Transverse-mode controlling of a large-mode-area multimode fiber laser

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Coiling technique is used to control the transverse mode of a large-mode-area (LMA) multimode fiber laser. By winding the fiber to a coil with different radius, high-order modes of a multimode fiber laser are suppressed one by one and finally 15.4-W single-transverse-mode output is achieved when the coil radius is 20 mm. It is found that as the coil radius decreases, the beam quality of a multimode fiber laser gets better but the slope efficiency drops for higher-order modes are discriminated. During the experiment, as the coil radius of multimode fiber changes, output characteristic of the laser has been measured. Meanwhile, the mode loss of different modes is calculated theoretically. It is proved that the experimental measured results fit well with the theoretically calculated results.

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The advent of double-clad fiber (DCF) technology has made high power fiber lasers possible[1]. However, power scaling of fiber lasers was limited by the amplified spontaneous emission (ASE) and various nonlinear processes, such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and self-phase modulation[2]. To overcome these limitations, low numerical aperture (NA) large-mode-area (LMA) fiber was commonly employed, which has a relatively low nonlinearity[3]. Such a LMA fiber has V-parameters in the range of $4-10$ and can therefore guide several higher order transverse modes. Fortunately, there are many ways[2,4−9] to suppress high-order lasing modes that allow designers to use even larger core diameters wherein essentially multimode fibers can be made to operate with a diffraction-limited beam quality.

In all these approaches, the coiling technique is the simplest and least expensive[8,9]. It does not require careful matching of the seed mode and does not rely on complex fiber designs. It is only necessary to choose the coil radius to discriminate high-order modes. The fundamental mode is the least sensitive to bend loss[10,11] and the attenuation due to bend loss is exponentially dependant on the coil radius. In this paper, high-order transverse modes of a China-made LMA multimode fiber laser are controlled and finally single-transverse-mode output is achieved.

The double-clad LMA fiber employed in the experiment is provided by FiberHome Telecom. Tech. Co. Ltd., China. It has a 16-μm-diameter Yb-doped core with a NA of 0.10 ($V \approx 4.61$ at 1090 nm), and a 350/400 μm D-shaped inner cladding with a NA of 0.37. The length and the effective coil length of the fiber are 8.5 and 8 m, respectively.

The experimental setup is shown in Fig. 1. The fiber laser is pumped by a laser diode whose central wavelength is about 975 nm. A double-clad LMA fiber is used as the gain material within a Fabry-Perot (F-P) cavity. A dichroic mirror (975 nm, $T \sim 95\%$; $1050-1150$ nm, $R > 99.8\%$) and an external cavity mirror ($1050-1150$ nm, $R > 99.8\%$) is used as the input feedback mirror. At the other end of the fiber, 4% Fresnel reflection is used as the output mirror. To filter the residual pump light in the collimated output light, another dichroic mirror is employed. Then beam quality of the laser is measured with a knife edge[8,9,12].

In the experiment, the fiber is winded into a coil, whose radii are 200, 93, 65, and 20 mm, respectively. Based on the measured results, the simulated results of beam quality factor M^2 for the fiber laser with different coil radii are illustrated in Fig. 2. The corresponding M^2 of the laser are 1.78 ± 0.17, 1.45 ± 0.06, 1.23 ± 0.05, and 1.03 ± 0.05 for 200, 93, 65, and 20-mm coiling radii, respectively. This means that the beam quality is improved as the coil radius r decreases. Figure 3 shows the beam profile of the fiber laser with $r = 20$ mm.

Output powers of fiber laser with various coil radii are also measured as shown in Fig. 4. The slope efficiency has the highest value 56.3% when $r = 200$ mm, while the lowest 48.6% when $r = 20$ mm and the corresponding highest output powers are 18.4 and 15.4 W, respectively. This indicates that the bend loss increases when coil radius becomes smaller. In the experiment, we also find that the pump power is not absorbed completely and

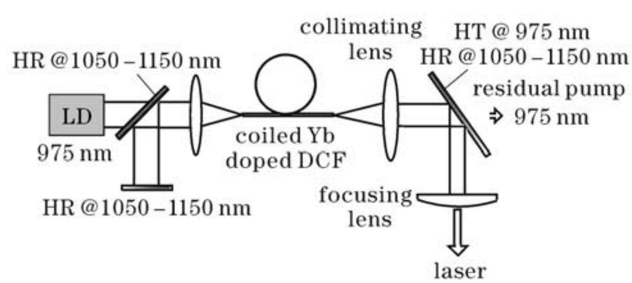

Fig. 1. Experimental setup.

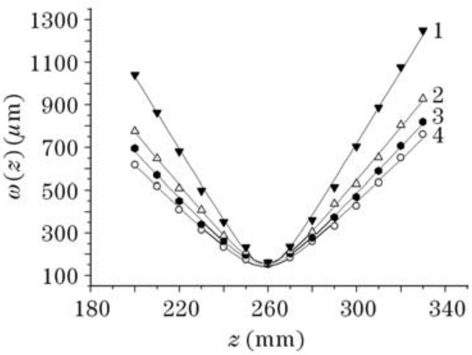

Fig. 2. Measurement of M^2 for the laser beam. (1) $r = 200$ mm, $M^2 = 1.78 \pm 0.17$; (2) $r = 93$ mm, $M^2 = 1.45 \pm 0.06$; (3) $r = 65$ mm, $M^2 = 1.23 \pm 0.05$; (4) $r = 20$ mm, $M^2 = 1.03 \pm 0.05$.

