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Invited Article

Fabrication of parabolic cylindrical microlens array by shaped femtosecond laser

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ABSTRACT

A simple and efficient technique for fabricating parabolic cylindrical microlens arrays (CMLAs) on the surface of fused silica by shaped femtosecond (fs) laser direct-writing is demonstrated. By means of spatially shaping of a Gaussian fs laser beam to a Bessel distribution, an inversed cylindrical shape laser intensity profile is formed in a specific cross-sectional plane among the shaped optical field. Applying it to experiments, large area close-packed parabolic CMLAs with line-width of 37.5 μm and array size of about 5 × 5 mm are produced. The cross-sectional outline of obtained lenslets has a satisfied parabolic profile and the numerical aperture (NA) of lenslets is more than 0.35. Furthermore, the focusing performance of the fabricated CMLA is also tested in this work and it has been demonstrated that the focusing power of the CMLA with a parabolic profile is better than that with a semi-circular one.

1. Introduction

Micro-optics is an irreplaceable key enabling technology for many products and applications today, which plays a crucial role in biomedical devices, fiber communication networks and most laser-based devices [1–3]. Even our modern smart phones contain a variety of micro-optical elements [4]. As one of the representative micro-optical elements, cylindrical microlens arrays (CMLAs), which modulate the wavefront phase of incident light in only one direction, have become increasingly interesting in recent years [5,6]. As it seems to be the appropriate solution for miniaturized vision systems. The CMLA has been widely used in various fields, such as photolithography, semiconductor laser array collimation [7], 3D imaging [8] and so on [9–11].

In the early stage of CMLAs fabrication, molding, micro-jetting, ion-exchanging, photolytic technique etc. have been developed [12–15]. However, the quality of CMLAs produced by these methods is not enough. Defects, lens profile accuracy, surface roughness and non-uniformities in the array greatly constrain their field of application to optical imaging tasks. Later, ultrasonic assisted hot embossing [16], electrohydro-dynamic deformation [17,18], electrically templated dewetting [19], liquid edge pinning [5], and so on are used to manufacture CMLAs. With these techniques, the CMLAs with high optical quality (smooth surface, low aberration) can be achieved, even an aspherical profile. However, the target materials for these methods would have to be low-threshold polymers, such as photocurable resin and Polymethyl methacrylate (PMMA). For directly processing CMLAs on the material of fused silica, which is selected as the substrate material for most micro-optical components, these methods are usually infeasible because of fused silica's intrinsic properties with high hardness and high ablation-threshold.

Ultrafast pulse laser assisted fabrication, a micro-/nano-processing method developed rapidly in recent years, can provide an alternative way for the CMLAs machining on fused silica [20–24]. The ultrafast laser pulse can easily achieve a very high power and can be powerful enough for fully ionization of almost any solid materials and can obtain a high-quality processed surface with essentially no recast, micro-crack, and heat-affected zone, so it is a desirable choice for the fabrication of microlens array [25]. In our previous research, convex CMLAs were obtained by fs laser fabricating [26]. As the envelope of shaped spatial intensity distribution matches the profile of cylindrical microlens perfectly, a CMLA can be fabricated by simple line scanning. However, the spatial intensity distribution model of the axicon-formed Bessel beam was derived simply from the first kind Bessel function with an axicon-introduced boundary condition, which cannot reflect the

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substance that the axicon-formed Bessel area is created by collimated beams interference. What is more, the profile of produced CMLAs could only be semi-circular. Then, the spherical aberration was attractive and needed to be improved.

In this paper, we simulate the spatial intensity distribution of the axicon-formed Bessel beam based on Fourier optics, which shows the actual situation of the propagation and interference of the fs laser beam behind each optical element. Then, the spatial intensity profile, referring to the profile that determines the outline of produced microlenses during shaped fs laser direct-writing, can be identified more clearly. More importantly, the fabrication of CMLAs with a parabolic profile, which is highly desirable for reducing spherical aberration in high-quality optical imaging, are achieved in this paper.

2. Theoretical analysis

In contrast to our previous work where the spatial intensity distribution model was derived from the first kind Bessel function and the model could only qualitatively reflect partial properties of the axicon-generated Bessel beam [26], herein the model is constructed on the basis of the wavefront phase modulation created by each optical element and the free-space propagation of the shaped beam behind each optical element, which will be demonstrated below that can simulate the actual situation of the axicon-generated Bessel beam. For the phase modulation, since it depends on the thickness of a lens at each point [27], the electric intensity E_B just behind each lens can be expressed as:

