



# Multiplexed multi-focal and multi-dimensional SHE (spin Hall effect) metalens

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**Abstract:** Metalenses are two-dimensional ultrathin metalenses composed of subwavelength artificial microstructures. In this paper, various multi-focal spin Hall effect (SHE)-based metalenses are designed to provide spin-dependent splitting in transverse and longitudinal directions, which possess spin-dependent two focal points under left-circularly polarized (LCP) or right-circularly polarized (RCP) incidence, and all four focal points can be observed under the linearly polarized (LP) incidence. A spin-independent bifocal metalens was investigated, which possesses the same bifocal focusing phenomena for LCP and RCP incidences. Our method is significant for designing high-efficiency multifunctional optics devices based on optical SHE.

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## 1. Introduction

Metasurfaces composed of subwavelength nano-structures that exhibit unprecedented potentials in developing ultrathin optics and integrated optics [1–5]. The metasurface can flexibly manipulate the amplitude, phase, and polarization state of the incident light to the expected form by changing the geometry parameters and orientation of nano-structures. Metasurfaces provide the new platform to develop the integrated optical elements in many fields, including polarization modulation [6–8], anomalous reflection [9–11], focusing [12–16], optical holography [17,18], cloaking [19,20], spin Hall effect (SHE) of light [21–24], and polarization encoded color image [25]. Lenses are important optical elements in optical imaging systems, conventional refractive lenses focus on the accumulation of optical path, but they possess bulky volume. In recent years, metalenses have received wide attention because of their planar, ultrathin, and miniaturized advantages, which focus on controlling phase mutation at the interfaces [26–37]. Polarization-insensitive metalens [38], achromatic metalenses [27,31,36,39], longitudinal multi-focal metalenses [14,40], tunable metalenses [41,42], metalenses with wide field of view [43,44] have been reported. The linearly polarization-selective metalenses have also been demonstrated [23,45,46]. Compared to conventional lenses, metalenses possess some unique fascinating properties.

SHE-based metalenses (SHEM) with circular-polarization sensitivity have attracted great attention, which are very sensitive to left-circularly polarized (LCP) and right-circularly polarized (RCP) light, and possess photonic SHE. The photonic SHE describes the transmission phenomenon that light is split into different trajectories for the LCP and RCP components [21,23,45,47–53]. The SHEM can be designed based on the Pancharatnam-Berry (PB) phase [54,55]. However, they have a real and virtual focus for LCP and RCP lights, respectively. The SHEM can also be developed by multiplexing two opposite polarity metalenses [34,56] to avoid this limitation.

Wang et al. achieved the SHEM through alternately arranged rotary silicon nanobrick [34], and Teng et al. achieved the plasmonic SHEM through alternately or partitioned arranged rotary cross hole etched in a silver film [56]. However, for the multiplexed multifunctional metasurfaces, the maximum efficiency of each function is the inverse of number of the functionalities. SHEM can also be designed based on pure geometric phase, which combine the two phase profiles for the different spin states together [57]. SHEM can also be designed based on propagation and PB phase [58–61], which possess high focusing efficiency. Wang et al. designed a metalens to focus the LCP and RCP light to different positions at infrared wavelengths [58]. Li et al. achieved the longitudinal focusing and transverse shifting of the different spin state photons simultaneously [59]. Dong et al. experimentally realized the independent focusing of both spins of light by V-antenna metasurfaces [60]. And Zhang et al. designed a metalens to focus the LCP and RCP light to different longitudinal positions, and the focal length can be tuned by controlling the incident polarization states [61]. These spin-selected metalenses [34,56–61] only maintain one focus for LCP or RCP incidences. The SHEM with two focal points for LCP or RCP light has rarely been reported. Zang et al. designed helicity multiplexed multi-foci metalens for LCP or RCP incident light based on pure PB phase, focusing efficiency only reached 36.8% [62]. Zang et al. also designed the spin-decoupled metalens with intensity-tunable multiple focal points based on the pure geometric phase, which is designed by integrating the functionalities of multiple convex lenses and concave lenses into a single metasurface [63]. And spin-selected metalenses with multiple focuses have potential applications in the optical data storage and multi-imaging technology. So far, it remains a challenge to design the SHEM with multiple focuses for LCP or RCP incident lights.

