Spatial multiplexing plasmonic metalenses based on nanometer cross holes

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Abstract
Metasurfaces enable a spatially varying optical response to mold optical wavefronts into shapes that can be designed at will. Recurring to the excellent metasurfaces, spatial multiplexing metalenss with multiple focal spots distributing along the transverse or longitudinal direction and vortex metalenss with controllable topological charge are performed. These metalenses are composed of identical cross holes etched on the silver film and each cross hole can be taken as an equivalent half wave plate. The proposed spatial multiplexing metalenses can focus the light beam and spin the wave front, and their advantages of multifunction, high signal-to-noise ratio and ease to manipulate are favorable for expanding the application of plasmonic metalenses in optical manipulation.

1. Introduction
Photonic metasurface has gained attention due to the advantages of ultrathin and compactness and its ability of light manipulation [1–3]. With comparison to the conventional optical device depending the propagation effect including refraction, reflection, diffraction of the light field and absorption of media, metasurface modifies the light field by introducing abrupt changes of optical parameters when the light field passes through the anisotropic metastructures [4–6]. The Pancharatnam–Berry phase is one promising approach for achieving an abrupt phase change in designing gradient metasurfaces [7, 8], and it also provides the degree of freedom in designing spatial heterogeneity over an optically thin interface. To date, metasurfaces have been applied in wave front manipulation [9, 10], surface plasmon polariton excitation [11, 12], optical spin hall effect [13], optical holography [14–17] and photon sieves [18]. The design of metasurface functional elements has become a research hotspot in nanophotonics.

Besides these single-function metasurface devices such as metalenses [19–22], wave plates [23–25] and optical vortex generators [26–29], multifunctional metalenses have been also proposed [30–32]. Zhao H et al presented a multiplexed vortex generator consisting of C-shaped slot array and realized orbital angular momentum multiplexing and demultiplexing in the terahertz band, but the polarization conversion efficiency is low [33]. Veksler D et al proposed multiple wave front shaping based on random antenna groups and obtained the vortices with different topological charge in the transverse plane [34]. Mehmood M Q et al presented a vortex generator based on nanoslits and formed three vortices at different propagation distances [35]. Zhang Z et al designed a polarization dependence metalens based on gold nanorod array and controlled the focal point through choosing the helicities of the incident light [36]. The polarization conversion in these studies is requisite, and the high polarization conversion ratio and the more spatial multiplexing functions are advantageous for the applications of metasurface.

This paper aims to design the transmission metasurfaces with the 100% polarization conversion, and realize the spatial multiplexing focusing with high signal-to-noise ratio (SNR). We choose the cross holes to construct the spatial multiplexing metasurface, and each cross hole can be taken as a half wave plate. The proposed spatial multiplexing metalens can act as the plasmonic focusing lens, the plasmonic vortex lens or the plasmonic compound lens. Theoretical analysis provides the foundation for the design of these metalenses and numerical
simulations show the focusing performance of the spatial multiplexing plasmonic metalenses (SMPMs). The functions of SMPMs are also verified by the practical experiment measurement. The advantages of compactness, high SNR, ease to fabricate and the higher efficiency are favorable for the applications of our proposed spatial multiplexing and multifunctional metalenses in optical manipulation and optical communication.

2. Design of basic unit

The abrupt phase change of the metasurface appears usually in the conversion of cross polarization state. As we know, a half wave plate can convert the circularly polarization state into its cross polarization state with the transformation rate of 100%, and its transmission Jones matrix in the Cartesian base can be expressed as

\[
T = \begin{pmatrix}
\cos 2\phi & \sin 2\phi \\
\sin 2\phi & -\cos 2\phi
\end{pmatrix},
\]

where \(\phi\) presents the direction angle of its fast axis with respect to the \(x\) axis. In the circular base, the transmission matrix of a half wave plate can be rewritten as \([37]\)

\[
T_c = \begin{pmatrix}
0 & e^{-j2\phi} \\
e^{j2\phi} & 0
\end{pmatrix}.
\]

When the light field with the components of \(b_1\) and \(b_2\) impinges onto the half wave plate, the transmission field can be expressed as

\[
t_{\text{out}} = \begin{pmatrix}
0 & e^{-j2\phi} \\
e^{j2\phi} & 0
\end{pmatrix}\begin{pmatrix}b_1 \\ b_2\end{pmatrix} = b_1e^{-j2\phi}\begin{pmatrix}1 \\ 0\end{pmatrix} + b_2e^{j2\phi}\begin{pmatrix}0 \\ 1\end{pmatrix}.
\]

The first term in the above equation corresponds to the left-handed circular polarization (LCP) and the second one corresponds to the right-handed circular polarization (RCP). Obviously, the transmission field can be completely changed into its cross polarization when the illuminating light is chosen as the LCP with \(b_1 = 1\) and \(b_2 = 0\) or the RCP with \(b_1 = 0\) and \(b_2 = 1\). The conversion ratio of cross polarization reaches 100%, and it makes our proposed metalenses have high efficiency. The higher efficiency is compared with the metasurfaces consisting of other units including quarter wave plates (QWPs), polarizers or other anisotropic nanoholes with the same duty cycle. Moreover, we notice that an additional phase of \(2\phi\) or \(-2\phi\) appears in the transmission polarization, which is just the origin for introducing the abrupt phase change in designing the metalenses.

