Femtosecond laser and arc discharge induced microstructuring on optical fiber tip for the multidirectional firing

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Abstract: Most optical fibers are designed for forward firing i.e. the light is emitted at the distal end along the optical axis of the fiber. In some applications such as the laser surgery and laser scanners, side firing of the optical fiber is required. In this paper, we present the microstructuring of an optical fiber tip using the femtosecond laser and an arc discharging process for the multidirectional firing of the beam. The distal end of the optical fiber with diameter of 125 μm was machined into a conical structure using a femtosecond laser. The surface of the machined tip was exposed to the arc discharge using a fiber splicer. The arc discharge leads to the melting and re-solidification of the fiber tip. This results in a smoothing of laser-induced conical microstructure at the tip of the fiber. We were able to demonstrate the multidirectional (circumferential) emission of the light from the developed fiber tip.

OCIS codes: (140.3390) Laser materials processing; (140.7090) Ultrafast lasers; (060.4005) Microstructured fibers; (220.5450) Polishing; (170.0170) Medical optics and biotechnology; (170.1020) Ablation of tissue.

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1. Introduction

A typical amplified femtosecond laser has a pulse with a duration in the range of tens to hundreds femtosecond and a maximum energy of 1mJ per pulse. The peak power of the femtosecond laser reaches into the tens of Terawatts (TWs). Due to its extremely high peak power, the femtosecond laser has been applied for the precise ablation of various materials including metal, semiconductor, and dielectric material. During the interaction of the femtosecond laser and the target material, the high peak power of the laser pulse leads to the nonlinear absorption of the photon energy on the target. It has been commonly accepted that the nonlinear absorption such as multiphoton ionization or tunneling ionization initiates the ablation process. The nonlinear absorption is followed by an avalanche ionization that leads to bulk material removal from the surface. Since the pulse duration of the femtosecond laser is shorter than the characteristic time for the electron-lattice energy exchange, the photon energy can be highly localized near the laser-affected zone. This localization of laser energy would make the femtosecond laser a popular tool for micromachining in various applications such as the machining on the semiconductor [1–3], the fabrication of precision machinery [4], the microstructuring on photonics [5,6], and the manipulation of the biological tissues [7,8]. It should be noted that the femtosecond laser can be applied for machining of the transparent materials (such as glasses and optical fibers) whose absorption coefficient for the visible and near IR spectrum is negligible. Because of the low linear absorption coefficient, conventional lasers with pulse durations longer than a few nanoseconds cannot be applied to machining of transparent materials. However, the femtosecond laser can be used for transparent material because the laser pulse is not absorbed through the excitation of atoms for the vibration mode of the material (i.e. linear absorption) but is absorbed through the excitation from the electronic energy level of the material (i.e. nonlinear absorption). Due to the mentioned advantage of the femtosecond laser, it has been widely used for direct writing of waveguides and microstructuring of glasses and optical fibers [9].

Most optical fibers are designed for forward firing i.e. the beam exit at the distal end of the fiber along the optical axis of the fiber. In some applications such as the laser surgery, laser printing, and laser scanners, it is necessary to change the direction or the pattern of the light emission. The side firing of light can be achieved by polishing the fiber tip to approximately 45 degrees or less with respect to the optical axis. The polishing angle was determined by the light travelling inside fiber being total-internally reflected at the fiber tip at a certain measured degree. In 2008 H. Y. Choi et al reported about machining the flat mirror on the ball lens tip of the photonic crystal fiber to be used as side-viewing probes for imaging system [10]. The diffusing fiber tip was manufactured by adding the scattering particles during the drawing process of the optical fiber [11]. Despite the extensive studies on the modification of the fiber tip, the multidirectional firing fiber tip has not been reported yet to the best of our knowledge.

In this paper, we demonstrate the microstructuring of optical fiber tip by using a femtosecond laser for the multidirectional firing of the light. The distal end of the optical fiber was machined into a conical shape. The surface of the machined tip was, then, modified with an arc discharge. The arc discharge leads to the melting and re-solidification of the fiber tip. This results in the smoothing of the micromachined conical surface of the fiber tip.