In this paper, metalenses focusing LCP or RCP light to two different positions are demonstrated, which are designed through multiplexing two metalenses based on both propagation and PB phases' modulations, rather than a pure PB phase. In this way, a spin-independent bifocal metalens is realized, which possess two same longitudinal focal points for LCP or RCP light. Three multifocal SHEMs, which can split and focus LCP and RCP light to multi-dimensional (longitudinal and transverse), are designed and achieved with four focal points. Our work demonstrates a new approach in designing multi-dimensional and multifocal SHEM, and has far-reaching influence on multifunctional optical devices.

## 2. Theoretical analysis

The proposed multifocal SHEM is composed of two spin Hall effect-based metalenses with one focus for LCP or RCP light. As far as we know, the propagation phase is spin-independent, which depends on the geometric parameters of nano-structures, while the PB phase is spin-dependent, which depends on the rotation angles of nano-structures and possesses opposite phases to LCP and RCP light. Taking advantage of these properties, the metalens with photonic SHE will maintain the high focusing efficiency. For designing the high-efficiency multifocal SHEM, the propagation phase ( $\phi^{\text{Pro}}$ ) and PB phase ( $\phi^{\text{PB}}$ ) are employed to realize the phase profile of sub-metalens 1 and 2 with one focus for LCP or RCP light, the unit cell of the metalens should be the half-wave plate. Considering that

$$\varphi^{L/R} = \phi_{L/R}^{\text{Pro}} + \phi_{L/R}^{\text{PB}}, \quad (1)$$

$$\phi^{\text{Pro}} = \phi_L^{\text{Pro}} = \phi_R^{\text{Pro}}, \quad (2)$$

$$\phi_L^{\text{PB}} = -\phi_R^{\text{PB}} = 2\theta, \quad (3)$$

$\phi^{\text{Pro}}$  and  $\theta$  can be expressed as

$$\phi^{\text{Pro}} = \frac{\varphi^L + \varphi^R}{2}, \quad (4)$$

$$\theta = \frac{\varphi^L - \varphi^R}{4}. \quad (5)$$

Therefore, the propagation and PB phases can meet the phase requirement for designing a metalens with spin-selection, which depends on the geometric parameters and orientation of the nano-structures, respectively.

### 3. Development of multifocal SHEM

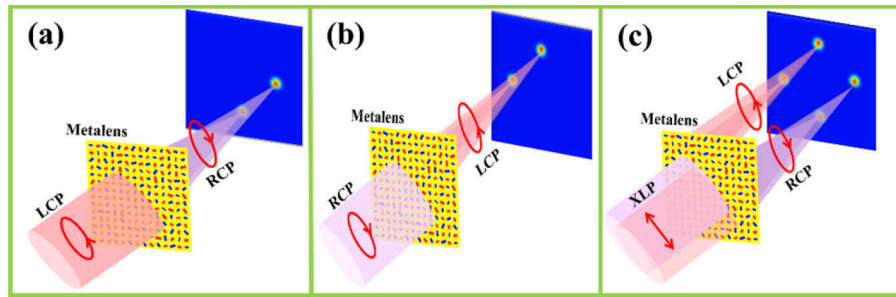
Figure 1 shows a schematic diagram of the multifocal SHEM. For LCP incident light, two focal points are observed (Fig. 1(a)). For RCP incident light, another two focal points are observed (Fig. 1(b)). Under the incidence of x-linearly polarized (XLP) light, the spin-dependent splitting in four positions is observed (Fig. 1(c)). Before giving the focusing effects of the multiplexing multifocal SHEM, we briefly present the design method of the customized phase. As everyone knows, the phase distribution of a metalens focusing at any position can be obtained by

$$\varphi = \frac{2\pi}{\lambda} \left[ \sqrt{x^2 + y^2 + f^2} - f \right], \quad (6)$$

where  $\lambda$  is the wavelength, and  $f$  is the focal length. To design a multi-dimensional and four focal SHEM, the phase profiles are expressed by

