Multifunctional Metasurface Lens With Tunable Focus Based on Phase Transition Material

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Metasurfaces have powerful light field manipulation capabilities, which have been extensively studied in the past few years and have developed rapidly in various fields. At present, the focus of metasurface research has shifted to the tunable functionality. In this paper, a temperature-controllable multifunctional metasurface lens based on phase transition material is designed. First of all, by controlling the temperature of the desired working area and the polarization of the incident light, switching among multiple focus, single focus, and no focus at any position can be achieved, and the intensity and helicity of the output light can be adjusted. In addition, a polarization-sensitive intensity-tunable metalens based on the P-B phase principle is designed, when the incident light is linearly polarized light, left-handed circularly polarized light, or right-handed circularly polarized light, it has the same focal point but with different light field intensities. Therefore, the focused intensity can be tunable by the polarization state of the incident light.

Keywords: multifunctional metasurface, tunable meta-lens, phase transition material, multiple focus, polarization-sensitive

INTRODUCTION

Metasurfaces, the corresponding two-dimensional metamaterials, can flexibly control the amplitude, phase, and polarization of light through sub-wavelength units, compared with the traditional lens that relies on the modulated light beam to accumulates the phase delay during the transmission, it is smaller in size, lighter in weight, and suitable for device miniaturization and system integration. Thanks to the special properties of metasurfaces, various new applications can be realized, such as hologram [1–4], polarization measurement [5–7], vortex beam generator [8, 9], non-linear dynamics [10–12], beam shaping, etc. [13, 14].

The bifocal and multifocal lenses that can focus on different positions can be used in imaging systems [15, 16], optical communication [17, 18], and medical applications [19], etc. Previous studies have also used Pancharatnam-Berry (P-B) phase metasurface to achieve multi-focus focusing function [15, 20]. However, their work has some limitations: firstly, once the lens structure is produced, its function cannot be changed; secondly, based on the principle of P-B phase modulation, it demands higher requirements of the helicity of the incident light. Usually, the requirement is circular-polarized incident light, and polarization-independent focusing cannot be achieved.
Phase transition materials are a good choice to provide a wide range of tunable metamaterials, whose electronic properties can be tuned in real time during structural phase transitions. By using phase transition materials, the optical response of metamaterials can be significantly adjusted by external excitations [21]. Currently, the common phase transition materials used in metasurfaces are Ge_{2}Se_{2}Te_{5} [22, 23], vanadium dioxide (VO_{2}) [24], or graphene [25], etc. In terms of thermal control materials, vanadium dioxide has the capability of insulating-metal phase transition, and its structure can change reversibly with temperature. Its phase transition temperature is \( T_{C} = 68^\circ \)C. When temperature is below the phase transition temperature \( T_{C} \), it exhibits a monoclinic phase structure, in a semiconductor insulation state (I-VO_{2}), the infrared transmittance is higher at this state; When temperature is higher than the phase transition temperature \( T_{C} \), it presents a rutile tetragonal phase structure, in a metallic state (M-VO_{2}), and has a lower infrared transmittance [26–28]. In recent years, there have been many studies on metasurfaces based on vanadium dioxide, including controlling temperature or heat flux [29, 30], asymmetric transmission [31], switchable focus lens [32–34], switchable wave-plates [35], beam control [36], and the like. However, most of these designs can only achieve fixed function, or only work under a specific condition [37].

In this article, we propose a temperature-controllable metalens based on VO_{2} material working in the mid-infrared band. By controlling the temperature, the conversions among bifocal, single focus, and no focus can be realized, and the helicity of the focal light is changeable, as shown in Figure 1. In addition, based on the principle of P-B phase, the co-focal lens which works for linear polarized light, left-handed circularly polarized light, and right-handed circularly polarized light is designed, and the intensity of the focal spot is different for different incident polarized light. Thus, a polarization sensitive lens with tunable intensity is realized.

More importantly, we showed a multifunctional lens made of thermally controlled phase transition materials, and provided a new design method for adjustable multifocal lenses. As an extension, other phase transition materials and different control methods, such as electric control, can also be used to complete focus switchable, polarization independent metasurface lenses.

