# Volume Fresnel zone plates fabricated by femtosecond laser direct writing

Pornsak Srisungsitthisunti
*School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907*

Okan K. Ersoy
*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907*

Xianfan Xu[a)]
*School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907*

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In this letter, volume Fresnel zone plates fabricated inside fused silica using femtosecond laser direct writing are demonstrated. A volume zone plate consists of a number of layers of Fresnel zone plates designed to focus light together. Results indicate that volume Fresnel zone plates increase the overall diffraction efficiency significantly. Phase zone plates yield considerably higher diffraction efficiency due to a number of reasons including negligible light absorption, robustness against fabrication phase errors, and minimum interference between different zone plates in a volume.
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Recently, femtosecond pulsed lasers have become a powerful tool for fabrication of microdevices inside bulk of transparent materials. Tightly focused femtosecond laser pulses induce nonlinear absorption within the focal volume and permanently modify the index of refraction of the materials.[1,2] By utilizing this effect inside a transparent material, many types of optical devices such as waveguides,[2,3] gratings,[4] and microlenses[5–7] have been fabricated.

Fresnel zone plates fabricated by femtosecond laser direct writing have gained much attention because they are compact and effective in many microimaging applications. A Fresnel zone plate having a focal length $f$ is constructed with a series of concentric zones with radii defined by[8]

$$r_n^2 + f^2 = \left(f + \frac{n\lambda}{2}\right)^2, \tag{1}$$

$$r_n = \sqrt{n\lambda f + \left(\frac{n\lambda}{2}\right)^2} \simeq \sqrt{n\lambda f}, \tag{2}$$

where the integer $n$ indicates the $n$th Fresnel zone. When the alternating zones have different transmission properties, the incident light onto a zone plate is diffracted, producing a focus spot. In general, there are two types of binary zone plates: amplitude zone plate and phase zone plate. In amplitude zone plates, either all the odd zones or even zones are opaque. If either the odd or even zones have a different index of refraction that induces a phase change over the zone plate's thickness, such zone plates are called phase or "phase-reversal" zone plates. The main advantage of phase zone plates is their high diffraction efficiency. Binary phase zone plates have maximum diffraction efficiency of about 40% whereas the amplitude zone plates have maximum efficiency of about 10%.[7]

Studies of direct laser fabrication of Fresnel zone plates inside fused silica have been reported for both amplitude-type zone plates[5] by utilizing scattering damage and phase-type[6,7] zone plates by refractive index change induced by femtosecond laser pulses. However, all the previously studied zone plates had low diffraction efficiency because of effects such as scattering from damaged regions, phase errors due to nonuniform index change inside fused silica, and planar zone plate geometry. In this work, we investigate the effect of increasing the number of Fresnel zone plates or modified Fresnel zone plates within a volume, which we call volume zone plates, to achieve high diffraction efficiency. These volume Fresnel zone plates having various numbers of layers were fabricated inside fused silica by femtosecond laser direct writing. Each volume Fresnel zone plate of amplitude type or phase type operates as a single diffractive optical element with a much higher diffraction efficiency than a single zone plate.

A volume Fresnel zone plate consists of a number of layers of zone plates or modified zone plates in a volume of a suitable material, such as fused silica. In this work, the zone plates were centered on the same optical axis. This is visualized in Fig. 1, together with variables of interest for further discussion.

A volume zone plate should satisfy focal point matching and phase matching. For this purpose, each zone plate should be designed according to its position along the optical axis ($z$ axis) so that all the zone plates focus light exactly at the same focal point. Furthermore, the diffracted light from all the zone plates must be "in phase," in other words, their

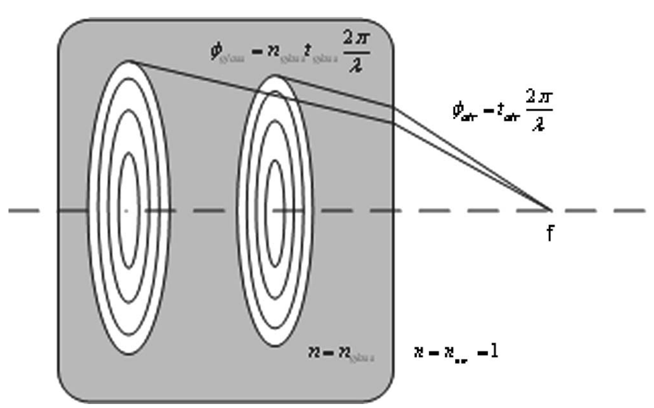


FIG. 1. Geometry used in phase computations with volume zone plates.