$$\left\{ \begin{array}{ll} \varphi_1^L = \frac{2\pi}{\lambda} \left[ \sqrt{(x - \Delta x_1)^2 + (y - \Delta y_1)^2 + (f_1^L)^2} - f_1^L \right] & x, y = 2n * P \\ \varphi_1^R = \frac{2\pi}{\lambda} \left[ \sqrt{(x + \Delta x_1)^2 + (y + \Delta y_1)^2 + (f_1^R)^2} - f_1^R \right] & x, y = 2n * P \\ \varphi_2^L = \frac{2\pi}{\lambda} \left[ \sqrt{(x - \Delta x_2)^2 + (y - \Delta y_2)^2 + (f_2^L)^2} - f_2^L \right] & x, y = (2n + 1) * P \\ \varphi_2^R = \frac{2\pi}{\lambda} \left[ \sqrt{(x + \Delta x_2)^2 + (y + \Delta y_2)^2 + (f_2^R)^2} - f_2^R \right] & x, y = (2n + 1) * P \end{array} \right. , \quad (7)$$

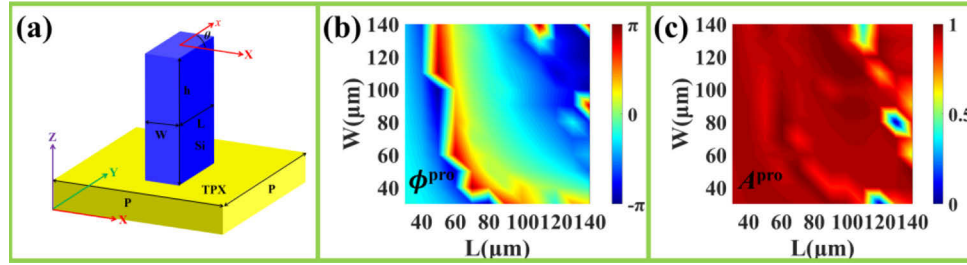
where “1” and “2” corresponds to first and second metalens with one focus for LCP or RCP incidence, “L” and “R” corresponds to LCP and RCP incidence, respectively.  $\Delta x$  and  $\Delta y$  is the lateral offset of the focal point from the center along the x- and y-axis, respectively.  $P$  is the period of the unit-cell of the metalens.



**Fig. 1.** Schematic of designed multifocal SHEM under the incidence of the LCP (a), RCP (b) and XLP (c) light.

The unit-cell of multifocal SHEM is the silicon micropillar with a height of 195  $\mu\text{m}$  located on the substrate of a 40- $\mu\text{m}$ -thick TPX layer, as shown in Fig. 2(a). The silicon possesses the high refractive index of 3.41 for the illuminating frequency of 1THz [64]. The polymer TPX with the refractive index of 1.4 is selected due to the neglected absorption loss in the designed frequency

of 1THz [65]. The period of the unit-cell is  $P=150\text{ }\mu\text{m}$ . On the one hand, when the rotation angle  $\theta$  varies from  $0^\circ$  to  $180^\circ$ , the PB phase can realize the phase shifts from  $0^\circ$  to  $360^\circ$ . On the other hand, the propagation phase can realize the phase shifts from  $0^\circ$  to  $360^\circ$  by tailoring the length and width of micropillars. All the numerical simulations and optimization are finished by the finite-difference time-domain (FDTD) method. Periodic boundary conditions are used at the x- and y- directions, and perfectly matched layer boundary conditions are used at the z-directions. Figure 2(b) and 2(c) show the propagation phase and amplitude, respectively, the propagation phase cover the entire  $2\pi$  with very high transmission efficiency. Therefore, independent phase modulation can be achieved for LCP and RCP light.

