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Light sheet based on one-dimensional Airy beam generated by single cylindrical lens

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ABSTRACT

We report on a novel method of generating light sheet with extended depth of field based on one-dimensional Airy beam by the use of single cylindrical lens. In the method, coma is intentionally introduced into the system by oblique illumination to approximate a cubic phase mask. Experimental studies were presented to validate this method. This technique can be easily applied to current light sheet generators where cylindrical lens is used, as only tilt of the cylindrical lens is needed.

1. Introduction

Light sheet has been widely used in a triangulation based laser scanner to measure the surface profiles in industry. Recently, it has attracted much attention from the scientific community as it has found applications in light sheet microscopy [1–3], where the light sheet provides an approach to achieve high-contrast imaging with minimal sample exposure. While the lateral resolution is determined solely by the numerical aperture (NA) of the objective, the axial resolution is related to the light sheet thickness. Generally speaking, the light sheet can be generated by a cylindrical lens [2] or scanning the beam focused by an objective [3], but in both cases, the used beam is Gaussian beam that has intrinsic limitation on the waist radius and depth of field (DoF). Therefore, it is difficult to get high axial resolution and extended DoF simultaneously. To overcome this problem, Bessel beam was first proposed [4,5], demonstrating that the DoF is dramatically increased. As light from outer rings of the Bessel beam deteriorates the image contrast, Airy beam was proposed in [6], showing that the asymmetric pattern contributes positively to the contrast. Besides, it also shows that nondiffracting beam is more robust to scattering than conventional Gaussian beam, which makes it desirable in an inhomogeneous and scattering media.

However, it is difficult to get the Airy beam. Generally speaking, Airy beam can be generated by a cubic phase mask (CPM). But the fabrication of CPM is high-cost and time-consuming. Therefore a spatial light modulator (SLM) is usually used to generate the wavefront of the CPM in the current experimental setup [6–10]. Although it is feasible, it can hardly be integrated into a commercial setup where cost, weight, volume and robustness have to be taken into account. Nonlinear processes have been employed to get the Airy beam at different wavelengths and overcome the limitation of the damage threshold of the SLM [11], but the setup is complicated. In Ref. [12], a combination of positive and negative cylindrical lenses of matching curvature radii was used to get the cubic phase. But it still requires further machining on the standard cylindrical lens. It will be very attractive to get the Airy beam by minor modification on the setup where only standard cylindrical lens is used.

The one-dimensional CPM is expressed by $W \propto x^3$, where W is the wavefront, x is the coordinate. And the term accounting for coma in the Seidel aberration is also x^3 on the x-axis. Therefore it should be possible to use coma to approximate the CPM. In Refs. [13,14], it shows that an optimized lens system can effectively eliminate spherical aberration and high-order aberrations and preserve solely coma. However, it still needs at least two optical components: one cylindrical lens generating high-order aberrations and the other lens (spherical or cylindrical) minimizing all but coma.

In this paper, we show that only single cylindrical lens is sufficient to generate light sheet with extended depth of field. The text is organized as follows. In Section 2, description of the problem is given. Experimental results are presented in Section 3 to validate the method. In Section 4, numerical simulation on the performance of the optical design by the diffraction theory is presented. Conclusions are drawn in Section 5.

2. Description of the problem

When a Gaussian beam incidents on a standard cylindrical lens, the beam is focused into a point in the yz plane, as shown in Fig. 1(a). The

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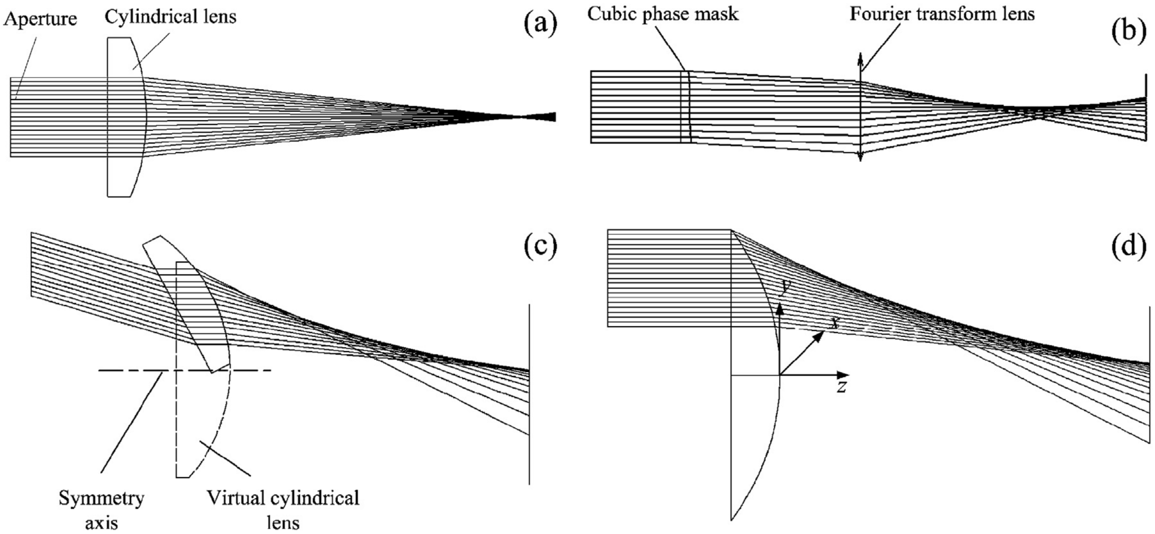

Fig. 1. (a) Cylindrical lens with a centered aperture under normal illumination. (b) System consisting of a CPM and an ideal paraxial cylindrical lens under normal illumination. (c) Cylindrical lens with a centered aperture under oblique illumination. (d) Cylindrical lens with a decentered aperture under normal illumination. The coordinate system defined here is used through the text.

