Mask-Free Production of Integratable Monolithic Micro Logarithmic Axicon Lenses

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***Abstract*—Although unique properties such as creation of non-diffracting beams and as a result the large focal depth have been exhibited from axicon lenses, and numerous important applications in optical signal processing and imaging have been demonstrated, axicons of dimensions smaller than a hundred of micrometers have not yet been reported. It is technically quite challenging for the currently available technologies including lithography and mechanical shaping to define complicated three-dimensional surface profiles depicted by lens functions in the small scale. Here, we report the solution of the issue by use of femtosecond laser nanofabrication via two-photon polymerization of resins. Not only well-defined monolithic micro axicons are attained, they demonstrate excellent optical characteristics: the cross-sectional Besselian beam intensity distribution was found almost unchanged for at least 200 μm within the focal range; imaging remains unblurred and in high contrast in a much wider range than that for a common lens. The direct laser nanowriting strategy would allow the lens integrated with other optical components produced the same way, or incorporated to an existing micro-optical system.**

***Index Terms*—Femtosecond laser, logarithmic axicon, micro, monolithic, refractive.**

I. Introduction

AN axicon [1] is an optical element that focuses paralleled incident light into a narrow line segment along the optical axis. Compared with a common lens that focuses in Rayleigh range, this element distinguishes itself by its very large focal depth as well as approximate-Besselian [2], [3] transverse intensity distribution almost unchanged along the optical axis. These distinctive properties have put axicons into a variety of applications such as plasma and atomic waveguides [4]–[7], energy concentration [8], spatial alignment [9], laser machining [10], optical readout and processing [11], and optical coherence tomography [12]. Long and thin polymer fibers made with axicon lenses have also been reported [13]. The classical axicon, generally known as a cone, is characterized by linear growth of the on axis intensity. But in some cases, such as optical scanning [9], light sectioning, etc., uniform intensity distribution along the optical axis is needed. Logarithmic axicon (LA) [14], which has a profile of a logarithmic-curved surface, provides the desired performance combining both the property of a cone axicon and uniform intensity distribution along the optical axis. This prominent characteristic may also find applications in complicated systems that integrate optical, electrical and mechanical functions. Substituting a common lens, an LA focuses a signal into a wider range rather than a focal spot and its vicinity, reducing wobble and connection errors in signal transmission. Capable of large-focal-depth imaging, an LA may be applied to improving the image processing ability of the system [15], [16]. In addition, this element can be used in generating uniform waveguides for plasma and atoms as well as in capturing and rotating [17]–[19] micro-particles, which may be involved in the functions of chip labs. All the applications in integrated multifunctional systems require the elements to be integratable and miniaturized. However, traditional technologies, such as grinding and photolithography, are against much difficulty in precisely controlling the shaping of complicated surfaces on the micro- and nano-scale.

Fortunately, laser direct writing technology, especially the microfabrication technology based on two-photon absorption induced polymerization, has provided an easy and efficient way of solving the problem. It allows the possibility of fabricating complicated surfaces and three dimensional (3-D) structures as well as their micro- nano-versions in high accuracy and material compatibility [20]–[23]. With the help of this technology, we are able to create an LA with a nonquadratic curved surface smaller than 200 μm in diameter, which is difficult to produce with either a grinding machine or a photoetching machine. Besides being sufficiently small in size, the LAs to be shown in this letter are more compatible to the system because part of or even the whole system could be created from the same material (e.g., photoresist) by right of the advantage in 3-D scanning fabrication. In addition, the material consistency of the system components also makes it possible to produce the mould of the whole system in one step if the system needs translating into another material. Since the refractive index of polymerized photo-resist is known beforehand, we are capable of depicting minute details of the logarithmic surface to make performance designs possible.

