Birefringent Fresnel zone plates in silica fabricated by femtosecond laser machining

Erica Bricchi, John D. Mills, Peter G. Kazansky, and Bruce G. Klappauf

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

Jeremy J. Baumberg

Department of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK

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We demonstrate maskless, single-step fabrication of strongly birefringent Fresnel zone plates by focusing of femtosecond laser pulses deep within silica substrates. The process allows us to produce alternate zone rings directly by inducing a local refractive-index modification of the order of $n \sim 10^{-2}$. The embedded zone plates shown in this Letter exhibit efficiencies that vary by as much as a factor of ~6 for orthogonal polarizations. Focal lengths of primary and secondary foci are shown to compare well with theory. © 2002 Optical Society of America

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Fresnel zone plates are attractive devices for micro-optics because of their focusing abilities and compactness.[1] However, methods of fabrication are usually based on either lithographic[2,3] or etching techniques.[4] In this Letter we report a system for producing zone plates by use of a femtosecond laser to machine individual zone rings within the bulk of silica. The process offers advantages compared with current zone plate fabrication because it is a one-step procedure and has the potential for creating polarization-sensitive, integrated multilens systems in three dimensions. Indeed, the microfabrication of structures within the bulk of transparent materials with focused femtosecond laser pulses has garnered increasing interest in recent years.[5,6] Within the focal volume, nonlinear absorption causes energy to be deposited that induces a permanent refractive-index modification.[7] By translation of a sample relative to the focus of the laser, a variety of photonic devices has been created.[8,9] Because of the facility of index manipulation, this direct-write procedure is well suited to creating the phase variations that are necessary for efficient production of Fresnel zone plates. Figure 1 shows the setup for the lens fabrication. A regeneratively amplified, mode-locked Ti:sapphire laser operating at wavelength $\lambda = 850$ nm with 150-fs pulse duration and 250-kHz repetition rate was utilized. Its beam passed through a shutter, a variable neutral-density (ND) filter, and a half-wave plate before a dichroic mirror reflecting in the 400–700-nm region. The laser light was then focused to a beam-waist diameter of ~1.5 μm via a 50× (N.A., 0.55) objective into a fused-silica plate at a depth of 0.5 mm. The sample was mounted upon a three-dimensional (3-D) translation stage of 20-nm resolution. A white-light source enabled the structure to be monitored by a charge-coupled device (CCD) camera to enable the writing process to be observed.

A Fresnel zone plate consists of a series of concentric rings whose outer radius R_m is determined by

$$R_m = \sqrt{mf\lambda}\,, \tag{1}$$

where m is the number of the mth Fresnel zone, λ is the wavelength of light in vacuum, and f is the primary focal length.[10] Figure 2 shows a microscope image of the central region of a zone plate (lens A) created by the direct-write method. The image, acquired by positioning of the lens between cross polarizers, demonstrates the strong birefringence of this structure. Lens A has a maximum radius of 1 mm, has 70 zones, and is designed to focus light with wavelength $\lambda = 632.8$ nm at a length of 2.4 cm. The writing energy was 1.3 μJ/pulse. To produce the quasi-uniform regions of index variation in odd-numbered zones we translated the sample in circles of ever-increasing radius at a constant speed of 400 μm/s. Even-numbered zones were not touched.

In addition to a primary focus, Fresnel zones plates have secondary foci positioned on an axis toward the lens, characterized by much weaker intensity.[11] To measure the positions of these foci in the case of directly written zone plates we examined a further sample (lens B). This lens was written with lower energy than lens A at 1.1 μJ/pulse but at an identical speed. It has a maximum radius of 1 mm, has 158 Fresnel zones, and is designed to focus light with wavelength 632.8 nm at a length of 1 cm. To enable

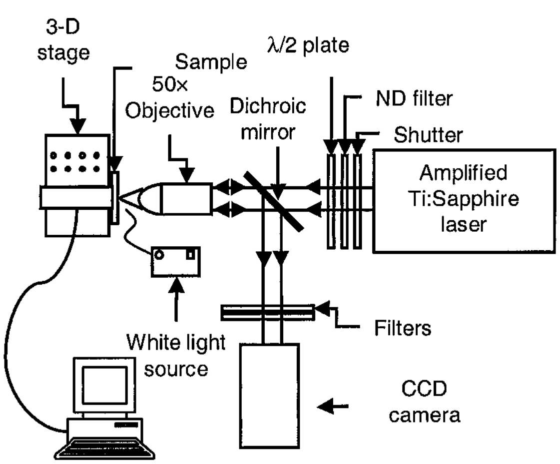

Fig. 1. Experimental setup for single-step fabrication.

