High power low-order modes operation of a multimode fiber laser

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Coiling technique is used to suppress high-order modes of a large mode area (LMA) double clad multimode fiber. Output powers and beam quality factors M^2 are measured under two different coiling radii. 217 W with M^2 of 2.96 can be obtained for coiling radius of 165 mm and 160 W with M^2 of 1.38 for 52 mm. The corresponding slope efficiencies are 60% and 48%. With smaller coiling radius, the brightness is 3.4 times as high as that of the larger one.

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Owing to the development of double clad fiber (DCF) and high power diode pumps, over 400-W DCF laser with single-mode can be obtained[1]. However, the scalability to higher power is limited by the amplified spontaneous emission (ASE) and various nonlinear processes, including stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and self-phase modulation[2]. As we know, the nonlinear effects are inversely proportional to the mode-field area[3], so they can be decreased by employing fibers of large mode area (LMA). Compared with the conventional fiber, LMA fiber has a relatively larger core but lower numerical aperture (NA). With the use of LMA double clad fiber, the output powers of fiber lasers increase dramatically[4−8].

LMA fiber is always too large to maintain single-mode operation (the normalized frequency $V < 2.405$) and multiple high-order modes are oscillated, which makes the beam quality degrade and the brightness of the laser drop. To achieve near single-mode laser with LMA fiber, experts have used many ways, such as coiling the fiber[2], manipulating the fiber index and dopant distributions[9,10], tapering the fiber sections[11], optimizing the seed conditions[12] and so on. Of all these, the coiling technique is the simplest and most economical. According to the fiber bend loss theory of Marcuse[13,14], high-order modes are more sensitive to bend loss, so they can be discriminated through coiling the fiber. As high-order modes are suppressed, the beam quality upgrades. In this paper, 160-W output with M^2 of 1.38 is obtained by coiling the homemade LMA double clad fiber.

The fiber used in the experiment is provided by FiberHome Telecom. Tech. Co. Ltd., China. To obtain high power output laser, it has a 43 μm diameter Yb-doped core with a NA of 0.08 ($V \approx 9.9$ at 1090 nm), and a 650/600 μm D-shaped inner cladding with a NA of 0.48. The length of the fiber is 8 m.

The experimental setup is shown in Fig. 1. Pump from a diode laser is focused into the double clad fiber with an aspheric lens, in front of which a dichroic mirror (975 nm, $T \sim 95\%$; 1050—1150 nm, $R > 99.8\%$) and an external cavity mirror (1050—1150 nm, $R > 99.8\%$) are placed to act as the input feedback mirror. In order to filter the residual pump light in the collimated output light, another dichroic mirror is employed. Then the beam is focused with an aspheric lens, whose focus length is 300 mm for visible light. By measuring beam radii along the propagation direction with a knife edge, we can determine the beam quality factor M^2 of the laser[15].

For a multimode laser beam, the radius $\omega(z)$ at propagation coordinate z can be obtained from the beam propagation equation[15]

$$\omega^2(z) = \omega_0^2 + \left(\frac{M^2\lambda}{\pi\omega_0}\right)^2 (z - z_0)^2, \qquad (1)$$

here ω_0 and z_0 are the radius and the coordinate of the waist, respectively, λ is the laser wavelength.

In the experiment, the fiber is coiled around a cylindrical mandrel, whose radius can be measured easily. To contrast the influence of the coiling over the high-order modes suppressing, mandrels with radii of 165 and 52 mm are employed respectively. Based on the measured value, the simulated result of M^2 is illustrated in Fig. 2.

As shown in Figs. 2(a) and (b), the corresponding beam quality factors M^2 are 2.96 for 165-mm coiling radius and 1.38 for 52-mm one. Under different conditions, z_0 is a little more than 300 mm because the laser has a larger wavelength than visible light and the waist radii of the

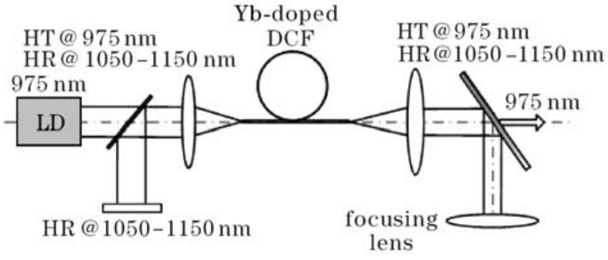

Fig. 1. Experimental setup.