II. Principle

In 1992, Sochacki *et al.* [14] developed the generalized design of an axicon with arbitrary axial intensity distribution. Shown in Fig. 1, a plane wave propagating along the optical axis z passes through the revolution-symmetric phase element of radius R and then gets concentrated between points d_1 and d_2. In order to specify the phase transmittance function

$$\mathrm{t}(r) = \exp\left[i\frac{2\pi}{\lambda}\varphi(r)\right], \quad r = \sqrt{x^2+y^2}, \qquad (1)$$

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we utilize the energy balance condition, which yields

$$2\pi P_\sigma(r)rdr = \pm P_z(z)dz \tag{2}$$

meaning that the two-dimensional power density $\mathrm{P}_\sigma(\mathrm{r})$ of the incident light wave is converted into the one-dimensional on axis power density $\mathrm{P_z(z)}$ between d_1 and d_2. There are actually two situations (corresponding to $+$ and $-$ in (2) that the incident wave is concentrated into the focal line segment: the one of $+$ is that the paraxial rays are focused in the vicinity of the point $\mathrm{z = d_1}$ while the off axis rays move towards $\mathrm{z = d_2}$ (Fig. 1(a)); the other is the opposite (Fig. 1(b)). By integrating (2) we get

$$2\pi \int_0^r P_\sigma(r)rdr = \int_{d_1}^{z(r)} P_z(z)dz \tag{3}$$

for the plus sign and

$$2\pi \int_0^r P_\sigma(r)rdr = \int_{z(r)}^{d_2} P_z(z)dz \tag{4}$$

for the minus sign, both of which help us to specify $\mathrm{z = z(r)}$ and then determine the phase-retarding factor $\varphi(\mathrm{r})$ by integrating the equation

$$\frac{d\varphi(r)}{dr} = -r[r^2 + z^2(r)]^{-\frac{1}{2}} \tag{5}$$

In the case of a focal line segment with uniform intensity distribution under the illumination of a uniform plane wave, both P_σ and $\mathrm{P_z}$ are supposed to be constant, thus we obtain

$$z(r) = d_1 \pm ar^2, \tag{6}$$

$$a \equiv \frac{\pi P_\sigma}{P_z} = \frac{(d_2 - d_1)}{R^2} \tag{7}$$

and then (5), finally we arrive at

$$\varphi(r) = -\frac{1}{2a}\ln\left\{2a\left[a^2r^4 + (1-2ad_2)r^2 + d_2^2\right]^{\frac{1}{2}} + 2a^2r^2 + 1 - 2ad_2\right\} + \text{const} \tag{8}$$

$$\varphi(r) = -\frac{1}{2a}\ln\left\{2a\left[a^2r^4 + (1+2ad_1)r^2 + d_1^2\right]^{\frac{1}{2}} + 2a^2r^2 + 1 + 2ad_1\right\} + \text{const} \tag{9}$$

(8) profiles a LA called forward logarithmic axicon (FLA) corresponding to the first situation mentioned above while (9), backward logarithmic axicon (BLA). In some cases, an optical element with a complicated curved surface determined by (8) or (9) is transformed into another version for easy fabrication. For instance, if photolithography is employed, a monolithic refractive LA is divided equivalently into two parts that include a focusing element (usually a common lens) and a focus-stretching element mainly to avoid a mask with too small linewidth. However, this method may result in new problems like alignment error and more uncertain fabrication error added up with that of each element. Apart from this, a hologram version of the LA is also usually adopted but a restricted diffractive efficiency should be considered. Despite these cases, when it comes to fabrication, the phase retardation functions defining the "original version" of the LA need to be transformed into the thickness function that determines the geometrical shape of the LA in common lens design.

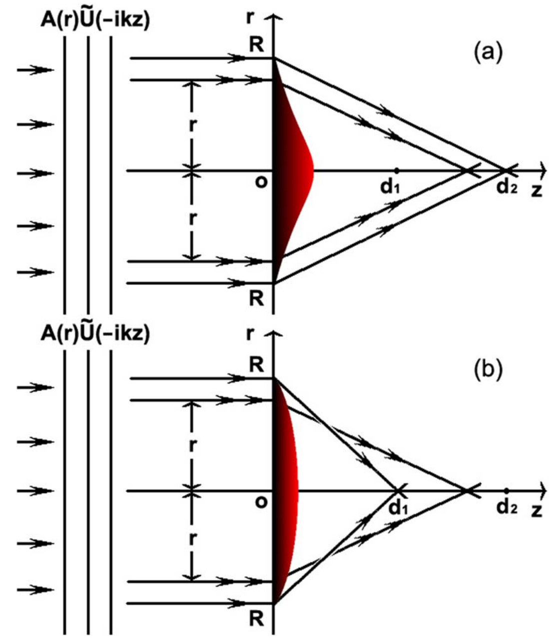

Fig. 1. (a) Forward logarithmic axicon and (b) backward logarithmic axicon.

