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# Phase lenses and mirrors created by laser micronanofabrication via two-photon photopolymerization

Qi-Dai Chen, Dong Wu, Li-Gang Niu, Juan Wang, Xiao-Feng Lin,
Hong Xia, and Hong-Bo Sun[a)]
*State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, Changchun 130012, China*

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The phase lens, also called kinoform, a promising focusing component in an integrated micro-optical system, was produced by femtosecond laser fabrication via two-photon photopolymerization. Kinoforms consisting of two-, four-, eight-level subzones with level thicknesses of 475, 238, and 119 nm demonstrate diffraction efficiencies of 30%, 54%, and 68%, respectively, which are comparable with the theoretical limit and with those from the commercial phase lenses. In addition, a reflective diffractive micromirror was proposed and realized with the aid of electroless plating. These works show the promising prospect of femtosecond laser fabrication in manufacturing optical micronanodevices and their integrated system with optical quality. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2798505]

A vital factor for the success of integrated circuits lies in the existence of silicon, a material on which transistors are integrated in a single chip by planar lithography. In contrast, integration of optical systems or photonic integrated circuits is progressing much slowly, largely due to the lack of a technology by which components of different optical functions are creatable from an identical material system. Femtosecond laser micronanofabrication has been recently considered as a promising solution to reach the above end due to its reasonably high-precision three-dimensional (3D) processing capability.[1,2] Optical structures such as photonic crystals,[3,4] waveguides,[5] couplers,[6] and beam splitters,[7] serving functions of beam emission control and propagation guidance, have been readily produced either by laser-induced microexplosion in transparent dielectrics[8] or by two-photon photopolymerization of resins.[9] What is still missing for realizing many compact integrated optical systems is a focusing element, for which diffractive lenses[10] have been considered as a candidate, and much effort has been therefore devoted to laser micronanofabrication of the devices.[11–14] Watanabe *et al.*[11] wrote in glass with strong femtosecond laser pulse voids that scattered the incident light to form the even-number zones of an amplitude-type diffractive lens, and then used[12] slightly weak pulses to create 30-$\mu$m-long filaments with refractive index change of less than 1% for phase-type diffractive lenses. Bricchi *et al.*[13] observed anisotropy behavior in the zone plates produced in silica, which demonstrated efficiencies that varied by as much as a factor of 6 for orthogonal polarizations. Srisungsitthisunti *et al.*[14] fabricated volume Fresnel zone plates by sequentially packing a series of zone plates along the optical axis for enhanced diffraction efficiency. These works would accelerate the practical use of the diffractive lens in integrated optical systems. However, the precise control of refractive index change and of the thickness of zone plates by laser writing in glasses are still problematic due to the simultaneous involvement of many nonlinear effects including self-focusing.

In this letter, we solve the problem by using femtosecond laser-induced two-photon photopolymerization of resins, a technology that has been employed in writing the delicate sculpture of "microbull,"[9] workable nano-oscillators,[15] and photonic crystals.[1,4] Since the refractive index of resins after polymerization is known beforehand and the layer thickness is depicted with an accuracy of better than 10 nm, precise shape and performance designs are thus possible.

Shown in Figs. 1(a) and 1(b) are the birds-eye view and locally magnified scanning electron microscopic (SEM) images of a zone plate prepared by two-photon photopolymerization of the commercial resin NOA 61 (Norland Optical Adhesive). Femtosecond laser pulses of wavelength of 790 nm and pulsewidth of 120 fs, mode locked at 82 MHz