DoF is determined by the NA of the cylindrical lens. Different from Gaussian beam, the intensity profile of Airy beam remains invariant but experiences constant acceleration along the propagation. As ideal Airy beam has infinite energy, finite-energy Airy beam was proposed [7], Fourier Transformation $\Phi_0(x)$ of which is proportional to $\exp(-ax^2)$ $\exp(ix^3/3)$, where a is a parameter to modulate the energy and x is the coordinate in the frequency space. The cubic phase indicates that the finite-energy Airy beam can be generated by inserting a CPM at the focal plane of a Fourier transform lens, as shown in Fig. 1(b). To approximate the CPM, coma is introduced into the system. As coma originates from oblique illumination, the cylindrical lens was set to be tilted in [13,14] and another lens was introduced to minimize other high-order aberrations. An optimization problem needs to be solved to get proper lens parameters. Here in our work, for simplicity, we assume that the cylindrical lens is plano-convex and the collimated beam first incidents on the planar surface, as shown in Fig. 1(c). Under this assumption, the beam incidenting on the convex surface is still collimated but decentered from the symmetry axis of the virtual cylindrical lens. The problem of oblique illumination can then be transformed into a problem of decentered aperture, as shown in Fig. 1(d). Note that in practical applications, it is better to use oblique illumination than decentered aperture so that more light can be collected with the same aperture. Comparison between Fig. 1(b) and (d) shows that the ray distribution with decentered aperture is almost the same as that with a CPM.

To explain this phenomenon, optical path difference (OPD) at the xy plane in Fig. 1(d) defined to be the phase difference between the ideal spherical wave and the actual wave is calculated from ray tracing, as shown in Fig. 2. In the ray tracing, the curvature radius R of the convex surface and refractive index of the lens are 1 mm and 1.5. The position of the observation plane is z=2 mm. It shows that the OPD is very small near the center part of the lens and gradually increases with the increment of y position. Since the OPD (coma) is an even (odd) function of y, only the upper or lower part of the lens can be used.

A cubic polynomial given by

$$\mathrm{OPD}/R = a + b(y/R - c)^3 \tag{1}$$

is then fitted to the OPD, where a, b and c are three nondimensional parameters to be fitted, a is a constant number, b corresponds to the amplitude of the CPM, c corresponds to the shift of the CPM in the y direction, R is the curvature radius of the convex surface.

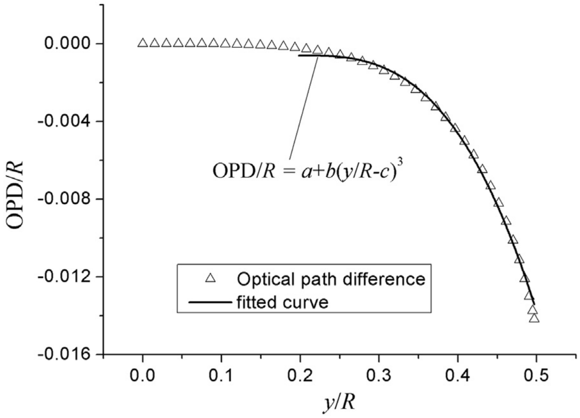

Fig. 2. Optical path difference at the xy plane versus different y positions.

Eq. (1) indicates that the OPD actually plays the role of a truncated and shifted CPM, which can be expanded into

$$\mathrm{OPD}/R = b(y/R)^3 - 3bc(y/R)^2 + 3bc^2 y/R + (a - bc^3) \tag{2}$$

In the right side of Eq. (2), the first term is a cubic phase which describes the CPM, the second term denotes additional defocus and the third term introduces a linear phase which leads to the tilt of the beam. The constant phase in the fourth term doesn't affect the beam and can be ignored. Since there is already a quadric phase provided by the ideal spherical wave, Eq. (2) depicts a system where a CPM is placed closed to an ideal lens with focal length slightly different from that of the original spherical wave and the beam is tilted after the lens, which is different from the conventional method where the CPM is placed at the front focal plane of the lens and there is no linear phase. Therefore the shift of the CPM results in a tilted focal line which moves away from the lens. As shown in Fig. 1(b), the light from different parts of the aperture intercepts the focal line at different positions, which means that the truncation of the CPM results in a reduction of the length of the focal line. The extension of DoF can thus be evaluated by the fitting error between the OPD and Eq. (1). Fig. 2 demonstrates that the OPD between y/R=0.2 and y/R=0.48 can be well fitted, where a=−6e-3, b=−0.465 and c=0.195. As these parameters remain invariant for cylindrical lens of different sizes, there is an intrinsic relationship between the OPD and the focal length. Therefore when different focal lengths are needed for a given OPD, another lens with a centered aperture should be used to provide additional optical power.