**MATERIAL AND DESIGN THEORY**

Based on the vanadium dioxide material, the conductor model parameter is used below the phase transition temperature \( T_{C} \) (when in I-VO_{2}), corresponding permittivity \( \varepsilon = 9 \) [38]. When temperature is higher than the phase transition temperature \( T_{C} \) (at M-VO_{2}), the Drude model is used to determine the parameters.

The complex permittivity of vanadium dioxide can be given by the following dispersion relation [39–41]:

\[
\varepsilon(\omega) = \frac{\varepsilon_{\infty} - \frac{\sigma_{0}}{\omega} \varepsilon_{\infty}}{\omega + i\gamma} \quad (1)
\]

Among them, the first item represents ultimate high frequency permittivity, \( \varepsilon_{\infty} = 12 \); \( \gamma = \frac{\sigma_{m}}{\omega} \) represents the collision frequency, here \( m^{*} \) is the optical effective mass of electrons. \( \sigma_{n} (\sigma) \) represents electrical conductivity, which is related to plasma frequency. Because \( \sigma \) are directly proportional to the free carrier density; According to the reference, it can be known as \( \sigma_{0} = 3 \times 10^{5}S/m, \sigma_{n} (\sigma_{0}) = 1.4 \times 10^{15}rad/s, \gamma = 5.75 \times 10^{3}rad/s \).

**Figure 2** shows the transmittance properties of VO_{2} film [40]. The two curves in Figure 2A represent the change of transmittance in the frequency range of 0.25–5eV when the temperature is 300 K and 355 K, respectively. We can get that when the temperature of the VO_{2} film is 300 K and 355 K, the transmittance of 0.31 eV (4\( \mu \)m) incident light shows a huge contrast. The red and blue curves in Figure 2B show the transmittance of VO_{2} film (at 4\( \mu \)m) between heating and cooling, respectively. It can be seen from the figure that there is a short temperature change interval within which the transmittance changes rapidly with temperature, and the change is reversible. Outside the corresponding temperature in the phase transition zone, the transmittance is relatively stable.

In summary, the transmittance of the VO_{2} film at 4\( \mu \)m changes drastically in the phase transition interval, and the heating and cooling process is reversible. Therefore, it can exhibit stable performance outside the phase change region.

**Theory**

According to the P-B phase modulation principle, The electric field generated by an incident plane wave of arbitrary polarization passing through the lens can be expressed as [42]:

\[
\eta_{E} = \sqrt{\eta_{R} |E_{in}|} + \sqrt{\eta_{L} e^{2\theta(x,y)}} |R| + \sqrt{\eta_{L} e^{-2\theta(x,y)}} |L| \quad (2)
\]

In the formula, \( \eta_{E}, \eta_{R}, \eta_{L} \) represents the polarization level coupling efficiency, which can be expressed as:

\[
\eta_{E} = \frac{1}{2} \left( t_{x} + t_{y} e^{i\phi} \right)^{2} \quad (3)
\]

\[
\eta_{R} = \frac{1}{2} \left( t_{x} - t_{y} e^{i\phi} \right) |E_{in}| L^{2} \quad (4)
\]

\[
\eta_{L} = \frac{1}{2} \left( t_{x} - t_{y} e^{i\phi} \right) |E_{in}| R^{2} \quad (5)
\]

Among them, \( t_{x}, t_{y} \), respectively, represent the real amplitude transmission coefficients perpendicular and parallel to the optical axis, and \( \phi \) represent the phase delay between the two polarizations. Symbols \( (E_{in} L) \) \( (E_{in} R) \) denote the dot product of the incident polarized plane wave \( E_{in} \) and left-handed circularly polarized plane wave \( L \) (right-handed circularly polarized plane wave \( R \)).

From the above formula, we can get that the outgoing electric field contains three components. The first component maintains the original polarization and phase of the incident beam; the second term is right-handed circular polarization with \( 2\theta(x,y) \) phase modulation; The last term is opposite to the previous term which is left-hand circular polarization light with a modulation phase of \( -2\theta(x,y) \).
For a special case: $t_x = t_y, \phi = \pi$, when the left-handed circularly polarized light is incident, the outgoing beam will undergo full polarization conversion:

$$|E_{\text{out}}\rangle = \frac{t_x + t_y}{2} e^{i\theta(x,y)} |R\rangle \quad (6)$$

It can be seen from the above formula that the phase modulation depends on the local orientation of the sub-wavelength grating.

