Angle Cleaving Optical Fibers using a CO_2 Laser

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Abstract Summary

A CO_2 laser at λ = 9.3 µm was used to cleave optical fibers at a given angle. The defects that might occur during the process are explained and resolved. The good surface quality obtained on the cleaved surface is demonstrated by SEM and AFM images.

Keywords-CO_2 laser machining; optical fibers; ablation; fiber cleave; angle cleaving; SEM; AFM.

I. INTRODUCTION

The growth of optical fibers for sensor applications is placing increasing demands on fiber-optic quality including the optical quality of the tip surface. Besides, recent applications in fiber optic technologies involve the presence of angle tips, to couple light in specific directions. What is required is a well polished end-face to minimize scattered light and optical losses, and fiber end-faces cut at given angles are ideal for surface-enhanced Raman scattering (SERS) applications [1], exciting long-range surface plasmon polaritons (LRSPP) on a membrane waveguide [2] and coupling vertical-cavity surface-emitting lasers (VCSELs) to fibers and waveguides [3]. In addition, it is common to use an 8º final angle tip for coupling applications, to minimize back reflections.

The main methods used to obtain angle tips include: mechanical cleavers, polishing tools and CO_2 lasers. Mechanical cleavers are quite common, despite the problems they have with wear and misalignment. Moreover they are usually designed for maximum cleave angles of 15º, which is less than required for some applications. Polishing is another common method that involves a holder supported at an angle, but unfortunately it is time consuming and generally increases the cost of the final product. CO_2 lasers were only recently introduced to obtain angle cleaving [4] and, even if they require a relatively high initial expense, they make it possible to automate the process and hence considerably decrease the cost of bulk manufacturing.

Previous work with CO_2 lasers has looked at polishing fiber ends and different angle cleaving. A study conducted by Udrea *et al.* with a low-power-density continuous-wave (CW) CO_2 laser demonstrated a decrease of the surface roughness by more than one order of magnitude on 0º angle tips, but no other angle tips were mentioned [6]. In a more recent paper it was demonstrated that different angle tips could be obtained with a 10.6 µm laser, but without any indication about surface quality [4].

In this present investigation, a 9.3 µm CO_2 laser is used to cleave fibers at given angles. The mechanism by which the cut is performed is absorptive, with strong thermal heating. It was demonstrated before that with this wavelength it's possible to reduce the heat affected zone and, as a consequence, the number of defects [5].

This paper has the objective to demonstrate not only the feasibility of obtaining different angles on the fiber tips, but also that the surface quality of the final product is preserved.

II. MATERIALS AND METHODS

A 100 W peak power radio-frequency (RF) pulsed CO_2 laser (Model LASY-20pp-9.3, Access Laser Company, USA) operating at a wavelength of 9.3 µm was used to cleave SMF-28 (Corning, USA). The laser can be programmed to perform both cleaving and stripping of SMF-28 and ribbon fibers (Oz Optics, Canada). Here, only the cleaving process of SMF-28 is presented.

In the cleaving arrangement shown in Fig. 1, the beam emitted by the CO_2 laser is reflected by Cu-Ni-gold plane mirrors M_1, M_2, M_3, M_4 and M_5 before being focused on the sample by the ZnSe aspheric lens L_1 (focal length of about 38 mm). The distances between the elements in the setup are indicated in Fig. 1, except for the one between the sample and L_1, which varied during the experiments. All of the optics are coated for 9.3 µm (ULO Optics, USA). The mirror M_5 is rotated on its horizontal axis by a brushless motor that is synchronized with the laser pulses to provide some flexibility in positioning the laser spot on the optical fiber.

To cleave fibers at an angle, a mechanical holder was built and mounted on a computer controlled X-Z translation stage (Model EPS 300, Newport). A micrometer was assembled on the Y axis of the holder to vary the position of the focused beam through the fiber. Before cleaving, the jacket of the fiber is mechanically stripped; then the cladding residue is removed with ethanol using a low abrasive tissue. After that, the fiber is fixed on a jig and the cleaving is performed.