2. Femtosecond laser induced microstructuring on the optical fiber tip

We have employed a typical Ti:sapphire regenerative amplified femtosecond laser as a machining tool. The laser produces 185 fs pulse at a repetition rate of 1 kHz with a maximum output power of 1 W and the wavelength of the light was set at 785 nm. The schematic diagram of the overall laser machining system is presented in Fig. 1. The fiber is placed on the automated XYZ stage with a home-made jig system that make the fiber tip aligned along the optical axis of the irradiating laser beam. The objective lens with a numerical aperture (NA) of 0.4 and the working distance of 10 mm was used in our experiment. The tip surface of the fiber was imaged onto a CCD sensor array. A DAQ Card equipped PC controls the laser pulse energy and the motion of the stage. The scanning pattern of the laser beam on the fiber tip was manipulated by moving the stage in an XYZ axis. A special scheme of stage scanning is required to achieve the three dimensional conical machining of the fiber tip. The conical engraving of the tip was made possible by producing the multiple-disk pattern at different depths of the tip. The first disk pattern whose diameter is slightly smaller than the cladding diameter of the fiber was engraved at the top of the fiber tip. Then, the second disk pattern whose diameter is 10 μm smaller than the first disk was engraved at a 7.7μm depth from the first disk pattern. The disk pattern engraving was repeated multiple times with a gradually reducing disk diameter. We used a commercial optical fiber with the core diameter of 100 μm and the cladding diameter of 125 μm. The spot size of the laser beam measures 3 μm at the sample plane and the used fluence was 10.1J/cm^2. The scan speed of the beam was set to about 10 μm/s. We were able to make a conical shaped machining of the tip by repeating the disk engraving at different depths. The Scanning electron microscopy (SEM) and optical microscope images of the fiber tip fabricated by the femtosecond laser are presented in Fig. 2. The base diameter of the conical shape is about 120 μm and the height of the cone measures 92.4 μm. Based on the refractive index of the core (n = 1.457) and the cladding (n = 1.44), we can calculate the maximum angle of the cone and ensure the total internal reflectivity. The calculated angle of the cone is about 43 degree from the optical axis of the fiber. We machined the conical structure with an angle of 33 degree from the optical axis; this angle is smaller than the maximum allowable angle for the total internal reflectivity.

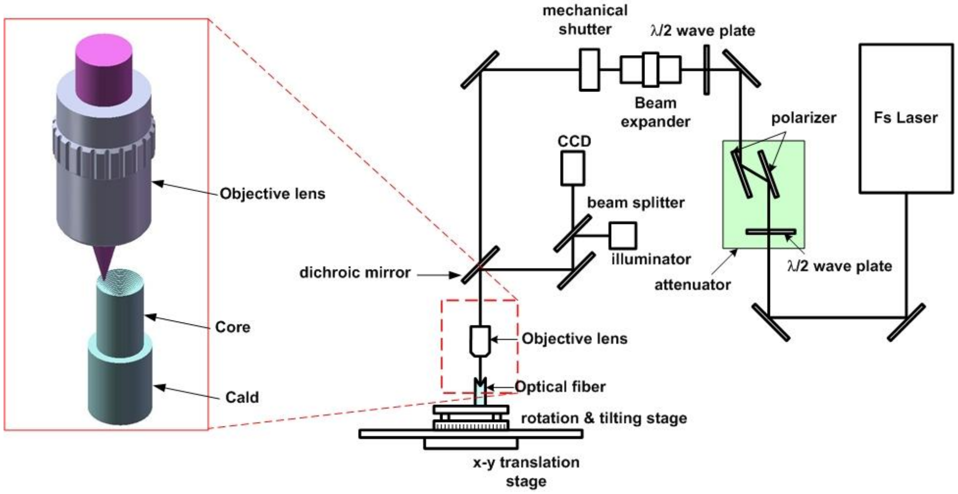

Fig. 1. Schematic set-up for femtosecond laser microstructuring of optical fiber.

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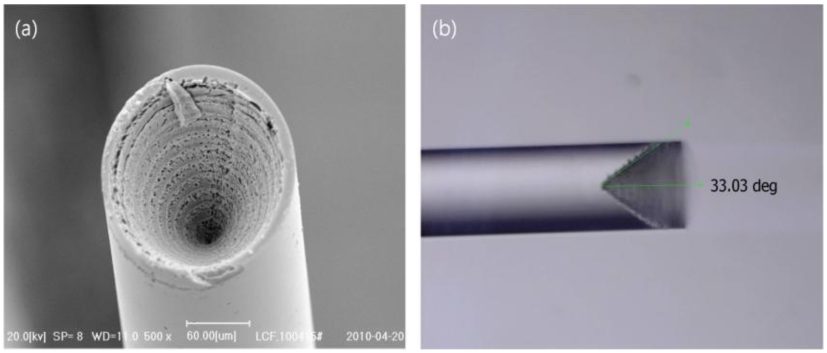

Fig. 2. SEM and optical microscope image of the optical fiber tip microstructured by using a femtosecond laser.

3. Polishing of the optical fiber tip by post-process of arc discharge

The stepped wall appearance of the machined cone can be observed because of the multiple-disk patterning from the ablation. The stepped structure of the wall induces the rough surface that results in the increased scattering and the diffusion of the reflection. To reduce the roughness of the wall surface, we decided to go through an additional smoothing process that can help the tip to perform in specular reflectivity rather than in diffused reflection. The arc discharge of the optical fiber splicer (Fitel, V2000S175) was employed as the post-processing method. The conically machined fiber tip was placed in the arc-discharging region of the splicer. The applied discharging voltage was about 0.09V and the discharging time was set to 3050 ms. The machined fiber tip was translated to about 7 μm during the process in order to ensure the overall treatment around the laser-machined cone region. By applying an arc with an appropriate intensity around the machined fiber, we were able to melt the tip superficially without modifying the overall conically shape of the fiber tip. The melted region of the fiber tip re-solidified and turned into a smoothly surfaced conical shape. The SEM and the optical image of the post-processed fiber tip are shown in Fig. 3. It is very clear that the surface of the cone shape tip is much smoother than the tip without the arc discharge process.

