y\) polarizations, the transmission coefficients should be located on the circumference of a unit circle with the center at 1/2 in a complex plane, as depicted in Fig. 1(d). Assuming that the metasurface in the off state is designed to act as a quarter-wave plate, which demands \(\tilde{t}_x^{(\text{off})} = \pm j \tilde{t}_y^{(\text{off})}\), possible solutions are provided as \(\tilde{t}_x^{(\text{off})} = (1 \pm j)/2\) and \(\tilde{t}_y^{(\text{off})} = (1 \mp j)/2\), respectively. They are shown as open circles in Fig. 1(d). In this case, the magnitudes of the transmission coefficients should satisfy the following conditions:\(^{26}\)

\[
|\tilde{t}_x^{(\text{off})}|(\omega) = |\tilde{t}_y^{(\text{off})}|(\omega), \quad \frac{d|\tilde{t}_x^{(\text{off})}|}{d\omega} \bigg|_{\omega_0} \cdot \frac{d|\tilde{t}_y^{(\text{off})}|}{d\omega} < 0,
\]

where \(\omega\) is an angular frequency. Babinet’s relations, as expressed in Eq. (1), ensure that the on state also functions as a quarter-wave plate with \(\tilde{t}_x^{(\text{on})} = (1 \pm j)/2\) and \(\tilde{t}_y^{(\text{on})} = (1 \mp j)/2\), where the slow and fast axes are interchanged compared to those for the off state.

Based on the above strategy, we design a metasurface by adjusting the dimensions of the structures as shown in Fig. 1(a), using a commercial software package (CST Microwave Studio). We suppose that the metallic sheets are composed of perfect electric conductors with zero thickness and that the variable resistive sheets are in an insulating state with \(Z = 100\Omega\), which is a typical sheet impedance of a 200-nm-thick VO\(_2\) film at room temperature \(\sim 25^\circ\text{C}\) (see in Supplementary Material). The metasurface is formed on a \(c\)-cut sapphire substrate with semi-infinite thickness and anisotropic refractive indices of \(n_x = n_y = 3.1\) in the \(x\)-\(y\) plane and \(n_z = 3.4\) in the propagation direction.\(^{26}\) We fixed \(s\) and \(a\) as \(s = 10\mu\text{m}\) and \(a = 60\mu\text{m}\), respectively, which determine diffraction frequency \(f = c_0/(\sqrt{2n_c}a)\) near 1.04 THz. Amplitude transmission spectra, which are normalized by that obtained for the substrate without the metasurface, for normally incident terahertz waves are calculated for the periodic system in the \(x\) and \(y\) directions under the periodic boundary conditions. From the simulation results, we determine the design parameters as \(b = 25\mu\text{m}, c_1 = 14\mu\text{m},\) and \(c_2 = 15\mu\text{m},\) such that Eq. (2) for the off state is satisfied. The details of the optimization procedure are described in the Supplementary Material. Figure 2(a) presents the calculated transmission spectra. The sheet impedance of the resistive sheets for the on state is set as \(Z = 10\Omega\). As expected, for the on state, two transmission

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**FIG. 1.** (a) Top view of schematic design of metasurface. (b) Off state \((Z \rightarrow \infty)\). (c) On state \((Z \rightarrow 0)\). (d) Amplitude transmission coefficients plotted on a complex plane for realizing quarter-wave plate.

**FIG. 2.** (a) Normalized amplitude transmission spectra and (b) phase differences between \(y\) and \(x\) polarization components derived from simulation results.
spectral range from 0.66 THz, and Eq. (2) is also automatically satisfied for the on state. Figure 2(b) shows the phase difference between the \( y \) and \( x \) polarization components, defined as \( \arg(t_x/\tilde{t}_y) \), for both the states. The practically flat response found in the broad spectral range from 0.4 THz to 0.9 THz is a unique property of this metasurface. The phase differences at 0.66 THz are estimated as \( +111^\circ \) and \( -78^\circ \) for the off and on states, respectively, and they slightly deviate from the ideal values of \( \pm 90^\circ \), respectively. This is because Eqs. (1) and (2) are not strictly satisfied, mainly because the substrate breaks the reflection symmetry required for Babinet’s principle. Nevertheless, the metasurface presents excellent performance as a linear-to-circular polarization converter, which will be discussed below using experimental results.

