Design of Metasurface Radial Shear Interference Plate

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***Abstract*—The radial shearing interferometer has increasingly attracted interests in various areas, such as adaptive optics systems, laser systems, optical inspection, and topographic surveys. However, traditional RSIs suffer from the enormous volume, irregular interferogram, and non-adjustable shear rate, which severely limits their application. Metasurfaces, as a latest breakthrough, can provide perfect building blocks for the optical wavefront operation of artificial materials at sub-wavelength scales. In this work, we have proposed a radial shearing interference plate with subwavelength spatial resolution based on all-dielectric compound metalenses. The incident beam to the compound metalenses is divided evenly and uniformly into a convergent and a divergent wavefront beam with no high-order diffraction, enabling the radial shearing interference plate high contrast interference in the overlapping region. There are at least 320 steply changed phases per 2π period within total 24π phase range, demonstrating high-precision phase modulation ability. The MRSIP have the advantages of ultra-compact structure, outstanding phase modulation ability, polarization insensitive, subwavelength spatial resolution, regular interferogram, high contrast, high energy utilization, and adjustable SR, implying its potential to transient wavefront detection, aero-optical, topographic surveys, particularly in the realm of outdoor applications and so on.**

Keywords—metasurface, radial Shear Interference, micro-nano optical design.

I. Introduction

Radial shearing interferometer (RSI) plays a critical role in precision optical measurements. It realizes an interference fringe by a convergent and a divergent wavefront beam, both of which are divided from incident light through a bulky optical system. Due to the obvious superiority of the RSI in measuring dynamic wavefront and in getting rid of its extra reference beam, it has been widely applied, such as adaptive optics systems [1], corneal topographic inspection [2], laser beam characterization [3], optical testing [4], wavefront sensing [5], etc. However, composed of complex optical systems, including lenses, mirrors, beam splitters, traditional RSIs suffer from the enormous volume, irregular interferogram, and difficulty in adjusting shear rate (SR), which severely limits their its application. Because of the compact volume and simple optical setup, various types of radial shearing interference plates with different performances have been applied in different fields since 1972.

Radial shearing interference plates based on diffractive components such as gratings [6] and double Fresnel zone plates (FZPs) have a relatively compact structure. Nevertheless, in these devices pinholes are necessary to filter out the higher-orders of diffracted beams, resulting in low-contrast irregular interferogram and low light throughput of the optical system. Metasurfaces, two-dimensional optical array composed of artificial sub-wavelength meta-atoms, have shown unprecedented ability in precise manipulation of electromagnetic waves. Accordingly, researchers have proposed many novel optical metasurface devices with unique functions such as focusing lenses, beam splitters, optical holograms, and waveplates, etc. Given these unique features, it is possible to realize miniature, compact, and integrated radial shearing interference plate. Here, we theoretically and experimentally demonstrate a novel all-dielectric compound metalenses-based radial shearing interference plate (MRSIP), operating at the wavelength of 1064 nm. The MRSIP of a single layer metasurface can realize radial shearing interference without any additional optical components. The high-precision phase modulation makes the MRSIP more close to the ideal cosinusoidal zone plates with high contrast, polarization insensitive, high utilization of energy and high spatial resolution. Our design notably expands the scope of the radial shearing interferometer, paving the way for the high-performance miniaturized radial shearing interferometer.

II. Design

The MRSIP is arranged in the form of rings with meta-atoms, in which only one single layer metasurface can realize radial shearing interference, as shown in Fig. 1(a). In Fig. 1(a), f is the focal length of the designed MRSIP, and Z is the distance between the imaging plane and the MRSIP. The shear ratio is defined as SR = (f-Z)/(f+Z). The electromagnetic wave incident to the MRSIP is divided into one convergent wavefront beam and one divergent wavefront beam, such that the two beams interfere in the overlapping region. We elaborately designed the phase distribution of the metasurface, resulting in the meta-atoms of even rings diverging the incident beam while the meta-atoms of odd rings converging the incident beam. Besides, the convergent and the divergent wavefront differ from the incident wavefront only in the aperture. Therefore, when the two wavefronts meet in the free space, a high contrast and regular shearing interferogram is formed. All the meta-atoms have the same size with different rotation angles θ which can contribute to a Pancharatnam–Berry (PB) phase $\varphi=2\theta$, as shown in Fig. 1(b). The meta-atoms are arranged with periodicity in both X and Y directions. The period of the meta-atom is less than the operating wavelength to avoid higher-order diffraction.

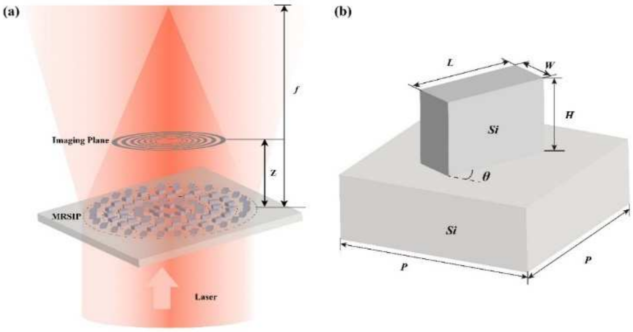

Fig. 1. Schematic illustration of the designed MRSIP device .