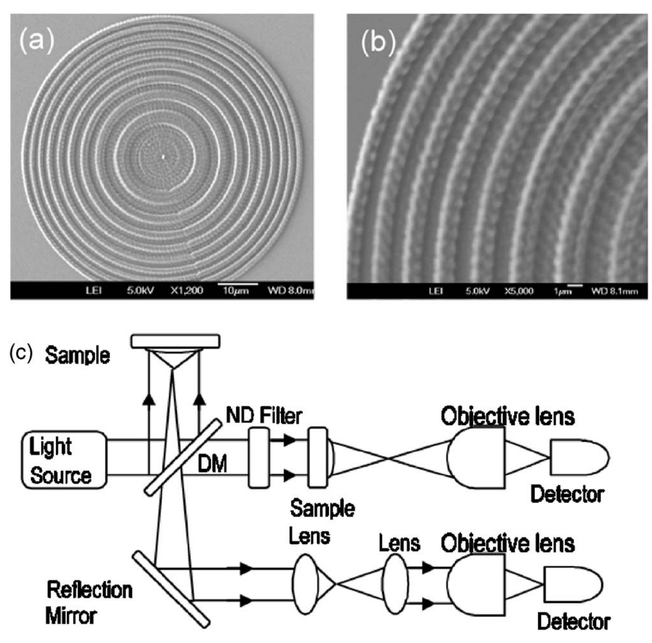


FIG. 1. Zone plate fabricated by two-photon photopolymerization. (a) Top-view SEM image and (b) its locally magnified view. (c) Focusing characterization system for the diffractive lenses (the horizontal line) and for the reflective diffractive mirrors (the vertical-lower line).

[a)]Author to whom correspondence should be addressed; electronic mail: hbsun@jlu.edu.cn and hbsun@ieee.org

 

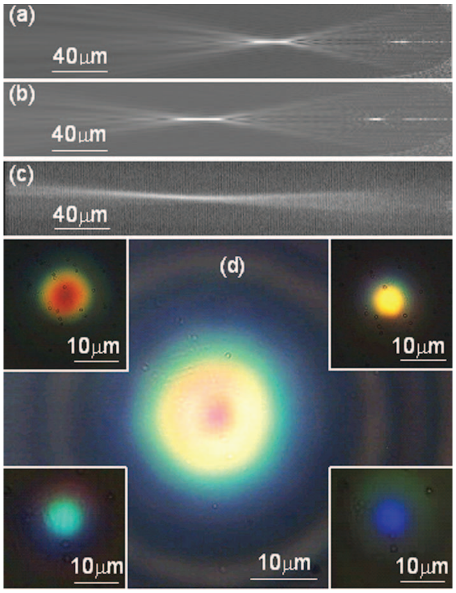


FIG. 2. (Color) Focusing characteristics of the zone plate. (a) Theoretical simulated intensity distribution of light incident from the zone plate placed in air at the right edge of the graphs and (b) placed in water solution of rhodamine B. (c) The measured light path. The incident wavelength is 532 nm for all cases. Note that the series of secondary foci at $f/3$, $f/5,\ldots$ are not identifiable. (d) Color dispersion in a plane particular to the optical axis. The insets correspond to focal planes of different colors.

(from Tsunami, Spectra Physics), were tightly focused by a high numerical aperture (NA=1.35) oil immersion objective lens. The focal spot was scanned laterally by steering a two-galvano-mirror set and along the optical axis by a piezostage, both with motion accuracy better than 1 nm. The laser scanning was performed with an annular mode.[16] The laser written structures were rinsed in ethanol for 10 min to remove the unsolidified liquid resin after the laser writing, leaving a solid skeleton. The diffractive lenses were characterized with the optical setup comprising a 3D positioning stage and a charge coupled device camera [Fig. 1(c)]. The zone plate in Fig. 1 consists concentrically of nine odd zones and nine even zones with the outer radius of the $m$th zone, $R_m$, determined by

$$R_m^2 + f^2 = (f + m\lambda/2)^2, \quad R_m = \sqrt{m\lambda f + (m\lambda/2)^2} = \sqrt{m\lambda f} \quad (\text{for } m\lambda \ll f), \tag{1}$$

where $\lambda$ is the wavelength of light in vacuum and $f=R_1^2/\lambda = 129\ \mu\text{m}$ is the primary focal length for $R_1=8.3\ \mu\text{m}$, $\lambda = 532$ nm [Fig. 1(a)].

By assuming the incident wavelength to be 532 nm and adopting the refractive index of the cured resin of $n_{\text{res}} = 1.56$, the capability of focusing in air of the above zone plates was numerically evaluated based on the Huygens-Fresnel principle, from which the light intensity distribution along the optical axis is attained [Fig. 2(a)]. In comparison, the experimentally recorded light path [Fig. 2(c)] is less sharp than the simulated one along beam propagation direction. This is a natural result of the low refractive index contrast between the lens and the ambient since the measurement was conducted by immersing the diffractive lens into a solution of rhodamine B ($n_{\text{sol}}=1.33$) that emits red light under 532 nm laser excitation. A good agreement was acquired when $n_{\text{sol}}$ is considered in the simulation [Fig. 2(b)].

