175-W continuous-wave master oscillator power amplifier structure ytterbium-doped all-fiber laser

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We report on hundred watts range ytterbium-doped all-fiber laser assembly based on the master oscillator power amplifier structure. It consisted of an oscillator and an amplifier with all-fiber components. And fiber fusion splice made the laser be an integrated fiber system. It generated up to 175.5 W of continuous-wave (CW) output power at 1085 nm with more than 75% extraction efficiency in the amplifier when the total coupled pump power into the double clad fiber was 270 W.

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In recent years, fiber lasers play an important role and are widely used in many fields, such as sensor, materials processing, and military applications[1,2]. The combination of small size, maintenance-free operation, ease of cooling, high efficiency, and outstanding beam quality has made the fiber laser become very attractive laser source[3−5]. In particular, ytterbium (Yb)-doped fibers offer a very low quantum defect and a very broad emission between 1 and 1.1 μm[6,7]. Triggered by the progress in high-brightness pump diodes and the availability of large mode area (LMA) double-clad gain fibers, several Yb-doped fiber lasers with output powers approaching the kW-range in the continuous regime have been reported[8]. These demonstrations typically employed a length of gain fiber pumped via free-space coupling and bulk optics as the reflector. However, the availability of integrated all-fiber laser is crucial for making this technology available for a variety of application. All-fiber laser employs all-fiber components to replace the bulk-optic interface in the present laser configurations and consequently becomes compact, rugged and reliable. There are fewer reports on the integrated all-fiber laser. For example, IPG photonics reported on the significant increase of all-fiber format single-mode Yb-doped continuous-wave (CW) fiber laser output power to 1.96 kW with $M^2 < 1.2$, demonstrated during a laboratory test in 2005[9]. During 2006, Norman *et al.* reported for the first time on the power-scaling extension of SPI's proprietary side coupled cladding-pumped GT-wave technology platform with 400-W output power[10]. In this paper, we report the development of a low noise, 175.5-W CW side-pumped Yb-doped all-fiber laser. To the best of our knowledge, this is the highest CW power of all-fiber laser ever reported in China.

The developed fiber laser consists of two stages: laser oscillator and booster amplifier. They are connected by the fusion splice, which make the all-fiber laser system require less maintenance and no misalignments. The experimental setup is depicted in Fig. 1.

The laser oscillator contained gain fibers, a 7 × 1 multi-mode combiner, and a pair of fiber Bragg gratings. We used commercially available LMA-YDF-20/400 Yb-doped double clad fiber as the gain medium whose length is 15 m. The fiber has a 20-μm diameter core with a low numerical aperture (NA) of 0.06. The geometric shape of inner cladding is octagonal as shown in Fig. 2, and the diameter and NA are 400 μm and 0.46 respectively. The 7 × 1 multi-mode combiner was used to couple the pump light into the inner cladding of gain fiber. The combiner has seven pump delivery fibers with standard diameter of 200/220 μm and a NA of 0.22. The laser cavity is formed by a pair of fiber Bragg gratings. One of them was used as the high reflector and the other was used as the output coupler. In our experiment, we employed six 20-W fiber-coupled pump diodes modules (200/220-μm 0.22-NA delivery fiber) to provide 975-nm

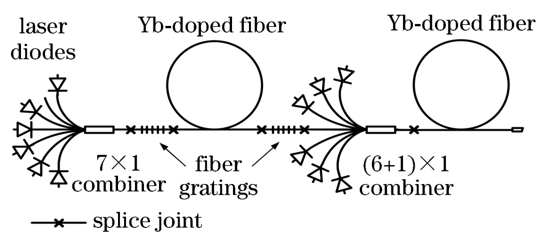

Fig. 1. Experimental arrangement of master oscillator power amplifier (MOPA) structure all-fiber laser.

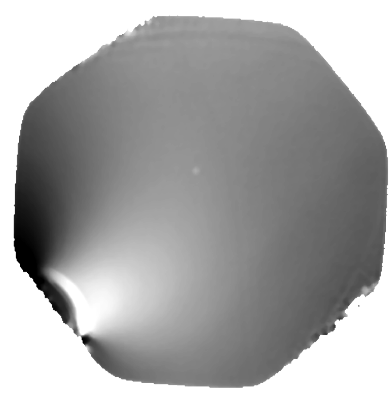

Fig. 2. Inner cladding shape of gain fiber.

pump power without the need of any free-space optics.

The booster amplifier has a similar design consisting of gain fibers and a $(6+1)\times 1$ multi-mode combiner, spliced to the delivery fiber of oscillator. The gain fiber used in the amplifier is the same to that in the laser oscillator and the length is 10 m. The $(6+1)\times 1$ combiner has a fiber bundle where the central fiber is replaced with a signal fiber. In this special configuration, six pump delivery fibers and one signal fiber are coupled to the inner cladding and the core of the double clad fiber, respectively. The pump fibers are also standard 200/220-μm fiber with a NA of 0.22. Both the signal input fiber and double clad output fiber are germanium-doped passive fiber with the core diameter of 20 μm (NA = 0.06) and inner cladding diameter of 400 μm (NA = 0.46), which are compatible with the gain fiber. At the output of fiber device, an angled end is employed to minimize back-reflection into the amplifier. The booster amplifier is pumped by six 25-W laser diodes of 975-nm pumping.