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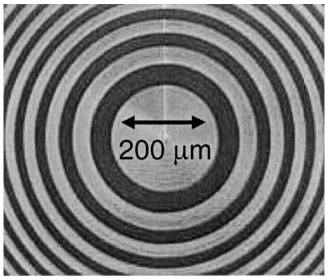

Fig. 2. Microscope image of the central part of a femtosecond directly written Fresnel zone plate positioned between cross polarizers. Bright regions correspond to the laser-processed area.

the positions of its primary and secondary foci to be recorded, we directed a white-light source through various transmission interference filters in turn before it became incident upon the zone plate itself. An objective mounted upon a translation stage was subsequently placed behind the zone plate such that it could be moved along the axis of the plate. We used a CCD camera to identify the focal positions. Effective focal positions were examined for wavelengths of 488, 550, and 642 nm. The results are displayed in Fig. 3, where focal positions (points) are compared with theory (lines). The theoretical plots given in Fig. 3 take into account the dual media of silica and air (see Fig. 3, inset) and are calculated from the standard equation[1]

$$f = f_1 \lambda_1 / \lambda\,, \tag{2}$$

where f_1 and λ_1 are the value of the focal length and the wavelength, respectively, used in Eq. (1), λ is the wavelength of interrogating light, and f is its particular focal length. The experimental results are within 1% of theory. However, theory predicts a series of odd secondary foci at $f/3$, $f/5$, etc.[11] only, but for lens B there are identifiable even secondary foci at $f/2$ and $f/4$. This anomaly can be explained in terms of the zones that have slightly unequal areas.[11] For the directly written zone plates this unequal area is due to the writing resolution, which for our setup is ~1.5 μm. To demonstrate the focusing quality of a directly written zone plate we show in Fig. 4 an image of the University of Southampton logo produced by lens B. The logo was illuminated with white light and imaged through the zone plate. An interference filter and a polarizer were positioned before the lens, and the focal plane was recorded with a charge-coupled device camera. The object size at ~4-mm diameter can be compared with the image size in the focal plane of ~600-μm diameter.

The technique of femtosecond direct writing has been observed to cause material anisotropy[12] and to create permanent birefringence above a certain threshold of writing fluence.[13] Recently, evidence of the primary cause of this anisotropic behavior, which occurs at ~0.5 μJ/pulse,[14] was published. It follows that different polarizations of light incident upon a zone plate created under these conditions will see different refractive indices and therefore phases at the written regions. With much higher writing fluence as for lenses A and B, strongly birefringent zone plates can be created with efficiencies that vary by as much as a factor of ~6 for orthogonal polarizations. These lenses show the interesting property of having a selective ability to focus orthogonal polarizations independently, which may be useful for integrated optical circuits or microelectromechanical systems applications that require both focusing and polarization sensitivity.

Table 1 elucidates these properties by listing a range of efficiencies calculated as a function of wavelength and polarization for lenses A and B. The direction of polarization of the interrogating light is either parallel (xx) or perpendicular (xy) to the direct-write laser polarization. The efficiency was derived as the ratio of power in each primary focus to total power incident upon the zone plates.

