Polarization Controlled Dual Functional Reflective Planar Metalens in Near Infrared Regime

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Abstract: The metalens has been a hotspot in scientific communications in recent years. The polarization-controlled functional metalens is appealing in metalens investigation. We propose a metalens with dual functions that are controlled by polarization states. In the first design, when applied with x- and y-polarized light, two focal spots with different focal lengths are acquired, respectively. The proposed metalens performs well when illuminated with adjacent wavelengths. In the second design, the reflected light is focused when applied with x-polarized light, and when applied with y-polarized light, the reflected light is split into two oblique paths. We believe that the results will provide a new method in light manipulation.

Keywords: polarization controlling; dual functional-metalens; focusing; splitting

1. Introduction

Metamaterials are novel artificial structures that are designed for specified functions like negative refractive index [1–3], polarization conversion [4–6] and perfect absorption [7–9]. Metasurfaces possess the advantages of small losses and are easy to manufacture [10,11], and have been attractive in recent years. Among various metasurfaces, metalens with its unit cell interacting with incident light and introducing abrupt phase shift along the interface of the metasurface have been widely presented to achieve the function of focusing [12,13] and anomalous reflection [14–16]. Lots of models like the nanoslit [17], nanohole [18,19], and graphene ribbons [20–24] have been introduced in metalens design, where 2π phase shift resulting from the designed antennas is needed in controlling the wavefront. Although a polarization-independent metalens [12,25] and polarization-conversion metalens [26] have been reported in former works, and the designed metalenses are always adjusted to manipulate different kinds of incident waves with various structures [27–30], the metalens, with its function controlled by incident polarization state [31,32], has not been fully investigated.

In this paper, a metal-insulator-metal (MIM) structure is proposed to achieve the polarization controlled dual functional two-dimentional (2D) cylindrical metalens, which consists of rectangle gold antennas and a gold mirror spaced by a dielectric layer. The proposed metalens possesses two functions that can be realized when illuminated with x- and y-polarized light. The x-direction and y-direction length of the rectangle gold antenna are adjusted to control the phase and reflectance of the reflected light, because the length of the dipole resonances along x- and y-directions are determined by the x-direction and y-direction lengths, respectively. We first investigate the influence of the y-direction length or x-direction length on the dipole along the x or y-direction. By presenting the phase and
The resonance antenna is a rectangle, which is denoted as Au with data acquired from \[d_t = 130\ \text{nm} \quad \text{and} \quad 30\ \text{nm} \quad \text{for} \quad 50\ \text{nm}\]. The thicknesses of Au antenna, MgF\(_2\) spacer and Au mirror shown in Figure 1b are set as \(t_d = 50\ \text{nm}\) and \(t_s = 130\ \text{nm}\), respectively. The top view of the unit cell of the metalens is shown in Figure 1c. The period in \(x\)- and \(y\)-directions are \(p_x = p_y = 200\ \text{nm}\). The resonance antenna is a rectangle, which possesses dipole resonances along both the \(x\)- and \(y\)-directions. The rectangle lengths along \(x\)- and \(y\)-directions are variable to control the phase and reflectance of the reflected light for \(x\)- and \(y\)-polarization incidences, respectively. Thus, we can separately control the wavefront of the reflected \(x\)- and \(y\)-polarized light by configuring the rectangle lengths along \(x\)- and \(y\)-directions. The working mechanism of the proposed metalens is shown in Figure 1a, where different polarization state leads to different function. For numerical analysis, all simulations are carried out by using the finite-difference time-domain software (Lumerical FDTD solutions 8.15.736.0). PML boundary condition is applied in \(z\)- and \(x\)-directions. Periodic boundary condition is applied in the \(y\)-direction. The minimal mesh size is 4 nm.

Figure 1. Schematic of the proposed metalens. (a) The fragment, (b) cross section view and (c) top view of the proposed metalens.
Generally, the influence of the y-direction length \( b \) or x-direction length \( a \) on the dipole along the \( x \) or y-direction cannot be ignored, which results in amplitude and phase deviations for the \( x \)- or y-polarization incidences. To explore this, we choose the working wavelength as 800 nm. We show the phase and reflectance of the reflected light for \( x \)-polarization incidence in Figure 2 with different lengths \( b \) and \( a \) of the rectangle antenna. A near \( 2\pi \) phase shift can be acquired when the length \( a \) increases from 10 to 190 nm, and the length \( b \) has little influence on it in most of the length range as shown in Figure 2a,b. Due to the symmetry property of the structure, an identical performance can be acquired for \( y \)-polarization incidence.

