

# Fabrication of Micro Fresnel Zone Plate Lens on a Mode-Expanded Hybrid Optical Fiber Using a Femtosecond Laser Ablation System

Jun Ki Kim, Jongki Kim, Kyunghwan Oh, Ik-Bu Sohn, Woojin Shin, Hae Young Choi, and Byeongha Lee

**Abstract**—We present a compact all-fiber zone plate lens directly ablated on the surface of a mode-expanded hybrid fiber end by using a high precision femtosecond laser processing technique. To achieve a sufficiently large beam size and focusing efficiency, a segment of a coreless silica fiber having a 200- $\mu\text{m}$  diameter was adapted. Focusing properties of the zone plate lens were experimentally investigated and compared with numerical simulations.

**Index Terms**—Coreless silica fiber (CSF), Fresnel zone plate, laser ablation, lensed fiber.

## I. INTRODUCTION

DEMANDS of compact Fresnel zone plates (FZP) are increasing in various areas of micro-optics such as free-space optical interconnections [1] and biomedical applications of optical tweezers [2], [3] for their high potential in compact integration and mass production. FZP can take advantage of its unique planar structure and flexible control of focal length. Recently, direct inscription of optical phase front surfaces have been intensively studied, taking advantage of high precision laser processing techniques. In most microoptic applications FZPs have been implemented on bulk silica plates by embedding voids or by inducing local birefringence [4], [5]. These conventional zone plates, despite their thin and compact design, have not been fully optimized for fiber optic systems. The main bottleneck has been the lack of processing technique to control the Fresnel lens shape in terms of spatial period, concentricity, and optical contrast between the rings on the fiber end face. A few methods have been attempted to fabricate FZPs directly on the end facet of optical fiber, including etching, drilling, or chemical deposition methods [6]–[8]. These methods, however, require elaborate fabrication processes both

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J. K. Kim is with the Department of Physics, Yonsei University, Seoul 120-749, Korea, and also with Fraunhofer Institute of Applied Optics and Precision Engineering, Jena 07745, Germany.

J. Kim and K. Oh are with the Department of Physics, Yonsei University, Seoul 120-749, Korea (e-mail: koh@yonsei.ac.kr).

I.-B. Sohn, W. Shin, H. Y. Choi, and B. Lee are with the Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Korea.

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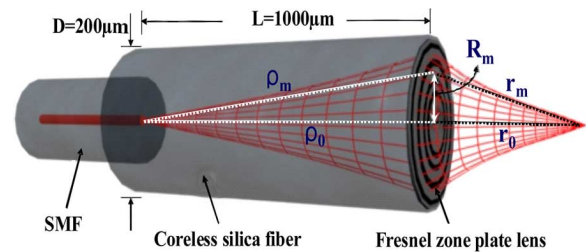


Fig. 1. Schematic diagram of the light propagation after engraving zone plate pattern.

before and after the fiber drawing and some of the prior reports were not compatible to directly conventional single-mode fibers (SMFs), which would be significantly detrimental for practical applications such as short reach optical interconnections.

In this letter, a new technique is explored combining a unique hybrid fiber optic beam expansion method and high precision femtosecond laser ablation process, which can significantly alleviate the prior bottlenecks in fiber integrated FZPs fabrication processes.

## II. EXPERIMENTS AND RESULTS

The hybrid structure consists of a coreless silica fiber (CSF) serially fusion-spliced with conventional SMF. The light exits from SMF will propagate along CSF very similar to a Gaussian beam [9]. At an optimal distance the beam diameter will cover most of the CSF cross-sectional area, where an FZP pattern will be inscribed. This will ensure the maximum overlap between the incident Gaussian beam and FZP pattern, which were not attempted in prior reports. The hybrid beam expanding structure is shown in Fig. 1. The radius of the  $m$ th zone is  $R_m$ ;  $\rho_0$  and  $r_0$  are a distance from center of the zone plate to source and focal point, respectively;  $\rho_m$  and  $r_m$  are a distance from point of the  $m$ th zone to the source and focal point, respectively.  $r_0$  is also referred to as the working distance of the device.

