

Metasurface Lens for both Surface Plasmon Polaritons and Transmitted Wave

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Received: 5 April 2016 / Accepted: 14 June 2016 / Published online: 30 June 2016
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Abstract Metasurface lenses which could simultaneously focus both surface plasmon polaritons (SPPs) and transmitted wave are designed. This kind of device is composed of slit antennas and is optimized with the simulated annealing algorithm to realize a single-focus or double-focus lens. Interestingly, the focusing of SPPs is polarization dependent while the focusing of the transmitted wave is immune from the polarization of incident light. The proposed methodology may inspire more designs of device steering both surface wave and transmitted wave.

Keywords Metasurface · Surface plasmon polaritons · Transmitted wave

Introduction

Since the discovery of the extraordinary transmission effect caused by surface plasmon polaritons (SPPs) [1, 2], SPPs have been extensively investigated due to their subwavelength and field enhancement property [3]. SPPs are excited

by light incident on the subwavelength metallic aperture. The amplitude and phase of SPPs are determined by the shape of the aperture [4] and the amplitude, phase, and polarization of the incident light [5–8]. Thus, different functionalities can be realized by changing the shape of the aperture or modulating the parameters of the incident light. Various SPP devices including SPP lens [9, 10], SPP vortex lens [11], and SPP airy beam generator [12] have been designed and demonstrated experimentally in the visible, terahertz (THz) [13, 14], and microwave regions [15].

Recently, manipulation of light transmitted through metallic apertures with different shapes and sizes attracts lots of attention. A metal film consisted of subwavelength spatial-variant metallic apertures, which is known as metasurface [16], can realize focusing [17, 18], hologram display [19], and vortex generating [20], just like traditional optical devices. Moreover, with the tremendous freedom to control light, the metasurface can readily implement some optical phenomena which cannot be easily realized with the traditional method, such as anomalous reflection and refraction [16] and giant spin Hall effect [21]. High-efficiency metasurface realized by the dielectric structure [22] or working in the reflection mode [19] paves an avenue for the practical applications.

However, the abovementioned researches have been mainly focused on either SPPs (surface wave) or transmitted wave. Although the coupling between SPPs and free-space light is also investigated [23], the surface wave and transmitted wave are mainly considered separately. Considering that the phase and amplitude of both SPPs and transmitted wave are closely related with the shape of the metallic aperture, it should be possible to steer the SPPs and transmitted wave simultaneously. In this paper, we use the metallic slit with orientation angle $-45^\circ/45^\circ$ as the building block and design a metasurface lens for both the surface wave and transmitted

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wave with the simulated annealing algorithm. Simulation results show that the surface wave and transmitted wave can be simultaneously converged to one focus or two focuses according to different designs. And the SPPs are focused on the left and right of the lens for the left and right circularly polarized (LCP and RCP) lights, respectively, while the focusing of the transmitted wave is independent of the chirality of the incident circularly polarized light. These interesting properties could enable the versatile metasurface lens to find applications in polarization-based sensing and information transmission.

Results and Discussions

Schematic diagram of the proposed metasurface lens is shown in Fig. 1a. The incident light is circularly polarized and its frequency is 0.75 THz. The metasurface consists of a gold film and a high resistance silicon substrate. The thicknesses of the gold film and the substrate are 100 nm and 1 mm, respectively. In the THz region, the gold film can be considered as a perfect electric conductor (PEC) and the refractive index of silicon is 3.42. The parameters of the

slit are shown in the inset of Fig. 1a. The width and length of the slit are 50 and 150 μm , respectively. The orientation angle α is set as -45° or 45° to achieve different phase modulations. The transversal interval s and longitudinal interval d are 100 and 200 μm , respectively. The transmitted wave and the surface wave generated by a single slit ($\alpha = 45^\circ$) are simulated with Comsol Multiphysics software and are shown in Fig. 1b–c. It can be seen that the transmitted wave propagates in the free space and the surface wave propagates along the gold/air interface. Because the metal can be regarded as PEC, the surface wave is weakly confined compared with the SPPs in the visible waveband. The wavelength of surface wave λ_{sp} is almost the same as that of the incident/transmitted wave $\lambda = 400 \mu\text{m}$.