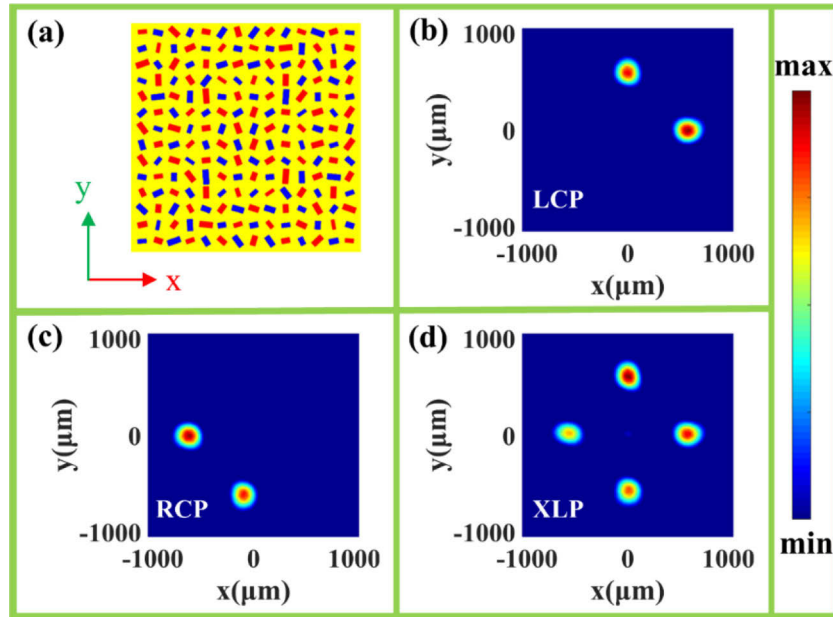


**Fig. 2.** (a) Schematic of the silicon micropillar. The propagation phase (b) and amplitude (c) of the Si micropillars as a function of length ( $L$ ) and width ( $W$ ).

#### 4. Results and discussions

The spin-dependent multi-foci metalens with transverse spin splitting is first demonstrated, generating transverse four focal points. The top view of the designed multifocal SHEM is shown in Fig. 3(a). And it can only be two-dimensional. According to Eq. (7), the metalens is designed by interleaving the unit cells of the two sub-metalenses through spatial multiplexing. Two sub-metalens can produce transverse symmetry two focal points along x- or y- direction, respectively. Because of the negligible coupling effect of adjacent unit cells, the scattered light can interference constructively in each designed focal spot for LCP and RCP incidence. Here, we set  $\Delta x_1 = \Delta y_2 = 600\text{ }\mu\text{m}$ ,  $\Delta y_1 = \Delta x_2 = 0\text{ }\mu\text{m}$ ,  $f_1^L = f_1^R = f_2^L = f_2^R = 1200\text{ }\mu\text{m}$  in Eq. (7). The corresponding electric field intensity distributions in the x- y plane are shown in Figs. 3(b-d). Under the incidence of LCP light, two focal points of focusing plane with the positions of  $(600\text{ }\mu\text{m}, 0\text{ }\mu\text{m})$  and  $(0\text{ }\mu\text{m}, 600\text{ }\mu\text{m})$  are shown in Fig. 3(b), and the focusing efficiency is 43%. Under the incidence of RCP light, two focal points of focusing plane with the positions of  $(-600\text{ }\mu\text{m}, 0\text{ }\mu\text{m})$  and  $(0\text{ }\mu\text{m}, -600\text{ }\mu\text{m})$  are shown in Fig. 3(c), and the focusing efficiency is 41%. Four transverse focal points are achieved under the incidence of XLP light, as shown in Fig. 3(d). This is because XLP light can be decomposed into LCP and RCP components. Two focal points result from the LCP component of the incident XLP light, and the other two focal points stem from the incident RCP component. However, multi-focusing results show inhomogeneous energy distribution, which may originate from the interaction between adjacent unit cells. Therefore, our designed multifocal SHEM can achieve spin-dependent transverse multifocal focusing. The focal plane, focal position, and spin-dependence can be manipulated flexibly and conveniently in the designing process.