III. Experiment

Shown in Fig. 2 are the SEM (Scanning Electron Microscopic) images of the geometrical shape of the LAs defined by (8) and (9). The one in the bottom is a skew view image, and the rest six are lateral ones, which belong to three FLAs (on the left side) and three BLAs (on the right side) respectively. We selected different pairs of d_1 and d_2 so as to show prominently the logarithmic profiles and the difference from one another. All LAs are made of commercial photo-resist SU-8 2075 photopolymerized. This photo-resist has been widely used due to high transmittance of from the visible to near infrared wavelengths, low volume shrinkage, good mechanical properties (Young's modulus $\sim$4$-$5 GPa and biaxial modulus of elasticity $\sim$5.2 GPa), and high thermal stability (degradation temperature $\sim$380°). The femto-second laser pulses of wave length 800 nm with pulsewidth of 120 fs, mode-locked at 82 MHz (from Tsunami, Spectra Physics) were tightly focused by a $100\times$ objective with a numerical aperture of 1.40 so as to induce polymerization in the focal spot of high power density. The power of the focused laser was 0.1 mW. An LA was first designed with a CAD (Computer Aided Design) program and transformed into data of point coordinates. Controlled by the fabrication program that had read the data, a two-galvano-mirror set along with a 1-D piezo stage where located the sample made the focal spot move three dimensionally relative

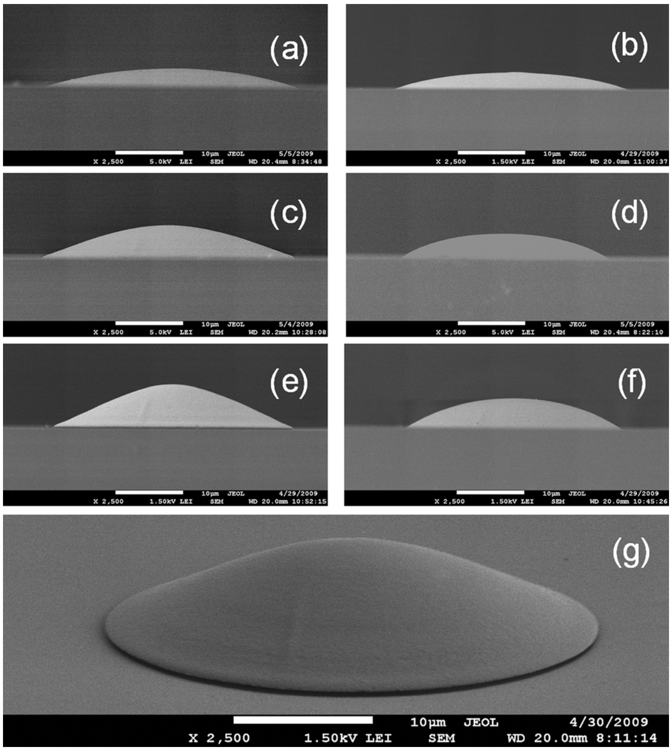

Fig. 2. Logarithmic axicons with different pairs of d_1 and d_2. (a), (c) and (e) are lateral views of FLAs; (b), (d), (f) are of BLAs. (g) is a skew view of (e).

to the sample resist, which had been coated on a cleaned glass substrate and treated in a standard procedure recommended by MicroChem (the manufacturer of SU-8). The smallest pace of the motion is as accurate as 1 nm. The photo-resist embedding the laser written structures was then immersed in the developer (containing 1-methoxy-2-propanol acetate) so that the unpolymerized photo-resist could be removed, leaving the expected structures for property examinations.

IV. Results and Discussion

We adopted a semiconductor laser with a wave length of 532nm for the focusing examination. The LAs were immersed in the acetone solvent of rhodamine B which gives off yellow fluorescence when excited by a 532 nm laser. The focal line segment shown in Figs. 3(a)–(c) is longer than another in order, as the parameters for each are: (a) $d_1 = 150\ \mu m$, $d_2 = 250\ \mu m$; (b) $d_1 = 150\ \mu m$, $d_2 = 400\ \mu m$; (c) $d_1 = 250\ \mu m$, $d_2 = 650\ \mu m$; $R = 50\ \mu m$ the same for all three. The mismatch of the parameters of design and that Fig. 3 shows may be qualitatively explained as follows: To some extent, an LA may be regarded as a combination of a series of annular-aperture lenses whose foci line up to be the focal line segment. Since the focal distance of a lens gets larger in a media with higher refractive index (still lower than that of the lens), the d_1 and d_2, which could be regarded as the foci of the lenses in the center and in the edge (or the opposite) of the LA, should scale up and so do their difference $(d_2 - d_1)$. This means the focal line segments of the LAs immersed in acetone $(n \approx 1.36)$ are longer and farther from the elements than in air $(n \approx 1)$. There was no obvious difference between FLAs and BLAs in

