Research article

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Metasurface integrated with double-helix point spread function and metalens for three-dimensional imaging

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Abstract: Metasurfaces are two-dimensional arrangements of antennas that control the propagation of electromagnetic waves with a subwavelength thickness and resolution. Previously, metasurfaces have been mostly used to obtain the function of a single optical element. Here, we demonstrate a plasmonic metasurface that represents the combination of a phase mask generating a double-helix point spread function (DH-PSF) and a metalens for imaging. DH-PSF has been widely studied in three-dimensional (3D) super-resolution imaging, biomedical imaging, and particle tracking, but the current DH-PSFs are inefficient, bulky, and difficult to integrate. The multielement metasurface, which we label as DH-metalens, enables a DH-PSF with transfer efficiency up to 70.3% and an ultrahigh level of optical system integration, three orders of magnitude smaller than those realized by conventional phase elements. Moreover, the demonstrated DH-metalens can work in broadband visible wavelengths and in multiple incident polarization states. Finally, we demonstrate the application of the DH-metalens in 3D imaging of point sources. These results pave ways for realizing integrated DH-PSFs, which have applications in 3D super-resolution microscopy, single particle tracking/imaging, and machine vision.

1 Introduction

Metasurfaces consisting of arrays of subwavelength antennas with well-defined shape, dimension, and arrangement have been extensively studied in manipulating the light wavefront at will [1–3]. Ultrathin metasurfaces have enabled a wide range of applications that conventionally rely on bulky optical elements, including beam deflectors [4, 5], lens [6, 7], waveplates [8, 9], vortex generations [10, 11], holograms [12, 13], and so on. Recently, more novel functionalities have been demonstrated by metasurfaces, such as twisted beams in both phase and intensity [14], photonic spin hall effect [15], hyperbolic dispersion [16], and retroreflectors [17]. However, most of previous metasurfaces are used to obtain the function of a single optical element. With an increasing demand of high-density nanophotonics platform, it is highly desirable to use a metasurface in place of multiple optical elements [7, 18, 19]. Here, we demonstrate, for the first time, a metasurface that represents the combination of a phase mask generating a double-helix point spread function (DH-PSF) and a metalens for imaging. We label this multielement metasurface as DH-metalens.

PSF describes the response of an imaging system to a point source or point object. Conventional PSF appears as a single spot diverging with defocus. Invented by R. Piestun and coworkers, DH-PSF is a three-dimensional (3D) PSF that exhibits two lobes rotating continuously with defocus [20–22]. DH-PSF is able to accurately provide the transverse information by the center of the two lobes and the axial information by the orientation angle of two lobes. Because of this feature, DH-PSF has been successfully applied in depth estimation with high Fisher information [20], 3D tracking [23–26], manipulation [27], and imaging [28, 29] of particles or molecules with super-resolution and single-shot 3D imaging [30]. In general, DH-PSF is formed by a superposition of Gaussian-Laguerre (GL) modes [20–22]. In previous

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works, DH-PSFs were realized either by computer generated hologram [20, 22, 30] or spatial light modulator [21, 23–25, 27, 29]. Both schemes modulate the wavefront via the light path difference accumulated in the beam propagation. In order to cover a range of 2π phase difference needed for the wavefront control, they rely on components with curved surfaces and thicknesses much larger than the wavelength. In addition, the large pixel size could result in severe issues of high-order diffraction and twin image. Furthermore, apart from the mask to generate DH-PSF, another objective and a couple of more lenses are typically required in their setups. Accordingly, the overall system used in previous works to apply DH-PSFs is complex, bulky, cumbersome, and difficult to integrate into a chip-scale optical system.

In this paper, we demonstrate an ultracompact DH-PSF realized by a plasmonic geometric metasurface (GM). Among the reported types of metasurfaces, GMs provide an orientation-controlled phase modulation that does not depend on the specific antenna design or wavelength, thus making them broadband and highly robust against fabrication errors and variation in the material properties [31]. In view of this, GMs have been exploited to achieve metalens with recorded high efficiency and broad bandwidth [32, 33]. Specifically, we first present a new design of a phase-only DH-PSF with optimized transfer function efficiency (TFE), which is defined as the ratio of the energy in two main lobes to the total incident energy. The planar configuration of metasurfaces allows us to utilize arbitrary shapes for the aperture window. By applying a square aperture and an improved optimization weight function, we obtain two symmetric lobes with TFE up to 70.3%, while in previous optimization work, the two lobes had different intensities and TFE was 56.8% [21]. Another advantage of using metasurface lies in that various functionalities can be combined and realized on one single metasurface, which benefits for achieving the maximization of integration. For example, here, we use one single metasurface to realize the regulation effect of both the DH-PSF phase mask and a metalens for imaging. The pixel area and overall dimension of this DH-metalens are close to three orders of magnitude more compact than the previous works [25, 28, 30]. A multipole plasmonic meta-atom with a thickness of only 210 nm and a transmission efficiency as high as 38% is designed and demonstrated as the building block of the GM. This obtained transmission efficiency is also significantly higher than previous plasmonic GMs [10, 11, 31]. Furthermore, we show that the demonstrated transmissive phase mask can work in two incident directions and for different input polarization states in a broadband visible range. Finally, we demonstrate the application of this DH-metalens in 3D imaging/tracking of micropoint sources. The reported that