The fiber splice is a critical technology in the investigation of all-fiber laser, which is employed to replace the bulk optics in a system. Low-loss splice of fibers has a significant impact on the performance of a fiber laser. In our experiment, the output fibers of diode modules were simply spliced to the pump delivery fibers of combiner without the use of isolators. More challenging work is the fusion splice between 20/400-μm fiber and 20/400-μm fiber, even between germanium-doped LMA 20/400-μm and Yb-doped LMA 20/400-μm fibers. The micrographs of typical splice results are shown in Figs. 3 and 4. Generally, it is difficult to achieve a high splice quality for LMA fibers, and the result would be worse than the splice between single-mode fibers. Fortunately, even for a 1 or 2 micron error in the core position, the splice loss will be small when the mode field diameter is large. During the operation of this all-fiber laser, the splice joint between germanium-doped fiber (GDF) and Yb-doped fiber (YDF) works well. In the laboratory, the most common method to measure fusion splice loss is cutback measurement. This measurement scheme

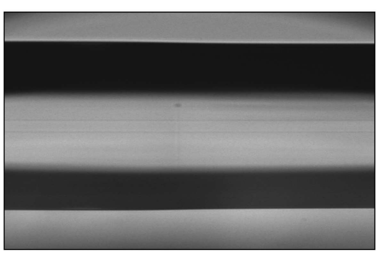

Fig. 3. Side view of the splice joint between GDF-20/400 μm and GDF-20/400 μm.

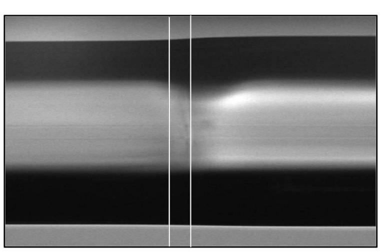

Fig. 4. Side view of the splice joint between GDF-20/400 μm and YDF-20/400 μm.

consists of a calibration step and a measurement step. After comparing the difference between the optical energy of two steps, optical loss introduced by the splice joint can be obtained. With this method, the insert loss between 200/220-μm fibers was measured to be less than 0.1 dB and the loss between GDF and YDF was approximately 0.2 dB.

The laser oscillator exhibited a threshold pump power around 9 W and achieved the output power of 61.9 W under 120-W pump power. Fiber laser oscillator had a slope efficiency of 73.17%, which was based on the pump power in the gain fiber. When the signal power of 24.2 W and 61.9 W were injected into the fiber amplifier separately, the characteristics of output power and extraction efficiency versus pump power were presented in Figs. 5 and 6 respectively. The maximum obtained CW power was 175.5 W at 61.9-W signal power and 150-W coupled pump power in the amplifier. The extraction efficiency of amplifier is defined by the difference

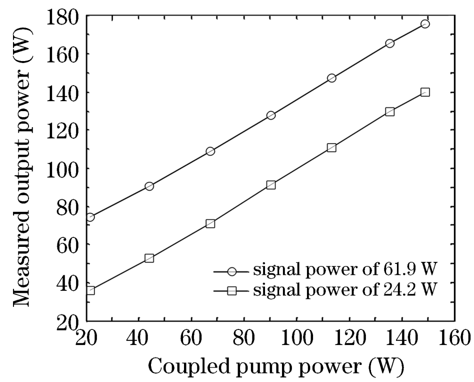

Fig. 5. Output power versus pump power in the amplifier.

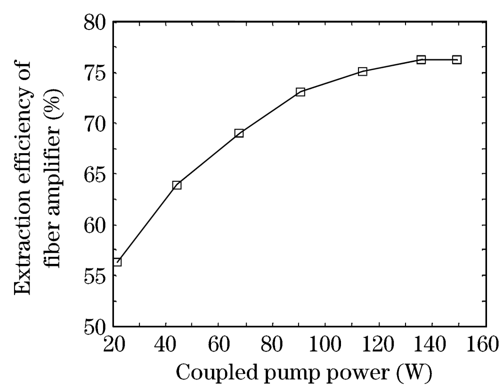

Fig. 6. Extraction efficiency of the fiber amplifier versus coupled pump power under signal power of 61.9 W.

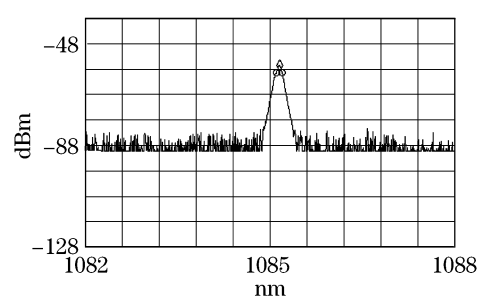

Fig. 7. Output spectra of all-fiber laser at high power level.

between the output power and signal power divided by the pump power. Note that, amplified spontaneous emission did not consume much up-level population and the extraction efficiency had been around 75%. It is expected that the increase of output power would not be limited by the amplified spontaneous emission. The output spectra are presented in Fig. 7, which were measured by an optical spectrum analyzer (Agilent Inc.). The optical spectra depend on the reflection characteristic of the fiber Bragg gratings and are centered at 1085 nm. At 146-W output power, the full-width at half-maximum of the emission spectrum is 0.1 nm. The signal to noise ratio of assembly presented in the spectra was more than 25 dB. LMA fibers were employed as gain fibers, which suppressed nonlinear effects. There was no stimulated Raman scattering present for any of power level. Gain fibers, multi-mode combiners, and fiber splice joints did not need any special method to be cooled in this all-fiber laser system.

In Conclusion, we have demonstrated an all-fiber laser system based on the MOPA structure with the output up to 175.5 W, and more than 75% extraction efficiency in the amplifier. Fiber splice exhibited low-loss and high-power handling performance. Both the laser oscillator and booster amplifier could convert pump energy to laser output effectively. We believe that increasing the pump power can produce much higher output power. CW MOPA structure fiber lasers have great potential to get high power output with all-fiber manner which will be benefit to various applications.

This experiment was a primary work in researching high power all-fiber laser. The system did not operate for long time and the beam quality was not measured. In the future, we plan to investigate these performances and have a discussion on them.

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