

Multi-coupler side-pumped Yb-doped double-clad fiber laser

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The side-coupler of angle polished method, using angle-polished multimode fiber and optical adhesive, is used to efficiently pump an Yb-doped double-clad fiber laser. The maximum coupling efficiency of 78.6% is achieved by the side-coupler for a multimode fiber with a circular core of 200 μm and a double-clad fiber with a 350/400 μm D-shaped inner cladding. While laser diodes (LDs) with three side-couplers are simultaneously used as pump sources, maximum output power of 1.38 W and slope efficiency of 48.9% are demonstrated in the fiber laser system.

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Laser diode (LD) pumped rare-earth-doped double-clad fiber lasers are very efficient system with high power and good beam quality, which have many potential applications in machining, optical measuring, sensors, telecommunication and medicine. End pump is the conventional method to couple pump lights into the inner cladding of such double-clad fiber. However, this pump regime has disadvantages. Firstly, since the LD pump sources are limited in power and brightness, the output power cannot be scaled without increasing the cladding size. Secondly, other devices, which should be mounted on the fiber ends, are limited by the end-pump arrangement. In the past, several techniques have been developed for launching pump light into double-clad fiber through the fiber side, such as multifiber side-coupling technology^[1], V-groove side-coupling technique^[2], angle-polished method^[3-5], embedded-mirror method^[6], diffraction grating method^[7], and micro-prism sided-coupling method^[8,9]. The angle-polished method is simple and does not change the parameters of double-clad fiber compared with other methods. Although the angle-polished method has been reported, the maximum output power of double-clad fiber laser is no more than 197 mW with slope efficiency of 20%^[4,5]. In this letter, we study multi-couplers side-pumped Yb-doped double-clad fiber laser with the angle-polished method. While LDs with multi-coupler pump simultaneously, maximum output power of 1.38 W and slope efficiency of 48.9% are demonstrated.

Figure 1 shows the side-coupler of the angle-polished method. The configuration consists of a multimode fiber, a double-clad fiber, and a thin layer of index-matching material between them. One end of the multimode fiber optically connects with the LD, and the other end is polished at angle γ to make a direct power coupling into the inner cladding. To form the side-coupler, in the joint region the outer cladding is removed and the angle-polished multimode fiber is connected to the double-clad fiber via index-matching material to minimize Fresnel reflective losses at interfaces. There are two interfaces in the joint region. The first interface is between the angle-polished end of multimode fiber and the index-matching material; the second one is between the index-matching material and the inner cladding.

To obtain high coupling efficiency is one of the pivotal targets of the side-pump method. The coupling efficiency of the side-coupler with the angle-polished method is mainly determined by the coupling angle γ and the refractive index of the index-matching material. If the coupling angle γ is much larger, the light enters the double-clad fiber in a large incidence angle and will be reflected by the boundary between the inner and outer claddings in the double-clad fiber in a small reflection angle. Thus more light power will transmit through the boundary and the coupling efficiency goes down. On the other hand, while the coupling angle γ becomes too small, the incident angles in both interfaces become significantly large. According to Fresnel's law, the total light transmissions in both interfaces decrease and the coupling efficiency goes down. The maximum coupling efficiency is the trade-off of these two effects. Choosing an appropriate index-matching material with the refractive index closer to that of fused silica can enhance the light transmissions in both interfaces. In experiments, the multimode fiber has a diameter of 200 μm and numerical aperture of 0.11. The double-clad fiber has a non-doped inner cladding with a D-shaped cross-section of 350/400 μm and a circular core of 12 μm . The Yb concentration in the core is about 0.65 mol-% and the numerical aperture of its inner cladding is 0.37. A heated-curable

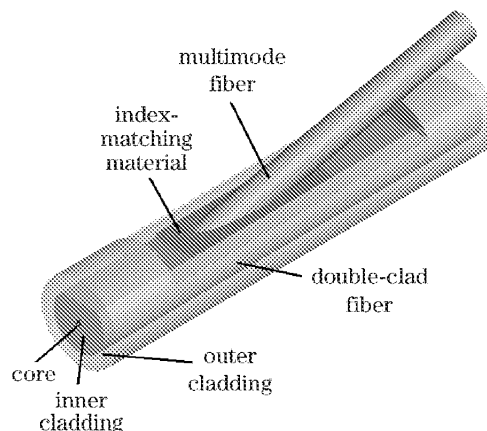


Fig. 1. The side-coupler of the angle-polished method.

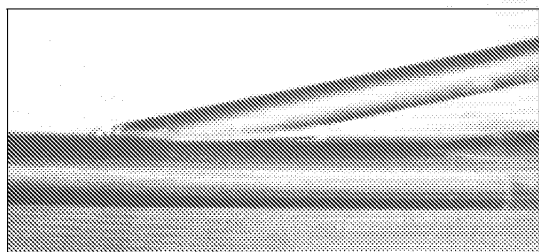


Fig. 2. The microscopic photograph of the side-coupler.