In addition to the transverse splitting multifocal focusing, a multifocal SHEM with longitudinal splitting four focuses is designed based on Eq. (7), which indicates that our design can ensure multi-dimensional focusing manipulation. In the design, we set  $\Delta x_1 = \Delta x_2 = \Delta y_1 = \Delta y_2 = y = 0$ ,  $f_1^L = 4200\text{ }\mu\text{m}$ ,  $f_1^R = 1200\text{ }\mu\text{m}$ ,  $f_2^L = 5700\text{ }\mu\text{m}$ ,  $f_2^R = 2700\text{ }\mu\text{m}$ . Hence, the LCP and RCP light at the frequency of 1 THz will show two focal points with different focal lengths, respectively. The top view of the designed mutil-focal SHEM is demonstrated in Fig. 4(a). And the one-dimensional



**Fig. 3.** (a) Top view of the multifocal SHEM with transverse spin splitting four focal points. The intensity distributions at the x-z plane of the transverse multifocal SHEM under (b) LCP, (c) RCP, and (d) XLP incidences.

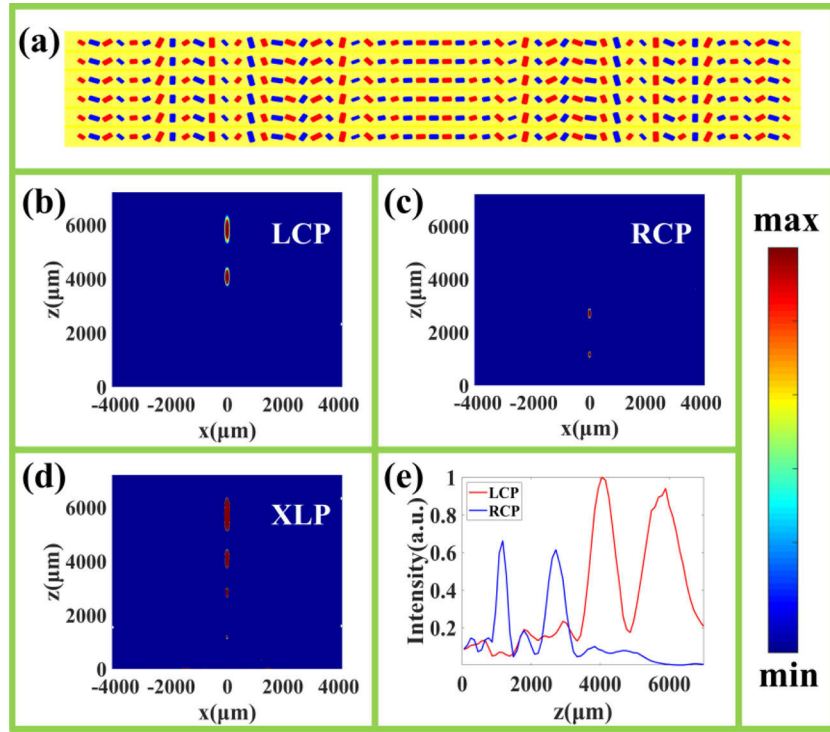
structure is selected in order to avoid the large amount of calculations in the two-dimensional structure.

Figure 4(b) shows the calculated electric field intensity distribution of the designed metalens under LCP incidence. Two focal points are found along the longitudinal direction. As shown in Fig. 4(b), two focal points are located at  $4075\mu\text{m}$  and  $5850\mu\text{m}$ , which are close to the expected position of  $4200\mu\text{m}$  and  $5700\mu\text{m}$ . The slight deviation in focal length between numerical simulation and theory may be due to the nonideal half-wave plate of each micropillar. The focusing efficiency is 46% for LCP incident light.