Two operations are necessary for the cleaving process. During the first one the fiber is roughly cut; then, after a small horizontal movement called the cleave gap, the tip is exposed to a second sequence of laser pulses that clean the surface. The technical parameters investigated in this work are the laser pulse length, the cleave gap and the position of the focused point with respect to the fiber.

To image the cleaved fibers an optical microscope (BX41, Olympus), a scanning electron microscope (SEM, Nova NanoSEM 200, FEI) and an atomic force microscope (AFM, Solver LS, NT-MDT Co.) were used. To obtain the SEM images, the fibers were coated with 20 nm of gold in a high vacuum evaporation system (Emitech K975X, Quorum Technology). The software used to analyze the pictures was Image J.

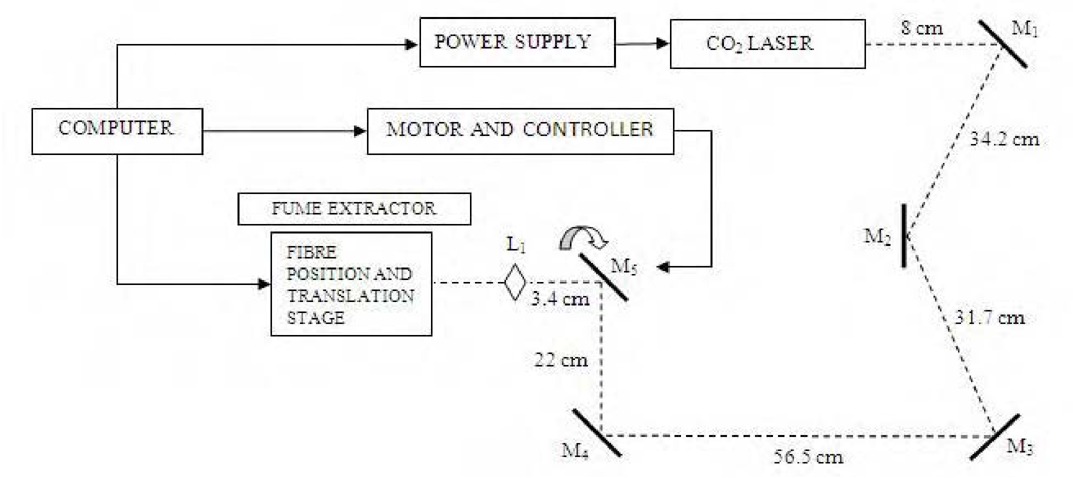

Figure 1. Laser cleaving system diagram. M_1, M_2, M_3 and M_4 are fixed mirrors while M_5 is a rotating mirror; L_1 is an aspherical lens.The dashed lines designate the beam path. The distances between the elements are expressed in cm.

III. RESULTS AND DISCUSSION

The main challenge we have observed with CO_2 laser fiber cleaving is the high probability of defect formation. Several parameters are involved during the process and all of them can be altered to obtain the optimal cleaving conditions. We observed many cases of severe fiber deformations after the cleaving, such as fiber-end flares, uncontrolled core diffusion, curved fiber facets, cavities, melting of material and rippled structures. The laser pulse length, the cleave gap and the relative position of the fiber with respect to the focal point of the laser were identified as the main laser parameters involved in the defect formation.

An incorrect pulse length provides a possible explanation for the appearance of rippled structures and cavities on the fiber surface (pictures not shown). To understand the role of this parameter, the energy was measured for each pulse length tested. It was observed that if the energy is too low (9.7 ± 0.2 mJ detected for pulse lengths of 100 µs with a frequency of 8.3 Hz, average and standard deviation of 5 measurements), the laser beam is not able to melt the silica effectively. On the other hand, if too much energy is applied on the fiber tip (23.5 ± 0.3 mJ detected for pulse lengths of 500 µs with the same frequency used before, average and standard deviation of 5 measurements) it can cause vaporization, or ablation of the materials.

