Research article

Xuan Liu^a, Junhong Deng^a, King Fai Li, Mingke Jin, Yutao Tang, Xuecai Zhang, Xing Cheng, Hong Wang, Wei Liu and Guixin Li*

Optical telescope with Cassegrain metasurfaces

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Abstract: The Cassegrain telescope, made of a concave primary mirror and a convex secondary mirror, is widely utilized for modern astronomical observation. However, the existence of curved mirrors inevitably results in bulky configurations. Here, we propose a new design of the miniaturized Cassegrain telescope by replacing the curved mirrors with planar reflective metasurfaces. The focusing and imaging properties of the Cassegrain metasurface telescopes are experimentally verified for circularly polarized incident light at near infrared wavelengths. The concept of the metasurface telescopes can be employed for applications in telescopes working at infrared, Terahertz, and microwave and even radio frequencies.

Keywords: metasurface; nanofabrication; metamaterials.

1 Introduction

Telescopes are designed to capture high-quality images of distant objects. Astronomical observation is certainly one of the most inspiring applications of telescope [1–3]. Five hundred years ago, Hans Lippershey applied for a patent

on his invention “looker,” which consisted of a converging and a diverging lens to magnify distant objects. This is the first telescope with written record [3]. Nowadays, various kinds of telescopes, including refractive and reflective types, have been developed [1–3]. Due to the advantages of chromatic aberration free and compactness, reflective telescopes are widely utilized. Among the designs of reflective telescopes, the Cassegrain telescope, which consists of a concave primary mirror and a convex secondary mirror, is very popular, such as Hubble Space telescope, Keck Telescope, and Very Large Telescope [1, 4]. In these facilities, the incident light is firstly reflected and converged by a primary mirror. Then it is deflected by the secondary mirror and focused after passing through the central aperture of the primary mirror. However, the fabrication and integration of the curved mirrors are complicated; thus, telescopes with planar mirrors are highly desirable.

Recently, the rapidly developing photonic metasurfaces composed of a two-dimensional spatially variant subwavelength structures arrays can flexibly manipulate the amplitude, phase, and polarization of light wave and provide an attractive approach for achieving flat optical components [5–30]. It has been widely utilized for various applications, such as metalens [8–18], optical holography [19–24], optical spin-orbit interactions [25–28], and so on. Compared with conventional lenses, metalens has subwavelength thickness and can focus light without spherical aberration. While most metalenses are designed for microscopy applications [9, 13], much less attention has been paid to the field of optical telescopes. While objective lens with high numerical aperture (NA) are preferred to magnify the fine features of objects, telescopes with low NA can be used to improve the angular resolution when they are utilized to differentiate the objects far away from the observers.

Here, we investigate the widely employed Cassegrain telescope configuration and realize a proof of concept of planar Cassegrain telescope with photonic metasurfaces. From the conventional optics, we know that the double-layer Cassegrain metasurface telescope will be more compact compared to the single layer metalens with the same focal length [1, 4]. The concave primary mirror

^aXuan Liu and Junhong Deng: These authors contributed equally to this work.

*Corresponding author: Guixin Li, Department of Materials Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China, e-mail: ligx@sustech.edu.cn.

<https://orcid.org/0000-0001-9689-8705>

Xuan Liu, Junhong Deng, King Fai Li, Mingke Jin, Yutao Tang, Xuecai Zhang and Xing Cheng: Department of Materials Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China

Hong Wang: Department of Materials Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China; and Shenzhen Engineering Research Center for Novel Electronic Information Materials and Devices, Southern University of Science and Technology, Shenzhen 518055, China

Wei Liu: College for Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China

and convex secondary mirror in the conventional Cassegrain telescope are replaced by a pair of planar reflective metasurfaces. The metasurface mirrors consisting of gold meta-atoms are designed based on the geometric Pancharatnam-Berry (P-B) phase and perform converging and diverging optical functionalities, respectively [5, 9, 14, 17]. The P-B phase $\varphi(x, y) = 2\sigma\theta(x, y)$ depends on the orientation angle $\theta(x, y)$ of the gold meta-atom at position (x, y) and the circular polarization state σ of the incident light, where $\sigma = \pm 1$ represents the left- and right-circular polarizations (LCP and RCP), respectively [31, 32]. For the meta-atoms based on P-B phase illuminated by a circularly polarized incident light, the residual light with the same circular polarization states as that of incident light is unavoidable if the meta-atom is not an ideal half waveplate. However, our designed planar Cassegrain telescope composed of two reflective metasurfaces is intrinsically free of residual light and thus is less demanding for the circular polarization states of the incident light [17]. Previously, we have studied the dual-layer Cassegrain metasurface systems with similar configuration which was mainly used for microscopy applications [17]. From the point of view of practical applications, the concept of Cassegrain

metasurface telescope is not just a simple extension of previous studies in metalenses [8–18], as it may provide a unique and reliable choice for making large area telescopes at microwave and radio frequencies [1, 2], where the curved surfaces inevitably involve the more complicated manufacturing and constructions than the planar version.

