Ultra-thin, planar, broadband, dual-polarity plasmonic metalens

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An ultrathin, planar, broadband metalens composed of metal rectangular split-ring resonators (MRSRRs) has been designed, which shows dual-polarity characteristics for different types of circularly polarized (CP) light incidence. The designed metalens can be considered as the focusing lens and the diverging lens under left-handed CP and right-handed CP light incidence, respectively. The phase discontinuity of the cross-polarized transmission light is produced by optical-axis rotation through modulating two arms' lengths of the MRSRR. The MRSRR metalens possesses a wavelength-controllable focal length and a relatively larger chromatic aberration compared with the conventional lenses. And the focal length changes from 9 to 7 μm with incident wavelength from 740 to 950 nm. The dual-polarity flat metalens opens a door for new applications of phase discontinuity devices, and it will promote the fabricating capability of on-chip or fiber-embedded optical devices.

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1. INTRODUCTION

The optical lens, as a basic optical tool, has been widely used in various scientific fields, and its operation is well understood on the basis of classical optics. Conventional optical components reshape the wavefront of light via gradual phase changes accumulating along the optical path, which are accomplished by varying either the spatial distribution of the thickness or the refractive index of the optical components. Early optical lenses possessed continuous curve surfaces to modulate the phase, which determines the bulkiness of the lens. A further designed Fresnel lens utilizes the 2π phase jump to reduce the mass and volume of the lens; however, the thickness is still on the wavelength scale. The Luneburg lens [1–3] is the gradient index (GRIN) lens, which attracts a lot of attention because of its advantageous imaging properties; however, it is difficult to manufacture in some cases. Recently, metamaterials have been used to further reduce the thickness of the optical components [4,5]. And a number of plasmonics lenses have been developed based on nanohole or nanoslit arrays [6–9]. Nevertheless, those designs do not provide the ability to tailor the phase of the transmitted light from 0 to 2π, which restricts their minimum sizes and thicknesses. In all of the above works, the mechanism of wavefront shaping is the phase accumulation along the optical path, and the thickness of the optical lens is larger than or comparable to the incident wavelength. In order to reduce the thickness further, a new phase modulation mechanism needs to be explored.

In recent years, the concept of interfacial phase discontinuities has been proposed [10], and the metasurfaces based on this new concept have been demonstrated experimentally [10,11]. A metasurface consisting of subwavelength plasmonic nanoantennas has been shown to create phase shifts covering the full range (from 0 to 2π) in cross-polarized scattered light and maintain the uniformity of amplitudes [12–17]. Based on this principle, the metasurface can bend light anomalously based on a generalized Snell's law [10,11]. In addition, a lot of optical functional metasurfaces have been realized including optical focusing [7,18–24], optical vortices [10,25,26], and computer-generated holograms [21]. Therefore, the advances in the fields of nanofabrication and metasurfaces have opened new doors for building compact, planar focusing devices. In previous papers, the focusing of linearly polarized light has been successfully realized by using a V-shaped gold nanoantenna [18–21] or a nanobrick [24], and the focusing of circularly polarized (CP) light has been successfully realized by using dipole antennas [23] or U-shaped nanoantennas [22], which are both dependent on the rotation of the nanostructures [23,24].

In this paper, an ultrathin flat metalens with polarity-dependent polarization has been proposed for CP light instead of linearly polarized light, which is constructed by metal rectangular split-ring resonators (MRSRRs) based on the concept of interfacial phase discontinuity. And the phase variation from 0 to 2π is determined by just the orientation of the optical axis of the MRSRR, which is dependent on the lengths of two arms of the MRSRR instead of conventional rotation of the nanostructures. Interestingly, the polarity of the designed metalens will be changed under different polarizations of the incident CP lights because the sign of the phase discontinuity will be reversed by changing the polarization of the input. The focusing distances of the metalens are only a few micrometers rather than the centimeter scale of the conventional lens. Our metalens also works across a broad