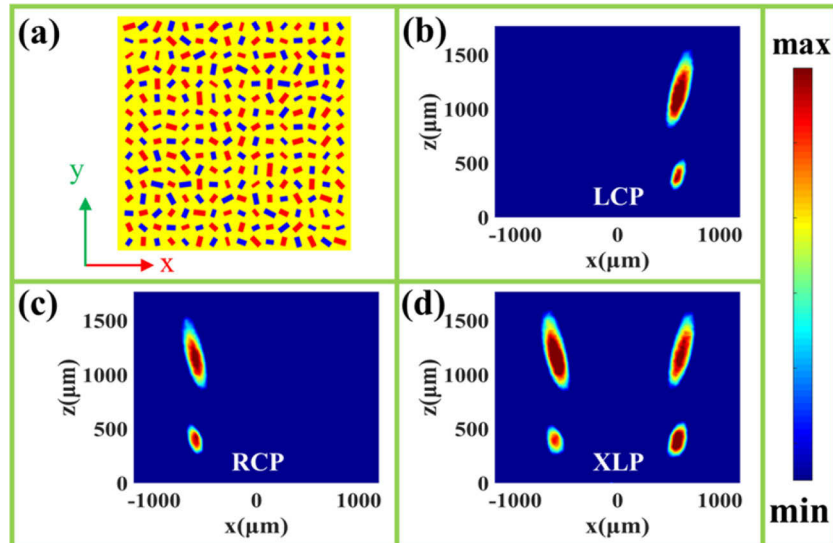
As shown in Fig. 4(c), the transmitted light for RCP incidence is focused at two positions of  $1150\mu\text{m}$  and  $2725\mu\text{m}$ , which are also very close to the expected position of  $1200\mu\text{m}$  and  $2700\mu\text{m}$ . The focusing efficiency is 40% for RCP incident light. Therefore, our designed multi-focal SHEM can independently produce two longitudinal focal points under the incidence of LCP and RCP light. In addition, four longitudinal focal points are generated under XLP incidence, as shown in Fig. 4(d).

Figure 4(e) shows the focal depth is inversely proportional to the focal length, and the focal depth of the positions of  $1200\mu\text{m}$  is far less than the focal depth in  $5700\mu\text{m}$ . These results show that our design method can realize multi-dimensional (transverse and longitudinal) and spin selected multi-focal focusing by multiplexed multi-focal SHEM. And most importantly, the focusing efficiencies are relatively high.

As shown in Fig. 5, the proposed philosophy can be extended to realize a multi-focal SHEM with the transverse and longitudinal spin splitting four focuses. The parameters in Eq. (7) are set as  $\Delta x_1 = \Delta x_2 = 600\mu\text{m}$ ,  $\Delta y_1 = \Delta y_2 = 0\mu\text{m}$ ,  $f_1^L = f_1^R = 450\mu\text{m}$ ,  $f_2^L = f_2^R = 1200\mu\text{m}$ . Hence, the LCP light will show two longitudinal distributed focal points, and the RCP light will offer two other longitudinal focal points in the transversely symmetric position. The top view of the designed multifocal SHEM is demonstrated in Fig. 5(a).



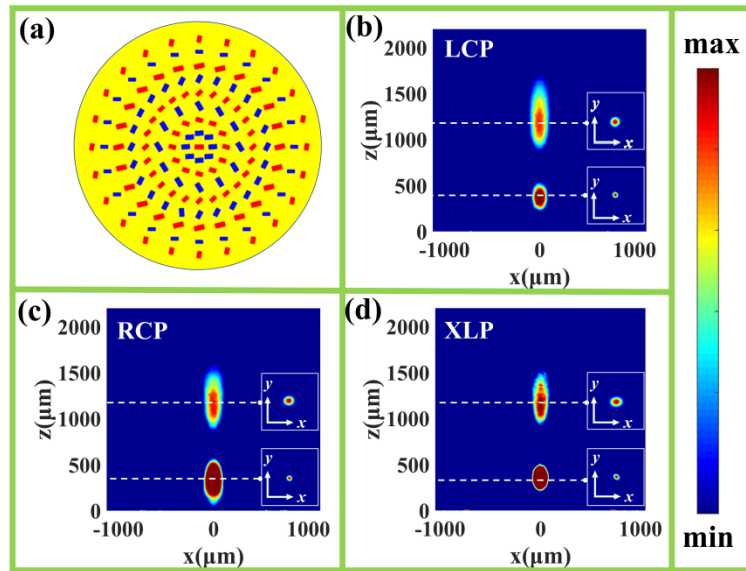
**Fig. 4.** (a) Top view of the multifocal SLEM with longitudinal spin splitting four focal points. The intensity distributions at the x-z plane of the longitudinal multifocal SLEM under (b) LCP, (c) RCP, and (d) XLP incidences. (e) The intensity distributions along the z-axis under the LCP and RCP incidences.



