

CO₂ Laser Assisted Fabrication of Micro-lensed Single-mode Optical Fiber

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This paper reports the fabrication of various micro-lensed single-mode optical fibers through the use of an enhanced peak power CO₂ laser beam. The end faces of the optical fibers are exposed to the CO₂ laser beam to form convex, concave, and conical shape optical fiber tips. Peak power of the CO₂ laser beam was varied from 0.8 W to 1.5 W depending on the shape of the optical fiber tip. We also discover the dependence of the angle of the optical fiber tip on the rotation angle and the number of CO₂ laser irradiations. The angle shows an increasing trend with both these parameters. We achieve a wide range of lenticular fibers with end face angle varying from 4.47° to 8.13°. Furthermore, we investigate the emission pattern of light from the developed micro-lensed fibers. The proposed CO₂ laser based optical fiber reshaping technique shows great consistency, and thus is suitable for commercial applications.

Keywords : CO₂ laser, Micro-lensed optical fiber, Beam pattern, Radiation pattern

OCIS codes : (060.0060) Fiber optics and optical communications; (060.2310) Fiber optics; (060.3510) Lasers, fiber; (140.0140) Laser and laser optics; (140.3510) Laser, fiber

I. INTRODUCTION

Due to the expansion of multimedia services such as video on demand, video-conferencing, e-learning, interactive services, and VOIP, the demand for an optical fiber based high speed Internet network has increased significantly. Although optical fibers have been designed primarily for optical communication, they show promise in a wide range of application areas including coupling [1], fiber lasers [2], optical sensors [3-9], imaging and spectroscopy [10, 11], and biomedical engineering [12]. In most of the cases, micro-structuring of the optical fibers is required to produce application specific optical fibers. During the last several decades, laser assisted micro-patterning has attracted researchers as well as the micro-machining industry. Lasers have proved their versatility in patterning various micro/nano-scale structures in various materials including optical fibers [3-7, 9, 11-25]. Since the arrival of the first functional CO₂ laser in 1964, they have played significant roles in a large variety of application areas [14-22].

Initially, CO₂ laser beams were extensively utilized for

melting and polishing of transparent materials [14-16]. Nowadays, CO₂ lasers have been widely used for micro-patterning of various materials [17-19] and micro-lens formation inside transparent materials [20-22]. Y. S. Kim *et al.*, proposed the polishing of glass materials by means of a CO₂ laser beam [14]. Optical fibers are simply passive wave guides that require supplementary active/passive devices to design a complete networking system. The interfaces between optical fibers and other optical/electronic devices may introduce losses in the system. One of the most critical issues arises when the reflection from the end face of an optical fiber causes any damage in the optical source or other active/passive elements. The most promising technique to resolve this issue is the polishing of the end faces of the fibers. Although mechanical polishing can decrease the roughness of the end faces of optical fibers, CO₂ laser assisted polishing can reduce the roughness of the optical fibers significantly, and the technique is simpler compared to traditional mechanical polishing [15, 16].

Formation of micro-lenses has attracted many researchers

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due to their applications primarily in imaging and spectroscopy. However, micro-lenses can also be used to connect light sources to detectors, modulators, and optical fibers. In-fiber micro-lenses can also be used for the surgery of soft tissues. M. Wakaki *et al.*, reported the fabrication of micro-lenses and micro-lens arrays on glass plates by use of a CO₂ laser [20]. When the surface of the glass plate is heated locally using a CO₂ laser beam, the working point tends to become a hyperboloid due to surface tension that results in a micro-lens. Another research group has shown the formation of rod and spherical shaped micro-lenses by CO₂ laser assisted melting of micro-metric glass substrate [21]. Cylindrical micro-lens array (MLA) has been reported by one research group by means of a CO₂ laser assisted reshaping technique [22]. In parallel with a CO₂ laser beam, femtosecond lasers have been extensively utilized to form MLA in various materials, even in optical fibers [23-25]. Femtosecond laser assisted formation of conical structure on the fiber tip causes multi-directional emission of light from the optical fiber [12]. C. H. Lin *et al.*, reported the formation of high fill-factor plano-convex cylindrical and spherical MLA on Foturan glass by femtosecond laser micromachining followed by thermal treatment, wet etching, and annealing [23]. 100 % fill factor aspheric MLA has been developed with sub-20-nm precision SU-8 photo-resist material by a femtosecond laser writing technique [24]. Fabrication of plano-concave MLA has been reported on PDMS by a femtosecond laser beam [25]. However, until now there is no report on CO₂ laser assisted direct fabrication of micro-lenses inside optical fibers.