For different orientation angle α ranging from -90° to 90° , the amplitude and phase of the transmitted wave and the surface wave at specific points (the red points in Fig. 1b–c) are simulated and extracted. With the illumination of LCP light, the corresponding results for the transmitted wave and surface wave are shown in Fig. 2a–b. The LCP and RCP lights are indicated by the counterclockwise and clockwise circles, respectively. For the transmitted wave, the phase modulation follows $\Phi = 2\alpha$ and covers the range from

Fig. 1 a Schematic diagram of the metasurface lens and the parameters of the slits. Transmitted wave (b) and surface wave (c) generated by a single slit

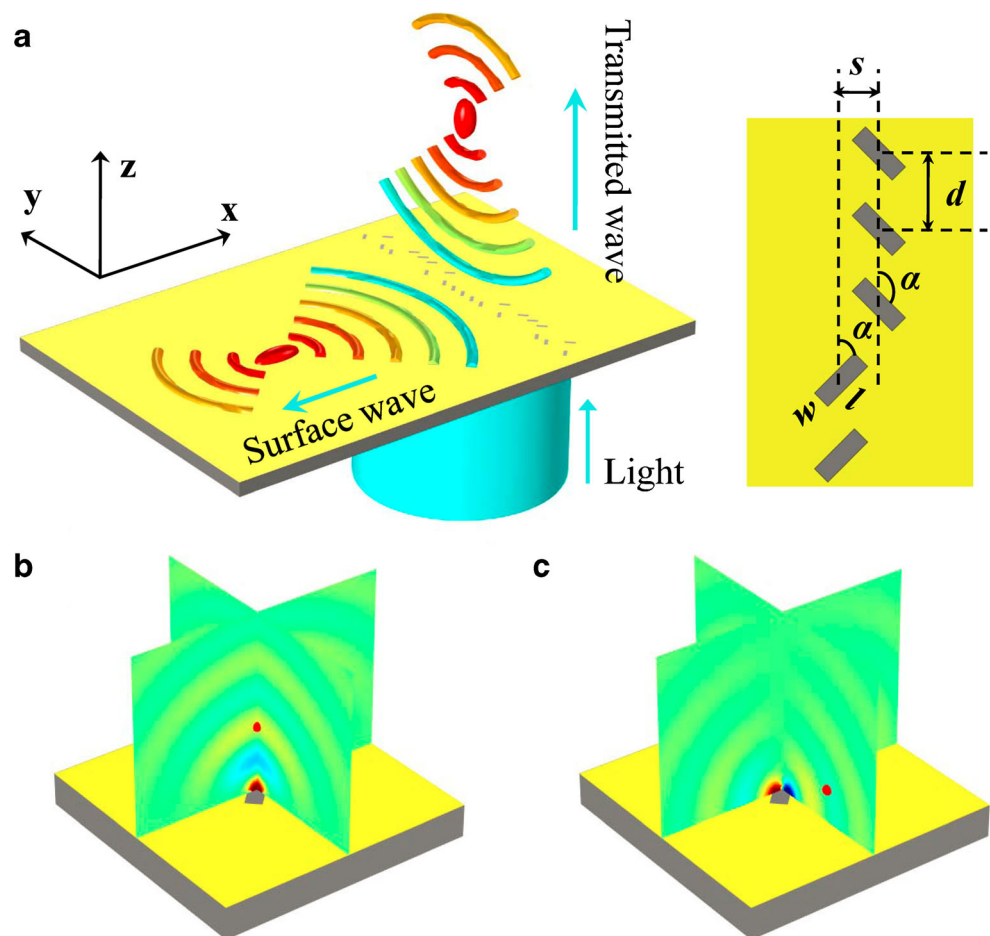
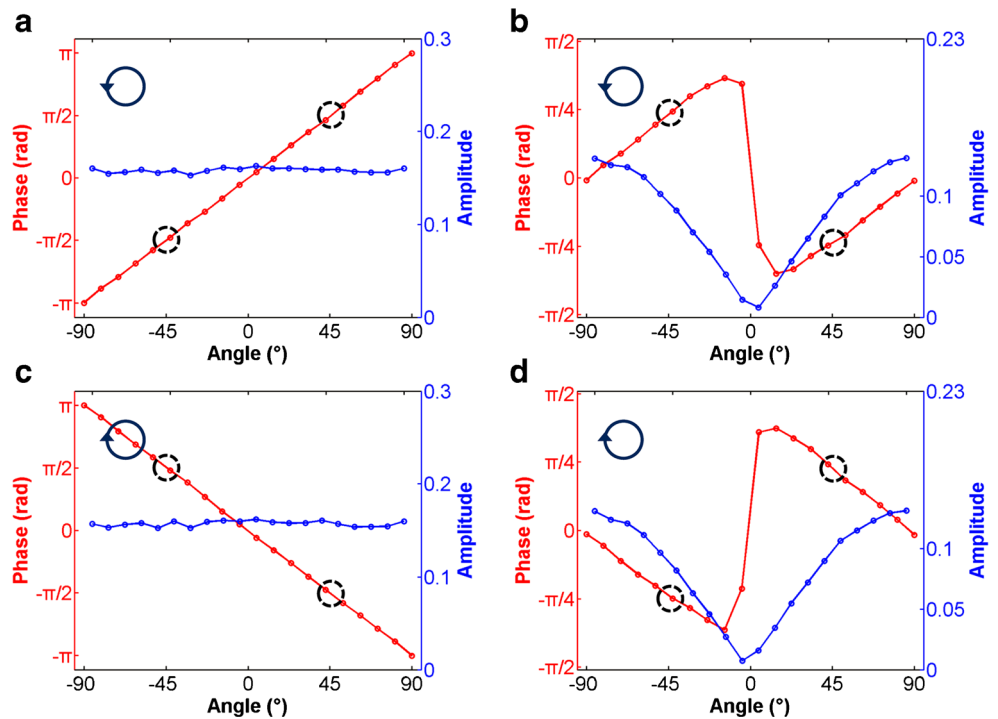


