Improving qualities of optical speciality fibre end faces with mechanical cleaving technology

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This paper provides possible ways and operation skills for obtaining quality fibre end faces with commercial fibre cleavers. At the same time, we measure the coupling efficiency with the fibre ends of different cleaving qualities. Results show that the roughnesses of the qualified cleaved end faces are around 20 nm, and the measured coupling efficiencies range from 64% to 76%, while a coupling efficiency of only 25% is obtained with the worse-cleaved fibre ends. Furthermore, some negative results are also shown about the cleaving of polarization-maintaining fibres, which may need more complicated work to improve their cleaving qualities.

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1. Introduction

High-power fibre lasers have already been one of the focused research topics in the field of optics for tens of years. With the development of the specialty fibre fabrication technology, the current record achieved with high peak power pulsed laser in a single fibre has already been at the megawatts level [1]. As the main part of the fibre lasers, the specialty fibre plays a key role in the transmission and amplification of the energy of the laser system. Usually, the first step to build up a fibre laser system is to obtain smooth and flat fibre ends. It should be noted that unsatisfactory results would happen if the fibre ends are not well-cleaved. For example, some scratches or spot defects on the end face would lead to light scattering and the decrease of the coupling efficiency, which may severely affect the efficiency and power of the fibre laser [2]. Furthermore, under extremely high power conditions, thermal loading problems may happen due to these defects and cause a breakdown on the end faces, as shown in Fig. 1. Thus only well-cleaved fibre can bear the heat effect of the high-peak-power operation [3,4]. Currently, since more focus is put on the laser performance rather than the fibre itself in the fibre laser research, there are only a few kinds of research working on the fibre itself, even though more and more findings show that qualified end faces play a key role in the fibre laser systems. Except for the traditional fibre cleavers, CO_2 lasers are the first kind of lasers used for fibre cleaving, but this method needs a high cost of CO_2 lasers and regular maintenance [5–8]. In 2021, Al Mamun et al. applied the femtosecond laser into fibre cleaving [9]. However, this is also not an economical method due to the cost of the laser. Until now, the traditional mechanical fibre cleavers are still the main tool for processing the fibre end faces. Consequently, this paper will give a full description of how the quality of the fibre end would affect the coupling efficiency and how to obtain a quality fibre end face.

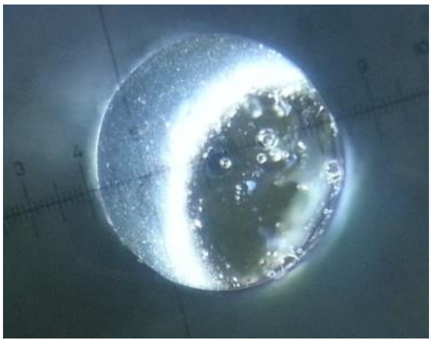

Fig. 1. Laser-induced breakdown on the fibre end (color online)

2. Experimental preparation and related principles

The current tools for cleaving specialty fibres are diamond cleavers and mechanic cleavers. Through intelligent programming, mechanic cleavers can produce more quality fibre end faces than diamond cleavers by carefully controlling the tensions applied to the fibre ends. In this experiment, the 3SAE LCC-II mechanic cleaver is mainly used (as shown in Fig. 2.)

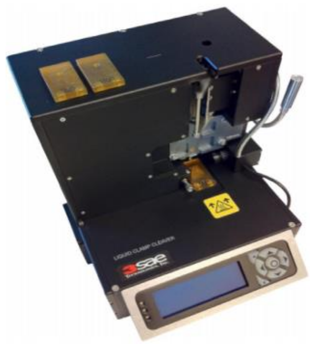

Fig. 2. 3SAE LCC-II mechanic fibre cleaver (color online)

Like the common brittle materials, the cleaved fibre end face can be divided into three regions which are the mirror, mist, and hackle zone from the blade intrusion side to the other side [10] (as shown in Fig. 3). Moreover, the roughness becomes higher and higher from the mirror to the hackle. There is no doubt that a qualified end face should be all covered with a mirror zone for the laser experiment.

