Design and research of dual-wavelength polarization multiplexing multifocal metalens based on superimposed nano-antenna array

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Abstract
In this study, based on the single-layer metasurface structure, a dual-wavelength polarization multiplexing metalens is designed at the communication wavelengths of 1310 nm and 1550 nm, respectively. Using the dual-phase modulation method, a single-wavelength polarization multiplexing metalens is proposed, which can simultaneously control left-handed circularly polarized light (LCP) and right-handed circularly polarized light (RCP). Furthermore, the cross superposition method is used to combine them to achieve the dual-wavelength polarization multiplexing metalens. The results show that the system can achieve polarization multiplexing at the two wavelengths of 1310 nm and 1550 nm, which is consistent with the expected results, and the focusing efficiency reached 61%. With the increase of the numerical aperture, the focusing intensity of the left and right focal points gradually approaches, and the difference between the full width at half maximum of the two focal points also decreases accordingly. It provides a new way for the optical imaging, information detection and the realization of multifunctional ultra-surface devices.

1. Introduction

Metamaterial [1−4] is a kind of artificial microstructure material, which has adjustable electromagnetic parameters. The two-dimensional array plane composed of metamaterials is called metasurface, which can realize effective control of the amplitude, phase, propagation mode and polarization state of the electromagnetic wave. It has great potential in many fields such as metalens [5−8], vortex beam generator [9−11], filter [12], beam deflector [13], stealth technology [14], digitally coded metasurface [15] and wearable devices based on system-on-chip [16]. As one of the most commonly used devices in many applications of metasurface, metalens can greatly reduce the size and the complexity of optical systems, and achieve higher optical quality compared with traditional lenses. Therefore, it has gradually become a research focus in recent years. In 2017, Wang of Harbin Institute of Technology designed a polarization-independent metalens at the wavelength of 808 nm. They use the material gold and adopt the sub-regional method to design [17]. The intensity ratio of each focus can be adjusted by altering the number of antennas in the corresponding area. However, due to the high ohmic loss of metal materials, it has been gradually replaced by dielectric materials in recent years. Metalenses based on dielectric materials such as Si, TiO2, GaN and ZnS have become a new research direction in recent years. In 2018, Capasso and others of Harvard University used TiO2 in the visible light range from 470 nm to 670 nm to design a broadband achromatic metalens, which was achieved by simultaneously controlling the phase, group delay, and group delay dispersion. It has important applications in lithography, microscopy, virtual reality and augmented reality [18]. In 2019, Wang et al designed the spin-selected dual-wavelength metalenses by cross arranged the scattering units with polarity-inverse designed at two wavelengths. It can achieve spin-selected metalens manipulating at two wavelengths simultaneously. At the same time, a three-dimensional spin selective dual-wavelength metalens is designed, which can focus four incident spin states of two wavelengths to the preset
position, and can be used as a linear/circular polarization and wavelength analyzer [19]. In 2020, Tang designed and implemented a dual-wavelength polarization multiplexing metalens at 633 nm and 1064 nm. It divides the plane into two regions, and each region only responds to one wavelength, which results in a complex structure, low space utilization and a large amount of simulation calculation [20]. However, the metalens designed by this method is bulky and the design process is complicated, which is not conducive to the development of highly integrated systems.

In this paper, at the wavelengths of 1310 nm and 1550 nm, the propagation phase and the geometric phase are combined to control the orthogonal circularly polarized light at the same time. The metalens can realize the focusing of LCP and RCP simultaneously. Using the cross superposition method, there are two structural units in one cycle at the same time, which can respond to incident light with two wavelengths of 1310 nm and 1550 nm respectively. This metalens not only overcome the limitations of traditional sub-regional method, but also improve the space utilization. Furthermore, the metalens can also be used as a wavelength and polarization detector, because the wavelength and polarization state of incident light are identified by each focal position on the focal plane.

2. Theory and method

This study is based on the finite element analysis method, using COMSOL Multiphysics software to build the simulation environment. First, a transmissive polarization multiplexing metalens was designed at the wavelength of 1310 nm. The incident light from the substrate enters the air after being transmitted through the metasurface. The continuous periodic boundary conditions are used around the structure, and the upper and lower parts are the perfect matching layer (PML) that can absorb electromagnetic waves, so that the incident wave can be quickly attenuated to zero after passing through the exit surface. The thickness of the PML is set to \(2\pi/k_0\), where \(k_0\) represents the wave vector in vacuum.