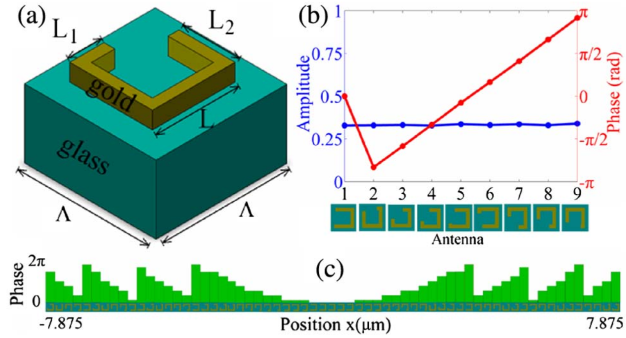

Fig. 1. (a) Sketch of basic MRSRR unit on top of the silica glass substrate, $L = 150$ nm, cell const $\Lambda = 250$ nm, and gold thickness $t = 100$ nm; $L_1 + L_2 = 175$ nm. (b) Phase shifts and scattering amplitudes of the cross-polarized transmittance with a LCP incidence at the wavelength of 808 nm. Images of the selected nine MRSRR antennas correspond to different phase delays. (c) Phase shifts at different x positions of the metalens, and the corresponding MRSRR antennas are also placed at the bottom of the image.

spectral range of 740–950 nm, and the metalens can be used as a filter for separating light at different wavelengths spatially. Moreover, the purely planar geometry of the metalens can be integrated into microdevices more easily.

2. DESIGN AND METHODS

The MRSRR unit is fabricated on the silica glass substrate, with locally varying optical-axis orientations in the x–y plane, as shown in Fig. 1(a). The optical axis of the MRSRR unit will be rotated by changing L_1 and L_2, in which $L_1 + L_2 = 175$ nm. The unit cell period Λ is 250 nm to avoid coupling between the adjacent MRSRR unit cells. The amplitudes and phases of the scattered cross-polarized field arising from nine designed antennas with left-handed CP (LCP) incidence at the wavelength of 808 nm are shown in Fig. 1(b), which clearly shows that the scattered fields have the same amplitudes and phases covering the whole 2π. The last eight antennas have incremental phase of $\pi/4$ between neighbors, and the phase of the first antenna is zero. Optical antennas with phase coverage over the whole 2π range and equal scattering amplitudes are necessary for designing planar metalenses with a large range of focal lengths. Antennas 1–5 have $L_1 = 30$, 120, 89, 62, and 31 nm, and $L_2 = 145$, 55, 86, 113, and 114 nm, respectively, and antennas 6–9 are rotated clockwise by 90° with respect to antennas 2–5.

A planar metalens that focuses in the x–z plane can be designed, and the phase distribution of the metalens at different positions for x can be easily obtained based on the equation of $\varphi(x) = 2n\pi + (2\pi/\lambda) \cdot (\sqrt{f^2 + x^2} - f)$, where λ is the incidence wavelength, and f is the focal length. Based on the numerical simulated results, a planar metalens can be designed as shown in Fig. 1(c).

3. RESULTS AND DISCUSSION

A. Dual Polarity of the MRSRR Metalens

We have designed an MRSRR metalens for focusing light under normally incident CP light with the wavelength of 808 nm. As shown in Fig. 1(c), the interface is created by arranging 63 MRSRR antennas according to the phase distributions of a cylindrical lens with a focal length of 8.08 μm, in which the numerical aperture (NA) is 0.71 according to the