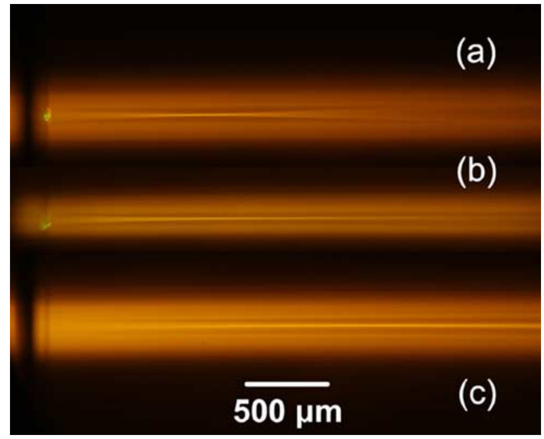

Fig. 3. Lateral view of focal line segments with different lengths.

appearance of focusing in rhodamine B, so we took only BLAs for comparison.

Besides the large focal depth, another remarkable property of an axicon is the generation of an approximation of Bessel-type beam, which preserves the transverse intensity distribution as propagates, as is also known as nondiffracting. Due to the finite aperture, no optical element can generate an absolutely nondiffracting wave. Nevertheless, the possibility that a wave front varies in an inconspicuous way within a certain range still exists on sophisticated designs. We took a He:Ne laser as the incident wave in order to observe the Bessel-beam-approximated distribution in the transverse planes normal to the optical axis. Shown in Figs. 4(a)–(f) are the images of the rear field, which were shot every 40 micrometers along the optical axis by a CCD camera and appear to be almost identical in a range of 200 μm (but note that the distribution does not preserve throughout the focal range, of which the 200 μm span is only part, where the distribution does not change that obviously, here $d_1 = 800\ \mu m$, $d_2 = 1300\ \mu m$, and $R = 50\ \mu m$). To some extent, these images could be looked upon as images of the source emitting the incident plane wave; in fact, an LA can go further into imaging.

Since one of the most important functions of a lens is imaging, an LA, which may be regarded as a combination of numberless annular-aperture lenses whose foci line up to be the focal line segment is certainly expected to have an imaging property, which enables the element to focus an object into infinite images standing along the focal line segment. As a matter of fact, an LA does act like a lens with a stretched focal point. As Figs. 5(a)–(f) show, a group of homogeneous images (we took the letters LA as the object) were observed in equidistant places (note that the range of images does not coincide with the focal range of an LA as if real images never reside in the focal point of a common lens). In contrast, a common lens with a focal length of $(d1 + d2)/2$ and the same radius as that of the LA shows full degradation of imaging soon after deviation from the in-focus area (Figs. 5(g)–(i)). The reason why the images formed by the LA is not as clear as the one in- focus formed by a common lens is attributable to the side-lobe rings that exist in a Besselian distribution. The side-lobe rings disperse the energy from the object space; as a result, the image of each point