Fig. 2 Phase and amplitude modulation of the transmitted wave (a) and surface wave (b) for LCP light. c, d Corresponding results for the RCP light



$-\pi$ to π , while the amplitude remains almost the same. The phase modulation of SPPs is symmetrical about the origin, and the range is about $3\pi/4$. The amplitude of SPPs varies with orientation angle α and follows the line shape of $|\sin \alpha|$. For the RCP incident light, the phase modulation of both transmitted wave and SPPs is reversed and the amplitude modulation is unchanged, as shown in Fig. 2c–d. To simplify the design, slits with $\alpha = -45^\circ$ and $\alpha = 45^\circ$, indicated by the black dotted circles, are chosen as the building block of the metasurface lens. The amplitude of transmitted wave is the same for $\alpha = -45^\circ$ and $\alpha = 45^\circ$, so does that of SPPs. The phase difference of transmitted wave for $\alpha = -45^\circ$ and $\alpha = 45^\circ$ is $\Phi_{tw} = \sigma_{\pm}\pi$ and that of SPPs is $\varphi = \sigma_{\pm}\pi/2$, where $\sigma_{\pm} = \pm 1$ is determined by the chirality of the incident circularly polarized light [17]. To compensate the difference in phase modulation between transmitted wave and SPPs, the slit can be transversely moved by a

distance of $s = \lambda_{sp}/4$ which corresponds to a $\pi/2$ phase modulation. Thus, the π phase modulation of SPPs can be achieved and the phase modulation of the transmitted wave remains to be unchanged.

Simulated annealing (SA) algorithm is a powerful tool to design binary optical devices in the free space. Here, it is utilized to design the metasurface lens for both SPPs and transmitted wave. The lens consists of 50 slits in the y-direction, and thus, the length of the lens is 10 mm. A single-focus lens and a double-focus lens are designed and their focal lengths are 6 and 5 mm, respectively. As discussed above, a binary phase modulation (0 and π) for SPPs and transmitted wave is adopted to realize the lens. In the SA algorithm, the initial temperature and the cooling rate are 10,000 and 0.996, respectively. The calculation is repeated 3500 times to obtain the desired phase distribution for these two lenses. Figure 3a–b corresponds to

Fig. 3 Phase distribution designed with the SA algorithm for metasurface lens with single focus (a) and double focus (b)