Thus, we first optimize a cross hole etched in a silver film on the basis of finite-difference time domain method as shown in figure 1(a), so as to obtain an equivalent half wave plate. In the practical calculations, the perfectly matched layers are used to prevent non-physical scattering at the boundaries. The minimum mesh step is set at 2.5 nm and the dielectric constant for the silver film takes \(\varepsilon = -15.92 - j1.075\) for the illuminating wavelength of 632.8 nm \([38]\). The optimized results are the thickness of silver film of \(h = 220\) nm and the size of \(l_1 = 600\) nm, \(l_2 = 220\) nm, \(w_1 = 150\) nm and \(w_2 = 180\) nm, and the fast axis of the cross hole is parallel to the longer edge. Figures 1(b) and (c) show the transmission phases of the optimized cross hole, and the phase variations of \(-\pi\) to \(\pi\) in a clockwise direction for LCP illumination and in a anticlockwise direction for RCP illumination indicate the incident polarization state completely changes into the cross polarization state. During the rotation angle of the cross hole increasing from 0 to \(\pi\), the addition phase delay appears among the transmission field. The detection results show the addition phase delay is twice of the rotation angle of the cross hole, as shown in figures 1(d) and (e). These results are consistent with the theoretic prediction.

3. Spatial multiplexing plasmonic metalenses

Our proposed SMPMs are based on two basic models of metalenses. One is the basic plasmonic focusing metalens consisting of the optimized cross holes arranged on the concentric rings. Where the additional phases of the cross holes at any position \(P(x, y)\) should satisfy

\[
\alpha(x, y) = -\frac{2\pi}{\lambda_{\text{pp}}} \sqrt{(x^2 + y^2) + f^2} - f, \tag{4}
\]

where \(f\) in above equation denotes the focal length of metalens, and \(\lambda_{\text{pp}}\) denotes surface plasmon polariton wavelength. And the second model is the plasmonic vortex metalens, and the additional phases of the cross holes should satisfy...
Cross holes. And the cross holes for our proposed metalens only rotate where the cross holes with the structure of metasurface. The annular intensities and inserted phase distributions in because of the incident polarization resulting in the noise to the optical vortex cannot pass through the spot appear at the set position, its length gets shorter with increase of the numerical aperture and the intensity (shown in functions distributing alternatively in the space for generating different focal spots or vortices, like the structure shown in layers, like the structure shown in figures 2, where the part (A) is for the plasmonic focusing metalens and the part (B) is the plasmonic vortex metalens.

Figures 2(d1)–(f1) give the intensity distributions of the focusing metalens with the structure of figure 2(a1) and its magnified part of figure 2(b1) as the numerical aperture takes 0.77, 0.86 and 0.91, respectively. The results in figures 2(b2)–(f2) are the longitudinal and transverse intensity and phase distributions of the vortex metalens with the structure of figure 2(a2). The one-dimensional intensity distribution of optical vortex is inserted in figure 2(b2), and the zero value of the central intensity shows the high SNR of vortex field. This is because of the incident polarization resulting in the noise to the optical vortex cannot pass through the metasurface. The annular intensities and inserted phase distributions in figures 2(d2)–(f2) indicate the topological charge of the plasmonic vortex takes −2, −3, −4 and −5, respectively.

Combining these two basic designs, we propose the SMPMs with different functions. The proposed SMPMs can realize the spatial multiplexing of many focal spots, many vortices and combination of focal spot and vortex. The design of the SMPMs includes two structures. One structure points to the cross holes with different functions distributing alternatively in the space for generating different focal spots or vortices, like the structure shown in figure 3(a). The other structure points to the cross holes with different functions locating in division regions, like the structure shown in figure 3(g). The magnified parts of two structures are shown in figures 3(b) and (h). Figures 3(c)–(f) and (i)–(l) show the spatial multiplexing functions of metalenses. The SMPM in figure 3(a) can generate two focal spots along the transverse or longitudinal direction, like the results in figures 3(c) and (d), or one focal spot and one vortex like the case of figure 3(e), or two focal vortices like the case of figure 3(f). The size of metalens A is about \( r = 13 \, \mu m \). Similarly, the SMPM in figure 3(g) can realize the similar focusing effect, yet the size of metalens B is about \( r = 11 \, \mu m \).

