Beam shaping technology based on optical fiber for applications in laser, optical tweezer, and free space interconnects

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Abstract
Various techniques to modify the phase front of the light wave out of an optical fiber facet are reported for beam shaping devices. The principles of beam shaping in the devices and their applications in lasers, optical tweezer, and photonic devices are discussed.

Introduction

The fundamental mode, LP_{01}, in conventional single mode fiber (SMF) can be well approximated as a Gaussian beam with a high precision especially when the light output from the SMF is propagating in free space. Beam shaping of the output from SMF in free space is getting more intensive attention recently for applications in laser processing [1], optical tweezers [2], and free space interconnects [3].

The LP_{01} mode's guiding properties are determined by the boundary condition between the core and cladding in SMF, whose beam shape is given by Bessel function of first kinds, such as J_0 and K_0 and maintained along the whole fiber length. At the end facet of the SMF, we can have ample degree of freedom to introduce phase changes and we can achieve micron level beam shaping technologies.

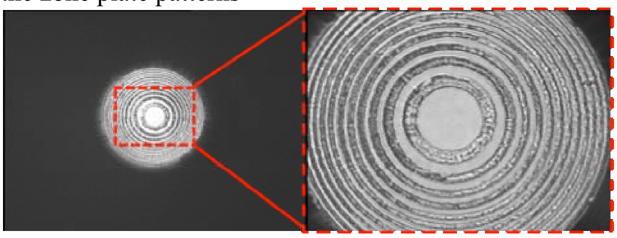
The authors have developed unique techniques to embed phase information over a thin polymer layer on the end face of fiber by developing rectangular [4] and circular gratings [5] under UV exposure. The grating structures have successfully generated diffraction patterns for the incoming LP_{01} mode. The authors also reported polymer lens formation on the fiber end, whose focal length have been flexibly controlled by the viscosity and volume of the liquid polymer[6]. The polymer lens tip on the SMF has shown efficient beam focusing to be readily adopted in fiber-fiber and fiber-VCSEL array free space interconnect applications [7].

Based upon these preliminary research results, the authors recently have reported novel beam shaping technologies to further integrate optical path controlling elements to modify the beam shape in the free space. In this letter, we review the principles of the new beam shaping technologies for Fresnel zone plate [8], and Bessel beam [9]. The applications of these devices are also discussed.

Fiber Fresnel Zone Plate

Compact Fresnel zone plates (FZP) are finding rapidly increasing applications in various area of micro-optics such as free space optical interconnections and bio-medical applications of optical tweezers for their high potential in compact integration and mass production capability. FZP can take advantage of its unique planar structure and flexible control of focal length. Recently the authors reported a new technique combining a unique hybrid fiber optic beam expansion method and high precision femto-second laser ablation process [8].

The hybrid structure consists of a coreless silica fiber (CSF) serially fusion spliced with conventional SMF. The cleaved end facet of the CSF is then exposed to a scanning femto-second laser processing system to ablate the zone plate patterns



(a) (b)

Fig. 1. The near field image of the fabricated surface with 600μm focal length. ; (a) 20x microscope image (b) 60x microscope image).

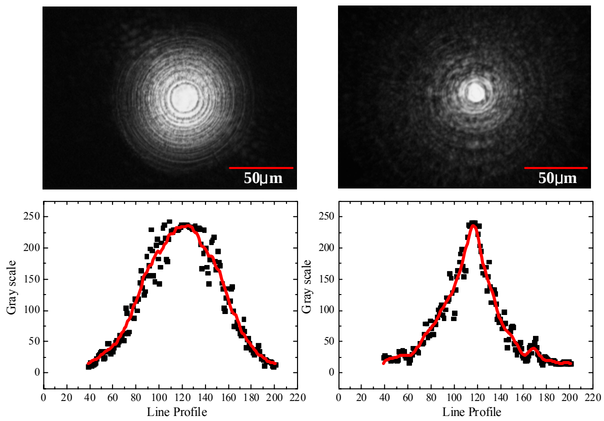


Fig. 2. Near field zone plate pattern images (left), the light intensity distribution at the focal point (right)

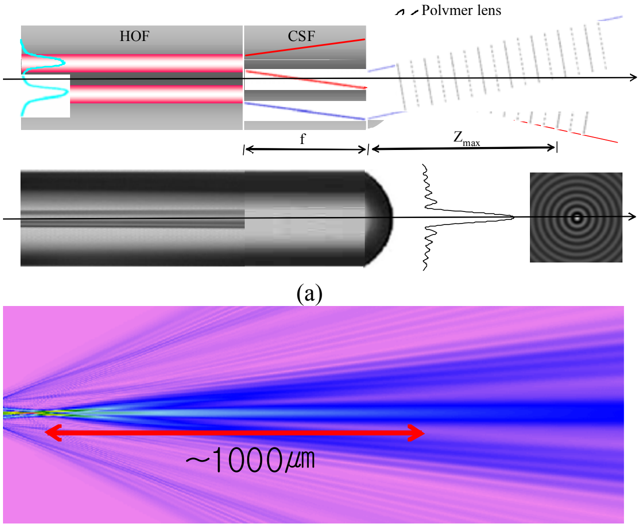
Fig. 1 shows the end facet of the processed FZP on the cleaved fiber end. The FZP pattern was designed assuming conventional on-off concentric binary ring structures. the net precision of the laser processing system was about ±1μm in the lateral direction and