The cleaved end facet of the CSF is then exposed to a scanning femtosecond laser processing system to ablate the zone plate patterns, which can take advantage of low thermal damage and high spatial resolution [10]. The FZP pattern was designed assuming conventional on-off concentric binary ring structures [11]. The radii and the number of the rings of a zone plate pattern are given by

$$\left\{ \frac{1}{\rho_0} + \frac{1}{r_0} \right\} = \frac{m\lambda}{nR_m^2}. \quad (1)$$

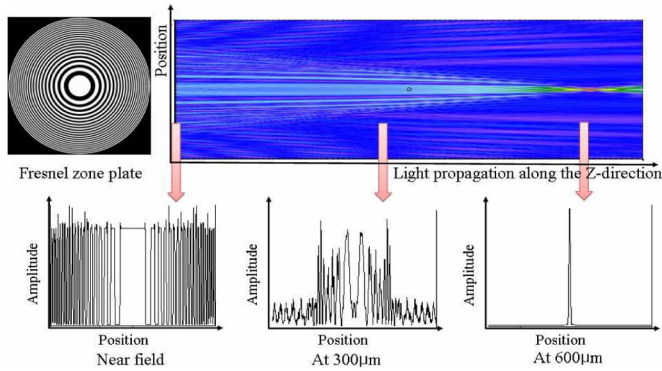


Fig. 2. Simulation results for the designed FZP utilizing a commercial optical simulation tool, Virtual-Lab.

Here,  $n$  is the effective glass/air index and  $\lambda$  is the operating wavelength. Note that in prior SMF-FZPs the order  $m$  had been very limited due to a small mode field diameter of  $10\ \mu\text{m}$  from SMF. In this experiment, we used the novel beam expansion structure to ensure a  $200\text{-}\mu\text{m}$  beam diameter so that we could fabricate zones from the 11th to 23rd orders.

Based on (1), for Fresnel rings we have designed binary FZPs with the focal lengths of  $300$  and  $600\ \mu\text{m}$ , as shown in the top-left of Fig. 2. We further simulated the beam propagation after the FZP utilizing a commercial optical simulation tool, Virtual-Lab, where Maxwell's equations are numerically solved using the rigorous Fourier Modal Method for light propagation in vectorial electromagnetic wave approaches. In the simulation, the focusing properties of the propagating light from the FZP pattern were investigated along the propagation axis using focused beam pattern analysis. Here, we assumed SMF spliced to a CSF segment of  $200\text{-}\mu\text{m}$  diameter and  $1000\text{-}\mu\text{m}$  length. The FZP was designed to have a focal length of  $600\ \mu\text{m}$ . For the designed binary FZP, we could expect efficient focusing capability with a tight beam diameter of  $4\ \mu\text{m}$  at full-width at half-maximum (FWHM).

The experimental setup is schematically illustrated in Fig. 3. An amplified Ti:Sapphire laser operating at the wavelength of  $785.5\ \text{nm}$  and an  $184\text{-fs}$  pulse duration was utilized at a  $1\text{-kHz}$  repetition rate. The pulse energy was about  $0.45\ \mu\text{J}$ . The beam passing through a shutter and a dichroic mirror reflecting in the  $400\text{--}700\text{-nm}$  region was focused using a  $50\times$  (N.A. 0.42) objective lens on the end face of CSF-SMF hybrid sample fiber. The FZP pattern was inscribed on the CSF surface by irradiating the focused femtosecond laser beam in a spiral manner having less than  $500\text{-nm}$  spatial resolution of the translation stages. Combining optical and mechanical perturbations, the net precision of the laser processing system was about  $\pm 1\ \mu\text{m}$  in the lateral direction and  $\pm 1.5\ \mu\text{m}$  in the depth. The roughness of the processed surfaces on the FZP was measured around  $\pm 0.3\ \mu\text{m}$  by using a 3-D surface profiling system (SIS-2000) [10].

Fig. 4 shows the microscope images of two fabricated zone plates. At the wavelength of  $632.8\ \text{nm}$ , the FZP were designed to have focal lengths of  $600$  and  $300\ \mu\text{m}$ , whose photographs are shown in Fig. 4(a) and (b), respectively. The dark rings in the figures correspond to the laser processed area.