2 Design and fabrication of the Cassegrain metasurface telescopes

The conventional Cassegrain telescopes shown in Figure 1A are composed of a concave primary mirror and a convex secondary mirror [1, 4]. Through designing suitable geometrical parameters of the mirrors, the Cassegrain telescopes can realize focusing and imaging functions with high quality [4]. The Cassegrain metasurface telescope is schematically shown in Figure 1B, where two reflective metasurfaces with optical converging and diverging functions are used to replace the curved mirrors

Figure 1: Schematic illustration of Cassegrain metasurface telescope and the design of meta-atom.

(A) The conventional Cassegrain telescope made of a concave primary mirror and a convex secondary mirror. (B) The Cassegrain metasurface telescope. Conventional curved mirrors are replaced by planar metamirrors based on geometric P-B phase. The incident circularly polarized light is reflected twice with the metamirrors and then focused with the same circular polarization state as incident light. (C) The geometric configuration of the meta-atom for the metamirrors: glass substrate is covered by a gold layer ($h_2 = 00$ nm) and a SiO_2 ($h_1 = 87$ nm) layer; the gold nanorod on top of the SiO_2 layer with length $L = 200$ nm, width $W = 85$ nm, and height $H = 30$ nm; φ is the orientation angle of the gold nanorods in the x - y plane. The periods along the x and y directions are $P_x = P_y = 300$ nm. (D) The numerically calculated cross-polarization and co-polarization polarization conversion efficiency for circularly polarized incident light upon reflections by the meta-atoms array.

in conventional telescope. The required phase profiles of the metasurfaces can be calculated with geometrical parameters of the designed Cassegrain metasurface telescope as shown in Figure 1B:

$$\Phi_p(r_p) = \int_0^{|r_p|} \frac{2\pi n}{\lambda} \frac{r_2 - r_1}{\sqrt{(r_2 - r_1)^2 + h^2}} dr_1, \quad R_2 \leq |r_p| \leq R_3 \quad (1)$$

$$\Phi_s(r_s) = -\int_0^{|r_s|} \frac{2\pi n}{\lambda} \left(\frac{r_2}{\sqrt{r_2^2 + f^2}} + \frac{r_2 - r_1}{\sqrt{(r_2 - r_1)^2 + h^2}} \right) dr_2, \quad 0 \leq |r_s| \leq R_1 \quad (2)$$

where λ is the wavelength of light in free space and $r_2 = (R_1 R_3 - R_1 r_1) / (R_1 - R_3)$; h is the distance between the primary and secondary metasurfaces (PM and SM); R_1 is the radius of SM; and R_2 and R_3 are the inner and outer radii of PM, respectively. The space between the focal spot and SM is defined as focal length f ; the focal ratio F of the telescope equals to $f / (2R_1)$. n is the refractive index of the background medium ($n = 1$ in this work).

The required phase distributions of PM and SM with $R_1 = 240 \mu\text{m}$, $R_2 = 250 \mu\text{m}$, $R_3 = 500 \mu\text{m}$, $h = 800 \mu\text{m}$, $\lambda = 780 \text{ nm}$, and $F = 6.25$ are calculated using Eqs. (1) and (2) and shown in Figure 2A and B, which are realized based on the geometric P-B phase. The left-/right-circularly polarized (LCP/RCP) incident light is converted to RCP/LCP light during each reflection. Therefore, the transmitted light is of the same circular polarizations with incident light after twice reflections by the metamirrors (Figure 1B).