This paper demonstrates a novel technique of fabricating a large variety of micro-lensed fibers with convex, concave, and conical shapes using a CO₂ laser assisted reshaping technique. The end faces of the single-mode fibers have been reshaped by focusing the CO₂ laser beam vertically on top of the fiber tips. We also investigated the impact of laser energy, number of laser irradiations, and the rotation angle of angled fibers on the angle of the lenticular fiber tip. The fiber angle shows an increasing trend with the increase of rotation angle and the number of laser repetitions. More importantly, the processing time has decreased significantly to several seconds from 5 to 10 minutes for mechanical polishing. Furthermore, we examined the radiation pattern of light coming out from the micro-lensed optical fibers. We strongly believe that the proposed technique would be suitable for fabricating various kinds of lenses in optical fibers.

II. EXPERIMENTAL DETAILS

2.1. Materials and Methods

During our experiments, we selected single-mode optical fibers as samples having core/clad diameter of 8 μm /125 μm and core and cladding refractive indexes of 1.467 and 1.445. To reshape the end faces of the single-mode optical

fibers, we utilized a pulsed CO₂ laser (Coherent, C-55L) operating at the central wavelength (λ) of 10.6 μm with a pulse repetition rate of 5 kHz. The pulse width of the CO₂ laser beam was 120 \pm 40 μs . The optical fibers were placed inside a mechanical holder that was placed vertically on the 3-axis translation stage having resolution of 100 nm in the x, y, and z directions. To fabricate micro-lensed optical fiber of convex, concave, and conical shapes, the CO₂ laser beam was focused on top of the fibers' end faces by means of an objective lens (clear aperture: 5 mm; numerical aperture: 0.08; focal length: 18 mm) and irradiated for approximately 5 seconds, the schematic diagram of the experimental setup is depicted in Fig. 1(a). The laser energies for fabricating convex, concave, and conical shape fiber tips were 0.3 mJ, 0.16 mJ, and 0.26 mJ, respectively.

In contrast, to fabricate lenticular fiber tips of variable curvature, the CO₂ laser beam with laser energy of 1 mJ was irradiated by means of a galvanometer scanner (magnification: 80 \times ; focal length: 170 mm) on the end faces of the single-mode fibers at a scanning speed of 500 mm/s and a scanning step of 20 μm . Figure 1(b) represents the schematic diagram of the experimental setup for fabricating angled fiber of variable angles. The optical fibers were placed inside a mechanically rotatable holder placed on top of a 3-axis translation stage. The fiber holder was manually rotated from 0° to 40° to achieve the desired fiber angle where the laser beam was emitted 3 times (forward & backward) in a 3 mm \times 3 mm area, which is shown in Fig. 1(c). To examine the impact of the repetition of laser irradiation on the curvature of the fiber tip, the single-mode angled fiber was exposed up to 7 times (forward & backward) under the CO₂ laser beam by positioning the angled fiber at an