ultracompact DH-metalens will have applications in realizing 3D super-resolution microscopy, biomolecule tracking and manipulation, and laser lithography for fabricating 3D metamaterials, at an integrated nanophotonics platform.

2 DH-PSF design

An exact DH-PSF is formed by taking the superposition of GL modes on a straight line in the GL modal plane [22, 34]. Figure 1A and B respectively shows the intensity and phase distributions of an exact DH-PSF superposed by five GL modes with indices (1,1), (3,5), (5,9), (7,13), and (9,17) with equal energy. The two lobes in Figure 1A rotate with propagation. The transfer function coded on the mask to realize this DH-PSF is the same, as each GL mode is an eigenmode to free-space propagation. However, realizing such an intensity distribution requires a lossy mask and thus imposes a large amount of losses to the system. In addition, it is hard to realize, particularly when applying metasurface masks. Furthermore, the TFE of such an exact DH-PSF is only 1.8% [21]. S.R.P. Pavani and R. Piastun presented an iterative optimization algorithm to improve the TFE to 56.8% by extending the superposition set to a cloud around the line defining the exact DH-PSF and taking only the phase of the superposition [21]. Note that a phase-only design is favorable to the GM realization.

In this work, we show that by applying a similar but improved approach, we are able to further optimize the TFE to 70.3%. First, as shown in Figure 1, we used a square aperture instead of a circular one to let more energy go through it. Second, we used a different optimization weight function to design the phase-only transfer function. Specifically, the optimization weight function consists of two spatially separated Gaussian functions and two-step functions. The expressions are defined as follows:

$$O_{\text{Gauss}} = \exp \left\{ - \left[\frac{(x-x_a)^2}{\omega_{G1}^2} + \frac{(y-y_b)^2}{\omega_{G2}^2} \right] \right\} + \exp \left\{ - \left[\frac{(x-x_b)^2}{\omega_{G1}^2} + \frac{(y-y_b)^2}{\omega_{G2}^2} \right] \right\} \quad (1)$$

and

$$O_{\text{step}} = \begin{cases} 1, & (|x-x_a| \leq \omega_{s1} \cap |y-y_a| \leq \omega_{s2}) \cup (|x-x_b| \leq \omega_{s1} \cap |y-y_b| \leq \omega_{s2}), \\ \gamma, & \text{else} \end{cases} \quad (2)$$

where O_{Gauss} is the double Gaussian function and O_{step} is the step function, $\omega_{G1,2}$ are widths of the Gaussian beam waist

Figure 1: Theoretical design of high-efficiency DH-PSF and DH-metalens.

(A–B) Intensity and phase distributions of the exact DH-PSF. (C) Iteration curve of the peak intensity of main lobes during the optimization iteration procedure. An enhancement of 40 times is obtained after the optimization. (D) Phase distribution of the optimized phase-only transfer function to realize high-efficiency DH-PSF. (E) Phase distribution of the designed metasurface combining the high-efficiency DH-PSF and a lens with focal length of 2.54 cm.

along the long and short axes of the main lobes, and $\omega_{s1,2}$ are widths of the step function. (x_a, y_a) and (x_b, y_b) are the locations of main lobes' maximum, respectively. γ is the attenuation factor lower than 1. More detailed description

of this improved optimization approach can be found in the Supplementary material.

The evolutions of peak intensities of the main lobes are shown in Figure 1C. The solid and dotted lines

correspond to two main lobes, respectively. After 23 iterations, the peak intensities tend to be saturated. Compared to the intensity before optimizing, this optimized result is 40 times higher. Moreover, as noticed, choosing such an optimization weight function makes two lobes symmetric during the iteration, which is also different from previous work [21]. Figure 1D shows the obtained phase distribution of the phase-only transfer function after 23 times of iteration. In order to make the system more integrated, we code the phase of the transfer function and a lens together in one single GM phase mask; the combined phase distribution of the DH-metalens is shown in Figure 1E. The phase mask is designed for a wavelength of 750 nm and the focal length of the lens is 2.54 cm.