The focusing of the metalens mainly depends on the phase distribution of the scattering unit at each position. According to the metalens focusing principle, the cross-polarized transmitted light corresponding to different positions should satisfy the following relationship:

\[
\varphi(x) = 2\pi x + \frac{2\pi}{\lambda} \left( \sqrt{(x + x_0)^2 + f^2} - f \right) \tag{1}
\]

where \(x\) is the coordinate position of each scattering unit, \(x_0\) is the offset in the x direction, \(\lambda\) is the incident wavelength, \(f\) is the focal length of the metalens, and \(n\) is an arbitrary integer to keep the phase within the range of \(0–2\pi\). By placing suitable scattering units in different positions, the incident light will be precisely focused. The propagation phase and the geometric phase do not affect each other, so they can be superimposed directly. When the RCP and LCP light are incident separately, the total phase is expressed as follows:

\[
\varphi_{RCP} = \varphi_{BR} - 2\theta \tag{2}
\]

\[
\varphi_{LCP} = \varphi_{LL} + 2\theta \tag{3}
\]
Here, $\varphi_{RCP}$ and $\varphi_{LCP}$ are the total phases, which are calculated according to formula (1). $\varphi_{RR}$ and $\varphi_{LL}$ ($\varphi_{RR} = \varphi_{LL}$) are the propagation phases, which can be achieved by changing the geometric dimensions. The geometric phase is equal to $2\theta$, where $\theta$ is the rotation angle of the scattering unit and can be obtained from the above two formulas:

$$\varphi_{RR} = \varphi_{LL} = \frac{\varphi_{LCP} + \varphi_{RCP}}{2}$$

$$\theta = \frac{\varphi_{LCP} - \varphi_{RCP}}{4}$$

3. Results and discussions

3.1. Polarization multiplexing metalens

Based on the above principles, two polarization multiplexing metalenses are designed at the wavelength of 1310 nm and 1550 nm. The scattering unit shown in figure 1 is designed with Si, and its substrate uses SiO$_2$ in order to reduce absorption loss. $\varphi_{\text{max}} = \frac{\lambda}{2\pi h}$, where $n_{\text{eff}}$ is the effective refractive index, $h$ is the height of the scattering unit, $\lambda$ is the incident wavelength. To satisfy $\varphi_{\text{max}} \geq 2\pi$, the height of the scattering unit must be greater than 619 nm. Moreover, in order to obtain greater phase retardation, the height of Si is set to 900 nm. The center distance $U$ between adjacent scattering units is 650 nm to meet the Nyquist sampling standard ($U < \frac{\lambda}{2\text{NA}}$). The scattering unit is shown in figure 1(a). The focus schematic diagram of the polarization multiplexing metalens is shown in figure 1(b). When linearly polarized light is incident on the metasurface, it is divided into two parts. The LCP component is focused on the left side of the $x$ axis at $x_1 = -1300$ nm, and the RCP component is focused on the right side of the $x$ axis at $x_2 = 1300$ nm. According to the results of numerical simulation, the phase distributions of 41 units selected at two wavelengths are shown in figures 1(c) and (d). (In
order to explain the design method more clearly, 21 scattering units are used as schematic diagrams in this paper just due to limited space. Their scattered fields have almost the same amplitude and the phase covers $2\pi$.

Figures 2 and 3 are the top views of the scattering unit of the polarization multiplexing system at wavelengths of 1310 nm and 1550 nm. As the result of a combination of the geometric phase and the propagation phase, the size of the scattering units at each position is determined by its corresponding propagation phase, and the rotation angle of the unit that is determined by the geometric phase. By placing the appropriate scattering unit in each position, the incident light can be correctly focused to the design position. The corresponding electric field intensity distribution of the polarization multiplexing metalens designed are shown in figure 4.

As shown in figure 4(a) with the focal length of 7000 nm and (b) with the focal length of 5000 nm, the LCP component of the incident light is focused at $x_1 = -1300$ nm, and the RCP component is focused at $x_2 = 1300$ nm. Due to the additional setting of the air height of 900 nm, the theoretical focus position is $z_1 = 7900$ nm, $z_2 = 5900$ nm. The simulated focal lengths at the two wavelengths are 7941 nm and 6053 nm, respectively. The difference from the designed focal length ($\Delta f_1 = 41$ nm, 0.005%, $\Delta f_2 = 153$ nm, 2.6%) comes from the discontinuous distribution of the phase, and this error can be reduced or eliminated by further optimizing the structural parameters.

Generally, system performance analysis is performed through numerical aperture (NA), the full width at half maximum (FWHM) and the focus efficiency. where $NA = \sin[\tan^{-1}(D/2f)]$, $D$ is the diameter of the metalens and $f$ is the focal length. The system is composed of 41 scattering units, so $D = 26650$ nm, $NA_1 = 0.89$, $NA_2 = 0.93$. The full width at half maximum refers to the curve width at half of the peak value of the electric field energy of the metalens. The smaller the full width at half maximum, the more concentrated the focusing energy. In theory, FWHM < $\frac{\lambda}{2NA}$, therefore, FWHM < 735 nm at 1310 nm and FWHM < 933 nm at 1550 nm.