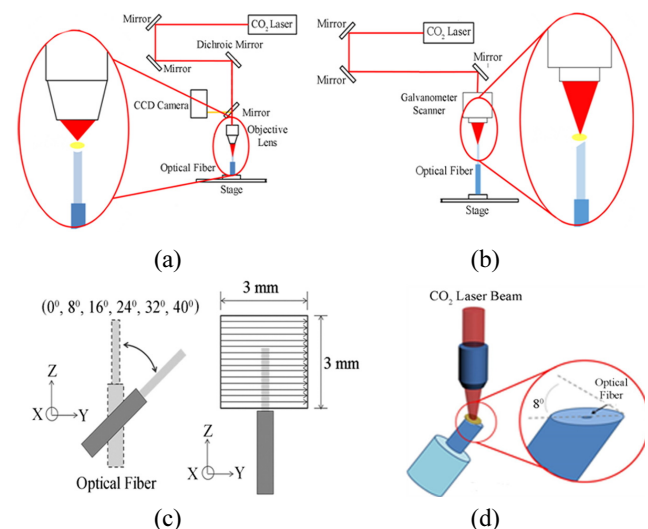


FIG. 1. Experimental setup. (a) Schematic diagram of the CO₂ laser system for fabricating micro-lensed optical fibers; (b) schematic diagram of the CO₂ laser system for varying the fiber angle; (c) vertical rotation of optical fiber to change the edge angle; (d) several times irradiation of the CO₂ laser beam at an angle of 8°.

angle of 8°, which is illustrated in Fig. 1(d).

2.2. Measurements and Analysis

Various micro-lensed optical fiber samples were placed on the stage of an optical microscope to examine the structure of the fiber tips. To investigate the beam pattern and radiation pattern of light from the micro-lensed optical fibers, a He-Ne laser (ThorLabs, HRP 020-1) operating at the wavelength of 633 nm with power of 32 μW was passed through the optical fibers. A white screen was placed 50 mm away from the end face of the fibers. We captured the front and side view images of the radiation pattern for various micro-lensed fibers using a high resolution camera. Furthermore, we also simulate the beam pattern and radiation pattern of light from various micro-lensed optical fibers using the LightTools simulator.

III. RESULTS AND DISCUSSION

As mentioned before, we fabricated micro-lensed fibers of various shapes by a CO₂ laser assisted reshaping technique. By varying the laser energy from 0.16 to 0.3 mJ, we encoded convex, concave, and conical shaped fiber tips. We also altered the fiber angle by polishing of the fiber tip several times by means of a CO₂ laser beam with laser energy of 1 mJ at a scanning speed of 500 mm/s and a scanning step of 20 μm.

3.1. Fabrication of Plano-convex Micro-lensed Optical Fiber

In order to convert the plane surface of the optical fiber of Fig. 2(a) to a plano-convex shape, a CO₂ laser beam of 0.3 mJ energy was focused on the top surface of the vertically positioned single-mode optical fiber. Due to the exposure of the laser beam for approximately 5 seconds, the end face of the optical fiber was melted and consequently reshaped to the plano-convex shape (plano-convex micro-lensed fiber), the optical microscope image of which is depicted in Fig. 2(b). The radius of curvature (R) of the plano-convex fiber can be calculated by the following equation, where the values have been measured using the schematic diagram of Fig. 3.

$$R = \frac{h^2 + X^2}{2h} \quad (1)$$

where h represents the height of the lens and X denotes half of the length of the lens. For the plano-convex micro-lensed fiber, the h and X values were 58 μm and 62.5 μm. Thus, the radius of curvature of the designed convex optical fiber was 63 μm.

Using the LightTools simulator, we simulate the beam profile of the traditional single-mode optical fiber of Fig. 2(a) and the plano-convex micro-lensed fiber of Fig. 2(b) at different positions (0.1 mm, 0.4 mm, 0.7 mm, and 1 mm) after the end face of the fibers. The simulation result regarding

the beam profile of the unpatterned single-mode optical fiber is illustrated in Fig. 2(d), whereas the beam profile of the plano-convex lenticular fiber is shown in Fig. 2(f).

Due to refraction, the natural tendency of any incoherent light coming out from optical waveguide is to broaden over distance. The beam profile of Fig. 2(d) indicates that the circular light beam is widened with the increase of distance from the fiber tip. The diameter of the circular beam was 50 μm when it was observed 0.1 mm away from the fiber tip, which was increased to 362 μm at 1 mm distance from the fiber tip. Similar beam pattern, i.e. increasing trend with the increase of distance from the fiber tip, was detected for