In order to obtain the designed phase profiles with high optical efficiency, we employ a metal-dielectric-metal configuration as shown in Figure 1C [20, 33]. The unit cell of the metasurface consists of a 100-nm-thickness gold layer as a reflecting mirror and a 87-nm-thickness SiO_2 dielectric spacer layer (see Supplementary SI-1) and a top layer of gold nanorods (length $L = 200 \text{ nm}$, width $W = 85 \text{ nm}$, and height $H = 30 \text{ nm}$) with in-plane orientation angle φ . Figure 1D shows the calculated cross-polarization conversion efficiency of a meta-atom with normally incident circularly polarized light. The cross-polarization reflectivity over 80% is obtained within a broad spectral range between 700 nm and 1000 nm. The

Figure 2: Design and fabrication of the Cassegrain metasurface telescope with $F = 6.25$ at a wavelength of 780 nm.

(A, B) The phase profiles of the primary and secondary metamirrors (PM and SM) with geometric parameters: $R_1 = 240 \mu\text{m}$, $R_2 = 250 \mu\text{m}$, $R_3 = 500 \mu\text{m}$, $h = 800 \mu\text{m}$. (C, D) The optical images of the fabricated PM and SM, respectively (scale bar: 200 μm). (E, F) SEM images of the PM and SM over the regions marked by red boxes in (C) and (D), respectively (scale bar: 1 μm).

working spectral regimes also can be further broadened by choosing proper materials and geometries of the meta-atoms. The PM and SM metasurfaces can be figured out according to the corresponding phase distributions shown in Figure 2A and B and fabricated through the standard electron beam lithography technique (see Supplementary SI-2 and SI-3). Optical photos of fabricated PM and SM are shown in Figure 2C and D. Figure 2E and F show the scanning electron microscope (SEM) images of the meta-atoms of the PM and SM, respectively.

3 Characterizations of focusing properties

We characterize the focusing properties of the fabricated Cassegrain metamirrors shown by using the experimental setup shown in Supplementary Figure S5. A

supercontinuum laser source (NKT) with tunable wavelength in the visible and near-infrared range is used. After passing through a linear polarizer and a quarter-wave plate, the incident light with LCP state is then focused by the Cassegrain metasurface telescope. An objective (Olympus, $\times 4$, N.A. = 0.1) and a tube lens with $f = 300$ mm are then used to magnify and image the focal point on a charge coupled device (CCD) camera (Thorlabs). In the experiment, the PM fixed at $z = 0$. The measured field profiles in the beam axis plane for incident light at wavelengths ranging from 660 nm to 820 nm are shown in Figure 3A. The brightest spots (white dashed line) shown in Figure 3A are the positions of focal points. The measured intensity profiles at corresponding focal planes of the Cassegrain metasurface telescope are shown in Figure 3B. The cross-sections of the focal spots along the y -axis are shown in Figure 3C. To further verify our design, we also fabricate a Cassegrain metasurface telescope with focal length $f = 9.6$ mm and $F = 20$ at wavelength of 780 nm (see

Figure 3: Focusing properties of the Cassegrain metasurface telescope with $F = 6.25$ at a wavelength of 780 nm.

(A) The measured intensity profiles along the propagating axial plane at various incident wavelengths. The white dashed lines indicate the position of the focal points. (B) The measured intensity profiles at the focal plane (scale bar: 5μ m). (C) The corresponding cross-sections of the focal spots along y direction. (D–F) The simulated and experimentally measured focal length (D), measured FWHM (E), and measured focal efficiency (F) spectra with respect to the wavelength of incident light.

Supplementary Figure S4) and experimentally characterize its focusing properties (see Supplementary Figure S6).

Figure 3D shows the simulated and experimental focal lengths as a function of incident wavelength for the Cassegrain metasurface telescopes. It is clear that the measured focal points are all close to the designed positions. The focal lengths decrease with the increasing wavelengths due to the negative dispersion of the metasurface. As shown in Figure 3E, all the measured focal spots exceed ideal full-width half-maximum (FWHM) values (Rayleigh limit $[1.22\lambda F]$), which should be due to the super oscillation effect [18, 34–36]. The focusing efficiencies for the Cassegrain metasurface telescopes at various wavelength are measured and shown in Figure 3F (see Supplementary SI-4). The efficiency is defined as the ratio of the optical power of the focused LCP light beam to that of the incident beam with same circular polarization state. The efficiency is wavelength dependent and has a value up to 25% around the wavelength of 780 nm, which is lower than the single layer dielectric metalenses [9] but higher than most of the plasmonic metalenses [10]. It is

also found that the measured focusing efficiencies are lower than the theoretical values predicted in Figure 1D, in which the normal incidence of light on a meta-atom is considered. Even for the oblique incidence on the second mirror is taken into account, the optical efficiency of the single meta-atom does not decrease too much (see Supplementary Figure S7). Therefore, the imperfection of the nanofabrication and the loss of the gold meta-atoms may play more important roles.