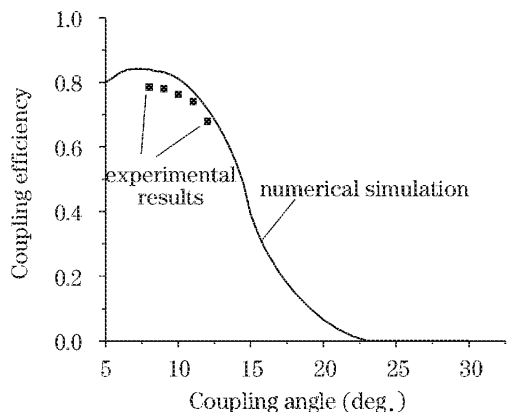


Fig. 3. The experimental results of coupling efficiency compared with the numerical simulation.

optical adhesive with refractive index of 1.47 is used as the index-matching material to transmit the high density pump light in the joint. The microscopic photograph of the side-coupler is shown in Fig. 2. Figure 3 shows the experimental results of coupling efficiency compared with the numerical simulation. The maximum coupling efficiency of 78.6% is measured with the coupling angle about 8° in experiment, which agrees with the optimum coupling angle obtained by Hakimi^[3]. The numerical simulation has been presented detailedly in Ref. [10].

The established multi-coupler side-pumped Yb-doped double-clad fiber laser consists of LDs, angle-polished multimode fibers and a Fabry-Perot cavity (see Fig. 4). These LDs are fiber-coupled output of 1.5 W with center wavelength of 0.98 μm. The output pigtail fiber of the LD is the same multimode fiber of the side-coupler. One end of the multimode fiber is attached to the pigtail fiber by connector. The other end is angle-polished and connected to the inner cladding through the

heated-curable optical adhesive to form the side-coupler. The Fabry-Perot cavity is constructed by one uncoated double-clad fiber end and a mirror butted to another end of the double-clad fiber. The mirror has the reflectivity > 99.5% for 1.05 – 1.15 μm, and the uncoated double-clad fiber end provides a reflectivity of about 3.5% to the laser oscillation. The double-clad fiber has already been used in a 10-W end-pumped fiber laser system, and its length of 38 m makes the pump power to be absorbed sufficiently^[11].

Firstly, one side-coupler is used for the fiber laser. The position of the side-coupler is about 0.3 m apart from the double-clad fiber end butted with the mirror. The maximum laser output is 282 mW and the slope efficiency to the LD pump power is about 55.6% (see Fig. 5). To scale the side-coupling technique several multimode fibers can be placed along the double-clad fiber. Hence, a second angle-polished multimode fiber is attached to the double-clad fiber apart from the first coupler about 0.1 m, and the laser radiation is measured before and after the application of the second side-coupler. A loss of 12.7% of the laser radiation is measured due to outcoupling of pump light at the second side-coupler. By using two couplers to launch the LDs, pump lights into the double-clad fiber, we obtain a laser power of 898 mW and slope efficiency of 51.1%. In order to observe the affection of interval between couplers, we apply the third coupler at the position of 0.5 m from the second coupler, and the total loss of 9.7% of the laser radiation is measured. The longer interval between couplers increases the absorption of pump light in the double-clad fiber. Consequently, it decreases the loss of laser radiation owing to the outcoupling of pump lights. When turning on all the three LDs, the laser output power of 1.38 W is achieved with the total pump power of 4.5 W. The laser slope efficiency is 48.9% with respect to the pump power. The high slope efficiency shows that multiple fiber couplers can be applied for the higher-power, compact double-clad fiber lasers. For the sake of both high coupling efficiency and low outcoupling loss, the coupling angle is chosen to be about 10° for side-couplers of the fiber laser in experiments. In summary, we have presented a three-coupler side-pumped Yb-doped double-clad fiber laser, which are fabricated by the angle-polished fiber side-coupler technique. Laser radiations have been demonstrated under one coupler, two couplers and three couplers regimes, and the slope efficiencies are 55.6%, 51.1%, and 48.9%, respectively. The drop of slope efficiencies is due to the outcoupling of pump light at the side couplers.

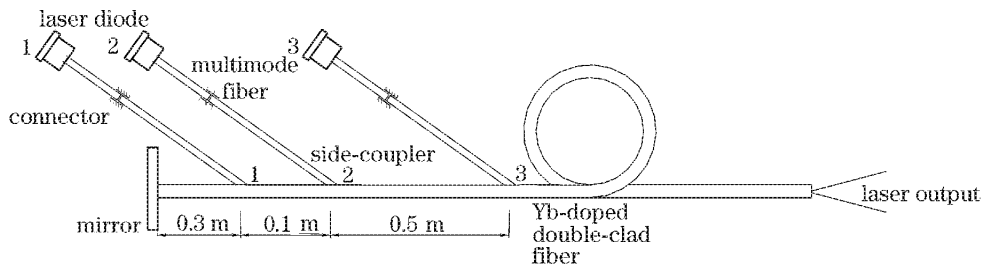


Fig. 4. The experimental setup of multi-coupler side-pumped Yb-doped double-clad fiber laser.

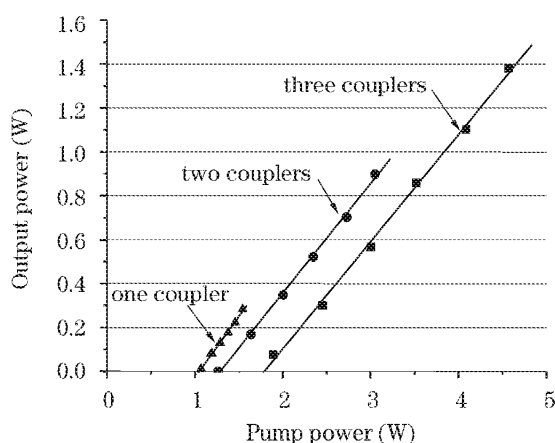


Fig. 5. Laser output power against laser diode pump power.

The laser output power is 282 mW, 898 mW, and 1.38 W, respectively. The experimental results show the fiber coupler can be applied for the higher-power, compact double-clad fiber lasers.

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