3 Metasurface design and fabrication

A plasmonic meta-atom schematically shown in Figure 2A is designed and utilized as the building block of the GM. It is constructed by a plasmonic rectangle-shaped nanorod separated from its inverted structure, i.e. a nanoaperture by a perforated dielectric resist layer. The length and width of the nanorod/nanoaperture are 230 nm and 130 nm, respectively. The thickness of the metal and resist are 30 nm and 180 nm, respectively. The period of the meta-atom, which is also the pixel size of the phase mask, is 320 nm $\times$ 320 nm. As we demonstrated in previous work [35], such a meta-atom design supports high circular polarization (CP) conversion in the transmission direction due to the excitation of multiple moments, including electric dipole, magnetic dipole, electric quadrupole, and magnetic quadrupole. Figure 2B shows the multipole analysis of the meta-atom with a CP input by using an exact multipole expansion approach [36]. Figure 2C shows the theoretically simulated and experimentally demonstrated cross-CP transmittance of a regular meta-atom array as a function of the wavelength. There is a good match between simulation and experiment. As can be noticed, the highest transmittance is demonstrated to be 38% around the wavelength of 750 nm, which is the wavelength we used to design the phase mask. Note that the transmission efficiency is different from the TFE we have optimized before in the DH-PSF design. The scanning electron microscope (SEM) image of the fabricated regular meta-atom array and a magnification of four meta-atoms are shown in Figure 2D, in which we can clearly see complementary nanoapertures and nanorods with different brightness.

The plasmonic metasurface was fabricated on a quartz substrate with a thickness of 500 microns. After cleaning with acetone and isopropyl alcohol (IPA), a layer of positive resist ZEP520 with thickness of 180 nm was spin-coated on the substrate followed by 2 min of baking at 170°C on the hotplate. Then, a thin layer of conductive polymer Espacer was spin-coated to dissipate charge during the electron beam lithography process. Next, the rectangle nanostructure patterns were defined on the resist layer by electron beam lithography. The patterned area was 655 $\mu\text{m} \times$ 655 μm , which includes 2048 $\times$ 2048 pixels. After exposure, the Espacer was removed by water rinsing. A low-temperature development with high contrast was implemented by successively developing the sample in ZED-N50 for 45 s, in methyl isobutyl ketone for 30 s, and in IPA for 30 s. The sample was then dried by nitrogen blow. After the development, 2 nm of chromium and 30 nm of gold were deposited by electron beam evaporation.

Then, the phase mask designed in Figure 1E is realized by transferring the phase distribution into the orientation distribution of meta-atoms. The microscope (top) and SEM (bottom) images of the fabricated DH-metalens are shown in Figure 2E.

4 Results and discussion

Figure 3A schematically shows the experimental setup we utilized to characterize the DH-metalens. It is custom built on an optical table with the optical axis parallel to the table. A Griffin Ti-Sapphire oscillator is used as the light source, it is set to work on the continuous wave (CW) mode, and the wavelength range can be adjusted from 730 nm to 860 nm. A 4f system comprised by two converging lens is placed after the light source to narrow the light spot of the oscillator. A polarizer and a quarter waveplate are used to control the polarization state of the incident light. The spatial response of DH-metalens is imaged by a charge coupled device (CCD), which is mounted on a translation stage moving along the axial direction to acquire images at different locations. First, we use a collimated input beam and change the imaging distance around the focus of the DH-metalens. The relationship between the rotation angle (θ) of two lobes and the imaging defocus (d) is theoretically calculated and experimentally measured. Figure 3B illustrates the results for different incident polarization states. The wavelength of the incident light is 750 nm. The black solid line and red, blue, and green dashed lines represent the theoretical calculation, experimental results with left-CP input, linear polarization input, and right-CP input, respectively. The theory and experiment fit well with each other.

Figure 2: Meta-atom design and DH-metalens realization.

(A) Schematic diagram of the plasmonic meta-atom. (B) Multipole analysis of the meta-atom with a CP input. The designed plasmonic meta-atom supports multipole moments, including electric dipole (ED), magnetic dipole (MD), electric quadrupole (EQ), and magnetic quadrupole (MQ). (C) Calculated and experimental cross-CP transmittance of the metasurface as a function of the wavelength. (D) SEM image of a general metasurface. The inset is the magnification of four meta-atoms, where two layers are clearly observable. (E) Microscope image of the fabricated DH-metalens. The inset is the SEM image of a representative antenna array at the center area of the DH-metalens.