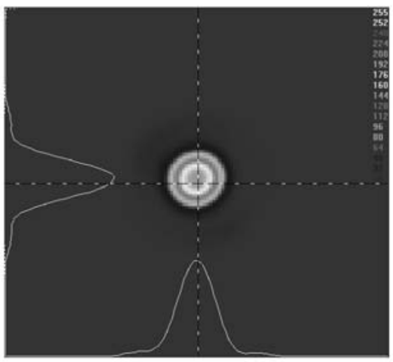

Fig. 3. Beam profile of the fiber laser with $r = 20$ mm.

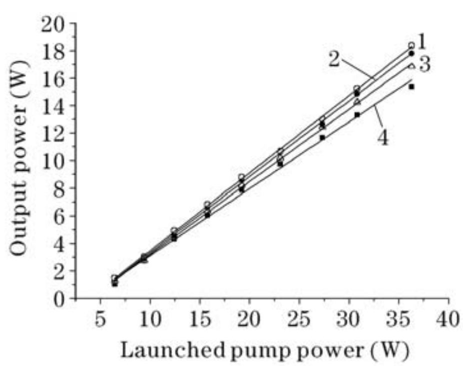

Fig. 4. Output power versus launched pump power. (1) $r = 200$ mm, slope efficiency 56.3%; (2) $r = 93$ mm, slope efficiency 55.1%; (3) $r = 65$ mm, slope efficiency 52.7%; (4) $r = 20$ mm, slope efficiency 48.6%.

higher slope efficiency can be obtained if longer fiber is employed.

For the fiber used in the experiment, the bend loss can be inferred from the following equations[10],

$$2\alpha = \frac{2ak^2 \exp\left(2\gamma a - \frac{2\gamma^3}{3\beta_g^2} r\right)}{e_\nu \sqrt{\pi\gamma r} V^2}, \tag{1}$$

$$k_0 = 2\pi/\lambda, \tag{2a}$$

$$k = \left(n_1^2 k_0^2 - \beta_g^2\right)^{1/2}, \tag{2b}$$

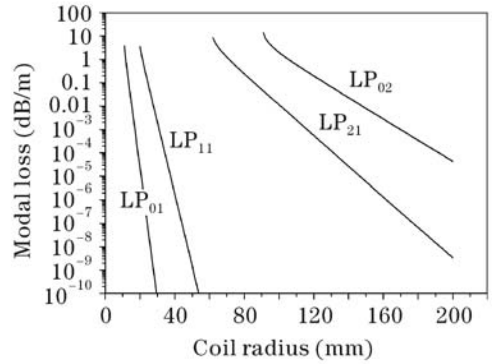

Fig. 5. Modal loss as a function of coil radius for different modes.

$$\gamma = \left(\beta_g^2 - n_2^2 k_0^2\right)^{1/2}, \tag{2c}$$

$$e_\nu = \begin{cases} 2, & \nu = 0 \\ 1, & \nu \neq 0 \end{cases}, \tag{2d}$$

where a is the fiber core radius, λ the laser wavelength, V the normalized frequency of the fiber, β_g the propagation constant of the guided mode in the straight guide, and r the coil radius of the fiber.

Figure 5 shows the modal loss versus the coil radius for different modes. For all modes, the bend-loss attenuation coefficient of high-order mode is larger than that of low-order one. When $r = 200$ mm, the modal loss of LP_{02} is nearly 5×10^{-5} dB/m, which can be ignored. When $r = 93$ mm, attenuation of LP_{02} is 51.2 dB (6.4 dB/m) while 0.24 dB (0.03 dB/m) for LP_{12}, which implies that LP_{02} is restrained completely but LP_{12} almost has no loss, and beam quality factor M^2 decreases but slope efficiency drops. When the coil radius r decreases to 65 mm, LP_{12} is differentiated but has no effect on lower-order modes. When $r = 20$ mm, the attenuation of LP_{11} is 28.8 dB (3.6 dB/m) but 1.6×10^{-4} dB (2×10^{-5} dB/m) for LP_{01}, and the laser has the best beam quality but the lowest slope efficiency because only LP_{01} is left. As shown in Fig. 5, if high output power is expected, the coil radius should be larger than 192 mm for the modal loss of LP_{02} is lower than 10^{-4} dB/m. And coil radius smaller than 20 mm can make us achieve single-mode output of the multimode fiber employed in the experiment. On the other hand, LP_{01} will experience high loss if the coil radius is too small.

As the coil radius decreases, high-order transverse mode of a LMA multimode fiber laser begins to undergo high bend loss and be controlled. As a result, the beam quality of a multimode fiber laser gets better but the slope efficiency drops. Finally, we demonstrate 15.4-W output with $M^2 = 1.03 \pm 0.05$. The experimental result agrees well with the theoretically result.

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