Another crucial parameter is the cleave gap, defined as a horizontal movement of the fiber after the first pass of the beam. This is performed to obtain a smooth surface of the fiber during the second pass of the beam. It was observed that if the value is too low (below 0.03 mm) the surface is not effectively cleaned and a lot of debris remains on the surface, while if it is too high (above 0.03 mm) additional ablation occurred leading to the formation of irregular cavities (results not shown).

The last key point is the position of the focused beam with respect to the fiber. This parameter was controlled with a micrometer positioned on the Y axis of the fiber holder. It was observed that if the focus is translated across the fiber, unwanted thermal conduction and diffusion effects arise, causing surface imperfections, cavities and rounded ends. Besides, if this parameter is not well-defined, the fiber might act as a lens, focusing the energy at a point of the tip surface [5]. In this case, the deposited energy is higher than at other points of the tip surface, leading to the formation of hollows with approximately rectangular shape. Fig. 2 shows an example of a cavity formed on the upper edge of the fiber tip believed to have resulted from localized heating. Additional SEM images showed the presence of melted materials inside and on the boundary of the cavity, and along the edge of the fiber (results not shown).

After analysis of all of the collected data, it was established that the optimum conditions for the cleaving process are the ones indicated in Table 1. These were applied to obtain all the results shown subsequently. With these values it was possible to cleave fibers at given angles, with few defects.

However, after applying the parameters shown in Table 1, it was not possible to obtain perfect results. In particular, the cleaved surface was found to exhibit some curvature in the majority of the samples. This was possibly due to the combination of (*i*) the waist of the focused laser beam, which is comparable to the size of the fiber and (*ii*) the high energy involved.

For cuts with a distal angle of 0º, the surface curvature involves the entire tip (Fig. 3A). AFM images showed that the distal point of the curve is about 6 µm higher than the base of the final edge (Fig. 4). In this specific case the transmission of the light out from the fiber might be affected. Additional measurements performed on the tip surface revealed that the radius of curvature was about 330 µm.

Regarding all the other cleave angles, the roundness is confined only on the upper edge of the tip (Fig. 3B). In this specific case the defect does not affect the core, preserving the final optical losses at the end of the fiber.

Figure 2. Example of the effects of uneven heating on the surface of a SMF-28 fiber. The cavity on the superior edge of the tip is caused by the fiber itself acting as a lens and focusing the laser beam to a small region. In this position, the deposited energy is higher than that on other parts of the tip surface.

TABLE I. PARAMETERS FOR THE CO_2 LASER IN CLEAVING MODE

Pulse length	***Pulse energy***	***Rotary mirror speed***[a]	***Repetition rate***[b]	***Cleave gap***	***Position of the fiber***[c]
300 µs	22.3 mJ	500 rpm	8.3 Hz	0.03 mm	38.22 mm

a. Speed of the rotating mirror M_5
b. Calculated from the rotary mirror speed
c. The distance between the fiber and L_1

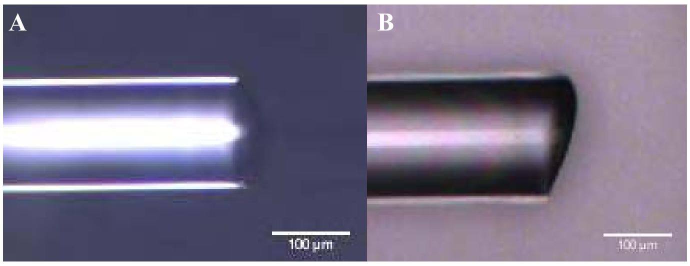

Figure 3. Example of SMF-28 fibers with 0º angle tip (A) and 20º angle tip (B). The round edge of the fiber is clearly visible in both samples. In particular in (A) it involves the entire tip surface, while in (B) it is confined to the superior edge of the tip.