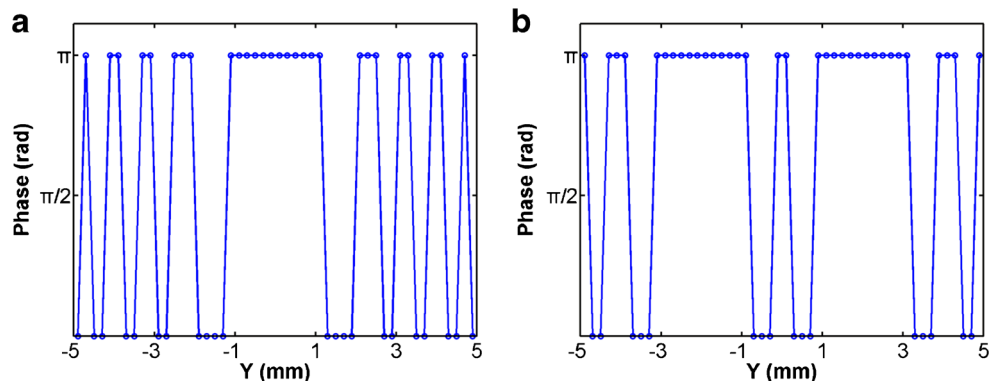
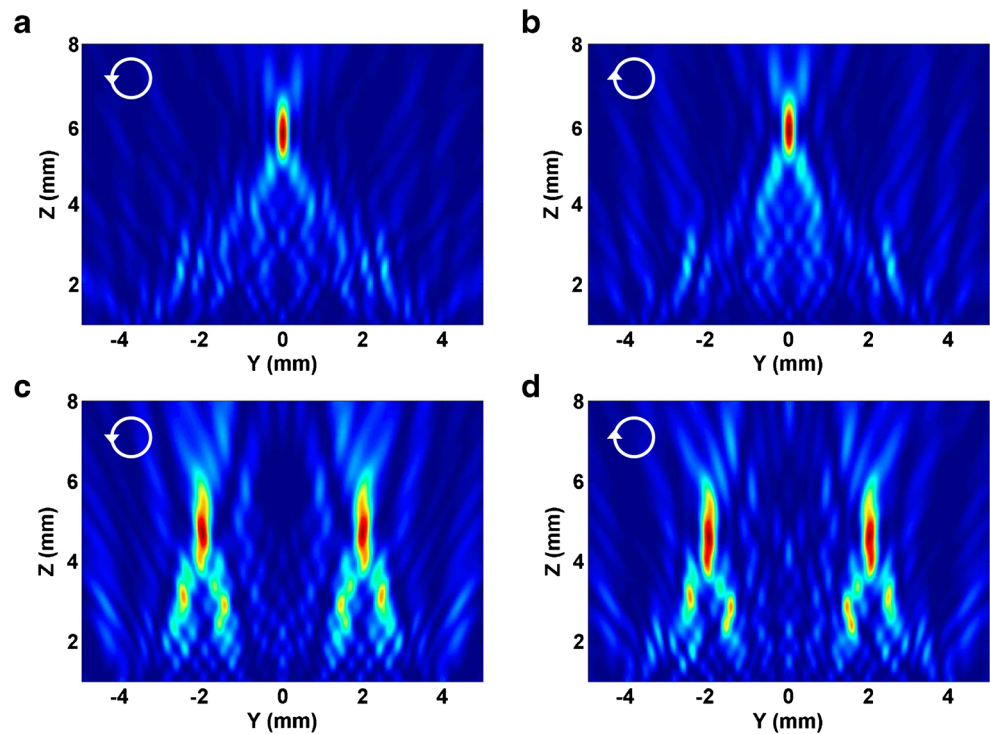


Fig. 4 Focusing of the transmitted wave with the illumination of LCP light (a) and RCP light (b) for the single-focus lens. c, d Corresponding results for the double-focus metasurface lens