**Design Method**

In the design of this article, glass is used as the substrate, and vanadium dioxide ($\text{VO}_2$) is used for the structural unit. We control the changing of temperature so that it undergoes a mutual
conversion from I-VO$_2$ state to M-VO$_2$ state. In order to achieve the purpose of lens focusing, the unit cell at different positions $(x, y)$ need to meet the phase condition [43]:

$$\varphi (x, y) = \frac{2\pi}{\lambda_{in}} \left( \sqrt{(x-x_0)^2 + (y-y_0)^2} + f^2 - f \right)$$  (7)

Here, $\lambda_{in}$ is the desired wavelength, $f$ is the focal length, and $(x_0, y_0)$ is the initial position of the focus. Based on the Equation (6), the unit cell at different positions $(x, y)$ need to meet $\theta = \pm \varphi / 2$ to ensure that the left-handed circularly polarized light or the right-handed circularly polarized light can pass through the structure and is converted into the opposite direction of rotation [44]. The rotation angle is:

$$\theta (x, y) = \pm \frac{\pi}{\lambda_{in}} \left( \sqrt{(x-x_0)^2 + (y-y_0)^2} + f^2 - f \right)$$  (8)

Figure 3A is a schematic diagram of the structure. The lens is composed of two areas, A and B, which are a circle in the area $(0, r_1)$ and a ring in the area $(r_1, r_2)$. Figure 3B is a schematic diagram of lens focusing when linearly polarized light is incident, and two focal points are formed. Figures 3C–E are perspective view, front view, and top view, respectively. We used a commercial three-dimensional (3D) finite-difference time-domain (FDTD) solver (FDTD solutions, Lumerical Inc.) to simulate the unit in the frequency domain with periodic
boundary conditions in the x and y directions, and a perfectly matched layer in the z direction. By optimizing the structure, we determine that the incident wavelength \( \lambda_{in} = 4 \mu m \), the period of each unit cell is \( P = 2.8 \mu m \), and the height of the structural unit \( H = 3.2 \mu m \). Scanning the phase change and transmittance of different circular polarizations light in I-VO\(_2\) and M-VO\(_2\) to determine the best choice of length and width. **Figure 4A** is a scan diagram of the phase delay varying with the length and width, **Figures 4B, C** are the schematic diagrams of the transmittance varying with the length and width in the two states of I-VO\(_2\) and M-VO\(_2\), respectively.

We choose the appropriate length and width to make the I-VO\(_2\) nanorods in the state of a half-wave plate, that is, the phase retardation \( \phi = \pi \), \( t_x = t_y \), and the transmittance is as high as possible in the I-VO\(_2\) state, on the contrary, the transmittance is as low as possible in the M-VO\(_2\) state. Through scanning optimization and data analysis, we choose the length \( L = 1.25 \mu m \) and the width \( W = 0.75 \mu m \) of the VO\(_2\) structural unit.

In order to verify the feasibility of the lens, we observe the changes in the transmittance of the corresponding I-VO\(_2\) and M-VO\(_2\) under different polarized light incidence when the rotation angle of the unit cell changes from 0 to \( \pi \). It can be seen from...
Figure 4D that the transmittance of I-VO$_2$ always remains at about 0.88, whether the incident light is left-handed circularly polarized light or right-handed circularly polarized light, while the transmittance of M-VO$_2$ varies between 0 and 0.2. It is in line with the situation that the transmittance of I-VO$_2$ is much greater than that of M-VO$_2$.

RESULTS AND DISCUSSION
Focus Switchable Lens Controlled by Combination of Polarization and Temperature

Here, we design a kind of adjustable lens that realizes multi-focus, single-focus, and non-focus conversion by incident different polarized light (LP, LCP, RCP) and temperature control. The lens consists of two areas, (0, $r_1$) area A, and ($r_1$, $r_2$) area B, respectively, focusing on the incident light of RCP and LCP, as shown in Figures 2A,B. Here, the radius of the lens are set as $r_1 = 50.4 \mu m$, $r_2 = 92.4 \mu m$. The conditions for the rotation angles of the structural unit in the two regions are as follows:

$$\theta_A = -\frac{\pi}{\lambda} \left( \sqrt{\rho^2 + f_A^2} - f_A \right), \quad \rho \in [0, r_1]$$

$$\theta_B = \frac{\pi}{\lambda} \left( \sqrt{\rho^2 + f_B^2} - f_B \right), \quad \rho \in [r_1, r_2]$$

Here, $f_A, f_B$ are the focal lengths of the two areas A and B, respectively.