**Fig. 5.** (a) Top view of the multifocal SLEM with transverse and longitudinal spin splitting four focal points. The intensity distributions at the x-z plane of the multifocal SLEM under (b) LCP, (c) RCP, and (d) XLP incidences.

Figures 5(b) and (c) show the designed metalens' calculated electric field intensity distribution under LCP and RCP incidence, respectively. The transmitted RCP light is closely focused at locations  $(600\mu\text{m}, 450\mu\text{m})$  and  $(600\mu\text{m}, 1200\mu\text{m})$ , and the transmitted LCP light is closely focused at locations  $(-600\mu\text{m}, 450\mu\text{m})$  and  $(-600\mu\text{m}, 1200\mu\text{m})$ . The focusing efficiency is 44% and 33% for LCP and RCP incident light, respectively. Although the focusing effects (LCP and RCP) are slightly different due to the asymmetry of the structure, the focusing effects of all SHEMs are both very good for LCP and RCP incidences, their focusing intensities are in the same order. In addition, four longitudinal focal points are generated under XLP incidence, as shown in Fig. 5(d). The sizes of focal points at transverse directions are comparative. The intensities of four focal points are not quite equal because of the nonuniform contribution coming from the micropillars at different distances. These results show that the multifocal SHEM can realize multi-dimensional spin splitting.

The design method enables the realization of the multi-dimensional and mutifocal spin selected focusing and can be used to design the spin-independent bifocal metalens. Here, we set  $\Delta x_1 = \Delta x_2 = \Delta y_1 = \Delta y_2 = 0$ ,  $f_1^L = f_2^R = 450\mu\text{m}$ ,  $f_1^R = f_2^L = 1200\mu\text{m}$  in Eq. (7). And the metalens will produce the same two focal points along the longitudinal direction under the illumination of LCP and RCP light. The top view of the designed metalens is shown in Fig. 6(a). Considering the symmetric distribution of the phase along the radial direction, the circular structure is chosen. The intensity distribution in the x-z plane is shown in Fig. 6(b) under the LCP incidence. Two longitudinal focuses are approximately focused at the designed positions. For RCP incidence, two longitudinal focal points with the focal length of  $450\mu\text{m}$  and  $1200\mu\text{m}$  are also found in Fig. 6(c). The focusing efficiency is 47%. Under the incidence of XLP light, as shown in Fig. 6(d), the transmitted light also exhibits two focal points with the focal length of  $450\mu\text{m}$  and  $1200\mu\text{m}$ . The upper and lower insets in the Fig. 6(b)-(d) show the intensity distributions at two focal planes (x-y plane), respectively, which also show the good focusing characteristics of the



**Fig. 6.** (a) Top view of the bifocal metalens with spin-independent property. The intensity distributions at x-z plane of the bifocal metalens under (b) LCP, (c) RCP, and (d) XLP incidences, and the insets show the intensity distributions in x-y plane at the corresponding focusing positions respectively.

bifocal metalens. The designed bifocal metalens can produce two focal points for both LCP and RCP incident light and possess the superior spin-independent characteristic. Our approach opens a new avenue for designing the high-efficiency spin-independent bifocal metalens.

## 5. Conclusions

In conclusion, we have numerically demonstrated a method to realize multi-dimensional and mutif-focal SHEM, achieving two focal points for the LCP or RCP incident light. These multifocal metalenses were designed by multiplexing two submetalenses based on propagation and PB phase. We designed a mutif-focal SHEM with transverse splitting four focal points for LCP and RCP light. We also designed a mutif-focal SHEM with longitudinal splitting four focal points for LCP and RCP light. We also developed a mutif-focal SHEM with the transverse and longitudinal splitting of four focal points for LCP and RCP light. The spin-independent bifocal metalens were demonstrated which possess two same focal points for LCP and RCP light. The obtained results showed that the proposed philosophy can realize multi-dimensional and multifunctional light manipulation based on photonic SHE and open the door for future polarization analyzer, sensing, holograms, optical communications and imaging systems applications.

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**Disclosures.** The authors declare no conflicts of interest.

**Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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