4 Imaging performance

We then characterize the imaging performance of the Cassegrain metasurface telescopes using the experimental setup shown in Figure 4A. The slits in a 100-nm-thickness gold film on glass substrate, which are fabricated using photo-lithography method, are used as the objects (Figure 4B). The center to center distances of the slits are 200 μm , 150 μm , and 100 μm (with a filling factor of

Figure 4: Imaging with the Cassegrain metasurface telescopes.

(A) The experimental setup for characterizing the imaging properties of the metasurface telescope with $F = 6.25$. A Tungsten-Halogen light source is used as an illumination. A bandpass filter (Thorlabs, FB780-10, 780-nm center wavelength, 10-nm FWHM) is placed behind the light source to reduce chromatic aberrations. Patterns milled in a 100-nm-thickness gold film on glass substrate are used as the objects. The image collected by the Cassegrain metasurface telescope is magnified by the combination of the objective lens (Olympus, 4 $\times$ magnification, NA = 0.1) and the tube lens with focal length $f = 300$ mm and then projected onto the CCD camera. (B) The optical photographs of the objects (scale bar: 100 μm). The center to center distance of the slit is 200 μm , 150 μm , and 100 μm from left to right. The dark areas (slits) are transparent and their widths are respectively 100 μm , 75 μm , and 50 μm . (C, D) Images taken with the Cassegrain telescopes with $F = 6.25$ and 20, respectively. (E, F) The corresponding cross-sections of the images in (C) and (D) along the x direction. The magnifying ratio of the imaging systems are ~ 0.3 and ~ 1 . Scale bar: 200 μm .

0.5), respectively. These objects are placed about 178 mm away from the secondary metamirror and illuminated by a Tungsten-Halogen light source. In order to reduce the chromatic effects, a band-pass filter with 780-nm center wavelength and 10 nm bandwidth (Thorlabs, FB780-10) is utilized. The image collected by the Cassegrain metasurface telescope is magnified by an objective (Olympus, $\times 4$, NA=0.1) and a tube lens with $f=300$ mm and then captured using a CCD camera (Thorlabs, DCC1545M). Figure 4C and D show the images observed with the Cassegrain metasurface telescope with $F=6.25$ and $F=20$. The measured magnifying ratios of the imaging systems with the Cassegrain metasurface telescopes with $F=6.25$ and 20 are about 0.3 and 1, which are consistent with the theoretically calculated results (see Supplementary SI-5). It can find that the Cassegrain metasurface telescope with larger F and longer focal length has larger magnification ratio. The angular resolution of the Cassegrain metasurface telescope according to Rayleigh criterion is $1.22\lambda/(2R_s)$, and the linear resolution is $1.22\lambda F$. The corresponding cross-sections of the images in Figure 4C and D are shown in the Figure 4E and F. It is clear that our designed metasurface telescopes can image an object with a resolution up to $150\text{ }\mu\text{m}$, which is larger than the theoretical resolution. In Figure 4C, the stripe at the center is clearer than its neighbors, which most probably results from the astigmatism (see Supplementary SI-6).

As discussed in Ref. [17], the dual-layer Cassegrain metasurface system is intrinsically free from residual light. Upon twice reflection on the metamirrors, light waves with unconverted circular polarization states are directly reflected out of the optical system [17]. Therefore, the Cassegrain metasurface telescope, which is free from residual light, can help reduce the compactness of the whole optical system. This means the polarization analyzers that are usually used to filter the residual light is now not necessary (see Supplementary SI-7). The quarter-waveplate and the linear polarizer in Figure 4A are used to verify the intrinsically residual light free feature of the Cassegrain metasurface telescope, which can be removed for practical applications.

5 Conclusion

In summary, we have demonstrated the planar Cassegrain metasurface telescopes in the near-infrared regime with reflective photonic metasurfaces, which can be utilized for optical focusing and imaging. The Cassegrain metasurface telescope in this work is experimentally verified by using a proof of concept experiment. We expect that

the concept of metasurface telescope can be applied to astronomical observations at infrared, Terahertz, microwave, and radio frequencies; in that situation the planar metasurface may play more important roles for easing the construction and providing more optical functionalities.

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