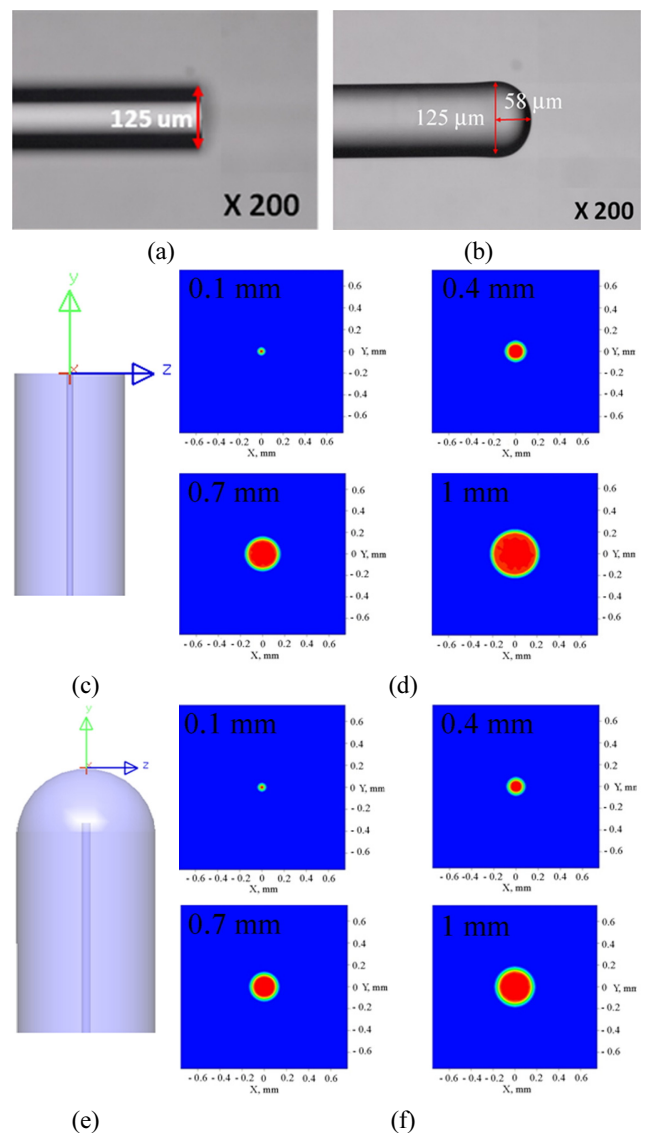


FIG. 2. (a) Side view of a single-mode optical fiber; (b) side view of the plano-convex micro-lensed fiber; (c) unmodified optical fiber during simulation; (d) beam profile of light at different positions coming out from the unmodified single-mode fiber of Fig. 2(c); (e) plano-convex optical fiber during simulation; (f) beam profile of light at different positions coming out from the plano-convex fiber of Fig. 2(e).

the plano-convex micro-lensed optical fiber of Fig. 2(e). Figure 2(f) gives us the diameter values of the circular light beam as 45 μm , 137 μm , 225 μm , and 305 μm for the positions of 0.1 mm, 0.4 mm, 0.7 mm, and 0.7 mm, respectively. Although the trends of beam profile is similar for the un-modified optical fiber tip and the convex fiber tip, the

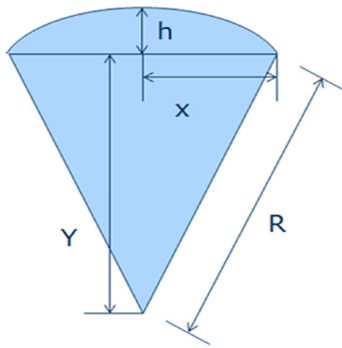


FIG. 3. Schematic diagram for calculating the radius of curvature.

light through the plano-convex optical fiber has less broadening compared to unmodified fiber. This result signifies the non-pervasive nature of the plano-convex fiber tip.