It is interesting to note by examination of Table 1 that wide ranges of efficiencies for lenses A and B are produced. This is a result of the varying degrees of interference that result from phase variations induced by the index-modified zones.[10] Zone plates that focus as a function of a phase variation induced in alternate zones have a theoretical maximum efficiency of approximately 40%, assuming a variation of π and 100% transmission. This result can be compared to that of absorbing zone plates that have a maximum efficiency of just 10%.[15] With a recorded efficiency of 39%, our

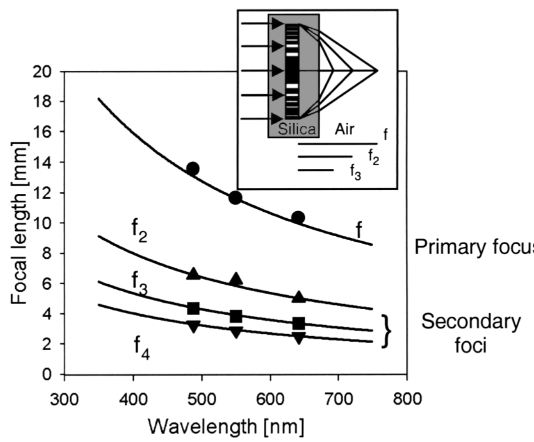

Fig. 3. Measured focal lengths (points) and theoretical focal lengths (curves) of lens B.

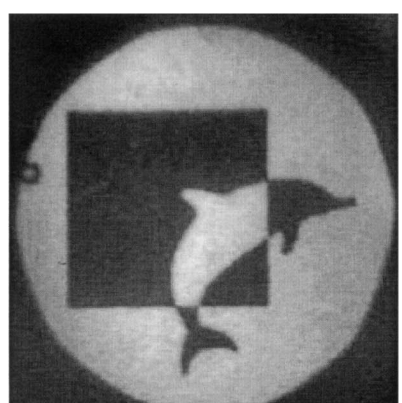

Fig. 4. Image of the University of Southampton logo produced by an embedded Fresnel lens.

Table 1. Experimental Results of Efficiency and Index Modification of Lenses A and B for Given Interrogating Wavelengths and Polarization

Lens	λ (nm)	Polarization	Efficiency (%)	Index Change ($\times 10^{-3}$)
A	404	xx	39	6.2
A	404	xy	11	2.4
A	550	xx	34	6.9
A	550	xy	10	3.1
A	642	xx	26	6.4
A	642	xy	9	3.4
B	404	xx	28	4.3
B	404	xy	7	1.9
B	550	xx	24	5.2
B	550	xy	4	1.9
B	642	xx	17	4.9
B	642	xy	3	1.9

results therefore indicate that the directly written zone plates behave as phase lenses. To estimate the phase variation produced by our particular writing parameters, we used two methods of characterization. First, we subsequently tested embedded diffraction gratings written into the bulk of silica under similar writing conditions to lens B by examining the diffracting orders of a He–Ne ($\lambda = 632.8$ nm) laser for both xx and xy polarizations. We then initiated numerical methods to simulate the results, using Fresnel–Kirchhoff theory. From this procedure, estimated index variations at the modified regions of $\Delta n \sim 2 \times 10^{-3}$ (xy) and $\Delta n \sim 9 \times 10^{-3} (xx)$ were deduced. Second, we utilized the recorded efficiencies given in Table 1 to estimate the refractive index from the thickness (~ 30 μm) and the transmission coefficient (~ 0.96) of the zone plates by using the integrals described by Kirz.[10] These values were then averaged to give estimated index variations of $\Delta n \sim (2, 3) \times 10^{-3} (xy)$ and $\Delta n \sim (5, 6.5) \times 10^{-3} (xx)$, where the greater value corresponds to the higher writing fluence. The phase variations between the silica (untouched) zones and the modified zones were subsequently estimated from the latter method to be $\sim 0.2\pi$, $\sim 0.3\pi$ (xy) and $\sim 0.5\pi$, $\sim 0.6\pi$ (xx), respectively, for an interrogating wavelength of 632.8 nm. Indeed, the high efficiencies listed in Table 1 indicate that phase variations between alternate zones of $\sim\pi$ can easily be achieved. This is interesting because full-range controllability of phase across these embedded objects offers the possibility of manufacturing other optical components such as embedded wave plates.

In summary, we have demonstrated the single-step production of strongly birefringent, embedded Fresnel zone plates by femtosecond laser direct machining. The process offers potential for polarization-sensitive, integrated multilens systems. We are currently working to maximize the potential of the anisotropic zone plates for individual design wavelengths.

E. Bricchi's e-mail address is erb@orc.soton.ac.uk.

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