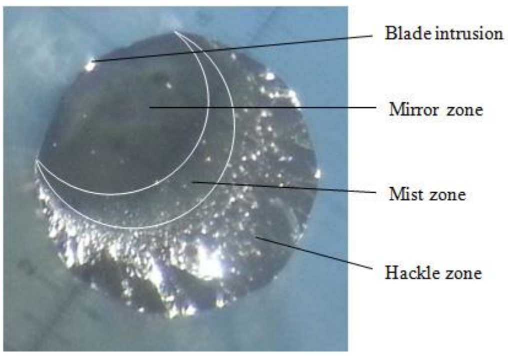

Fig. 3. Microscopic image of the surface quality of a cleaved fibre (color online)

To have a reasonable of control the tension applied to the fibre, it is found that there is a close relationship between the tension and the fibre cleaving quality. According to the fracture theory, the equation for the brittle materials is shown as follows [11]

$$\sigma_a^2 D_{mist} = K_{fract}^2 \tag{1}$$

where σ_a^2 is the square of the tension applied to the fibre ends, D_{mist} is the distance between the blade intrusion and the mist zone, K_{fract} is a constant related to the material. The formula shows that the cleaving result mainly depends on the tension and the material itself. When D_{mist} is longer than the fibre diameter, the fibre end face will be entirely occupied by the mirror zone. Consequently, the optimum parameters for cleaving can be found by gradually decreasing σ_a until D_{mist} is greater than the fibre diameter. Additionally, σ_a cannot be a very small value, otherwise, the fibre could not be successfully cut off.

3. Experimental results

The fibre-cleaving experiment is first carried out with the ytterbium-doped fibres produced by the No.46 Research Institute of China Electronics Technology Group Corporation (cladding diameter of 400 μm, core diameter of 25 μm), and the tension is applied to both ends of the fibre. As shown in Fig. 4, when the tension decreases from 13 N to 9 N, the mirror area on the fibre end face would become larger and larger, and the area of both the hackle zone and the mist zone is gradually decreased until the tension of 9 N is reached, where the perfect mirror area fully appears. Consequently, the proper tension applied to this kind of fibre is considered to be 9 N. Then the photonic crystal fibre (cladding diameter of 350 μm, core diameter of 20 μm) produced by South China Normal University is also used as the sample fibre for the cleaving experiment. As shown in Fig. 5, there is no doubt that it also follows the law of brittle materials cleaving equation. When the tension is decreased from 10 N to 6 N, the mirror zone gradually becomes larger on the end face. Thus, the optimum tension applied to this kind of photonic crystal fibre is considered to be 6 N. From Figs. 5 and 6, it is obvious to see that the K_{fract} of these two kinds of fibres are different due to the σ_a^2 and D_{mist} shown in the figure are different. Consequently, the two experiments also show that different kinds of fibres would have different optimum tensions due to their compositions.

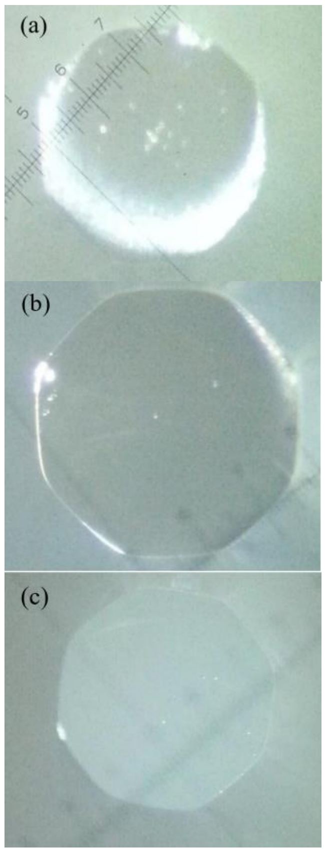

Fig. 4. Microscopic images of the Yb cleaved fibre under different tensions ((a) 13 N, (b) 11 N, and (c) 9 N, respectively) (color online)