Furthermore, we investigated the variation of angle of single-mode angled fiber due to the variation of the rotation angle during laser processing and to the number of laser scannings. The optical fibers were vertically rotated with rotation angle varying from 0° to 40° and the CO₂ laser beam was scanned 3 times (forward & backward) on the end faces of the optical fibers. Consequently, angled fibers of different angles varying from 4.47° to 8.13° have been evolved. Figure 4(a) shows the optical microscope images and the corresponding fiber angles of various angled fibers due to the variation of rotation angle. We also investigated the influence of number of laser irradiations on the angle of the fibers. In order to do so, we positioned an optical fiber at an angle of 8° and scanned the laser beam several times (maximum 7 times) by focusing the laser beam on the end face of the fibers. As a result, angled fibers with fiber angles in the range of 4.87° to 7.47° were detected. Figure 4(b) illustrates the optical microscope images and the corresponding fiber angles for variable number of CO₂ laser irradiations. Figure 5 plots the

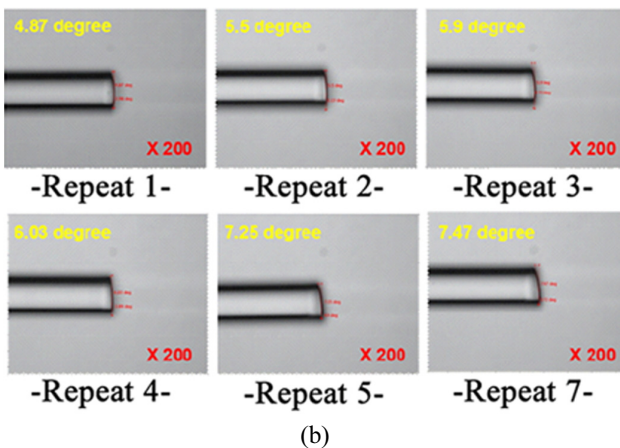
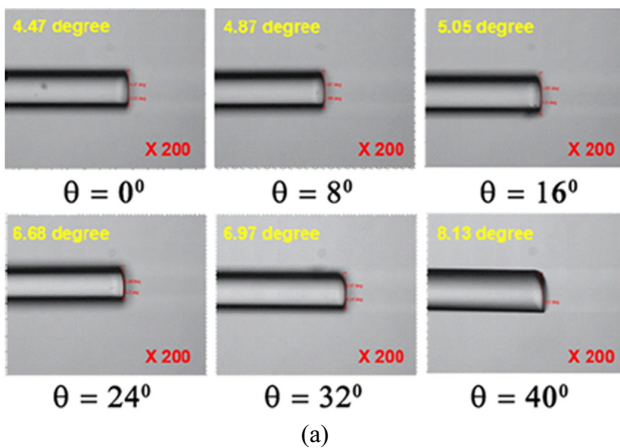


FIG. 4. (a) CO₂ laser polishing of single-mode optical fibers at different rotation angles; (b) CO₂ laser polishing of single-mode optical fibers after repetitive application of laser beam at a rotation angle of 8°.

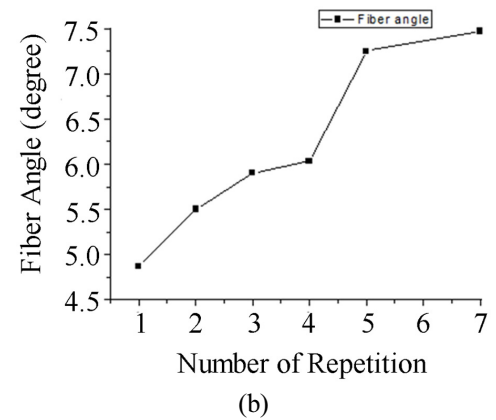
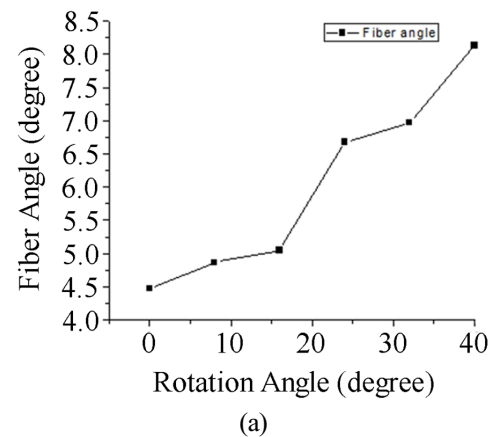


FIG. 5. (a) Relationship between rotation angle and fiber angle for single-mode angled fibers, polished by 3 times CO₂ laser beam irradiation; (b) relationship between number of laser repetition and fiber angle for single-mode angled fibers at a rotation angle of 8°.

fiber angles of the angled single mode optical fibers against rotation angle (Fig. 5(a)) and number of laser irradiations (Fig. 5(b)).