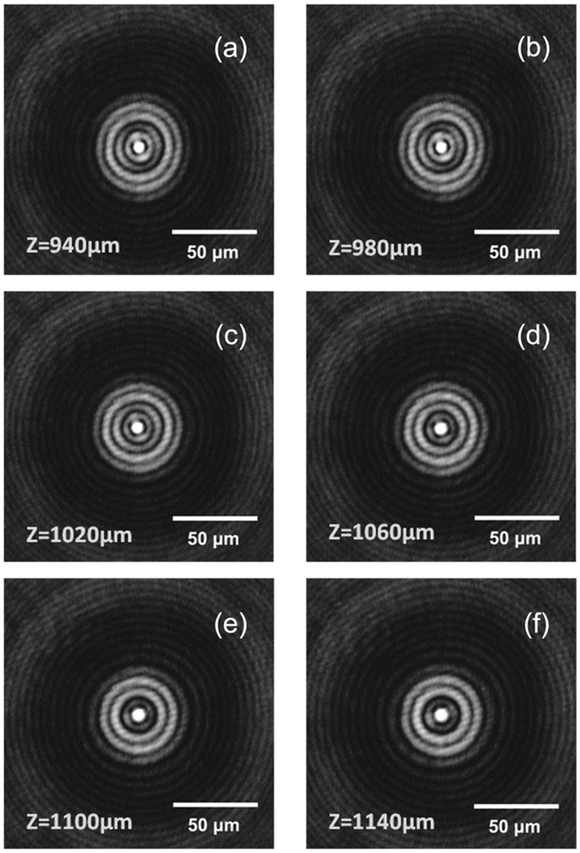

Fig. 4. Approximate Bessel distribution on different cross sections.

of the object is no longer a single spot, but a spot with countless concentric rings around, which decreases the definition of the whole image. Another noticeable point is that, as Figs. 5(a)–(f) show, the image grows, though not in a rapid way, as Z increases. A qualitative analysis can be given by the analogy mentioned above that an LA may be regarded as a combination of numberless annular-aperture lenses. According to the transverse magnification formula of thin lenses

$$V = -\frac{f}{x} \tag{10}$$

where V is the transverse magnification, f the focal length, x the distance between the object and the focal point in the object space ($x > 0$ when the object is farther than the focal point is from the lens; otherwise $x < 0$), the size of an image only depends on f of the corresponding infinitesimal lens, for x is constant. So the image grows in direct proportion to the distance Z, which may be considered as f. Despite all the weaknesses above, the micro LA still holds an advantage as an imaging element due to its distinctive property-large focal depth. With the micro LA substituting a common lens, a super micro camera would have a larger depth of field, meaning not only the object, but also both the foreground and the background would be recorded sharply when especially taking a close shot. This would improve significantly the performance of cameras or monitoring devices applied in many fields.

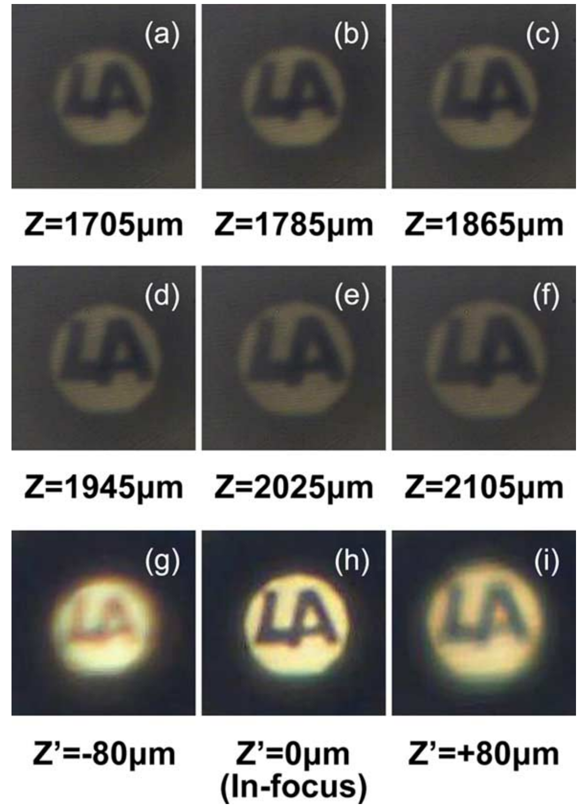

Fig. 5. (a)–(f) Images formed by a logarithmic axicon along the optical axis and (g)–(i) those formed by a common lens.

V. Conclusion

In conclusion, we fabricated the micro monolithic refractive logarithmic axicon, which has comparatively large (compared with Rayleigh range) focal depth, by the laser direct writing technology. And some outstanding properties that distinguish this element from others are presented. The microscale size along with the distinctive properties may qualify the logarithmic axicon for applications in micro-optics, guided-wave optics and other complicated integrated systems involving multiple functions concerning optics, electronics, and mechanics. This work shows the promising prospects of micro logarithmic axicons as well as the power of micro-nano fabrication technology of laser direct writing.

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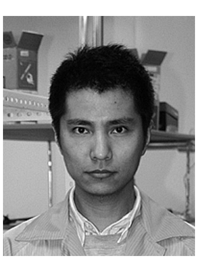

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