The designed metalens system has the focus efficiency of 64% and 67% at the wavelength of 1310 nm and 1550 nm, where the focusing efficiency is calculated according to the fraction of incident light in a circular area whose radius is three times the FWHM spot size on the focal plane [21]. Figures 4(c) and (d) are the electric field energy intensity distribution diagrams along the x direction of the two structures when X-polarized light is incident. It can be seen from the simulation results that the designed metalens system can independently focus RCP and LCP incident light, and obtain two symmetrical focus distributions with basically the same intensity. The full width at half maximum is 610 nm, 603 nm and 676 nm, 680 nm, which are close to the diffraction limit. In addition, the focused energy around each focus is not strictly uniformly distributed just because of the diffraction effect of the periodic arrangement of resonant elements, which can be adjusted by appropriately increasing the value of NA.

The electric field distribution diagrams of the metalens system are shown in figure 5 with the numerical apertures of 0.85, 0.93 and 0.97 at the wavelength of 1550 nm, respectively. Simulation results show that, as the numerical aperture increases, the difference between the two full-width at half maximum of the focus gradually decreases, the focus intensity of the two focal points gradually approaches, and uniform focus can be achieved.

![Figure 5. The electric field energy distribution of the focal point under different numerical apertures at the wavelength of 1550 nm; The electric field energy distribution of the focal point along the x direction when NA = (a) 0.85; (b) 0.93; (c) 0.97.](image-url)

![Figure 6. Schematic diagram of the dual-wavelength polarization multiplexing metalens unit structure.](image-url)
3.2. Dual-wavelength polarization multiplexing metalens

The cross superposition method is used to combine the polarization multiplexing metalenses shown in figures 2 and 3 to achieve dual-wavelength multiplexing with utilization efficiency improved.

Figure 6 is the top view of the scattering unit of the dual-wavelength polarization multiplexing metalens. Among them, the yellow and blue scattering units are designed at wavelengths of 1310 nm and 1550 nm, respectively. Two types of units can exist simultaneously in a cycle, which not only meets the needs of different wavelengths and different polarization states without repeating to design the metalens, but also has a simple structure, high system utilization and smaller simulation calculations.

The electric field intensity distribution of the dual-wavelength polarization metalens designed with a superimposed structure is shown in figure 7. At the wavelength of 1310 nm and 1550 nm, the focal lengths are \( f_1 = 7000 \text{ nm} \) and \( f_2 = 5000 \text{ nm} \), respectively. Therefore, double focus uniform focusing can be achieved at \( z_1 = 7900 \text{ nm} \) and \( z_2 = 5900 \text{ nm} \), where the left and right focuses correspond to the LCP and RCP components respectively. It can be seen from figures 7(a) and (b) that actual focusing positions at the two wavelengths are at \( z_1 = 8029 \text{ nm} \) and \( z_2 = 5966 \text{ nm} \). The errors of 0.016\% and 0.011\% are due to the interference between the scattering units corresponding to the two wavelengths. The size of the scattering unit at each position can be adjusted accordingly by further optimizing the phase. The designed dual-wavelength polarization multiplexing metalens system has a focus efficiency of 61\%, it can achieve high-quality focusing.

Finally, some works are summarized in table 1 on dual-wavelength multiplexing metalenses in respect of the focal length, numerical aperture, focus efficiency. The results show that the metalens which designed in this paper can well realize dual-wavelength polarization multiplexing. Compared with literature [20] and [22], the cross superposition method in this work has fewer scattering units, a larger focal length and a higher numerical aperture. That is to say, this design greatly reduces the device size, improves the system space utilization, simplifies the simulation calculation, and provides a new direction for realizing multi-wavelength multiplexing and multi-function devices.

4. Conclusion

In this paper, the dual-wavelength polarization multiplexing metalens is designed at the wavelengths of 1310 nm and 1550 nm. Using the dual-phase modulation method, the RCP and LCP components of the linearly polarized light are simultaneously and independently focused at any symmetrical position. A cross superposition method for dual-wavelength multiplexing is proposed. There are two kinds of scattering units in the same period, responding to the incident light with two different wavelengths accordingly. In terms of multi-wavelength incidence and multi-focus focusing, this superimposed structure greatly reduces the volume of the metalens and improves the utilization of the system, which is conducive to the development of highly integrated systems. By increasing the numerical aperture, not only the FWHM is reduced, but also the difference in the focus intensity of the two focal points is reduced. The focusing efficiency reached 61\%. The work in this paper provides a new
approach for designing high-performance optical imaging and information detection systems and realizing multi-functional metasurface devices.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declarations