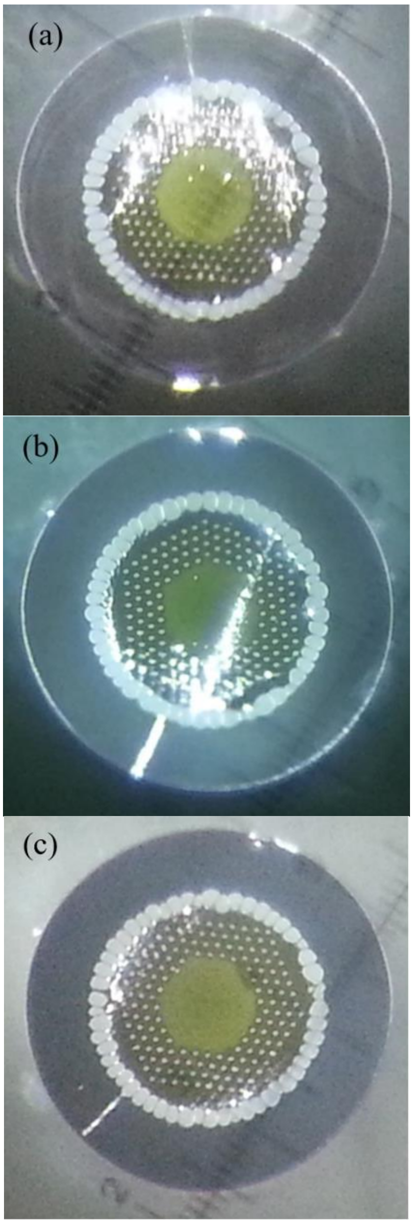

Fig. 5. Microscopic images of the cleaved photonic crystal fibre under different tensions ((a) 10 N, (b) 8 N, and (c) 6 N, respectively) (color online)

Due to the air holes on the end faces, the roughness measurement of the PCF end faces is severely disturbed. Thus we only measure the average roughness of the 25/400 Yb fibres under different cleaving qualities. With the same kinds of fibre, tensions ranging from 6 to 10 N are applied when the cleaving experiment is done, and each tension value is tried by ten times. After each time of cleaving, the roughnesses of the fibre ends are measured by the AEP Technology interferometer. Fig. 6 shows the result of the measurement. From the figure, we can see that the roughnesses increase with the decrease of the tension. With the 9 N tension applied to the fibre, the lowest roughness could be achieved.

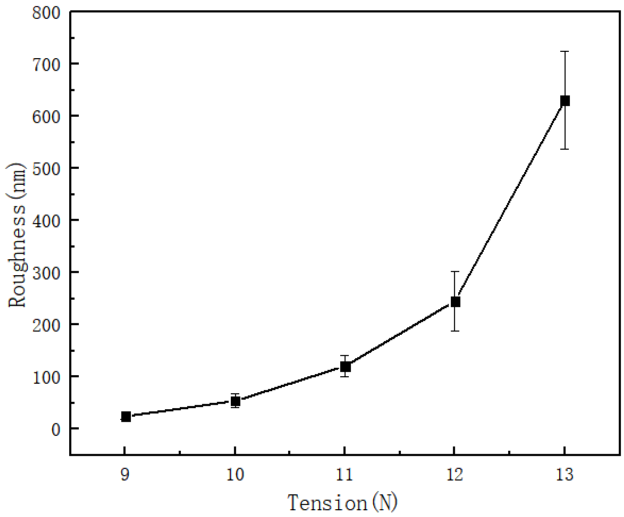

Fig. 6. The roughnesses of the surface vary with the tensions

Furthermore, we also measure the coupling efficiency of three same fibre samples under different cleaving qualities. First of all, both ends of the three fibre samples are cut by the mechanic cleaver under three different tensions (9 N, 11 N, and 13 N), and the lengths of the three fibres are 25 cm. Then the roughness is measured on both ends of each fibre, as shown in Table 1.

Table 1. The measured roughness of the fibre ends

Fibre	**Roughness (end face 1)**	**Roughness (end face 2)**
Sample 1	24.5 nm	28.9 nm
Sample 2	110.3 nm	127.4 nm
Sample 3	673.8 nm	735.9 nm

Finally, we measure the coupling efficiency of each fibre. Since 793 nm is not located at the absorption band of the Yb fibre, here a 91 w 793 nm diode laser is used to be coupled into the fibre by a 1:1 coupling system, and the coupling efficiency can be easily calculated through launched pump power divide by total pump power. As shown in Fig. 7, there is no doubt that sample 1 gains the highest coupling efficiency, and sample 3 comes to the last. For sample 1, it shows a coupling efficiency of 64%, this is because a relatively higher quality end face will not scatter too much light on the end face. However, when it comes to sample 3, only 22.2% of the power comes through the fibre, which means much more light is lost on the end faces. Results show that the coupling efficiency can be enhanced by at least 40% if the fibre could be better cleaved.

