High efficiency multilevel phase-type Fresnel zone plates produced by two-photon polymerization of SU-8

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Abstract
In this paper, we report on high quality two-level phase-type Fresnel zone plates (FZPs) produced by femtosecond laser two-photon polymerization of the resin SU-8. The optical focusing property was tested using a simple experimental setup. Moreover, the lens imaging functions ‘JLU’ and ‘吉大’ (English and Chinese abbreviations for Jilin University) were also demonstrated. In order to further enhance the diffraction efficiency, four-level and eight-level FZPs were designed using theoretical calculation and rapidly realized by point-to-point femtosecond laser scanning. In this way, the diffractive efficiency was enhanced from 35.8% for the two-level phase lens to 67% for the four-level phase lens and 73.9% for the eight-level phase lens, which are the largest values reported so far.

Keywords: two-photon polymerization, Fresnel zone plate, diffractive efficiency

In the past few years, femtosecond laser two-photon technology has been widely used to fabricate high precision micro-optical devices because of its many unique advantages. For example, compared with conventional lithography [1], femtosecond microfabrication does not need various expensive masks and all the models were designed by computer programs, so it is very simple to fabricate complex microstructures. In addition, femtosecond laser technology which is based on nonlinear absorption of two photons has higher resolution (~30 nm). Most importantly, it has a true three-dimensional processing capability due to its point-to-point scanning method. Therefore, femtosecond technology [2] has been recently considered as a promising approach for integrating various complex micro-optical devices towards integrated optical circuit use, e.g. for 3D photonic crystals [3–7], waveguides, couplers, beam splitters, Dammann gratings [8] and so on [9, 10]. Among these components, the Fresnel zone plate is an important kind of integrated optical device, usually used for microfocusing and microimaging. Many researchers have realized Fresnel zone plates in glass or polymer by femtosecond direct writing, and tried to improve its optical performance, especially as regards high efficiency, because diffractive efficiency is one of the most important parameters for diffractive optics. For example, Watanabe et al [11] first reported an amplitude-type Fresnel zone plate obtained by writing voids in glass that scattered the incident light through strong femtosecond laser pulses. Then they [12] fabricated phase-type diffractive lenses using filaments 30 μm long with refractive index change induced by a femtosecond laser. In this way, the diffractive efficiency was increased from 2% to 56.9%. In 2007, Xu et al [13] demonstrated volume Fresnel zone plates further enhancing the diffractive efficiency to 59.1% by sequentially packing a series of zone plates along the optical axis. These works made great progress towards FZP practical application in integrated optical systems. However, all the above research focused on glasses, in which the precise control of the refractive index change and the
thickness of the zone plates by femtosecond laser writing were
difficult due to the simultaneous existence of many nonlinear
effects including self-focusing. In 2006, Guo et al [14]
reported the first amplitude-type Fresnel zone plate fabricated
by femtosecond two-photon polymerization of the liquid resin
SCR 500. Then, Sun et al [15] realized multilevel phase-
type Fresnel zone plates in the liquid resin NOA61 by two-
photon polymerization. The maximum diffractive efficiency
reached 68%, much bigger than the largest values for glass.
Although great progress has been made towards achieving high
efficiency Fresnel zone plates, there are still big differences
between the measured values and the theoretical maximum.
In this paper, we report on high quality multilevel phase-
type Fresnel zone plates produced by femtosecond two-photon
polymerization [16–23] and further improve the diffractive
efficiency. In particular, here the resin used was commercial
epoxy-based SU-8, which is widely used for producing high
quality micro-optical devices due to its high transmittance for
light from the visible to the near infrared wavelengths, low
polymer volume shrinkage, good mechanical properties and
high thermal stability [6, 7, 24]. Furthermore, the lens imaging
function was also systemically investigated.

Shown in figures 1(a) and (b) are tilted view and locally
magnified SEM (scanning electron microscopic) images of a
two-level phase-type Fresnel zone plate prepared by two-
photon photopolymerization of the commercial negative resin
SU-8 (2075, MicroChem). In the experiment, a 790 nm mode-
locked Ti:sapphire femtosecond laser, capable of producing laser pulses of 120 fs at a repetition rate of 80 MHz, which
was focused into the resin by a high numerical aperture (NA =
1.35, oil immersion) objective lens, was used for the two-
photon polymerization. The laser spot was scanned on the focal plane using a two-galvano-mirror setup and along the
optical axis using a piezostage, both controlled by a computer.
In order to obtain a Fresnel zone plate with better optical
property, we adopted an annular scanning mode. The SU-8
films were prepared by spin-coating on a glass substrate which
was cleaned with acetone and absolute ethanol. After a soft-
bake step of 30 min at 95 ◦C, the solvent evaporated and a
20 µm thick film formed. On irradiation with a femtosecond
laser, the photoinitiator generated spatial distribution acid.
In a post-exposure bake from 65 to 95 ◦C for 10 min, the latent
image was converted into a cross-linked solid skeleton by the
chain propagation of the cross-linking process [25]. Then, the
sample was developed in the SU-8 developer (1-methoxy-2-
propylacetate) for 60 min, leading to a positive image of the scanned pattern.

The Fresnel zone plate consists of a series of concentric
zones with radii defined by

\[ r_m^2 + f^2 = \left( f + m\lambda/2 \right)^2 \]

\[ r_m = \sqrt{m\lambda f + \left( m\lambda/2 \right)^2} \approx \sqrt{m\lambda f} \]  \hspace{1cm} (m\lambda \ll f)

where \( f \) is the focal length. Given \( r_1 = 8 \mu\text{m}, \lambda = 532 \text{ nm}, \)
we get \( f = r_1^2/\lambda = 120 \mu\text{m}. \) The thickness of the 64 \( \mu\text{m} \)
diameter FZP is 475 nm, in order to induce the phase change
of \( \pi \) at the light wavelength of 532 nm.