Where φ is the phase profile caused by the MRSIP, λ is the operating wavelength, f is the focal length, and i =1, 2, 3, … is the ring numbers of the MRSIP. When i is an odd integer, the meta-atoms there converge incident wavefront. When i is an even integer, the meta-atoms there diverge incident wavefront. The incident plane wavefront can be properly converted into converged wavefront and divergent wavefront under an optimum phase profile. The MRSIP was designed with a focal length of 390.7mm and a radius of 3.2 mm. The detailed phase profile of the odd and that of the even rings are plotted in Fig. 2(a) and Fig.2 (b), respectively. They are hyperbolic phase curves with opposing phase distributions. It is noteworthy that there are at least 320 steply changed phases per 2π period within total 24π phase range, demonstrating the outstanding phase modulation ability of the MRSIP.

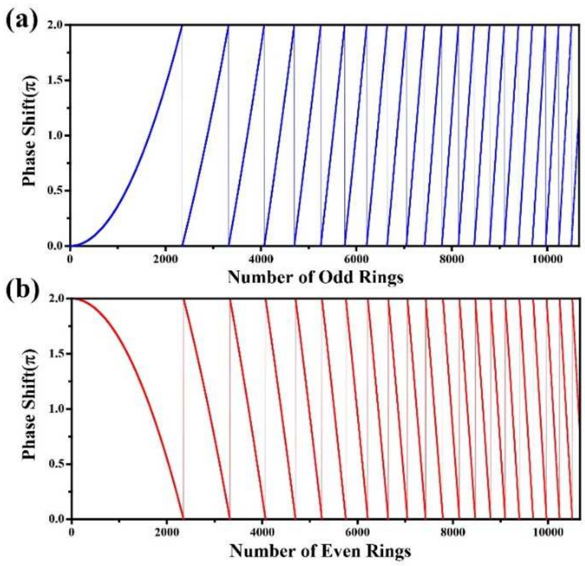

Fig. 2. Phase profile of the MRSIP at different positions.

The interference patterns under different shear rates of the MRSIP were then estimated using the 2D angular spectrum method (2DASM), with the optical field assumed to be uniform in each meta-atom unit. In this configuration, the SR may be constantly changed from 0.9 to 0.7 by adjusting the distance between the imaging plane and the MRSIP from 20.5 mm to 68.9 mm. Regular interferograms can be obtained when an collimated left-handed circularly polarized (LCP) beam is incident, as illustrated in Fig. 3(a) ~ (c). The width of each ring of the interferograms decreases successively from the center to outside. The outermost interference ring, i.e. the minimum interference ring, has a width of 70 μm. Furthermore, when the SR increases, so does the number of the rings in the interferograms. When the SR is 0.9, 0.8, and 0.7, the number of the interference rings in this design is 22, 19, and 17, respectively. We also calculate the interferograms and the corresponding radial intensity distributions when the collimated right-handed circularly polarized (RCP) beam is incident to demonstrate that the MRSIP can be applied to any polarized incident light.

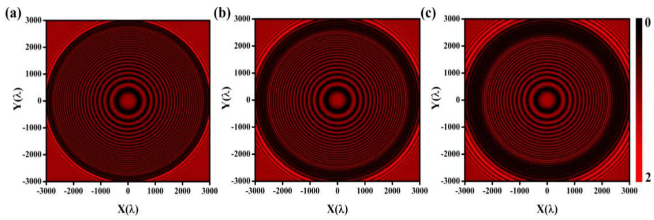

Fig. 3. Interference patterns generated by MRSIP under the incidence of the collimated LCP beam. (a) ~ (c) The optical intensity profile with the SR = 0.9, 0.8, 0.7.

The finite difference time domain (FDTD) method is adopted to optimize the meta-atom size. Here we take LCP light as an example. At the wavelength of λ_0=1064 nm, the refractive index of the Si was 3.553+0.0001i, which was experimentally obtained with a spectroscopic ellipsometer. We use Marine Predators Algorithm (MPA) to obtain the optimized parameters of L=324 nm, W=150 nm, H=595 nm, and P=420 nm. Fig. 4 plots the TRL, TLL, and phase shift of the transmitted cross-polarization wave with respect to rotation angle θ for LCP incident wave at λ_0. TRL and TLL are the transmissions for the cross-polarized and co-polarized transmission. The first and second subscripts represent transmitted and incident polarized light, respectively. According to the curve results, the TRL is maintained at about 0.7 under different rotation angles while TLL is less than 0.06, and the phase shift is twice the rotation angle with good linearity.

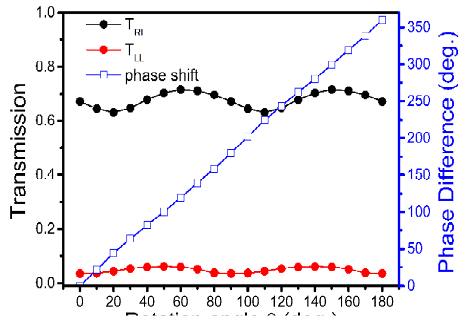

Fig. 4. Simulation performances of the meta-atom. TRL (black curve), TLL (red curve), and phase differences (blue curve) of the transmitted cross-polarization wave with respect to rotation angle θ for LCP incident wave at λ_0

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