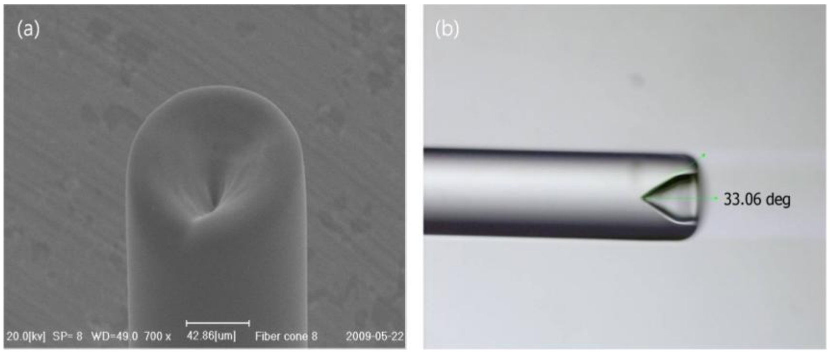

Fig. 3. SEM and optical microscope image of the optical fiber tip polished by post-process of arc discharge.

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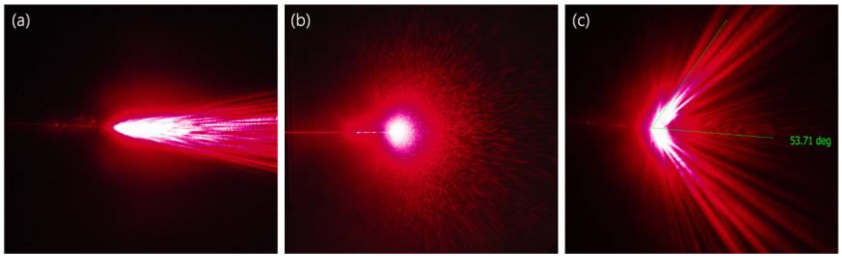

Fig. 4. The images of the beam emission at the tip of the fiber. Images are taken with a digital camera (a) before and (b) after the femtosecond laser microstructuring to the conical shape, (c) after the arc discharge following the laser machining.

4. Multidirectional firing of the laser beam by using the fiber tip

The beam emission from the fabricated fiber tip was tested by using a 660 nm laser diode (Fiber checker, VFL250). The 660 nm laser beam was coupled into the proximal end of the fiber tip by using the fiber adapter equipped with the laser diode. In order to examine whether the beam is emitted circumferentially with respect to the optical axis, the beam at the distal end was imaged at multiple circumferential viewpoints with respect to the fiber axis. The images were taken with a digital camera and typical images are presented in Fig. 4. The beam from the un-machined fiber tip is concentrated into the direction parallel to the fiber; however the machined fiber demonstrates the multidirectional firing at the distal end of the fiber. In the experiment of the tip without the arc discharge processing, it is clear that the emission from the fiber tip was not originated from the specular reflection, but from the emission that was initiated by diffused scattering due to the rough surface of the conical tip. In case of the tip with the arc discharge process, the image demonstrates that the beam is reflected specularly by the conical surface of the fiber. No matter which viewpoint from the fiber side is chosen, the majority of the beam is emitted at approximately 54 degrees with respect to the optical axis. Based on Snell's law, the emission angle of the laser can be calculated using the refractive index of the core, the refractive index of air and the angle of the machined cone. If we assume that the light inside the fiber travels along the optical axis, the emission angle of the beam can be calculated to be 53.7 degrees with respect to the optical axis. The calculated emission angle corresponds well to the measured value. We measured the forward transmission (the transmission along the optical axis of the fiber) by putting a power meter one mm away from the fiber tip. The forward transmission ratio of the femtosecond laser machined tip is less than 10% while the ratio of the bare tip (non-machined tip) reaches more than 90%. The reduction of the forward transmission at machined tip may attribute to the side transmission out of the fiber, the absorption at the tip and the back reflection to the proximal end of the fiber. Even though we cannot exclude the absorption and the back reflection, the contribution of the absorption and the back reflection to the reduced forward transmission would be minimal considering the clear surface of fiber tip (Fig. 3) and the emission profile (Fig. 4).

5. Conclusions

We presented the microstructuring of an optical fiber tip using the femtosecond laser in conjunction with arc discharge. The distal end of the optical fiber with a diameter of 125 μm was engraved conically using the femtosecond laser first and the surface of the engraved cone was polished using the arc discharge process. We were able to demonstrate the multidirectional (circumferential) emission of the light from the fiber tip. We expect the developed multidirectional firing fiber will be applied for various medical and industrial applications such as laser surgery, laser printing, and laser scanner.

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