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Conflict of interest/Competing interests

All authors declare that there is no conflict of interest.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

The code generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Authors’ contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Shuyuan Lv], [Jie Jia], [Wenfeng Luo] and [Xinhui Li]. The first draft of the manuscript was written by [Jie Jia] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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References

[1] Veselago V G 1968 The electrodynamics of substances with simultaneously negative values of ε and μ Sov. Phys. Usp. 10 509–14
[2] Smith D R, Padilla W J and Vier D C 2000 Composite medium with simultaneously negative permeability and permittivity Phys. Rev. Lett. 84 4184–7
[3] Pors A, Nielsen M G, Valle G D and Willatzen M 2011 Plasmonic metamaterial wave retarders in reflection by orthogonally oriented detuned electrical dipoles Opt. Lett. 36 1626–8
[4] Chen K, Feng Y J, Cui L, Zhao J M, Jiang T and Zhu B 2017 Dynamic control of asymmetric electromagnetic wave transmission by active chiral metamaterial Sci. Rep. 7 1–10
[5] Zhongyi G et al 2018 High-efficiency visible transmitting polarizations devices based on the GaN metasurface Nanomaterials 8 1–10
[6] Han Y S, Lu X Q, Lv H R, Mou Z, Zhou C D and Teng S Y 2020 Bifocal metalens with diverse polarization combination Plasmonics 16 575–9
[7] Ding X Y, Kang Q L, Guo K and Guo Z Y 2020 Tunable GST metasurfaces for chromatic aberration compensation in the mid-infrared Opt. Mater. 109 110284
[8] Ji R, Hua Y A, Chen K J, Long K W, Fu Y J, Zhang X F and Zhuang S L 2018 A switchable metalens based on active tri-layer metasurface Plasmonics 14 165–71
[9] Genevet P et al 2012 Ultra-thin plasmonic optical vortex plate based on phase discontinuities Appl. Phys. Lett. 100 169–72
[10] Wang W, Guo C, Tang J L, Zhao Z H, Wang J C, Sun J H, Shen F, Guo K and Guo Z Y 2019 High-efficiency and broadband near-infrared Bi-functional metalens based on graphene metasurfaces Sensors 21 4784
[11] Wang W, Zhao R K, Chang S L, Li J, Shi Y, Liu X M, Sun J H, Kang Q L, Guo K and Guo Z Y 2021 High-efficiency spin-related vortex metalenses Nanomaterials 11 1485
[12] Ding X, Yang X, Wang J, Guo K, Shen F, Zhou H, Sun R, Ding Z, Guo K and Guo Z. 2019 Theoretical analysis and simulation of a tunable mid-infrared filter based on Ge2Sb2Te5 (GST) metasurface Superlattices and Microstructures 132 106169
[13] Ai H, Kang Q, Wang W, Guo K and Guo Z 2021 Multi-beam steering for 6G communications based on graphene metasurfaces Sensors 21 4784
[14] Ni X J, Wang Y and Zhang X 2015 An ultrathin invisibility skin cloak for visible light Science 349 1310–4
[15] Dong F L, Feng H, Xu L H, Wang B, Song Z W and Yan L 2019 Information encoding with optical dielectric metasurface via independent multichannels ACS Photonics 6 230–7
[16] Yang R, Shi Y Y, Dai C J, Wan C W and Li Z Y 2020 On-chip metalenses based on one-dimensional gradient trench in the broadband visible Opt. Lett. 45 5640–3
[17] Wang W, Guo Z Y and Zhou K Y 2017 Metals focusing the Co-/cross-polarized lights in longitudinal direction Plasmonics 12 69–75
[18] Chen W T, Zhu Alexander Y, Sanjeev V and Capasso F 2018 A broadband achromatic metalens for focusing and imaging in the visible Nat. Nanotechnol. 13 1–8
[19] Wang W, Zhao Z H, Guo C, Guo K and Guo Z Y 2019 Spin-selected dual-wavelength plasmonic metalenses Nanomaterials 9 761
[20] Tang L L, Jin R C, Cao Y, Li J Q, Wang J and Dong Z G 2020 Spin-dependent dual-wavelength multiplexing metalens Opt. Lett. 45 5238–61
[21] Tian S, Guo H M and Hu J B 2019 Dielectric longitudinal bifocal metalens with adjustable intensity and high focusing efficiency Opt. Express 27 680–8
[22] Dong H G, Wang F Q, Liang R S, Wei Z C and Jiang L H 2017 Visible-wavelength metalenses for diffractionlimited focusing double polarization and vortex beams Opt. Mater. Express 7 4029–37