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Transverse superresolution and focal shift with rotational tunable phase mask ☆

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ABSTRACT

This paper reports the imaging characteristics of an optical system can be modified by our designed polarization pupil mask. The novel rotational symmetric polarization pupil mask design based on combination of half-wave and quarter-wave plates is introduced for realizing the focal shift and extending focal depth of an optical system and the procedure for designing is presented. Numerical results show when an appropriate rotational symmetric polarization pupil mask is used as an apodizer in the optical imaging system, it not only can effectively achieve the continuously focal shift in a small range and extend focal depth of the optimized system, but also can evidently increase the transverse resolution of the optimized system at the genuine focal plane.

1. Introduction

It is well known that, a circular aperture followed by a lens will produce a focus point, when illuminated with a monochromatic, uniform spherical wave, the point of maximum irradiance in the focal region is not at the geometrical focus but is displaced toward the aperture, giving rise to the so-called focal shift effect [1]. In the past few decades, focal shift [2–6] and high focal depth [7–10] in optical imaging system have been the goal of extensive researchers. We know that the imaging properties of an optical system can be modified by introducing different kinds of pupil mask, and it has been extensively studied [11–13]. Such studies showed that the performance of an optical imaging system, which is characterized by the point spread function and optical transfer function, can be tailored by modifying its pupil function in terms of phase, amplitude, or both of them. The possibility of the imaging properties which can be modified by using polarization masks in the aperture plane has already been explored, and utilization of the polarization property may give an optical system additional dimensions and flexibility unachievable in scalar-wave optics [14–19]. The fact that one can vary the response of such a system continuously by changing the orientation of polarization masks included in the system gives an enhanced flexibility to the system that is unobtainable by the use of conventional pupil masks. Furthermore, Roy Chowdhury et al. showed that by suitable choice of the polarization parameters the polarization phase that is introduced can compensate for spherical aberration of an imaging system [18,20]. The versatility of this technique for modifying the imaging characteristics of the system stems from the fact that one can continuously vary the polarization induced phase difference between light emerging from the masking polarizers either by changing the state of polarization of the incident beam or by reorienting the polarizers.

Here we report a technique for realizing the optical focal shift and high focal depth with a three-portion half-wave plate and two quarter-wave plates combination (see Fig. 1). If the half-wave plate is sandwiched between two parallel quarter-wave plates, and the angle between their fast axis can be tunable, such system behaves likes a tunable phase retarder. We have already reported that by changing the angle between their fast axis it is possible to realize the tunable transverse optical superresolution [21]. In this paper, such system with phase variation has been investigated numerically to show that it can be used to obtain the tunable optical focal shift and high focal depth. It should be noted that, in this paper, the focal shift is the distance between the geometrical focal and genuine focal planes. We assume that the acceptable intensity variation near the focus along the axis is 10%. With the proposed pupil mask, the focal depth is about two times longer than that of the original optical system. Comparing with the conventional pupil mask, with such designed pupil mask the transverse superresolution and the focal shift can be tunable by rotating any zone of the half-wave plate. Furthermore, it is relatively simple to

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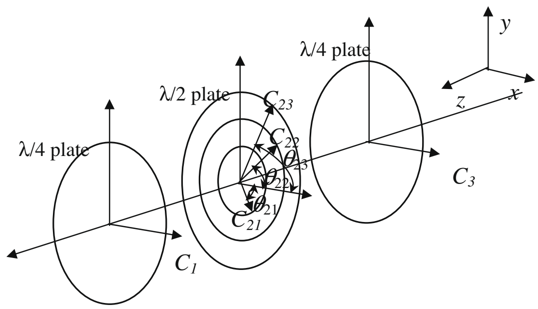

Fig. 1. Schematic diagram of the designed rotational polarization pupil mask: C_1, C_3, C_{21}, C_{22}, C_{23} are the direction of the fast axis.

produce and adjustment. The remainder of this paper comprises five sections divided as follows. Section 2 describes the structure and pupil function of the new polarization pupil mask. In Section 3 the general theory and the focal region intensity distribution of an optical system with defocus parameter are given in detail. The tunable focal shift and high focal depth of such polarization pupil mask are analyzed in Section 4. And our main conclusion is summarized in Section 5.

2. Structure of the rotational symmetric polarization pupil mask

If the polarization pupil mask is circularly symmetric, the polarization phase difference introduced between the polarization masked zones of the aperture will also have circular symmetry. This polarization induced phase in effect modifies the pupil function and is shown to bring about a change in the best focal plane, and the best focal plane shifts away from the Gaussian image plane. For the polarization mask focusing system considered, we can control the polarization phase and hence the best focal plane by changing the orientation of the wave plate included in the system.

