

Influence of bending diameter on output capability of multimode fiber laser

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Abstract The output capability of large mode area (LMA) multimode fiber laser depends on the fiber bending. To study the relationship, the output capability of multimode fiber laser was measured under various bending diameters, and it was also theoretically calculated. Measured respectively were the beam quality factor M^2 , by means of knife edge for the different bending diameters of LMA fiber, and the slope efficiency. When the bending diameters 285, 195 and 130 mm were used, the corresponding beam quality factors were 2.88, 1.82 and 1.67 with the slope efficiency at 39%, 35% and 34%, respectively. In addition, for the LMA multimode fiber used in the experiment, losses of different modes were calculated theoretically under various bending diameters. The experimental results correspond to the calculated results.

Keywords fiber laser, output capability, knife edge, bending diameter, large mode area (LMA) multimode fiber

1 Introduction

Compared with other kinds of lasers, fiber laser is attractive for its excellent beam quality. However, its scalability to higher power is limited by various nonlinear processes [1], restricting its applications in medicine, industry and other fields. To overcome these limitations, large mode area (LMA) multimode fiber is employed. With the use of LMA double clad fiber, the output powers of fiber lasers is increased dramatically [2–8]. However, LMA fiber is always too large to maintain single-mode operations and multiple high-order modes

are oscillated, leading to the degrading of the beam quality. To achieve near single-mode laser with LMA fiber, many methods have been used to suppress high-order modes, such as manipulating the fiber index and dopant distributions [9–10], adopting special cavity configuration [11], fiber tapering [12–14], coiling the fiber [15–16] and so on. Of all these, the coiling technique is the simplest and most economical [17].

According to the fiber bending loss theory of Marcuse D [18–20], fiber bending brings energy loss and various modes have different bending losses. Under the same conditions, high-order modes are more sensitive to bend loss, which can be discriminated through coiling the fiber. In this paper, for various coiling diameters, beam qualities and output powers of LMA fiber laser were measured. At the same time, losses of different modes were also theoretically calculated. The findings agree with the experimental results.

2 Experiment measuring and analysis

The double clad LMA fiber employed in the experiment is provided by FiberHome Telecom. Tech. Co. Ltd., China. It has a 26 μm diameter Yb-doped core with a NA of 0.10, and a 450/400 μm D-shaped inner cladding with a NA of 0.37. The length and the effective coil length of the fiber are 9 m and 8 m, respectively.

The experimental setup is shown in Fig. 1. The pump from a diode laser is shaped with a spatial filter and then focused into the double clad fiber with an aspheric lens. A dichroic mirror (975 nm, $T=95\%$; 1050–1150 nm, $R>99.8\%$) just in front of the fiber is served as the input mirror. To filter the residual pump light in the collimated output light, another dichroic mirror is employed. Then the laser is focused with another lens whose focus length is 400 mm. Power meter is placed just behind a knife edge to detect the transmission power. By moving the knife

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edge, the beam radius along the propagation direction can be determined.

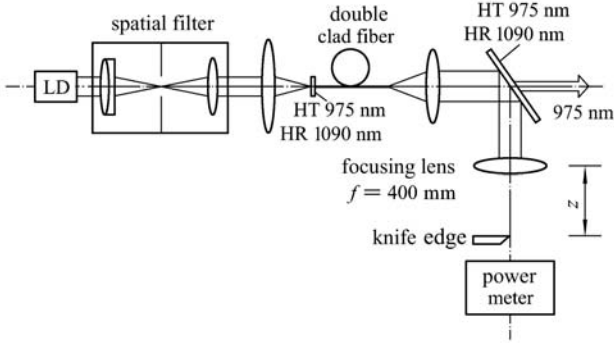


Fig. 1 Schematic diagram of spot diameter measurement using knife edge

2.1 Influence of bending diameter on the output beam quality

For a multimode laser beam, the radius $\omega(z)$ at propagation coordinate z can be obtained from the beam propagation equation [21,22] as

$$\omega^2(z) = \omega_0^2 + \left(\frac{M^2 \lambda}{\pi \omega_0} \right)^2 (z - L_0)^2, \quad (1)$$

where ω_0 and L_0 are the radius and the coordinate of the waist respectively and λ is the laser wavelength.