The primary focal length of the diffractive lens is $f = R_1^2/\lambda$ according to Eq. (1), implying marked phenomenon of dispersion. This is discernible from the color images taken in a plane perpendicular to the optical axis under illumination with white light from a halogen lamp. The colors are further purified by translating the probe position to focal plane of light of different colors [Fig. 2(d)]. In contrast to spherical lenses, here, the incident light of longer wavelength is more significantly bent and is nearer to the lens center. This effect is useful to compensate the dispersion in spherical lenses when they are utilized in combination.[17]

The diffraction efficiency, defined as the ratio of the power collected to the primary focal spot to the total incidence, of the zone plate in Fig. 1 was measured to $\eta=30\%$ for $\lambda=532$ nm light, much larger than that measured from general laser-fabricated *amplitude-type diffractive lens*, called *Fresnel zone plate* (FZP), where either all even or all odd zones are blocked. Due to the power loss in the opaque zones in a FZP, its diffraction efficiency is quite low, with a theoretical maximum value of $\eta_{\text{FZP}}=1/\pi^2=10.1\%$. The underlying reason for the high diffraction efficiency of 30% is the good transparency of the cured resin, resulting in that the diffractive lens in Fig. 1 is not an ideal FZP but functions as a phase lens with its thickness around 475 nm.

In a *phase-type lens*, also *called kinoform*, both the even and odd number zones are transparent. A pair of even-odd number zones as existing in the FZP is divided into series of subzones with sequentially varied refractive indexes or thicknesses. If light passing through all zones and subzones is constructively interfered at the focal spot, a larger intensity maximum will be obtained at the focal spot. For $N$-level kinoform, its diffractive efficiency is

$$\eta_{\text{KNF}}(N) = \frac{\sin^2(\pi/N)}{(\pi/N)^2} = \sin c^2(1/N). \tag{2}$$

For $N=2$, $N=4$, and $N=8$, theoretical efficiencies are 40.5%, 81.0%, and 95.1%, respectively. Experimentally, the phase change in subzones was achieved by thickness variation. For $N$-level kinoform, its thickness is defined by $d=\lambda/[N(n_{\text{res}}-1)]$. For two-, four-, and eight-level kinoforms for 532 nm incidence, the single level (or subzone) thicknesses are 475, 238, and 119 nm in order to induce the phase changes of $\pi$, $\pi/2$, and $\pi/4$, respectively, at each subzone. Shown in Fig. 3 are the SEM images and the cross-sectional focal spot photographs: (a)–(c) for the four-level and (d)–(f) for the eight-level structures. Their diffraction efficiencies are 54% and 68%, respectively, which are comparable with those from kinoforms prepared by other technologies such as planar lithography on silicon.

The high focal spot positioning accuracy (<1 nm) of the motion stage and the good reproducibility of the focal spot size (within ±5%) are considered as the major factors for the high quality of the lenses. It is also worthy to mention that the laser scanning duration for the eight-level kinoform with outer diameter of 70 $\mu$m is only 30 min, much shorter than that used for fabrication in glass, where the refractive index change in the laser-irradiated region is less than 1%. The accumulation of phase change of $\pi$ for the glass lenses requires hundreds of micrometer irradiated thickness. If the protrusions visible on the surfaces of diffractive lenses [Figs. 1(a), 1(b), 3(a), 3(b), 3(d), and 3(e)] are to be diminished, reaching the limit level of surface smoothness fluctuation,