$$E_B = E_I \cdot \exp\{ikn[\delta_0 - z(r)]\}\exp[ik \cdot z(r)] \quad (1)$$

where E_I is the electric intensity in front of the lens, k is the wavenumber, n and δ_0 are the refractive index and the maximum thickness of the lens respectively, $z(r)$ is the profile equation of the lens surface. All of these parameters are defined in a cylindrical coordinate system (r, φ, z). $kn[\delta_0 - z(r)]$ is the phase delay caused by the lens and $k \cdot z(r)$ is the phase delay caused by the free space region, the portion of a cube that is cut away to produce the lens. For the free-space propagation, it is difficult to digitally simulate the variation of the spatial intensity distribution directly in the space-domain. Then, we turn to the frequency-domain to do it, since the beam propagates by a distance of z in the space-domain equivalent to a simple phase shift of $\exp(ikzZ)$ in the frequency-domain based on the time-shifting property of the Fourier transform [27,28]. Moreover, since the field discussed herein is azimuthally independent, the two-dimensional Fourier transform can be simplified to the form of a zero order Hankel transform. Therefore, the spatial-frequency spectrum in any plane behind the axicon can be expressed as:

$$H(R, z) = k\int_0^\infty E_B r J_0(kRr)dr \cdot \exp\left(ikz\sqrt{1 - R^2}\right) \quad (2)$$

where the coordinate R is the normalized k-vector projection into the r coordinate ($R = k_r/k$). Finally, the electric intensity in each lateral plane can be obtained by the inverse Hankel transform of Eq. (2) as:

$$E(r, z) = k\int_0^\infty H(R, z)RJ_0(kRr)dR \quad (3)$$

Replacing these integral functions by summations and being handled in MATLAB, the spatial intensity distribution of the whole fs laser shaping process can be obtained, as shown in Fig. 1. The incident laser is a fundamental transverse Gaussian beam. The inset is a partial enlarged view of the final formed Bessel area, which will be employed to fabricate cylindrical microstructures directly. It can be clearly seen that both the first Bessel beam and the final Bessel beam are created by the interference of two collimated beams in the axial section plane, which is consistent with the actual situation and could never be revealed from the previous model. The greatest benefit of the model constructed in this paper is that the intensity profile in each cross-sectional plane can be directly captured by intercepting the laser beam. As shown in Fig. 2, the laser intensity profile is obtained from a plane in the final Bessel beam region about 0.6 μm from the central plane, as shown the red dash line in the inset of Fig. 1. It can be seen that the profile matches the outline of two adjacent quarter-cylinders. Below, we will perform experiments to verify that only with such an intensity profile, the fs laser could cut cylindrical microstructures from the surface of a sample.

3. Experimental setup

Fig. 3 displays the setup for fabricating CMLAs, which is made up of a fs laser source with a central wavelength of 800 nm, a pulse duration of 120 fs, a repetition rate of 1 kHz, a horizontal polarization, and a mechanical shutter for turning on/off the laser beam automatically, and a laser power regulator consisting of a quartz half-wave plate and a Glan-Taylor polarizer, and an axicon with conical angle of 2.5°, and a 4f system comprised of a bi-convex lens and a plano-convex lens, whose focal lengths are 300 mm and 25.4 mm, respectively. After passing through the 4f system, the final Bessel beam is focused on the front surface of target samples (fused silica). The samples are mounted on a three-dimensional (3D) linear translation stage, which is constituted by three high-precision motorized linear stages. During CMLAs fabricating, the samples move along the X-axis at a constant velocity to engrave grooves and skip along the Y-axis by a constant distance after each processed groove. The third stage, which moves along the Z-axis, is used to control the relative distance between the final Bessel focus and the front surface of samples (defined as the defocus distance). In order to determine the interval between two adjacent grooves and combine processed grooves into microlenses, a monocular microscope coupled with a high-resolution charge-coupled device (CCD) camera is employed, as shown in Fig. 3. This gives the width of the groove during experiments without unloading the samples. After irradiation with the shaped fs laser beam, the samples will be placed into an ultrasonic cleaner with power of 80 W and repetition rate of 42 kHz for 5–7 min to get rid of recast drips. Next, Cerium Oxide (CeO_2) powder is employed to polish patterned cylindrical

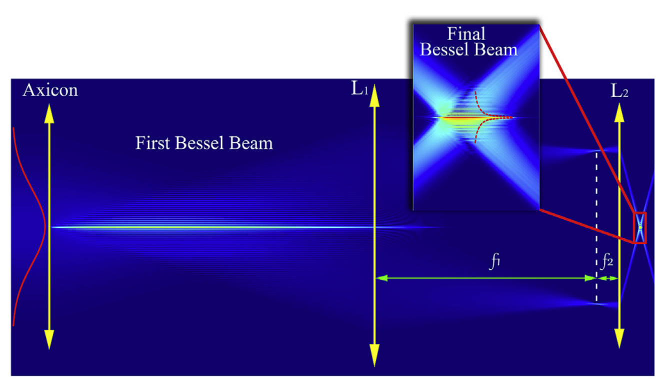

Fig. 1. The simulation result of the spatial intensity distribution of the whole fs laser shaping process.