From AFM images of the 0º angle tip it was also possible to evaluate the roughness, to have a better idea of the final quality of the surface. The measurements were taken on an area of about 9 μm^2, in order to reduce the effect of the curvature of the tip. The roughness measured was about 1.3 ± 0.1 nm (average and standard deviation of 3 samples). This value was compared with the roughness obtained after a standard 0º mechanical cleave (1.6 ± 0.4 nm), confirming the high quality of the surface cut with a CO_2 laser. Unfortunately, it was not possible to perform the same evaluation with an angle tip fiber, due to the intrinsic limitations of the AFM.

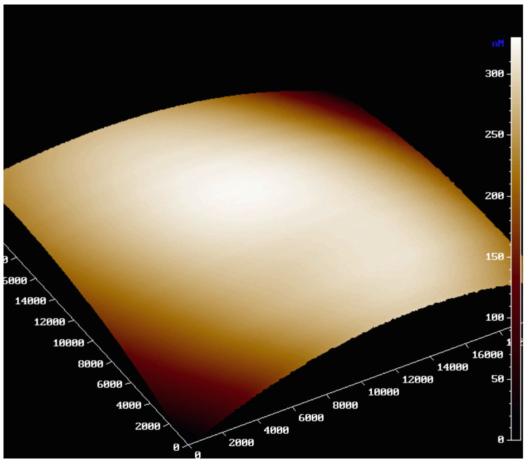

Figure 4. AFM image of an SMF-28 fiber tip cut with 0º angle. The curvature of the surface is clearly visible. The highest point of this curve is about 6 µm higher than the horizontal base plane of the surface.

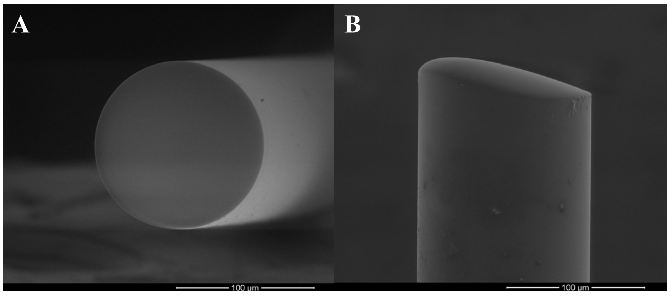

Figure 5. Examples of SEM images of SMF-28 fiber tip with 20º angle. The tip surface is clean and uniform (A), although a rounded upper edge was detected on the tip itself (B).

To evaluate the quality of the surface for fibers cut at a given angle, SEM images were carried out. Fig. 5 shows two images of a tip surface after a 20º cleaving. The entire surface appears clean and uniform, without any remarkable defects. A small curvature was detected only on the upper edge of the tip. This was not considered to be a significant defect because it is not expected to affect the transmission of the light out from the fiber. Despite the curvature detected, the angle appears quite sharp and well-defined, making the fibers ready for further applications.

IV. CONCLUSIONS

In the present work, the feasibility of cleaving fibers at a given angle without severe deformations is demonstrated. The final quality of the surface was evaluated with AFM and SEM images. AFM tests revealed that the roughness is at the same order of magnitude as that obtained with a standard mechanical cleaving. SEM tests showed that the surface of tips cut at a given angle is clean and uniform. Unfortunately, the final surface of the fibers was not as flat as that obtained by mechanical cleaving. A curve was detected on the entire surface of 0º tips and on the upper edge of the fibers cleaved with other angles. However, for fibers cut at given angles the roundness does not affect the core of the fiber and, possibly, neither the transmission of light out from it.

Further work is necessary to reduce the observed rounding of the edges and to evaluate the total optical loss after coupling the cleaved fibers with a light source. Moreover, further studies are necessary to evaluate the laser beam shape and the time of interaction of the beam with the fiber.

The good results obtained for fibers cut at given angles show that it is possible to use these fibers for further applications in laser delivery and sensing.

ACKNOWLEDGMENT

Thanks to Dr. G. Kostovski (RMIT University – Melbourne) for assisting with SEM images. The CO_2 laser stripper cleaver was supported by the Ramaciotti Foundation and ARC LIEF Grant No. LE0989726.

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