±1.5μm in the depth. The roughness of the processed surfaces on the FZP was measured around ±0.3μm by using a 3D Surface Profiling System (SIS-2000).

Fig. 2 shows the near and far field from the FZP whish clearly shows the focusing capability of the device. At the focal length of 580μm the laser beam showed the beam diameter of 10.9 μm, which is very close to mode field diameter of the LP01 mode guided in conventional SMF.

Fiber Bessel Beam Generator

Bessel beam is an ideal diffraction-free mode solution of Helmholtz equation to provide tightly confined light propagation along a long distance in free space without using extra optics. Various optical devices have been developed to generate Bessel beam or Bessel-like beams. Presently the most widely used device for Bessel beam generation is a bulk axicon, which is a conical shaped lens element to provide interference of incoming plane wave in the radial direction. Bessel beams have been used in optical tweezer to trap multiple particles in the longitudinal direction over a few mm [10]. Integration of



(a)

(b)

Fig. 3. (a) Device structure of fiber optic Bessel beam generator, (b) beam profile of the output from the proposed device

Bessel beam generating optical elements into fiber optics would be of high importance for future biological applications such as in-vivo optical trapping of cells. Recently the authors reported an innovative method to imbed all the optical elements for Bessel beam along a strand of optical fiber [9]. The device structure is shown in Fig. 3. The LP_{01} mode of SMF is adiabatically transformed to a ring shape mode in hollow optical fiber (HOF) [11]. The HOF serves as an annular aperture and its output will propagate along coreless silica fiber (CSF), which provides an overlap within the HOF output mode. A polymer lens on the end facet of CSF will form a concentric ring interference pattern.

For the given device structure in Fig. 1, we carried out simulations using a beam propagation method (BPM) tool. Figure 3-(b) shows the BPM simulation result for the output beam from the proposed device. It is noted that the beam shows concentric ring patterns with non-diffracting central part that extends over ~1000μm, very similar to Bessel beam. In experiment the beam showed a concentric ring interference pattern with the central non-diverging part with the beam diameter of ~20μm extending over 1,000μm, which was a very good agreement with BPM simulations.

The generated Bessel or Bessel-like beam out of fiber has been successfully used to demonstrate optical trapping of polystyrene beads and further studies are being pursued by the authors.

Fiber optic Bessel beams can find variety of applications especially in conjunction with optical coherence tomography and optical trapping for bio-medical applications. The device can also find high potential in laser marking, laser scanning displays, and optical interconnects.

Conclusions

In summary, we successfully fabricated all-fiber beam shaping devices such as fiber Fresnel zone plate (FZP) and fiber Bessel beam generator. Precise femto-second laser ablation techniques and unique hybrid polymer-silica structures have shown a strong potential for axial integration of optical elements into a single strand of optical fiber. Laser beam shaping has been experimentally demonstrated, which showed good agreements with theoretical predictions. Further design optimization is being pursued by the authors for applications in laser marking, optical trapping, and free space interconnection.

Acknowledgments

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References

1. B.N. Chichkov et al., Appl. Phys. A, 109-115, 1996
2. A. Constable et al., Opt. Lett., vol.18, no. 21, 1867-1869, 1993
3. K.H. Hahn et al., Elect. Lett., vol. 29, no. 16, Aug. 1993
4. S. Choi et al., Appl. Phys. Lett., vol. 83, no. 6, Aug. 2003
5. Junki Kim et al., Opt. Fiber Technol., 13 (2007) 240-245
6. Kyung-Rok Kim et al., Appl. Opt., vol. 42, no. 31, 6261-6266, 2003
7. J.K. Kim et al. Photonics. Technol. Lett., vol. 19, no. 13, Jul. 2007
8. Junki Kim et al., Photonics. Technol. Lett. vol. 21, no. 1, Jan. 2009
9. Jongki Kim et al. in Optical Trapping Applications, Proc. OSA spring congress. OTuA6, 2009
10. V. Garces-Chavez et al., Nature, vol. 419, Sep. 2002
11. K. Oh et al. J. Lightwave Technol., invited paper, vol. 23, no. 2, Feb. 2005