To test its optical performance, we set up the evaluation
system for lens optical performance, as shown in figure 1(c).
The diffraction efficiency of the two-level phase-type diffractive lens was measured using a semiconductor laser at a
wavelength of 532 nm. The diameter of the output laser
is about 1 mm. The diffraction efficiency is the ratio of the intensity of diffracted light at the focal spot to the intensity
of light incident onto the zone plate. The laser beam was
first focused by the Fresnel zone plate and the focal spot was
amplified by a 60 × objective and imaged into a detector. The
iris placed in front of the detector (C30724, Hofoo, Co. Ltd)
blocks unwanted light selectively. Then, a bright focal spot was
obtained, as shown in figure 2(a). The measured focal length
was about 125 \( \mu\text{m} \), which agreed well with the theoretical
value. To measure the diffractive efficiency, first, we tested
the light power of the focal spot when the laser was incident
onto Fresnel zone plates. Then, the valid incident light power
which passed through Fresnel zone plates was measured.
The ratio of the intensity of the focal spot to the incident valid
light intensity was the diffractive efficiency. The measured
diffractive efficiency for the two-level lens reached 35.8%,
which was much bigger than the one reported by Sun et al
[15], although it was still a little lower than the theoretical
maximum 40.5%. It is thought that the difference may be
due to disagreement between the theoretical thickness and the fabricated thickness. Furthermore, the imaging ability of the
lens was also tested. The FZP not only generated real ghost
images, but also formed spurious ghost images. The real ghost
images were generated along the optical axis between the lens
and the primary focal spot, as shown in figures 2(c) and (d).

### Figure 1. High quality phase-type two-level Fresnel zone plate fabricated by two-photon polymerization of SU-8: (a) the tilted view SEM image of FZP and (b) its locally magnified SEM image, and (c) the optical test setup system.

The imaging names ‘JLU’ and ‘吉林大学’ are English and Chinese abbreviations of Jilin University, respectively. The inverse
spurious ghost image was formed in front of the lens, as shown in figure 2(b), just as we expected from the diffractive theory.

To enhance the diffractive efficiency, we tried to design
high level phase-type Fresnel zone plates. For an \( N \)-level
kinoform, its diffractive efficiency was [15]

$$\eta_{KNF}(N) = \sin^2\left(\frac{\pi}{N}\right) = \sin^2\left(1/N\right).$$  \hspace{1cm} (2)

For $N = 2$, $N = 4$, and $N = 8$, the theoretical efficiencies are 40.5%, 81.0%, and 95.1%, respectively. For the four-level phase-type lens, it needs a phase $\pi/2$ change over the zone plate’s thickness. The layer thickness is defined by $d = \lambda/(n - 1) = 237.5$ nm. Then, according to the theoretical model, the four-level phase-type lens was fabricated by one-step point-to-point scanning, as shown in figure 3(a). Shown in figures 3(b) and (c) are the tilted view SEM image and locally magnified image of the four-level lens. From the magnified image, we clearly see that every zone is divided into four subzones. The focal spot was detected along the optical axis, as shown in figure 3(d). The measured diffractive efficiency is enhanced to 67%, which is much bigger than the value of 54% reported. The achievement of such a high diffractive efficiency may arise from the low polymer shrinkage during the photopolymerization process. The designed thickness is very approximately the theoretical value. The measured height for every subzones (the inset of figure 3(c)) is about 225 nm, which is approximately the theoretical value. The smaller difference between the designed height and the measured value may be caused by the polymer shrinkage during the polymerization process. In addition, the surface of the lens is very smooth and the protrusions previously visible on the surfaces of diffractive lenses [10] are diminished because the scanning step during the fabrication process is reduced from the previous 200 nm/step to the current value of 100 nm/step. The surface roughness was about 4 nm, according to AFM measurement, which is crucial for high quality micro-optical devices.

The eight-level lens has higher efficiency in theory than the four-level lens, so we also tried to fabricate it. For the eight-level phase-type lens, one needs a phase $\pi/4$ change over the zone plate’s thickness. The layer thickness is given by $d = \lambda/(8(n - 1)) = 118.8$ nm. Shown in figures 4(a) and (b) are the bird’s eye view and tilted view magnified SEM images of the eight-level Fresnel zone plate. The efficiency measured at the focal spot reaches 73.5%, the largest value for phase-type Fresnel zone plates fabricated by femtosecond technology. For the eight-level zone plate, every zone was divided into eight smaller subzones, as seen from the magnified SEM image (figure 4(c)). As a result, its shape was closer to the kinoform lens. The height, according to AFM measurement (the inset of figure 4(c)), is about 104 nm, which is a little smaller than the theoretical value. The bright focal spot is shown in figure 4(d), demonstrating excellent focusing ability.
In conclusion, multilevel phase-type Fresnel zone plates were fabricated using a femtosecond laser via two-photon polymerization of SU-8. The diffractive efficiencies were significantly improved to 35.8%, 67% and 73.9% for two-level, four-level and eight-level phase-type Fresnel zone plates. Moreover, the imaging ability of the lens was demonstrated. This work shows that two-photon photopolymerization is a rapid and precise means for fabricating micro-optics and integrated optics. The improved diffractive capabilities may lead to wide applications of Fresnel zone plates in fields such as terahertz imaging, tomography and integrated circuits.

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