Comparing the focusing effect of SMPMs with two different structures, we can see that for the first structure, the intensities for focal spots or vortices at transverse and longitudinal directions are almost equal and the sizes of focal spots are comparative. However, the spatial multiplexing capacity of this structure is limited by the size of cross holes. For the second structure, the intensities for focal spots or vortices at different positions are

\[
\alpha(x, y) = -\frac{2\pi}{\lambda_{spp}} \left[ \sqrt{(x^2 + y^2) + f^2} - f \right] + 2\theta, \tag{5}
\]

where \( l \) is an integer representing the topological charge of optical vortex and \( \theta \) denotes the angular position of cross hole. And the cross holes for our proposed metalens only rotate \( \varphi = \pm \alpha / 2 \) with the positive sign for the LCP illumination and the negative sign for the RCP illumination. The structures of two basic plasmonic metalenses with the focal length of \( f = 10\lambda_{spp} \) with \( \lambda_{spp} = 0.613 \, \mu m \) for the illuminating wavelength of 0.633 \( \mu m \) and their focusing effect are shown in figure 2, where the part \( A \) is for the plasmonic focusing metalens and the part \( B \) is the plasmonic vortex metalens.
different because of the unequal contribution coming from the cross holes at different distance. Moreover, the longitudinal length of focal spots are different because of the different effective numerical apertures. Certainly, the intensity difference can be adjusted through changing the sizes of two regions, but the longitudinal length of focal spots are difficult to equate because of the different numerical apertures. This structure stands the high

Figure 2. Plasmonic focusing (A) and vortex (B) metalenses and their focusing effect (c1)–(f1), (b2)–(f2), where (a1) and (a2) are their structures and (b1) is the magnified part of (a1), (d1)–(f1) are the intensity distributions of focusing metalens with NA = 0.77, 0.86 and 0.91, respectively, and (c1) gives the variations of spot sizes and spot intensity with the numerical aperture, (b2) is the longitudinal intensity distribution of vortex metalens, and (c1)–(f1) are the transverse intensity and phase distributions with the topological charge of −2, −3, −4 and −5, respectively.

Figure 3. Two structures of SMPMs and their focusing effects (A) and (B). The cross holes distribute alternatively (a), (b) for one SMPM and in two regions for the other (g), (h), and the intensity distributions (c)–(f), (i)–(l) show the spatial multiplexing functions of metalenses.
Multiplexing capacity. Certainly, the high multiplexing degree needs the larger structure. Therefore, two SMPM structures have their respective advantages in focusing effect.

4. Experiment measurement

In order to testify the performance of the proposed SMPMs, the practical experiment is performed. The experiment setup is depicted as figure 4(a). Where QWP denotes a quarter wave plate, BS1 and BS2 represent the beam splitters, S points to the metasurface sample, MO1 and MO2 denote the microscope objectives, M1 and M2 are the mirrors and DF is the dense filter. SEM images of two SMPM samples with two longitudinal focal spots (b) and two longitudinal vortices (e) and the measured intensity distributions (c), (d), (f), (g) and the interference results (h), (i) at different distance are given. Where the focal length is 10 μm for (c), (f) and (b), and 20 μm for (d), (g) and (i).

**Figure 4.** Experiment setup to testify the performance of the SMPMs (a). Where QWP denotes a quarter wave plate, BS1 and BS2 represent the beam splitters, S points to the metasurface sample, MO1 and MO2 denote the microscope objectives, M1 and M2 are the mirrors and DF is the dense filter. SEM images of two SMPM samples with two longitudinal focal spots (b) and two longitudinal vortices (e) and the measured intensity distributions (c), (d), (f), (g) and the interference results (h), (i) at different distance are given. Where the focal length is 10 μm for (c), (f) and (b), and 20 μm for (d), (g) and (i).
5. Conclusion

Spatial multiplexing devices including focusing and vortex metalenses based on the plasmonic cross holes are proposed in this paper. Multiplexing focal spots and optical vortices with arbitrary topological charge distribute optionally along the transverse or longitudinal directions, which achieve only through rotating the cross holes. Since the cross holes are equivalent to half wave plates, the utilization of the equivalent half wave plates effectively improves the polarization conversion ratio and the SNR of metalenses. To some extent, it also improve the efficiency of SMPM. Theoretical analysis, numerical simulations and experiment measurement provide powerful confirmations for the performance of the proposed SMPMs. The distinct characteristics of compactness, multifunction, high polarization conversion and signal-to-signal ratio pave the wider way for the applications of the proposed SMPMs in optical communication, optical integration and quantum information processing.

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