[a)]Electronic mail: xxu@ecn.purdue.edu

 

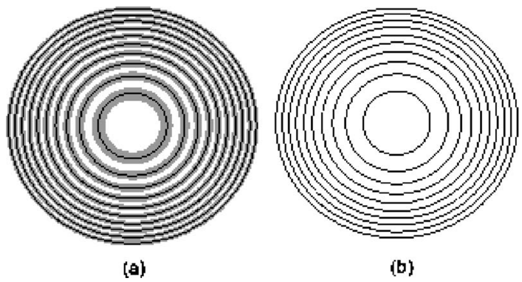


FIG. 2. (a) "Full" Fresnel zone plate showing central rings in the middle of each zone. (b) Modified zone plate with central rings, with thickness determined by laser writing.

phase shifts are matched at the focal point so that the diffracted light from all the zone plates constructively interfere at the focal point. Equations (1) and (2) are valid only when a Fresnel zone plate diffracts light in a medium of constant index of refraction. For our case, we also take into account the effect of the refractive index of fused silica and the refraction of light at the air-silica interface.

The phase shift due to wave propagation in a homogeneous medium is given by[9] $\phi(z)=nt2\pi/\lambda$, where $n$ is the index of refraction of the medium, and $t$ is the propagation distance, as shown in Fig. 1. Numerically, we adjust the radii of the zones in each Fresnel zone plate to satisfy the phase matching requirement. For this purpose, two zone boundaries as shown in Fig. 2 are adjusted during design by using Eqs. (3) and (4) below, such that their phase remainders are equal ($b_1=b_2$) at the end of numerical iterations:

$$\phi_1 = \phi_{\text{air},1} + \phi_{\text{glass},1} = \frac{2\pi}{\lambda}(t_{\text{air},1} + n_{\text{glass},1}t_{\text{glass},1}) = \frac{2\pi}{\lambda}m_1 + b_1, \tag{3}$$

$$\phi_2 = \phi_{\text{air},2} + \phi_{\text{glass},2} = \frac{2\pi}{\lambda}(t_{\text{air},2} + n_{\text{glass},2}t_{\text{glass},2}) = \frac{2\pi}{\lambda}m_2 + b_2. \tag{4}$$

When all the modified zones have the same phase shift at the focal point, the volume Fresnel zone plate has the highest efficiency.

A rigorous analysis of wave propagation through a volume Fresnel zone plate involves diffractive interactions of all the modified zone plates. The light diffracted from each modified Fresnel zone plate could be considered to be a small percentage of the total beam in this preliminary work. Hence, only the main input wave is assumed to be diffracted from each modified Fresnel zone plate.

This assumption is more true when central rings instead of full zones are used, especially with phase zone plates. In this approach, each complete zone is replaced by a single central ring in the middle of the zone, as shown in Fig. 2. Such zone plates are also fabricated in this work, as will be shown below. With this approach, several advantages are achieved. Implementation time is greatly reduced. Since the central circle of each ring corresponds to the exact phase desired, the method is robust against small implementation errors.[10] Therefore, the advantages of central rings replacing full zones are especially amplified in the implementation of volume zone plates.

In experiments, we placed a fused silica sample with optically polished surfaces on a computer-controlled $x$-$y$-$z$ air bearing stage which had a translational accuracy of 200 nm. The sample was irradiated by 90 fs pulses delivered by a Ti:sapphire amplified laser system at a central wavelength of 800 nm and 1 kHz repetition rate. The laser beam was attenuated by a polarizer before being focused inside the bulk of fused silica using either 5× [numerical aperture (NA) of 0.15] or 50× (NA of 0.55) objective lens. An electronic shutter was connected to the computer controller, allowing the laser exposure and the stage movement to be synchronized. The fabricated volume Fresnel zone plate had the primary focal length of 20 mm at the wavelength of the He–Ne laser (632.8 nm). The volume Fresnel zone plate consisted of up to 20 zones, each with a diameter of about 1 mm.

Our first study was to fabricate single layer Fresnel zone plates and to characterize the effects of pulse energy and writing speed. We fabricated phase zone plates by utilizing the change of the index of refraction induced in the medium by the femtosecond laser beam. Using the 5× objective lens, we fabricated phase zone plates at a writing speed of 10 $\mu$m/s and pulse energy of 7–14 $\mu$J. When using such a low numerical aperture lens, the change of the index of refraction was induced over a long length which is determined by the Rayleigh range,[8] i.e., a 100 $\mu$m-long filament of refractive index change was produced by each pulse. The maximum increase of index of refraction caused by the femtosecond laser irradiation was reported[1–3] in the order of $10^{-3}$. Thus, a $\pi$ phase shift, which is required for a phase zone plate, could be achieved when the length of the modified region reaches $t=\lambda/2\Delta n=300$ $\mu$m. To obtain a $\pi$ phase shift, we either need to increase the refractive index change or extend its length to approximately 300 $\mu$m. The latter was more feasible but very time consuming. For a single layer phase zone plate, the fabrication time was about 18 h. Clearly, this long fabrication time was a drawback, especially for implementing volume zone plates.

To reduce the fabrication time as well as other reasons discussed above, the phase zone plates were modified by replacing each "full" zone with a single central ring in the middle of the zone, as shown in Fig. 2. The width of each ring was determined by laser writing conditions; our linewidth of the refractive index change was about 5 $\mu$m. With this approach, the fabrication time of a modified phase zone plate was reduced to 1 h.