Figure 2 shows the phase and reflectance of the reflected light for \( x \)-polarization incidence when \( x \)-direction length \( a \) increases from 10 to 190 nm and the \( y \)-direction length \( b \) is fixed as 100 nm. Figure 2d shows the phase and reflectance of the reflected light for \( y \)-polarization incidence when \( y \)-direction length \( b \) increases from 10 to 190 nm and the \( x \)-direction length \( a \) is fixed as 100 nm. The insets show the \( z \) component electric field distributions at the resonant length. Two dipole resonances along \( x \)- and \( y \)-directions are acquired, together with the Fabry–Perot resonance, a near \( 2\pi \) phase shift can be achieved. We use this approach to design the metalens that possesses different functions controlled by the polarization states of the incident light.

3. Results and Discussion

As illustrated above, we utilize the phase shift in Figure 2c,d to design the focusing metalens, which possesses the focal length of \( F = 5 \) \( \mu \)m for \( x \)-polarization incidence and \( F = 15 \) \( \mu \)m for \( y \)-polarization incidence. To design a metalens to focus incident light, the phase profile of the metalens should follow the expression [34]:

\[
\varphi(x) = \frac{2\pi}{\lambda_0} \left( \sqrt{x^2 + f^2} - f \right)
\]

(1)
where \( x \) is the horizontal position from the center of the metalens, \( \Delta x \) is the horizontal shift of the focal point, \( \lambda_0 \) is the incident wavelength, and \( F \) is the focal length. Based on Equation (1), we calculate the phase distribution curves for \( F = 5 \) \( \mu \)m and \( F = 15 \) \( \mu \)m, and show them in Figure 3a,b. The corresponding length distributions of x-direction and y-direction lengths \( a \) and \( b \) are shown in Figure 3c,d, according to which we design and simulate the planar metalens with 60 unit cells with x- and y-polarization incidences, respectively. The electric field intensity distributions for x- and y-polarization incidences are shown in Figure 3e,f, respectively. The reflected lights are well focused in the air side except for a little deviation in the focal length (4.95 and 13.32 mm for x- and y-polarization incidences) from the theoretical values. Because the phase shift resulting from the length change cannot cover the full \( 2\pi \) range, we select the adjacent unit cell instead as an approach. The longitudinal and transverse sizes of the focal spots are represented by full width at half maximum (FWHM) of the focal spots along x- and z- directions. For x-polarization incidence, the FWHM values along x- and z- directions are 0.78 and 2.72 mm. For y-polarization incidence, The FWHM values are 1.1 and 9.2 mm, respectively. The focusing efficiencies, defined as the proportion of the incident light energy going to the central focal spot, are calculated to be 41% and 45% for x- and y-polarization incidences. Thus, the metalens with two polarization-controlled focal points is achieved. In practice, a minor inclination of polarization plane is inevitable, which results in a negligible focusing effect for another polarization state.

![Figure 3](image-url)  
**Figure 3.** Phase profile to focus incident light for (a) x- and (b) y-polarization incidences. Corresponding lengths of (c) x-direction length \( a \) and (d) y-direction length \( b \) of the rectangle antenna in metalens design. The electric field intensities for (e) x- and (f) y-polarization incidence, respectively.

To investigate the influence of the x-direction length \( a \) and y-direction length \( b \) on the focusing effect of y- and x-polarization incidences, we design two metalenses that focus x-polarized light and y-polarized light only. For x-polarization incidence, only the x-direction length \( a \) is designed for focusing with a focal length of \( F = 5 \) \( \mu \)m as shown in Figure 4a, while the y-direction length \( b \) is fixed as 100 nm as shown in Figure 4c. For y-polarized light focusing, x-direction length \( a \) is fixed as 100 nm as shown in Figure 4b, while the y-direction length \( b \) is designed for focusing with a focal length of \( F = 15 \) \( \mu \)m as shown in Figure 4d. We simulate the two metalenses with x- and y-polarization incidences, and the results are shown in Figure 4e,f, from which we can see that the results are nearly...
the same as that shown in Figure 3e,f. Therefore, the influence of the x-direction length \( a \) and y-direction length \( b \) on the focusing effects of y- and x-polarization incidences are negligible.