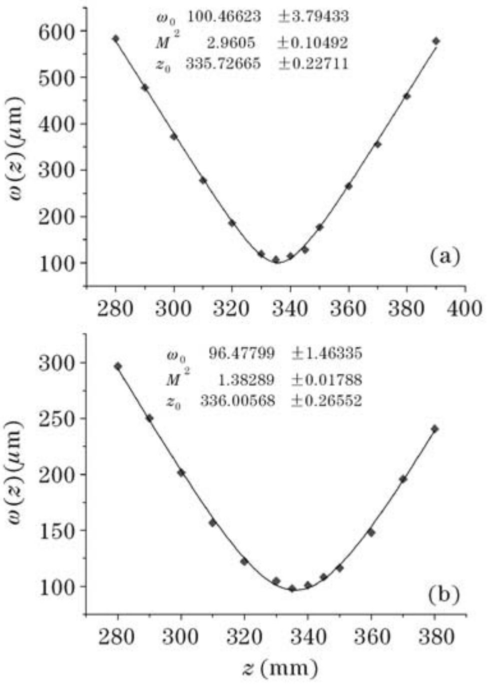

Fig. 2. Measurement of M^2 for coiling radii of (1) 165 and (b) 52 mm.

beams are almost the same. But when the coiling radius is 165 mm, the beam radius $\omega(z)$ increases more remarkable and the curve is sharper. Obviously, it has a larger divergence than that of the 52-mm coiling radius. For the reason higher mode has a larger divergence, the beam of 165-mm coiling radius has more high-order modes. When the coiling radius reduces to 52 mm, some high-order modes have a larger loss[13,14], so they are discriminated and the low-order modes remain to make the corresponding beam quality better.

Output powers respect to the incident powers are measured for different coiling radii as shown in Fig. 3. When the input power is 380 W, 217- and 160-W output powers for 165- and 52-mm coiling radii are achieved, respectively. With the brightness equation of laser beam[16], the smaller coiling radius increases the brightness by a factor of 3.4. The corresponding slope efficiencies are 60% and 48%, which can be explained as follows. Firstly, some high-order modes are suppressed with 52-mm coiling radius but remained with 165 mm. On the other hand, with smaller coiling radius, part of the pump light is not confined by the inner cladding and leaked out of the cladding, which leads a lower absorption of the pump. And just as can be seen in Fig. 3, under high launched power, the measured output powers of 165-mm coiling radius have an agreement with the fit line but those of 52 mm are a little smaller than the simulated values. Perhaps this is caused by the thermal effect because smaller coiling radius is not beneficial for heat dispersion, which makes the power decline.

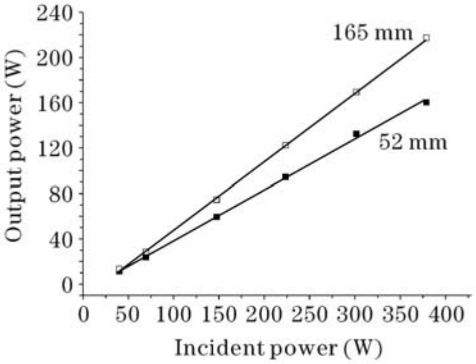

Fig. 3. Output power versus incident power.

In summary, we demonstrate 160-W output power with beam quality factor M^2 of 1.38 by means of a LMA double clad fiber with 52-mm coiling radius, whose slope efficiency is 48%. Compared with 165-mm coiling radius, the brightness is increased by a factor of 3.4 with power penalty of ~26%. In the experiment, we also find there is some remained pump behind the output dichroic mirror, and this means that the fiber is not long enough to absorb the pump power completely. So we can use longer fiber and double-end pump to get higher output power with low-order modes. Furthermore, with the limit of the homemade fiber's bend strength, we have not coiled the fiber to fewer radii, and optimizing the fiber can assure us to get single-mode output.

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