In our experimental demonstration, variable resistive sheets are composed of VO\(_2\), which exhibits insulator-to-metal transitions above the critical temperature of approximately 65°C. Figure 3(a) shows a photomicrograph of the metasurface fabricated on a \( c \)-cut sapphire substrate. The thicknesses of the VO\(_2\) and aluminum films are estimated as approximately 200 nm and 400 nm, respectively. The whole structure is presented in Fig. 3(b). The VO\(_2\) patterns are formed by wet etching for the VO\(_2\) film deposited by reactive magnetron sputtering, and metallic patterns are formed by lift-off process. The details of the fabrication procedure are provided in the Supplementary Material. A metasurface with a size of 12 mm \( \times \) 9 mm is fabricated at the center of the substrate. For monitoring and controlling the electric state of the VO\(_2\) films, two electrodes are introduced at the top and bottom ends of the metasurface, to inject electric currents into the VO\(_2\) patches. The electric currents are applied through electric wires, which are connected to each electrode with a conductive adhesive. Both left and right sides of the metasurface are covered by 24 nm-thick-titanium films with a width of 1.5 mm. The role of the titanium films is discussed subsequently.

Before terahertz measurements, the current–voltage (I–V) characteristics between the electrodes are evaluated using a direct-current power source operated in a constant-current mode. The results observed at room temperature around 24°C with increasing current at a rate of 0.5 mA/s are shown as a solid line in Fig. 3(c). The dashed line represents the I–V characteristics when the mount holding the metasurface is heated at 85°C. The resistance characteristics \( R = V/I \) derived from the I–V characteristics are shown in Fig. 3(d). For small current \( I < 20 \text{ mA} \), the voltage increases almost linearly with increasing current. In this region, most of the electric current is concentrated on the titanium films at the sides of the metasurface, and the resistance \( R \sim 4 \text{k}\Omega \) can be regarded as the resistance of the titanium films. This is because the sheet impedance of the VO\(_2\) films is extremely high (\( \sim 67 \text{k}\Omega \)) at room temperature. The Joule heat in the titanium sheet increases the temperature of the sapphire substrate with a high heat conductance and facilitates the phase transitions of the VO\(_2\) films. At approximately \( I = 45 \text{ mA} \), the voltage across the electrodes abruptly drops from \( V = 90 \text{ V} \), which suggests that some of the VO\(_2\) patches undergo a phase transition, and conducting paths in the metasurface are formed. The required voltage for the phase transition would be considerably higher without the titanium sheets, which effectively reduce the threshold voltage. With increasing \( I \), a ratio of VO\(_2\) patches in the metallic state is gradually increased. The I–V characteristics present a small drop close to \( I = 130 \text{ mA} \) and asymptotically approach those of the dashed line. This suggests that the VO\(_2\) patches are completely in the metallic state for \( I > 130 \text{ mA} \), because the dashed line represents the I–V curve at a temperature considerably higher than the critical temperature. The resistance approaches to a constant value around 120 \( \Omega \), which is much smaller than the resistance of the titanium films \( \sim 4 \text{k}\Omega \), and most of the current is concentrated on the metasurface without the titanium films. The two-step transition in Fig. 3(c) is also observed for the conduction of a single VO\(_2\) gap, owing to the percolation processes associated with the metallic and insulating phases coexisting in a metastable state. The state at \( I = 189 \text{ mA} (V = 21 \text{ V}) \), which corresponds to a power consumption of 3.8 W, was used as the on state in the following experiments. The power consumption in the titanium films is estimated to be 0.11 W, which is three percent of the total power consumption.