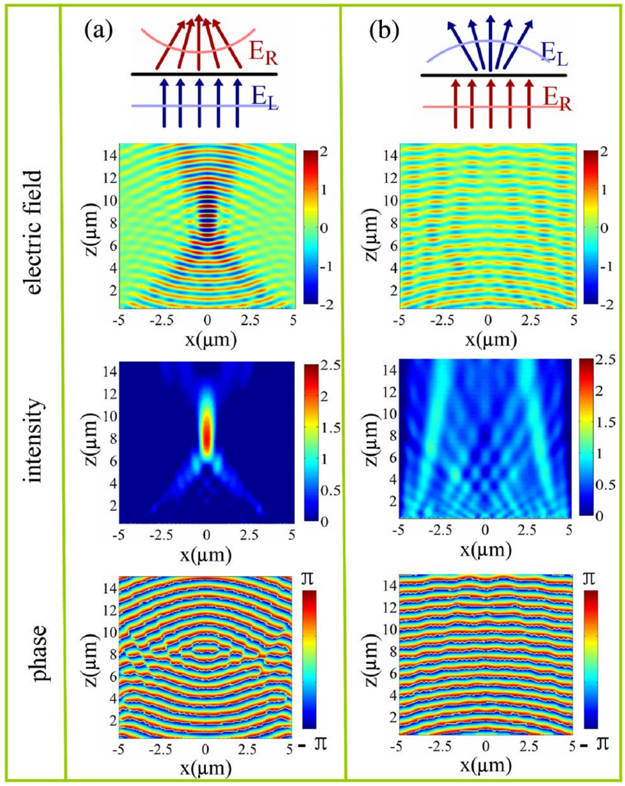

Fig. 2. Full-wave simulations are performed for the propagation of a normally incident CP wave at 808 nm through the MRSRR metalens. (a) The electric field, field intensity, and phase distribution indicate that the metalens is a positive lens for LCP incident light, and (b) shows that the metalens is a negative lens for RCP incident light.

equation of $\mathrm{NA} = \sin[\tan^{-1}(D/2f)]$. If the metalens is composed of 41 MRSRR antennas, the NA will be 0.53. When different types of CP lights propagate through the metalens with $\mathrm{NA} = 0.53$, the electric field, field intensity, and phase distributions are shown in Figs. 2(a) and 2(b), respectively. As depicted in Fig. 2(a), when it is irradiated by LCP light, the electric field distribution and wavefront of the transmitted right-handed CP (RCP) light are concave parabola and converging, which implies that the designed metalens is a focusing (positive) lens with a focus length of 8.08 μm. However, when irradiated by RCP light, the electric field distribution and wavefront of the transmitted LCP light are convex parabola and diverging (negative) as shown in Fig. 2(b). The transmitted electric field energy distribution demonstrates the focusing (diverging) phenomenon for LCP (RCP) incidence, which shows that the designed metalens has a dual-polarity characteristic. More interesting, if the phase distribution of the planar lens at different positions for x follows $\varphi(x) = 2n\pi + (2\pi/\lambda) \cdot (f - \sqrt{f^2 + x^2})$, the polarity of the MRSRR lens will be negative (diverging) and positive (focusing) for LCP and RCP incidence, respectively.

B. MRSRR Metalenses with Different Focal Lengths

To further confirm the effectiveness and universality of the designing method of the MRSRR metalens, two other MRSRR metalenses with the same width but different focal lengths of $f = 4.04$ μm and $f = 12.12$ μm have also been designed and simulated. All three metalenses are composed of 41 MRSRR antennas; therefore, the NAs get smaller with increasing focal

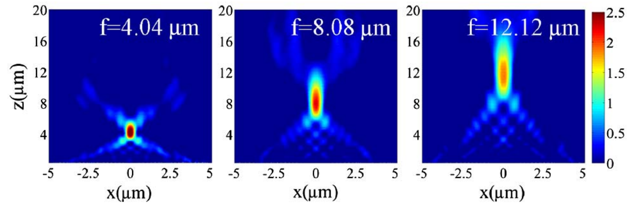

Fig. 3. Intensity distribution of the transmitted RCP light through the designed MRSRR metalenses with different focal lengths of 4.04, 8.08, and 12.12 μm, respectively, on the x–z plane, under LCP incidence at the wavelength of 808 nm.

lengths. The intensity distributions of the transmitted RCP light through three different metalenses under the incidence of LCP light are presented in Fig. 3, and transmission light is strongly focused at the expected position for each design. At their focal planes, the diameters of the focus spots are approximately on the scale of the operational wavelength; the focal depths will become larger with increasing focal length because of the decreasing NAs, and the intensities of the transmitted RCP light will also get smaller with increasing focal length. Here, the typical transmittance of our metalenses is about 10%, in which the transmittance is defined by the ratio between the intensity of the transmitted cross-polarized light and the total input intensity.