3.2. Fabrication of Plano-concave Micro-lensed Optical Fiber

We also fabricated plano-concave micro-lensed optical fiber by exposure to the CO₂ laser beam of 0.16 mJ energy for approximately 5 seconds. The optical microscope image of the plano-concave micro-lensed fiber is represented in Fig. 6(a). The h and X values of the concave fiber tip are 38 μm and 62.5 μm , which gives us the radius of curvature for the concave fiber tip as -70 μm . During simulation, we considered the optical fiber of Fig. 6(b). The circular beam profile is evident in every position after the optical fiber tip, as shown in Figs. 6(c-f). The diameter of the beam was measured after 0.1 mm, 0.4 mm, 0.7 mm, and 1 mm, where

the values were 133 μm , 283 μm , 467 μm , and 633 μm , respectively. Like Figs. 2(d) and 2(f), the diameter of the circular beam was increasing with the distance. However, the increasing rate of beam diameter is higher than for the un-modified optical fiber of Fig. 2(c) and the convex fiber tip of Fig. 2(e), which indicates the pervasive nature of the plano-concave micro-lensed optical fiber. Due to the spreading of the light, the center intensity of the beam coming out from the concave fiber tip has decreased compared to the beam intensity of the unmodified fiber and convex fiber.

3.3. Fabrication of Conical-shape Micro-lensed Optical Fiber

Conical-shape micro-lensed optical fiber was produced by irradiating a CO₂ laser beam of 0.26 laser energy for approximately 5 seconds on top of a single-mode optical fiber.

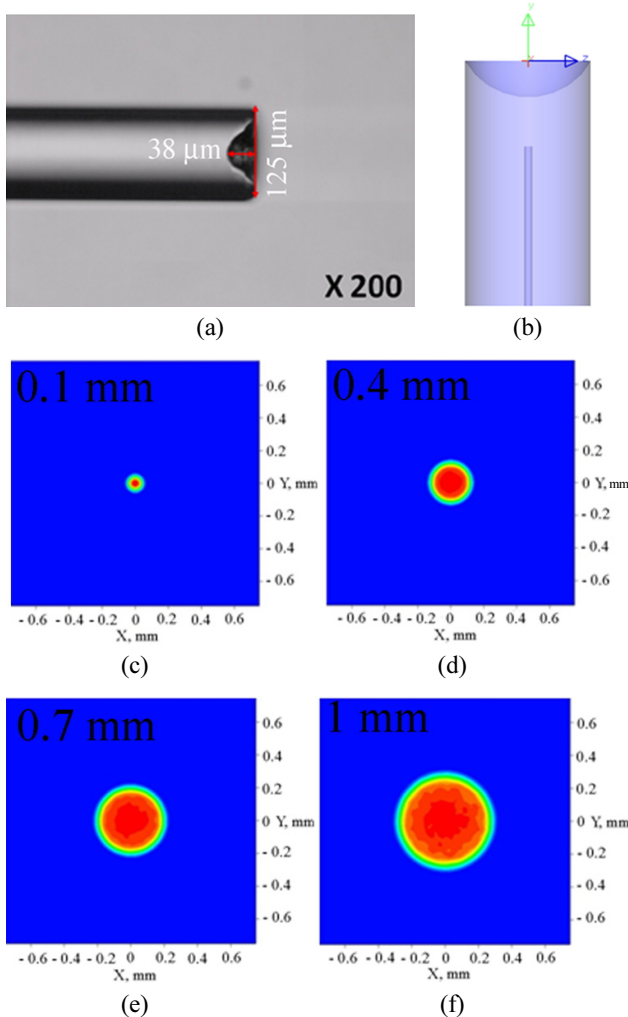


FIG. 6. (a) Side view of the plano-concave micro-lensed fiber; (b) plano-concave micro-lensed fiber during simulation; (c-f) beam profile of light after 0.1 mm, 0.4 mm, 0.7 mm, and 1 mm distance from the end face of the plano-concave fiber tip.