Subsequently, we evaluated the transmission characteristics of the metasurface via conventional terahertz time-domain spectroscopy, in which complex transmission coefficients \( t_x^{\text{off}}(\omega) \), \( t_y^{\text{off}}(\omega) \), \( t_x^{\text{on}}(\omega) \), and \( t_y^{\text{on}}(\omega) \) are derived by the Fourier transformation of the obtained signals in the time domain. The amplitude transmission is normalized by the reference signals, which are obtained using the sapphire sub-
strate without the metasurface. The derived magnitudes of the transmission coefficients are shown as solid lines in Fig. 4(a), where \( t_x^{\text{(off)}} \) and \( t_y^{\text{(off)}} \) are obtained without current injection and \( t_x^{\text{(on)}} \) and \( t_y^{\text{(on)}} \) are obtained at \( I = 180 \text{ mA} \). The dashed and dash-dotted lines represent transmission spectra \( t_x^{\text{(hi)}} \) and \( t_y^{\text{(hi)}} \) for the \( x \) and \( y \) polarizations, respectively, when the holder of the substrate is heated at \( 85^\circ \text{C} \) without current injection into the metasurface. For both the polarization states, the obtained results at \( I = 180 \text{ mA} \) are almost the same as those for \( 85^\circ \text{C} \), and it is evident that the current injection at \( I = 180 \text{ mA} \) is sufficient to induce a complete phase transition in the VO\(_2 \) patches. The four transmission spectra, \( |t_x^{\text{(off)}}|, |t_y^{\text{(off)}}|, |t_x^{\text{(on)}}|, \) and \( |t_y^{\text{(on)}}| \), obtained in the experiment agree well with the simulation results shown in Fig. 2(a). Some discrepancy possibly arises from the experimental limitations, such as wavefront deformation of the incident terahertz waves, fabrication error of the metasurface, and finite conductivity of the aluminum films. Figure 4(b) presents the phase differences between the \( y \) and \( x \) polarization components for both the states. At 0.66 THz where \( |t_x^{\text{(off)}}| = |t_y^{\text{(off)}}| = 0.60 \) and at 0.69 THz where \( |t_x^{\text{(on)}}| = |t_y^{\text{(on)}}| = 0.57 \), the phase differences are estimated as \( +99^\circ \) and \( -71^\circ \) for the off and on states, respectively. The absolute power transmissions, including the Fresnel reflection loss of \(-46\%\) at both sides of the substrate, are estimated as \( 20\%\) and \( 18\% \), respectively.

To evaluate the function of the metasurface as an active quarter-wave plate, we use \( S_3/S_0 = 2\text{Im}(t_x^{\text{(hi)}})/(|t_x^{\text{(hi)}}|^2 + |t_y^{\text{(hi)}}|^2) \), which provides one of the normalized Stokes parameters for the incidence of a 45-degree linear polarization. When the output wave is perfectly circularly polarized, \( S_3/S_0 \) becomes \( \pm 1 \), whose sign corresponds to the helicity of the waves. Figure 4(c) presents the derived Stokes parameters for the off and on states. The solid and dashed lines correspond to the experimental and simulation results, respectively. It is confirmed that the helicity of the output terahertz wave is reversed from \(+0.99\) to \(-0.95\) close to \( f_0 = 0.66 \text{THz} \), where the difference in \( S_3/S_0 \) is maximized, and the fabricated metasurface acts as an active quarter-wave plate, as expected. Defining the operation bandwidth, \( \Delta f \), as a spectral region satisfying \( |S_3/S_0| > 0.5 \) for both the states, represented by the gray-shaded area in Fig. 4(c), we estimated \( \Delta f = 0.35 \text{THz} \) and the relative bandwidth, \( \Delta f/f_0 = 0.52 \). The present study achieves a 4.2 times broader bandwidth compared to a previous result, \( \Delta f/f_0 = 0.12 \), with a dipole-nested checkerboard metasurface, which presents complex spectral shapes. Because the metasurface in this study is topologically equivalent to a simple checkerboard structure with a broad resonance, we can achieve a flat phase response, as shown in Fig. 4(b), which results in the broadband operation as an active quarter-wave plate.