Figure 3: Experimental setup and characterization of the DH-metalens.

(A) Schematic diagram of the experimental setup to characterize the PSF of the DH-metalens. (B) Theoretically calculated and experimentally obtained relationship curves between the rotation angle (θ) and the imaging defocus (d) at wavelength of 750 nm. (C–F) The rotation of DH-PSF images at different defocus positions in theory (C) and in experiment with left-CP input (D), linear polarization input (E), and right-CP polarization input from the back side (F). (G) Relationship curves between θ and d at wavelengths of 730 nm, 790 nm, and 860 nm; the insets are two DH-PSF images at a wavelength of 730 nm.

Figure 3C–F shows the images at five positions near focus in theory and in experiment with left-CP, linear polarization, and right-CP inputs, respectively. Variation of images at all defoci can be found in the Supplementary Video 1. Every image clearly shows two distinct lobes, whose peaks have been analyzed to obtain the axial dependence of $\theta(d)$ shown in Figure 3B. They basically have the same trend of variety changing with the axial position. The opposite direction of rotation result with a right-CP light is obtained by irradiating the sample from the opposite side. Furthermore, although the phase mask was designed at 750 nm, we show that it can work in a broadband wavelength range in the visible and near-infrared. Figure 3G shows the results at wavelengths of 730 nm, 790 nm, and 860 nm. It clearly indicates that the results are broadly independent of the wavelength. The insets in Figure 3G depict the recorded images at two positions for wavelength of 730 nm.

On account of the results above, we experimentally prove that the PSF of the DH-metalens we designed has the characteristic of rotation along the axial variety. Next, we will demonstrate the application of the DH-metalens in

3D imaging and tracking of point source located on and off the axis. The point sources are microholes of radii of around 5 μm in an aluminum foil that are fabricated by precision femtosecond laser ablation. In the experiment, the aluminum foil is placed on a translation stage before the DH-metalens in Figure 3A. In the first experiment, we demonstrate the estimation of the axial position of a single microhole located on the axis. We measure the relationship between the rotation angle θ of two lobes in the image and the object distance of the microsource by fixing the CCD at the focal plane and changing the axial position of the aluminum foil, as shown by the schematic diagrams in Figure 4A. The obtained relationship is shown in Figure 4B. It can be seen that an approximately linear relationship is maintained over a large range of 120° . The effective depth range that can be utilized is around 20 cm. The related resolution of the depth measurement is $6^\circ/\text{cm}$. We note that this resolution can be improved simply by coding a lens with a shorter focal length or a larger numerical aperture on the metasurface phase mask. Indeed, a focal length on the order of tens of microns and a numerical

Figure 4: Experimental imaging of a moving microhole. (A) Images of an on-axis point source (microhole) moving along the optical axis by fixing the imaging distance at 2.54 cm, i.e. at the focal plane of the DH-metalens. Images for five object distances are shown. (B) Theoretically calculated and experimentally obtained rotation angle (θ) in the image as a function of the object distance.

aperture around 1 have been reported by using metasurfaces [37–39].

In the second experiment, we used two off-axis microholes and show that the DH-metalens are able to retrieve their 3D position. The diagram of this experiment is shown in Figure 5A. The relationship between the rotation angle (θ) in the image at a fixed imaging distance of 6.9 cm and object distance is shown in Figure 5B. The transverse positions of the two microholes are also measured to be $(-242.5 \mu\text{m}, 471.3 \mu\text{m})$ and $(457.6 \mu\text{m}, -162.5 \mu\text{m})$ according to the images. Based on the results above, the 3D position information of the micro-sources can be obtained. These two experiments show the potential of our DH-PSF in 3D tracking and imaging of fluorescent molecules or particles.

Figure 5: Experimental imaging of two moving microholes. (A) Images of two off-axis point sources (microholes) moving along the optical axis by fixing the imaging distance at 6.9 cm. Images for five object distances are shown. (B) Theoretically calculated and experimentally obtained rotation angle (θ) in the image as a function of the object distance.

5 Conclusions

On the basis of a plasmonic GM, we have demonstrated an ultracompact DH-PSF with subwavelength thickness for the first time. By adopting a new optimization method, the designed phase mask is more efficient than previous works. The integration of a DH-PSF and a metalens on a single metasurface provides a compact, ultralight, and cost-efficient system with an extended distance of both the object depth and the imaging distance. Moreover, the optical setup can work in different polarization states and a broad bandwidth. The demonstrated experiments on 3D imaging of micro-sources prove that this DH-metalens can be used in real-world imaging technologies with compressed and integrated imaging system.

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