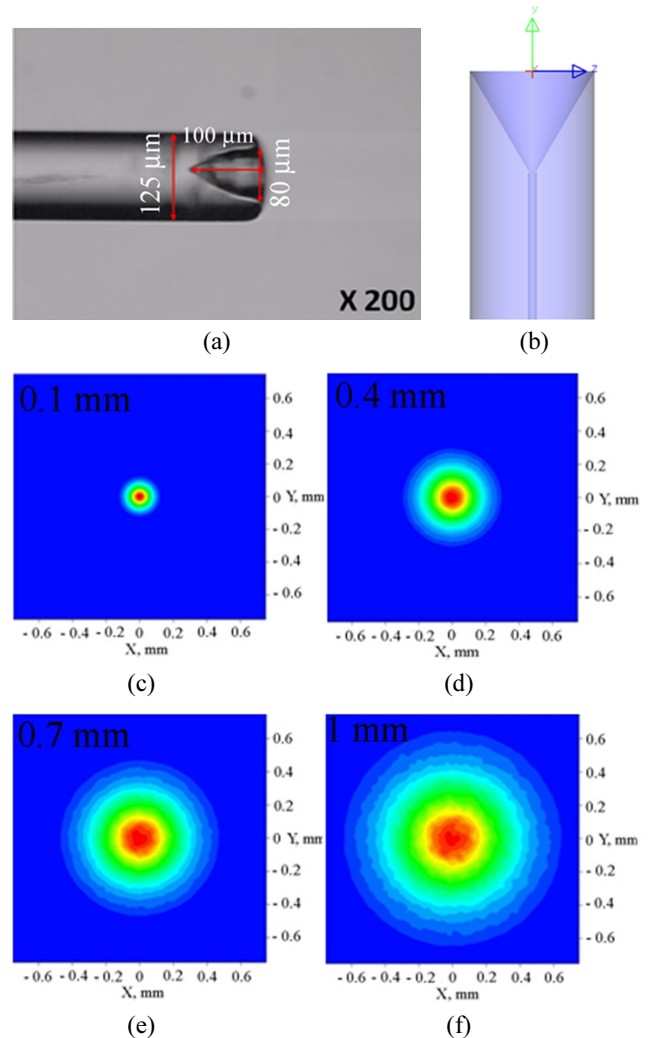


FIG. 7. (a) Side view of the conical-shape micro-lensed fiber; (b) conical-shape micro-lensed fiber during simulation; (c-f) beam profile of light after 0.1 mm, 0.4 mm, 0.7 mm, and 1 mm distance from the end face of the conical-shape fiber tip.

TABLE 1. Beam diameter at different positions after the unmodified, convex, concave, and conical fiber tips

Distance (mm)	Beam Diameter (μm)			
	Unmodified Fiber Tip	Convex Fiber Tip	Concave Fiber Tip	Conical Fiber Tip
0.1	50	45	133	227
0.4	210	137	283	600
0.7	250	225	467	967
1	362	305	633	1333

Consequently, the conical-shape fiber tip of Fig. 7(a) was evolved. The depth and diameter of the micro-cone were approximately $100\ \mu\text{m}$ and $80\ \mu\text{m}$, as shown in the figure. The similar kind of conical micro-lensed fiber was designed during simulation, the schematic diagram of which is presented in Fig. 7(b). Figs. 7(c-f) shows the beam pattern of light at different positions after the end face of the conical fiber tip. The beam diameter of light at 0.1 mm, 0.4 m, 0.7 mm, and 1 mm distances were $227\ \mu\text{m}$, $600\ \mu\text{m}$, $967\ \mu\text{m}$, and $1.3\ \text{mm}$ respectively. Compared to the concave micro-lensed fiber, the conical-shape fiber showed better pervasive property. As a consequence, the intensity of the light at the center was decreased significantly, as shown in Figs. 7(c-f). The beam diameter for all four cases is summarized in Table 1.