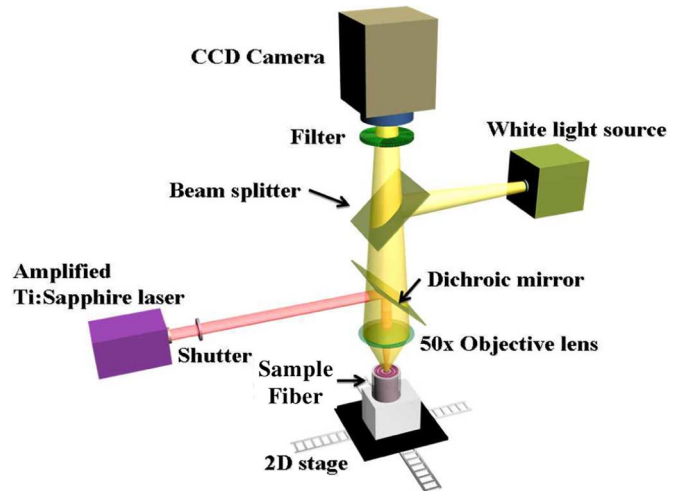


Fig. 3. Experimental setup to form a zone plate pattern.

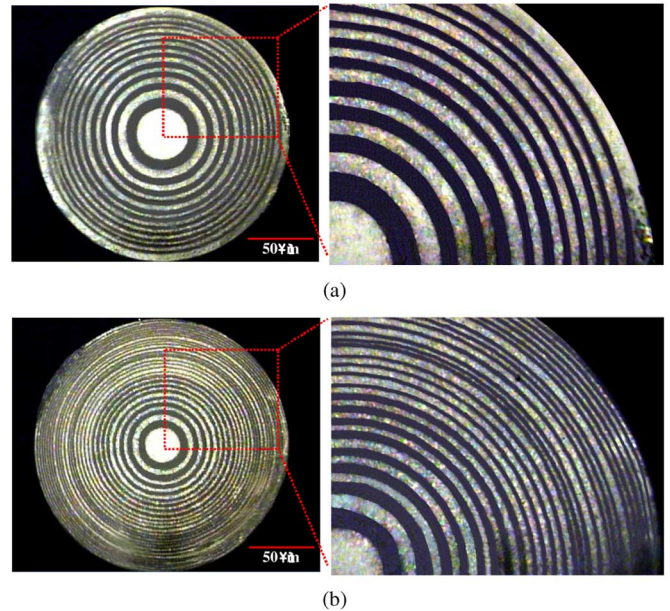


Fig. 4. Microscope images ( $\times 20$ ) and blow up images ( $\times 50$ ) of the engraved zone plate pattern. (a) Fabricated zone plate pattern having the focal length of  $600\ \mu\text{m}$ . (b) Focal length of  $300\ \mu\text{m}$  at  $632.8\ \text{nm}$  wavelength.

By launching an He-Ne laser beam into the SMF end of the proposed hybrid structure, focusing properties of the fabricated FZP were investigated. Fig. 5 shows the intensity distribution and line profiles of the light field taken at the zone plate plane (left) and at the focal plane (right) for the  $600\text{-}\mu\text{m}$  focal length case [Fig. 5(a)] and for the  $300\ \mu\text{m}$  case [Fig. 5(b)], respectively. In the figures, we could clearly see that the beam incident on the zone plate plane had a wide distribution across its whole surface and then was effectively focused due to the diffraction at the zone plate. At the focal points, the spot sizes were estimated to be  $10.9$  and  $10.4\ \mu\text{m}$ , for the cases of (a) and (b), respectively. Note that corresponding spot sizes of the prior arts were around  $20\ \mu\text{m}$  [6], [8] and the experimental results prove that the proposed scheme can enhance the focusing efficiency significantly.

By monitoring the variation of the optical power, we can see that the actual focal plane of the implemented zone plate was