Without loss of generality, we set $f_A = 30 \mu m$, $f_B = 60 \mu m$ as an example. When the temperature is lower than $T_C$, the two areas A and B are both in I-VO$_2$ state (pass state), which can maintain high transmittance. As we all know, LP can be regarded as a combination of LCP and RCP of equal amplitude. Linearly polarized light will form two focal points with focal lengths $f_A$ and $f_B$ after passing through the metalens, as shown in Figure 5A. The helicity of $f_A$ and $f_B$ is RCP and LCP, respectively, so as to realize dual focus focusing. When the temperature is higher than $T_C$, the two regions A and B are in the M-VO$_2$ state (close state), as shown in Figure 5B, no focus is formed at this time.

Figure 5E is a schematic diagram of the normalized electric field intensity along the z-axis in the above two cases. It can be seen from the figure that the intensity of the light field at the focal point in the passing state is much greater than the intensity in the closed state. In contrast, the intensity at high temperatures can be approximately ignored. The focal depth at $f_2 = 60 \mu m$ is longer. This is because the NA at the two focal points are different, and the focal plane size is different, which results in different intensity distributions. Large depth of focus, has great advantages in many fields such as microscopes, endoscopes, inspection cameras, etc. [45].

In addition, we control the two regions A and B to result in different states. As for the isolation of the states of the VO$_2$ materials in area A and area B, a thin insulating material can be added between the area A and the area B to avoid heat conduction. Both active heating and passive heating can achieve. Our cell structure is on the micron scale, and the temperature of each nanofins can be controlled by the semiconductor Partier effect. In order to maintain the optical transparency, one can select transparent semiconductor for desired wavelength to construct temperature controller. Let area A in the M-VO$_2$ state...
while area B in the I-VO$\text{\textsubscript{2}}$ state (B pass state). At this time, when the LCP beam is incident, a focal point with a helicity of RCP will be formed, and its focal length is $f_B$, as shown in Figure 5C. In the same way, the area A is in the I-VO$\text{\textsubscript{2}}$ state, and the area B is in the M-VO$\text{\textsubscript{2}}$ state (A pass state). At this time, the RCP beam is irradiated to form a focal point with a helicity of LCP, and its focal length is $f_A$, as shown in Figure 5D.

Figure 5F demonstrates the normalized intensity map of the electric field corresponding to the $f_A$ and $f_B$ focal points in Figure 5A. The FWHM is 2.53 $\mu$m and 2.15 $\mu$m, respectively. Figures 5G, H correspond to the normalized intensities figures of the focal spot shown in Figures 5C, D, respectively, and the FWHM is 2.17 $\mu$m and 2.39 $\mu$m, respectively. The focusing efficiency in the case of pass state, A pass state and B pass state are 31.53%, 32.45%, and 41.76%, respectively (focusing efficiency is defined as the ratio of the energy of the focal spot to the energy of the incident light).

We can also extend the focus to any position in space. As shown in Equation (7), the initial value $(x_0, y_0)$ can be set to change the position of the horizontal plane of the focus. We assume $f_A = (-20\mu m, 0\mu m, 30\mu m)$, $f_B = (10\mu m, 0\mu m, 60\mu m)$. Through the simulation of FDTD SOLUTIONS, we obtain the simulation figures of the focal spot in four states.

It can be seen from Figures 6A–D that the switching of dual focus, single focus, and no focus can be achieved at any position.
in a certain space, and the focusing effect is good. In the pass state, the FWHM corresponding to the two focal points are 2.55 µm and 2.21 µm, respectively. In A pass state and B pass state, the FWHMs of the two focal points are 2.55 µm and 2.19 µm, respectively. The focusing efficiency under pass state, A pass state, and B pass state are 32.74%, 29.78%, 41.92%, respectively.

**Intensity-Controllable Lens by Polarization**

Assigning the same focal point \( f_A = f_B = 50 \mu m \) to the two regions A and B, so that under different incident polarized light, combining with temperature control, the intensity-adjustable polarization sensitive lens with same focal point can be obtained. When LP, RCP, LCP light is incident, adjusting the regional temperature so that the meta-lens is in the passing state, A passing state and B passing state. After the radius parameter is determined (here, \( r_1 = 47.6 \mu m, r_2 = 84 \mu m \)), the intensity of the focal point is different under the incidence of different polarized light, thus realizing a polarization-dependent lens, and its intensity can be controlled by the polarization state of the incident light.