![Figure 4](image.png)

**Figure 4.** (a) X-direction length \( a \) and (c) y-direction length \( b \) of the metalens for x-focusing only. (b) X-direction length \( a \) and (d) y-direction length \( b \) of the metalens for y-focusing only. The electric field intensities for (e) x- and (f) y-polarization incidence, respectively.

In addition, we also investigate the cases of the proposed metalens working in other incident wavelengths. The simulated results are shown in Figure 5. Figure 5a,b show the electric field distributions when illuminated with 750 nm wavelength x- and y-polarized light, respectively. Figure 5c,d show that of 850 nm wavelength incident light. From Figure 5 we can conclude that the proposed metalens can work well within a broadband wavelength that ranges from 750 to 850 nm. In addition, we investigate the focusing effects for other incident wavelengths. The focal lengths for different incident wavelengths are listed in Figure 5e,f, from which we can see that the focal length changes when incident light wavelength is changing, and the focal length is inversely proportional to the wavelength of light.
The simulated results of both x- and y-polarization incidences are shown in Figure 6e,f. For x-polarization incidence, the reflected light is well focused at the point of (x = 0, z = 5 μm), and the y-polarized light is split.

Furthermore, another function called the beam splitter can be considered in the dual functional metalens design, which manipulates the normal incident light into two opposite oblique paths [35]. To bend the normal incident light to an oblique reflected light, a phase gradient should be introduced along the interface of the structure following the generalized Snell’s law [36]. For normal incidence, the reflected angle can be expressed by:

$$\sin(\theta_r) = \frac{\lambda_0}{2n_i} \frac{d\phi}{dx} \tag{2}$$

where $\lambda_0$, $x$, $\phi$ and $n_i$ are the incident wavelength, surface length, phase shift and refractive index of the incident side material, respectively. In our design, the reflection angle of the oblique beams are ±30°, then the calculated phase shift between two adjacent unit is 45°. The phase profile calculated from Equation (2) is shown in Figure 6b. The corresponding y-direction length $b$ distribution is shown in Figure 6d, based on which the normal incident y-polarized light can be split. However, the reflection angle is less than 30°, because the phase shift produced by the gold antennas cannot cover the full 2π range, and we take some approximations in the designing process. Then for x-polarization incidence, the x-direction length $a$ is designed according to Figure 6a,c, which focus the x-polarized incident light with the focal length of $F = 5$ μm. The simulated results of both x- and y-polarization incidences are shown in Figure 6e,f. For x-polarization incidence, the reflected light is well focused at the point of (x = 0, z = 5 μm), and the y-polarized light is split.
The proposed metalens can achieve two functions by applying two orthogonal polarized lights. Two functions can be achieved by adjusting the incident light with two polarization states. Therefore, the proposed metalens can achieve two functions by applying two orthogonal polarized lights.

The advantage of our results is listed in Table 1 to compare with other works.

| Literature | Characteristics       |
|------------|-----------------------|
| Ref. [12,25] | Polarization independent |
| Ref. [20–24] | X-polarization         |
| This work  | Polarization dependent |

4. Conclusions

In summary, we proposed a dual functional metalens controlled by polarization state of the incident light. Two functions can be achieved by adjusting the incident light with two polarization states. The proposed metalens is designed according to the approach that the dipole resonance is not influenced by the width of the rectangle gold antenna. A metalens working at 800 nm wavelength with focal lengths of $F = 5 \, \mu m$ for $x$-polarization and $F = 15 \, \mu m$ for $y$-polarization incidence is designed, which agree well with the two exact metalens that focus $x$- and $y$-polarized light only. The proposed metalens works well within a broadband wavelength that ranges from 750 to 850 nm. We also designed a metalens with two functions of focusing and splitting controlled by incident polarization states. Therefore, the proposed metalens can achieve two functions by applying two orthogonal polarized lights.

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**Conflicts of Interest:** The authors declare no conflict of interest.
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