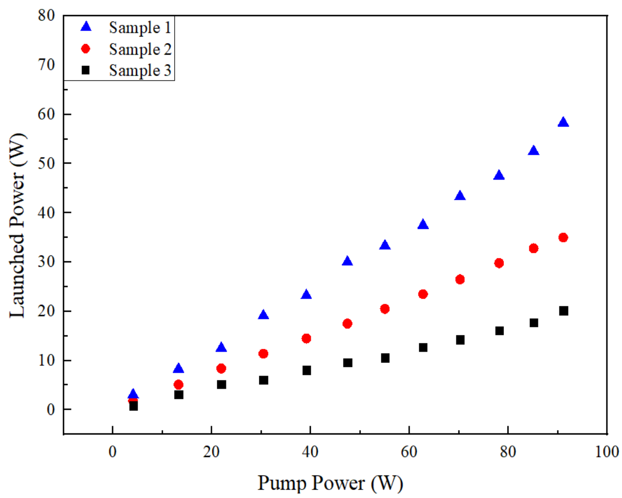

Fig. 7. The launched power versus the total pump power based on Yb fibre (color online)

At the same time, we also measure the coupling of three sample PCFs mentioned above, and Fig. 8 shows the launched power versus the total pump power with the tested fibres. Three PCF samples are selected with different cleaving qualities, and both ends of the three samples are cut by the mechanic cleaver under three different tensions (6 N, 8 N, and 10 N). Consequently, the cleaving qualities become worse and worse from sample 1 to sample 3. It is obvious that the highest coupling efficiency (76.2%) is obtained with the best-cleaved end face, which is sample 1. The lowest coupling efficiency is 25.4% under the condition of the worst cleaving quality, which is sample 3.

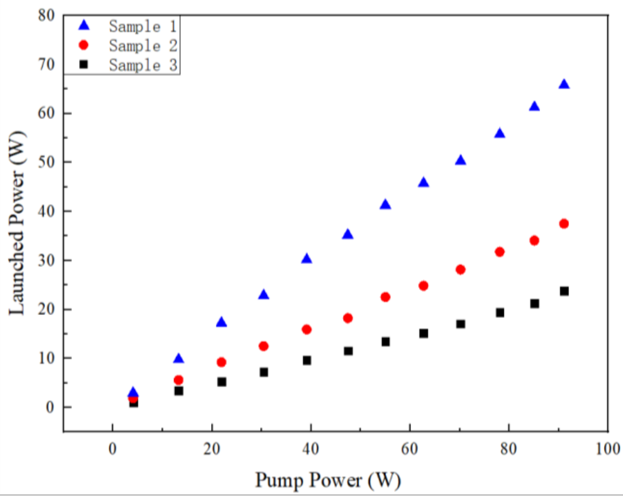

Fig. 8. The launched power versus the total pump power based on PCF (color online)

Finally, we also try to use the cleaver to obtain a quality end face of the photonic crystal fibre. However, by changing the tension applied to the fibres many times, cracks are still inevitable. Fig. 9 shows the cleaving results of the thulium-doped polarization-maintaining fibres produced by Nufern. This is because the fracture principle may not be applied here, especially when the fibre has a fine inner structure. In this case, the cleaving causes cracks on the end face due to uneven internal stress, and this kind of fibres needs a further polishing process [12].

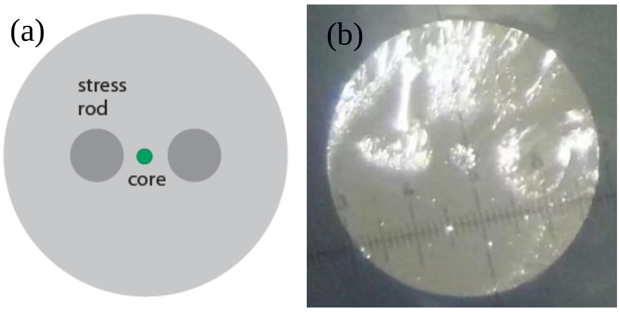

Fig. 9. (a) Model and (b) experimental cleaving result of the polarization-maintaining fibre end face (color online)

4. Conclusions

This paper provides guidance to those who want to do fibre-cleaving experiments. Generally speaking, for the common fibres, it would be easy to obtain an ideal fibre end face if the fracture principle of the fibres is followed. Furthermore, the quality of the fibre end face would significantly affect the coupling efficiency of the fibre, since the lower the roughness of the end face, the higher the coupling efficiency is. However, it can also be seen that some kinds of fibres mentioned above do not conform to the fracture principle. For the polarization-maintaining fibres, the stress distribution during the cleaving process is uneven due to the internal embedded boron-doped silica rods. Consequently, it is necessary to adopt the polishing method further for this kind of fibre [12].

Acknowledgements

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