In the experiment, the fiber is coiled around a mandrel whose diameter is 285, 195 and 130 mm, respectively. Beam qualities of the fiber laser are measured. Based on the measurements, the simulated results of M^2 for the fiber laser with different coiled diameters (D_c) are illustrated in Fig. 2.

From Fig. 2, we can see that the corresponding beam qualities of the laser are 2.88, 1.82 and 1.67 respectively, which means that the beam quality is improved as D_c decreases. Under different conditions (as shown in Table 1), waist radii of the beams are almost the same while the beam diameter increases more remarkably as D_c becomes larger. As a result, higher mode has a larger divergence and fiber

Table 1 Different conditions shown in Fig. 2

	(a) $D_c = 285$ mm	(b) $D_c = 195$ mm	(c) $D_c = 130$ mm
M^2	2.88036 ± 0.01866	1.81771 ± 0.02044	1.66806 ± 0.01873
ω_0	173.51562 ± 1.40104	172.12068 ± 1.32707	170.56814 ± 1.20636
L_0	400.22094 ± 0.22016	399.81186 ± 0.43795	399.83047 ± 0.45141

laser with larger D_c has more high-order modes. As D_c decreases, some high-order modes are discriminated and beam quality of the laser drops.

Furthermore, compared with D_c changes from 285 to 195 mm, the decrement of M^2 is smaller as D_c changes from 195 to 130 mm, which means that the loss of laser modes is less. If D_c keeps decreasing, lower order modes will have a great loss and M^2 decreases. Finally, single mode output can be derived.

2.2 Influence of bending diameter on the output power of fiber laser

At the same time, high-order modes exist when D_c is large and the output power of the laser is high. When D_c decreases, some high-order modes are suppressed and the output powers drop. The output powers of the fiber laser for different D_c are measured and illustrated in Fig. 3.

As can be seen in Fig. 3, the slope efficiency of the fiber laser drops as D_c decreases. When D_c are 285, 195 and 130 mm respectively, the corresponding slope efficiencies are 39%, 35% and 34%. It can be concluded that some high-order modes escape from the fiber core and that slope efficiency drops when the fiber is coiled. Compared with D_c changes from 285 to 195 mm, the decrement of M^2 is smaller as D_c changes from 195 to 130 mm, which is consistent with the fact that the mode loss is larger in the former condition. We also find that the threshold of the fiber laser is almost unchanged for different D_c , which indicates that the fundamental mode LP₀₁ suffered no loss in the experiment.

3 Experiment results and discussion

For a fiber laser, the bending loss can be inferred from the following equation [18] as

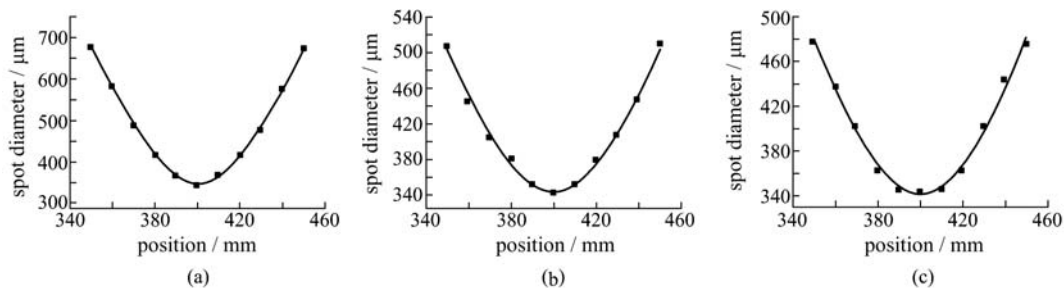


Fig. 2 Nonlinear curve fit of spot diameter. (a) $D_c = 285$ mm; (b) $D_c = 195$ mm; (c) $D_c = 130$ mm