In this study, we have demonstrated the broadband operation of a metasurface functioning as an active quarter-wave plate, whose fast and slow axes can be interchanged. Both the simulation and experimental results confirm that the metasurface presents excellent performance as an active quarter-wave plate, and the available bandwidth is 4.2 times broader than that in a previous study. The states of the metasurface are controlled by directly injecting electric currents, which can also be utilized to monitor the electric states of vanadium dioxide. Compared with other related studies of electrically controllable metasurfaces with VO\(_2 \) films, which are connected in parallel with metallic elements, the VO\(_2 \) films of this metasurface are connected in series in the current direction.
To substantially reduce the critical voltage for the series structures, a supplementary heater formed of titanium sheets is also integrated in the metasurface. This method can be applicable to various types of active metasurfaces employing vanadium dioxide. The response time is estimated to be 60–90 seconds from the transient measurement of I−V characteristics for sudden current change. Some studies have shown that W-doped VO$_2$ films have lower critical temperature, which could reduce the transition time. Photoinduced phase transition by ultrafast optical pulses might be the most effective way, which could reduce the transition time to picosecond order. The broadband active quarter-wave plate enables the polarization switching of short terahertz pulses with a broad spectrum, which opens a new route for sensitive detection of chiral molecules and terahertz data transmission.

See the Supplementary Material for the electric property of VO$_2$ film, the optimization of the design parameters, and the fabrication procedures.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author on a reasonable request.

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Supplementary material:
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I. ELECTRIC PROPERTY OF VO$_2$ FILM

Figure 5 shows a typical sheet impedance of a 200-nm-thick VO$_2$ sheet, which is fabricated by the procedures given in Sec. III in the Supplementary Material, for various temperatures. This is obtained by a four-probe method, whose results can be applied for terahertz waves. The solid (dashed) line corresponds to the sheet impedance with increasing (decreasing) temperature. The typical sheet impedances of 200-nm-thick VO$_2$ sheets are $40\,\text{k}\Omega$–$150\,\text{k}\Omega$ at 25°C and $8\,\text{Ω}$–$12\,\text{Ω}$ at 100°C, respectively. Hence, we assume the sheet impedances as 10Ω for the metallic state and as 100 kΩ for the insulating state when designing the metasurface.

II. OPTIMIZATION OF DESIGN PARAMETERS

Figures 6(a) and (b) represent the normalized amplitude transmission spectra $|\tilde{t}(\text{off})_x|$ and $|\tilde{t}(\text{off})_y|$, respectively, for three sets of parameters: (i) $b = 15\,\mu\text{m}$, $c_1 = c_2 = 15\,\mu\text{m}$ (solid lines); (ii) $b = 20\,\mu\text{m}$, $c_1 = c_2 = 15\,\mu\text{m}$ (dashed lines); (iii) $b = 15\,\mu\text{m}$, $c_1 = c_2 = 20\,\mu\text{m}$ (dash-dotted lines). The other parameters are fixed as $s = 10\,\mu\text{m}$ and $a = 60\,\mu\text{m}$. The transmission spectra are normalized by that without the metasurface, to exclude the Fresnel reflection at the surfaces of the sapphire substrate. For the $x$ polarization, the spectra present significant red shifts with increasing $c_1$ (or $c_2$), whereas they are insensitive to the change in $b$. However, for the $y$ polarization, the spectra present red shifts with increasing $b$, whereas they are almost independent of $c_1$ (or $c_2$). Consequently, it is possible to tailor the transmission spectra for the $x$ and $y$ polarizations almost independently, and we can easily adjust the dimensions of $b$, $c_1$, and $c_2$ to satisfy the conditions to realize a quarter-wave plate, as expressed in Eq. (2).

III. FABRICATION PROCEDURES

The metasurface is composed of three layers: a vanadium dioxide layer as a variable resistive sheet, an aluminum layer as a conductive sheet, and a titanium layer as a supplemental heater. The fabrication procedure of the metasurface is as follows. A VO$_2$ film is deposited on a $c$-cut sapphire substrate of size 20 mm × 20 mm × 1 mm by reactive magnetron sputtering with a vanadium target. The thickness of the film is estimated as approximately 200 nm. After the VO$_2$ pattern is formed by wet etching, metallic structures are patterned by a lift-off process using a 400-nm-thick aluminum film, which is deposited by electron-beam evaporation. Finally, a supplemental heater is fabricated by a lift-off process using a 24-nm-thick titanium film formed by electron-beam evaporation.