Single layer amplitude zone plates were fabricated using much higher pulse intensity to create scattering damage. In this study, we used a 50× objective lens and a high pulse energy of 10–30 $\mu$J to fabricate amplitude zone plates with a writing speed of 0.5 mm/s. Fabrication of an amplitude Fresnel zone plate took 15 min. When the full Fresnel zone plate was approximated by the zone plate with central rings, the fabrication time of an amplitude zone plate was reduced to 1 min.

After characterization of the single layer zone plates, we fabricated volume Fresnel zone plates for both amplitude type and phase type, with and without central rings used. The volume zone plates were fabricated layer by layer starting from the deepest layer from the surface facing the laser. Each layer was carefully placed according to the design to assure that all layers would focus light together with constructive interference. The separation distance between the layers was of the order of 100 $\mu$m, and the zone plate closest to the

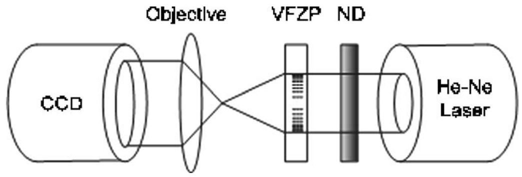


FIG. 3. Experimental setup for efficiency measurement.

surface was fabricated approximately 500 $\mu$m beneath the silica surface.

We measured the diffraction efficiency of the volume Fresnel zone plates using a He–Ne laser at a wavelength of 632.8 nm. The diffracting efficiency of each zone plate was calculated as the ratio of the intensity of diffracted light at the focus point to the intensity of light incident onto the zone plate. The experimental setup for the efficiency measurements is shown in Fig. 3. The He–Ne laser beam was attenuated by a natural density filter and focused by the Fresnel zone plate. The diffracted beam at the focal point was first imaged by a 10× objective lens and then imaged onto a charge coupled device (CCD) camera. The CCD camera was connected to a frame grabber which converted the analog intensity input into a digital output, which was analyzed by the BEAMVIEW analyzer software (Coherent, Inc.). Alternatively, we also measured diffraction efficiency directly by using a low-power detector that had sensitivity up to picowatts ($10^{-12}$ W). Pinholes with different sizes were placed in front of the detector to selectively block unwanted light when measuring the light intensity at the focal point.

Our single layer phase zone plates showed maximum efficiencies of 16.4% for a full zone and 5.3% for a zone plate with central rings. This low efficiency was due to the small change of the index of refraction which was insufficient to induce a $\pi$ phase shift. By adding more layers to build a volume phase zone plate, the efficiency of a volume zone plate with central rings was improved to 59.1% with eight layers of phase zone plates. Figure 4 shows the measured efficiencies of volume Fresnel zone plates as a function of the number of layers of zone plates.

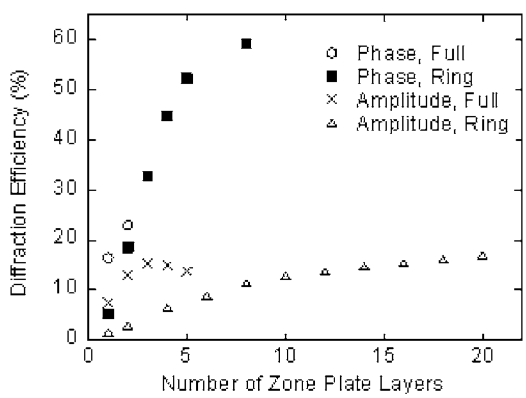


FIG. 4. Diffraction efficiency as a function of the number of modified phase and amplitude zone plates in a volume.

The fabricated single layer amplitude zone plates had an efficiency of 7.5% for a full amplitude zone plate and 1.5% for an amplitude zone plate with central rings. The volume amplitude zone plate reached a maximum efficiency of 15.4% with three layers and further adding of more layers caused decrease in efficiency. With volume modified amplitude zone plates based on central rings, the efficiency reached 17.0% with 20 layers, which was the maximum number of layers we fabricated.

The focal spot produced by the eight layer phase volume zone plate was 20 $\mu$m which agreed with the theoretical value of 19.3 $\mu$m. We also measured the transmission of total light passing through volume zone plates. We found out that the transmitted light of phase volume zone plates was constant, whereas the transmitted light of amplitude volume zone plates decreased as more zone plates were added (86%, 75%, 72%, and 68% of transmission for 1, 6, 10, and 20 layers of amplitude volume zone plates with central rings, respectively). This is a factor that affects the efficiency of the volume amplitude zone plates as the number of the zone plates was increased. The volume phase zone plates had a significant increase in efficiency as more layers were generated due to the fact that no light is lost in the zone plates. In general, the results confirmed that all the zone plates worked in coherence together, as a result of using the design of modified zone plates, as discussed previously.

In conclusion, we designed and fabricated volume phase and amplitude Fresnel zone plates inside fused silica by femtosecond laser direct writing. These multilayer zone plates constructively focused light at the focal point and increased the diffraction efficiency significantly. Light absorption and attenuation were a diminishing factor in limiting the increase in efficiency in amplitude zone plates. The phase volume zone plate with central rings is more effective than others in achieving high diffraction efficiency.

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