C. Broadband Characteristics of the MRSRR Metalens

Because the MRSRR array will exhibit broadband characteristics, the designed MRSRR metalens will also show broadband focusing characteristics. As depicted in Fig. 4, there are still high focusing qualities in the wavelength range of 740–950 nm, and the focal length will also rapidly decrease from 9 to 7 μm when tuning the wavelength from 740 to 950 nm. The phenomenon of different focal lengths under different incident wavelengths is called chromatic aberration (CA) for conventional lenses. In our designed metalenses, because of their ultrashort focal length of micro size, the wavelength-tunable focal shift is the same order of magnitude as the focal length itself, and the focal length of a metalens can be dynamically controlled by adjusting the incident light wavelength. Nevertheless, the focal shift is at least an order of magnitude smaller than the focal length itself for a conventional dielectric lens. Therefore, it is hard to have such dynamic control of the focal lengths for the conventional dielectric lenses because the effect is rather small [18]. However, the focal length of our designed metalens can be modulated slightly by manipulating the incident wavelength, which is interesting and will bring about new applications. Finally, it is worth noting that the obvious dependence of the focal length on wavelength can be used for spatially separating light

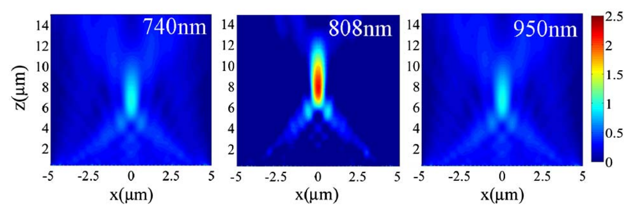

Fig. 4. Intensity distribution of the transmitted RCP light through the designed MRSRR metalens on the x–z plane, under LCP incidence at different incident wavelengths of 740, 808, and 950 nm, respectively.

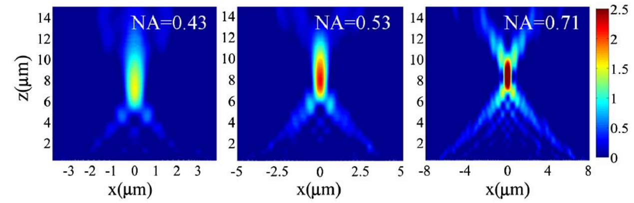

Fig. 5. Intensity distribution of the transmitted RCP light for the designed MRSRR metalenses with different NAs of 0.43, 0.53, and 0.71 on the x–z plane, under LCP incidence at a wavelength of 808 nm.

at different wavelengths, which can be used in Raman and nonlinear spectroscopies.

D. MRSRR Metalenses with Different NAs

The focusing ability of the lens is proportional to the NA that is defined as $\mathrm{NA} = \sin[\tan^{-1}(D/2f)]$, where D and f are the width and the focal length of the lens. As shown in Fig. 5, the transmitted cross-polarized intensity distributions of the MRSRR metalenses with different NAs show that there are better focusing properties with larger NA by increasing the lens's width. With the increase of NA, the size of the focal spot will be smaller, and the focus field will also be stronger, which is in accord with the conventional lens.

4. CONCLUSION

In summary, an ultrathin, planar, broadband MRSRR metalens with dual polarity is designed, which is based on the interfacial phase discontinuity of the transmitted cross-polarized light under CP light incidence. The metalens can be seen as a convex lens and a concave lens under LCP and RCP light incidence, respectively. In particular, the phase discontinuity depends on the optical-axis rotation through modulating two arms of the MRSRR rather than the previously reported conventional rotation of the antenna itself, which provides discrete phase shifts ranging from 0 to 2π for cross-polarized scattered light. The MRSRR metalens possesses a wavelength-controllable focal length and a larger CA compared with the conventional lens, and the focal length will change from 9 to 7 μm with incident wavelength from 740 to 950 nm, which shows that the designed metalens can separate light of different wavelengths in microscale areas. Our proposed MRSRR unit will enrich the metamaterial design method, and the dual-polarity planar metalens opens a door for new applications of phase discontinuity devices, which is quite promising for their use in system integration.

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