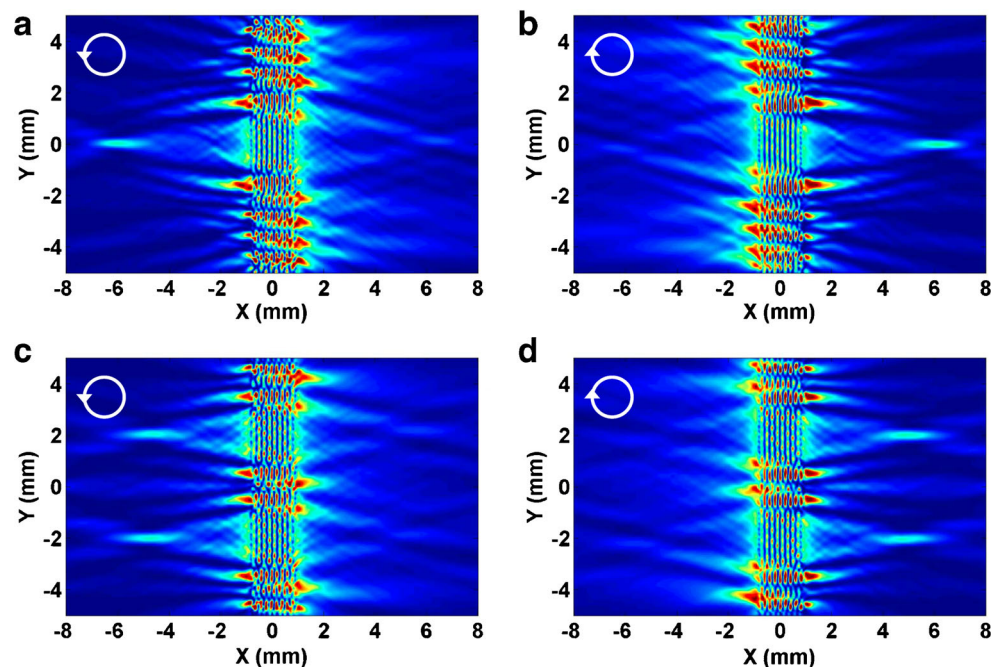


the phase distribution for the single-focus and double-focus lenses, respectively. Five columns of the designed slits with a period of λ_{sp} comprise the final lens to enhance the intensity of the focus.

The designed lenses are numerically simulated to verify their functionality. As shown in Fig. 4a–b, for the single-focus lens, the transmitted wave is focused at 6 mm away

from the incident plane, which consists with the designed value. And the focusing of the transmitted wave is not affected by the chirality of the circularly polarized light, which is clearly distinct from the dual-polarity [17] or spin-selected [24] metasurface lens reported. This property arises from the fact that the π phase difference between $\alpha = -45^\circ$ and $\alpha = 45^\circ$ slit for the LCP light is equal to the $-\pi$

Fig. 5 Single-focus SPPs lens for the LCP (a) and RCP (b) lights. Double-focus SPP metasurface lens for the LCP (c) and RCP (d) lights



phase difference for the RCP light. The focusing of transmitted wave for the double-focus lens is shown in Fig. 4c–d. Two focuses with a separation of 4 mm can be observed at $z = 5$ mm, and the double-focus lens is also polarization independent.

For the single-focus lens, the focusing of SPPs excited by the LCP light and RCP light is shown in Fig. 5a, b, respectively. It can be seen that the focus is 6 mm away from the lens and the focusing of SPPs is chirality dependent, which is different from the focusing of the transmitted wave. The SPPs excited by the LCP light are focused on the left of the lens, and the focus of SPPs is on the right of the lens for the RCP light. The phase of SPPs propagating to the right Φ_{sp}^R and left Φ_{sp}^L can be written as [5]:

$$\Phi_{\text{sp}}^R = -K_{\text{sp}}s + \varphi, \quad \Phi_{\text{sp}}^L = K_{\text{sp}}s + \varphi, \quad (1)$$

where $K_{\text{sp}} = 2\pi / \lambda_{\text{sp}}$ is the wave number of SPPs, $s = \lambda_{\text{sp}} / 4$, and $\varphi = \sigma_{\pm} \pi / 2$ is the phase induced by the circularly polarized light. Thus, for the LCP incident light, the phase of SPPs propagating to the left $\Phi_{\text{sp}}^L = \pi$ satisfies the phase modulation shown in Fig. 3a and the SPPs are focused. But the phase of SPPs propagating to the right is $\Phi_{\text{sp}}^R = 0$, which means the SPPs propagate like a plane wave. For the RCP light, focusing of SPPs is reversed because $\Phi_{\text{sp}}^L = 0$ and $\Phi_{\text{sp}}^R = -\pi$. For the double-focus lens, two focuses on the left and right can be observed for the LCP and RCP lights, respectively, as shown in Fig. 5c–d. It should be noticed that the single-slit unit here is different from the fishbone-slit unit which consists of two slits in one unit [5, 25].

Conclusions

In summary, by arranging orthogonal slit antennas with the simulated annealing algorithm, metasurface lens for both SPPs and transmitted wave are realized. The polarization-independent focusing of transmitted wave and the chirality-controlled focusing of SPPs are studied and analyzed in detail. The multifunctional metasurface lens can be fabricated with micro photolithography and measured with THz near field and far field imaging system [18, 25]. Moreover, the proposed methodology can be extended to the visible region by scaling the structure and considering the deviation of wavelength of SPPs and free space light.

Acknowledgments This work was supported by the 973 Program of China (No. 2013CBA01702), the National Natural Science Foundation of China (Nos. 11474206, 91233202, 11374216, and 11404224), the Scientific Research Project of Beijing Education Commission (KM201310028005), and the Scientific Research Base Development Program of the Beijing Municipal Commission of Education.

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