3.4. Emission Pattern of Light from Various Fibers

In order to examine whether the light beam is emitted circumferentially with respect to the optical axis, we investigate the emission pattern of light coming out from various fibers including the unmodified single-mode fiber and plano-convex, plano-concave, and conical-shape micro-lensed optical fibers. Figure 8 represents the radiation pattern of light from various optical fibers. The light beam from the unmodified fiber tip is concentrated into the direction parallel to the fiber axis, which is obvious from the front view of Fig. 8(b). From the side view of radiation pattern of the unmodified optical fiber we observed that, the light emitted at a maximum angle of 18.5° , as evident from Fig. 8(c). Like unmodified optical fiber, the plano-convex micro-lensed fiber showed circular radiation pattern, as depicted from Fig. 8(e). However, due to the nonpervasive nature of the convex fiber, the maximum radiation angle for the convex fiber tip reduced down to 12.6° (shown in Fig. 8(f)) indicating concentration of light in parallel with the fiber axis.

Figure 8(h) showed that the plano-concave fiber tip radiates light in multiple directions from the end face of the fiber tip indicating pervasive nature of the concave fiber tip. This result is also evident from the side view of the radiation pattern for the concave fiber tip. From Fig. 8(i) we determined the angle of light radiation for the plano-concave micro-lensed fiber as 37.2° . The highest angle of radiation (115.5°) was measured for the conical fiber tip, as shown in Fig. 8(l). This result exemplifies the conical fiber tip as the most pervasive micro-lensed fiber.

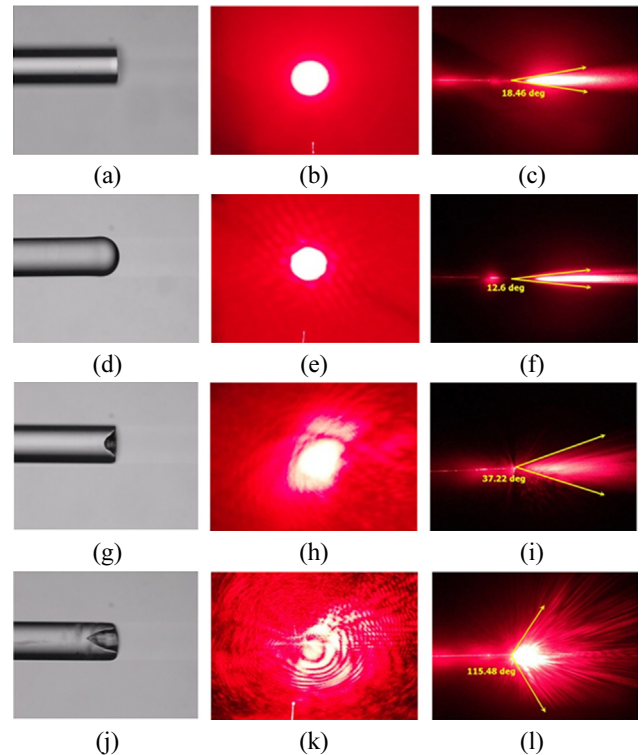


FIG. 8. Beam radiation pattern according to fiber tip geometry. (a,d,g,j) Side view of the unmodified, convex, concave, and conical fibers; (b,e,h,k) front view of radiation pattern for unmodified, convex, concave, and conical fibers; (c,f,i,l) side view of radiation pattern for unmodified, convex, concave, and conical fibers.

IV. CONCLUSION

In summary, we fabricated various kinds of micro-lensed fiber tips including convex, concave, and conical shapes by means of a CO_2 laser assisted beam shaping technique. We also examined the formation of variable angle single-mode fibers by varying the rotation angle during laser processing and number of CO_2 laser irradiations. Experimental results showed that, with the increase of the rotation angle and laser repetition, the angle of the single-mode angled fiber was increased. Furthermore, we analyzed the beam profile and radiation pattern of the light beam coming out from the micro-lensed fibers. The convex and conical fiber tips showed pervasive nature and those radiated light in multiple

directions, whereas unmodified and convex fiber tip radiates light in parallel to the fiber axis. The conical fiber tip showed highest radiation angle of 115.5°. We strongly believe that the proposed CO₂ laser assisted fiber tips would be valuable in a large variety of applications areas. In the future, a precision machining method using a high order objective lens will be approached for making non-uniform beam to uniform in conical or concave shape of micro-lens.

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