The configuration of the rotational symmetric polarization pupil mask is sketched in Fig. 1. It consists of one three-portion half-wave plate between two identical quarter-wave plates, and the three potions of the half-wave plate can rotate with respect to each other. The two quarter-wave plates are parallel and their fast axis, C_1 and C_3, are parallel to the x axis. The half-wave plate is made of three zones that can rotate with respect to each other. The radii of the three-portions are r_1, r_2, and 1 (which is normalized to the aperture of the optical system). The angles between the x axis and the fast axis of the corresponding zone of the half-wave plate are θ_{21}, θ_{22}, and θ_{23}. With the Jones calculus, it can be proved that such system is corresponding to an equivalent phase retarder, whose retardation is $\phi = 2\pi - 4\theta_2(\theta_2 = \theta_{21}, \theta_{22}, \theta_{23})$, and the angle between identical fast axis and x axis is $\pi/4$ [21]. So the phase can be continuously changed by rotating corresponding portion of the half-wave plate.

3. Operating principle of the optimized optical imaging system

Fig. 2 shows that the collimated light passes through the designed polarization mask and then converges through an objective lens onto the image plane. From Section 2, we know the aperture of the optical imaging system consists of three-portions, and the phases of the three-portions are $\phi = 2\pi - 4\theta_2(\theta_2 = \theta_{21}, \theta_{22}, \theta_{23})$,respectively. So there will be different pupil functions for the different zone of the aperture:

$$P(r,\theta_2) = \begin{cases} \exp[i(2\pi - 4\theta_{21})] & 0 < r < r_1 \\ \exp[i(2\pi - 4\theta_{22})] & r_1 < r < r_2 \\ \exp[i(2\pi - 4\theta_{23})] & r_2 < r < 1 \end{cases} \quad (1)$$

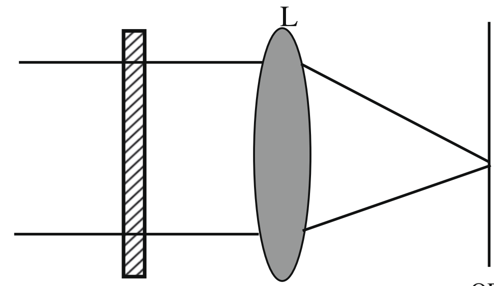

Fig. 2. Principle of the designed rotationally symmetric polarization pupil mask in the optimized optical system, where L is lens, OP is observation plane.

The amplitude point spread function, $G(\rho, \theta_2, w_{20})$ of a radially symmetric optical system with a generalized pupil function, $P(r, \theta_2)$, is defined as [22]

$$G(\rho, \theta_2, w_{20}) = 2\int_0^1 rP(r,\theta_2)J_0(2\pi r\rho)\exp(i2\pi w_{20}r^2)dr \quad (2)$$

In Eq. (2) r is the radial coordinate of the pupil plane, and $\rho = \frac{2\pi}{\lambda}(NA)r$ is the normalized radial coordinates at the plane of observation, where NA is the numerical aperture of the system. $P(r, \theta_2)$ is the pupil function which is given by Eq. (1), $J_0(2\pi r\rho)$ is the zero-order Bessel function of the first kind, and w_{20} is the focal shift distance of the optical system. So the corresponding intensity point spread function of the proposed system under focused and defocused conditions may therefore be written as

$$I(\rho, \theta_2, w_{20}) = \left|2\int_0^1 rP(r,\theta_2)J_0(2\pi r\rho)\exp(i2\pi w_{20}r^2)dr\right|^2 \quad (3)$$

So the irradiance distribution along the optical axis of the system will be obtained by substitution of $\rho = 0$ in the above expression and can be given by

$$I(0, \theta_2, w_{20}) = \left|2\int_0^1 rP(r,\theta_2)\exp(i2\pi w_{20}r^2)dr\right|^2 \quad (4)$$

The axial irradiance at the Gaussian image plane can be obtained from the above expression by substitution $w_{20} = 0$. Here in order to obtain the focal shift and high focal depth by rotating the three-portions of the half-wave plate, we focus on $I(0, \theta_2, w_{20})$. In order to get a simple criterion to evaluate the imaging quality of defocus optical system, we considered a Strehl definition after Tsujiuch [23], defined as the axial irradiance distribution is normalized against the total light flux available for that specific system, which may be represented by the following integral

$$I(0, \theta_2, 0) = 2\int_0^1 rP(r,\theta_2)dr \quad (5)$$

and the Strehl ratio definition for the proposed system will be

$$S(\theta_2, w_{20}) = \frac{I(0, \theta_2, w_{20})}{I(0, \theta_2, 0)} \quad (6)$$

According to the analysis above, properties of the optical system can be described by pupil function. Consequently, the system can be modulated if a mask is added in the pupil plane. By virtue of the designed polarization mask being circularly symmetric and centered on the axis of the imaging system, phase difference of three-portions is of a similar nature. It is therefore reasonable to expect that the peak irradiance of the axial intensity will present to an axial point, which in turn will depend on the above