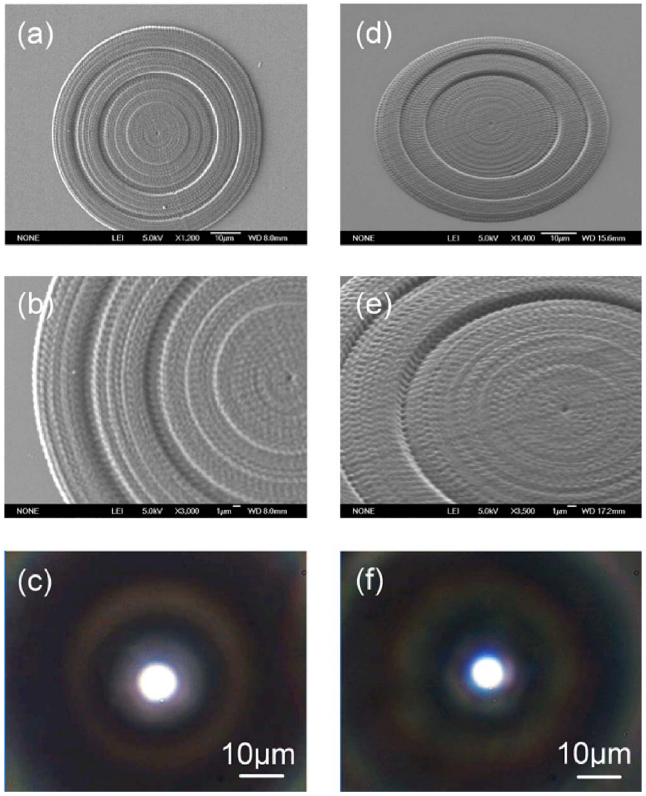


FIG. 3. Multistep diffractive phase lenses. (a)–(c) and (d)–(f) are from four-level and eight-level structures, respectively. (a) and (d) are top views of the lenses, (b) and (e) are locally magnified views, and (c) and (f) are photographs of foci for the two lenses.

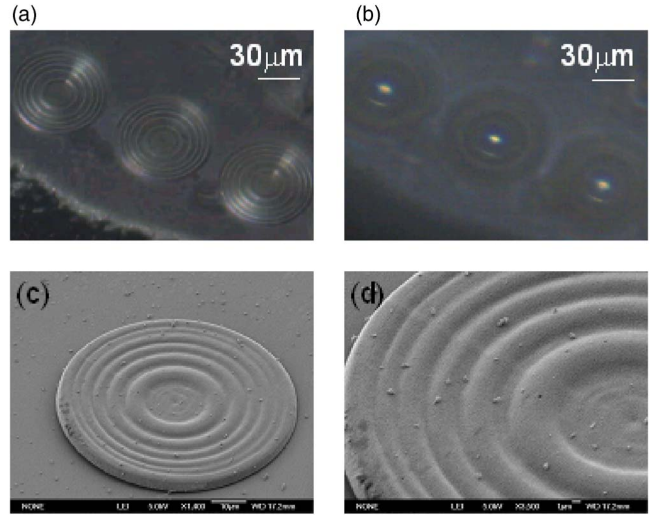


FIG. 4. Reflective diffractive phase micromirrors produced with electroless plating on a polymer mirrors template with silver. (a) The photograph of the mirrors. (b) The images of reflective foci. (c) Top view and (d) locally magnified view of SEM images of a mirrors.

~10 nm, the scanning step in fabrication should be reduced from the current 200 nm/step to smaller values, i.e., 100 nm/step or 50 nm/step, wherein the fabrication efficiency would still be acceptable.

Besides directly focusing transmitted light, kinoforms may be utilized to form reflective diffractive phase mirrors if their surface is coated with metal. A two-level phase lens was used as the template of electroless plating, on which a 50 nm silver layer was formed [Fig. 4(a)]. Even if the lenses are of planar structure, their focusing capability is evident as manifested by the primary focal spot image in Fig. 4(b). The diffraction efficiency, measured to 25.6%, is not as high as expected for a reflective mirror. This should be closely associated with the fact that the thickness of the zones was not designed to guarantee that light from different regions of the zone plates is in phase. Also in the characterization system [Fig. 1(c)], the focused light reflected from the reflective element passes through a tilted beam splitter. It is known that an astigmatism is introduced when a focused light passes through a tilted plan parallel plate. This means the quality of devices could be better than seen in the figure although it is already satisfying. With careful choices of structures and materials, the reflective diffractive phase micro devices may find important use in soft x-ray focusing.

In conclusion, we fabricated diffractive lenses as the example of micro-optical components that are indispensable in integrated optical systems. The two-, four-, and eight-level kinoforms demonstrate the diffraction efficiencies of 30%, 54%, and 68%, are comparable to those obtained from commercial products. In addition, a reflective diffractive phase micromirror is proposed and realized with the aid of electroless plating technology. These works show the merits of the two-photon photopolymerization in micro-optical fabrication: the reasonably high fabrication accuracy and efficiency, the high tolerance to the structural complexity of devices, and the technological compatibility to varied types of optically functional devices.

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