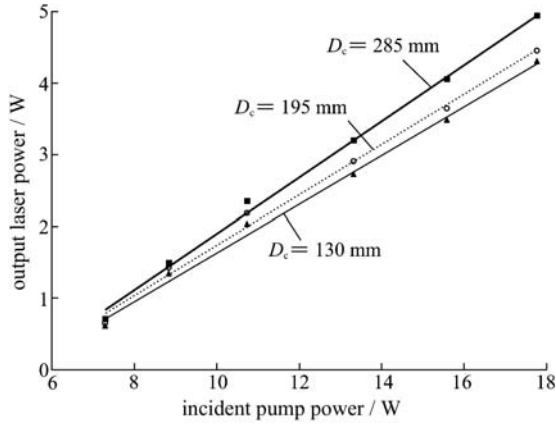


Fig. 3 Output power vs incident power

$$2\alpha = \frac{2ak^2 \exp\left(2\gamma a - \frac{2\gamma^3}{3\beta_g^2} R\right)}{e_v \sqrt{\pi\gamma} R V^2}. \quad (2)$$

In the experiment, the radius of the fiber core is 13 μm and NA of it is 0.10. The index of inner coating is 1.45 and the normalized frequency V of the core is 7.49. With these parameters, we can get the modal loss in cases of different coil diameters as shown in Fig. 4.

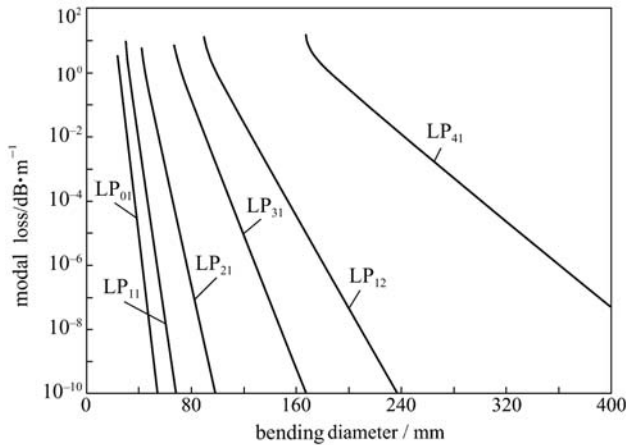


Fig. 4 Calculation of modal loss as a function of bending diameter for different modes

As we can see in Fig. 4, the higher order mode has a larger loss for the same D_c . When D_c is 285 mm, mode LP_{41} has almost no loss while higher modes do not exist. When D_c is 195 mm, the modal loss of mode LP_{41} is nearly 0.8 dB/m. As the effective coil length is 8 m, attenuation of it is 77%. Meanwhile, modal loss of mode LP_{12} is less than 10^{-6} dB/m and can be ignored. When D_c is 130 mm, mode LP_{41} will disappear and the modal loss of mode LP_{12} is 0.005 dB/m and its attenuation can be neglected.

In the experiment, only mode LP_{41} has a significant loss and the lower order modes have almost no loss. When D_c changes from 285 to 195 mm, mode LP_{41} has a larger loss which causes the output powers and slope efficiency of the laser to drop and the beam quality of the laser to improve. When D_c changes from 195 to 130 mm, the loss of mode LP_{41} is less and the reduction in slope efficiency and M^2 of the laser is smaller.

When the bending loss of a mode is 2 dB/m and attenuation of it is 97.5%, the corresponding bending diameter of the fiber is defined as modal critical bending diameter. As shown in Fig. 4, the critical bending diameter of mode LP_{11} is 36 mm. To get diffraction-limited laser beam, D_c of the fiber in the experiment should be less than 36 mm.

4 Conclusions

The high-order modes of LMA fiber laser can be discriminated when D_c is small enough. Then the beam quality of the laser improves and its slope efficiency drops. The experimental results is in agreement with the calculated results. However, with the limit of the homemade fiber's bend strength, the fibers with fewer radii have not been coiled. Optimizing the fiber can expectably assure us to get single-mode output.

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