The metalens has a numerical aperture \( NA = 0.859 \), which has a larger resolution. In the above three cases, different polarized light has the same focal point but different intensities, which realizes the intensity-adjustable polarization-dependent metasurface lens based on the P-B phase principle.

**Figures 7A–C** represent the focal spots on the y-z plane formed by X, LCP and RCP incident light after passing through the lens, and the focal spots on the x-y plane correspond to **Figures 7D–F** respectively. From the comparison in the figure, it can be seen that the focal lengths show good consistency in these three cases, and polarization-insensitive focusing under the conditions of X, RCP, and LCP is realized. Corresponding to X, RCP, LCP polarized light incident, the focusing efficiency is 38.33%, 42.94%, 35.38%, respectively. **Figure 7G** gives the normalized transmitted intensity under different polarized light incidence. The three intensities have certain differences, and the maximum intensity of x-polarized light is between the LCP and RCP intensities, realizing the focus of different incident light. This function can be applied in biomedical technology, through the polarization of incident light to control the intensity of the focal electric field after passing through the lens, which can adjust the resultant of all the external forces of cells, thereby achieving the function of capturing cells. In addition, we can also adjust the area size of the unit cell in the A and B areas to control the intensity ratio of the focus.

We change the angle between the linearly polarized light and the x-axis to explore the effect of linearly polarized light with different deflection angles on the focus. **Figure 7H** shows the normalized distribution of electric field intensity on the propagation plane \((x = 0, y = 0)\) of linearly polarized light with different polarization angles after passing through the metalens.
It can be found that the position of the focal spot under different polarization angles is about 50 µm, and the intensity is basically the same. Therefore, we can conclude that the focus of linearly polarized light with different angles to the x-axis is basically the same after passing through the metalens.

The metalens designed in two regions: A and B, and there will be some optical losses in the two regions when different light sources incident, which is also the main cause of optical losses. There is a scheme in which the two types of structural elements can be interlaced. This arrangement can reduce optical loss to a certain extent. Our future work will also focus on this aspect.

**Characterization of Aberration**

In order to characterize the performance of the above designed metasurface lens, we simulated the change of the focal length when it deviated from the design wavelength, as shown in Figure 8A, where the focal change simulated here is consistent with the focal shift of the diffractive lens. The focal shift of the diffractive lens can be given by [46]:

$$f(\lambda) = \frac{f(\lambda_0) \lambda_0}{\lambda} \quad (11)$$

Here, $\lambda$ represents the wavelength of the incident light, $\lambda_0$ represents the design wavelength, and $f_0$ represents the design focal length. Figures 8B, C, respectively, show the normalized electric field distribution on the propagation plane and the horizontal focal plane when the incident wavelength is changed from 3.8 µm to 4.5 µm. We can intuitively see that as the incident wavelength increases within a certain range, the focal length gradually decreases, and when the incident wavelength is far from the design wavelength, the focal spot intensity gradually decreases. It can be seen from Figure 8D that the designed metasurface lens (symbol) is very consistent with the focal position of the diffractive lens (line) with the same geometric parameters.

**CONCLUSIONS**

In conclusion, we design a multifunctional metalens based on vanadium dioxide material. By changing the state of the two areas of the temperature control lens, it is possible to switch among dual focus, single focus and no focus at any position, and the lens with the opposite helicity conversion and adjustable focus can be realized. The focusing efficiency in pass state, A pass state and B pass state are 31.53%, 32.45%, and 41.76%, respectively. At the same time, we verify that the focal point of the lens can be extended to any position within a certain area and has a good focusing effect. In addition, a polarization dependent lens is designed based on the same principle, and a polarization sensitive lens with adjustable intensity under LP, LCP, and RCP is realized by controlling the incident light of different polarization combining with temperature adjustment of the region. Finally,
we investigate the aberration of the lens, which showed good consistency with the diffraction lens.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

YS: conceptualization, software, data curation, writing—original draft preparation, and visualization. YS and WL: methodology.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer QS declared a shared affiliation with one of the authors, XW, to the handling editor at time of review.

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