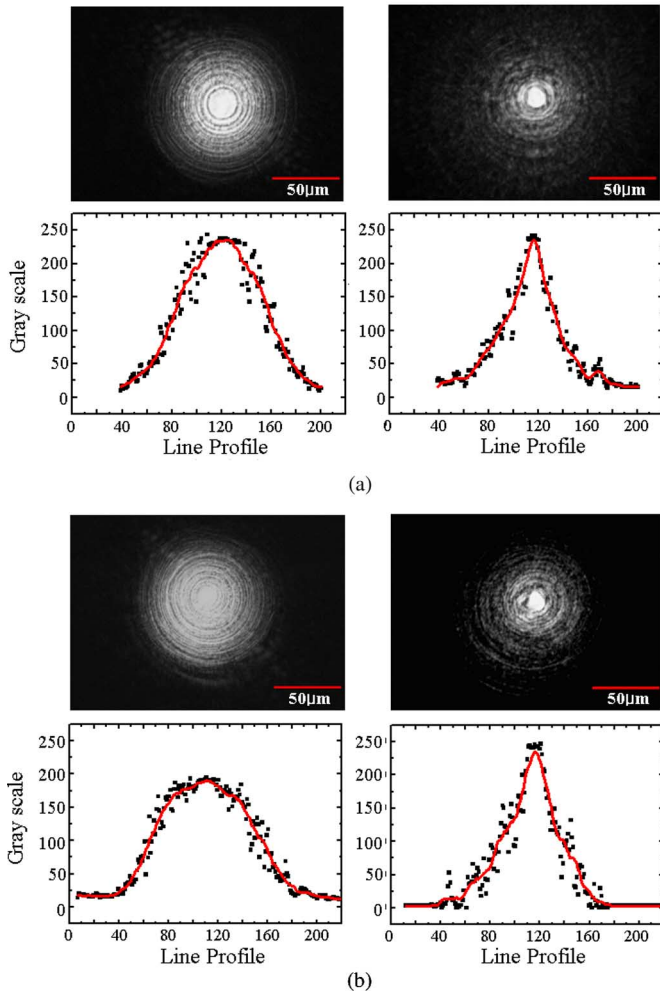


Fig. 5. (left) Near field zone plate pattern images and (right) light intensity distribution at the focal point. (a) Intensity distribution and line profile at the 580- $\mu\text{m}$  focal point and (b) focal point of the 255  $\mu\text{m}$ .

placed at a distance of 580  $\mu\text{m}$  for the 600- $\mu\text{m}$  design case (solid line) and of 255  $\mu\text{m}$  for the 300- $\mu\text{m}$  design case (dashed line) in Fig. 6. The deviation of focal length measurements from the designed values are mainly attributed to finite precision of the laser processing system, which caused deformations in the concentric rings. However, these results are allowable enough to confirm that the Fresnel zone plate pattern inscribed on an end face of an optical fiber could act as a Fresnel lens, and there was good agreement between the designed focal length and the experimentally obtained one.

### III. CONCLUSION

In summary, we have demonstrated the fabrication of the all-fiber FZP lens inscribed on an optical fiber end face by using a femtosecond laser. A CSF segment with a larger diameter of 200  $\mu\text{m}$  has been adapted in order to provide an expanded modal field. The focusing properties of the implemented zone plate were investigated by launching a He-Ne laser beam into

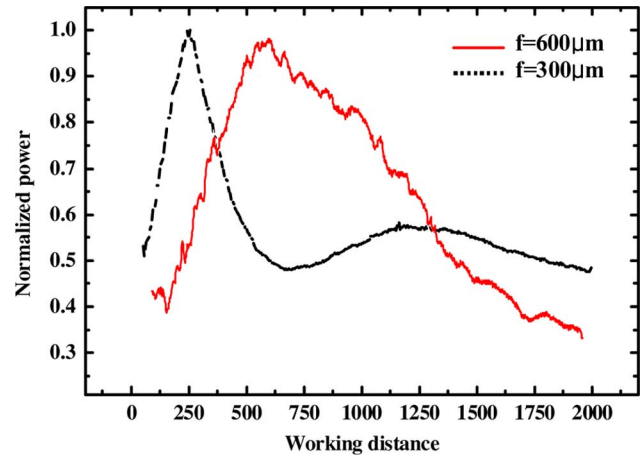


Fig. 6. Working distance along with normalized power. Solid line and dashed line represent the case of 600- and 300- $\mu\text{m}$  focal lengths, respectively.

the optical fibre. The beam coming from an SMF and expanded at a segment of a CSF was well focused by the zone plate inscribed on the CSF surface. The working distance of the implemented device was well matched with the designed one. In effect, all-fiber FZP lens benefits a number of applications that require precision integrated optical manipulating. Furthermore, we can confirm that the proposed device has ample potential for optical free-space interconnection, which can find direct applications for optical communications as well as for biophotonics including optical imaging and trapping systems.

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