A $2 \times 3$ kW-level bidirectional output fiber oscillator is realized by combining the specially designed spindle-shaped ytterbium-doped fiber, non-wavelength-stabilized 976-nm LDs, and grating bandwidth optimization to balance transverse mode instability and stimulated Raman scattering. The maximum output powers at both ends are 3265 and 2840 W, respectively, with a total efficiency of 73.2%. The $M^2$ factors of the lasers at both ends are about 1.98 and 2.38, respectively. The beam profile at both ends shows that a bidirectional output annular beam fiber oscillator has been realized, which has great potential in practical applications.

Keywords: fiber laser; bidirectional output fiber oscillator; spindle-shaped ytterbium-doped fiber.

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1. Introduction

Fiber lasers have been widely used in industrial processing, scientific research, and other fields due to their advantages of good beam quality, convenient thermal management, and good flexibility\cite{1,2}. High average power fiber lasers are an important development direction in fiber laser technology. In the past 20 years, the rapid development of large-mode-area (LMA) fibers, cladding pump technology, high-brightness LDs, and fiber devices has enabled fiber lasers to achieve leaps from hundreds of watts to several kilowatts and 10 kW\cite{3-11}. Fiber laser amplifiers based on master oscillation power amplification (MOPA) structures consist of low-power seeds and high-power amplifier stages, which have relatively low requirements on fiber devices, especially fiber gratings. Therefore, the early high-power fiber lasers are mainly fiber laser amplifiers with MOPA structures\cite{12,13}. With the improvement of the technology and performance of the fiber grating and other devices, high-power fiber laser oscillators have achieved rapid development in recent years. The oscillator solution with an output power of several kilowatts has been very mature, and the output power is gradually approaching 10 kW\cite{11,14-16}.

As far as we know, almost all publicly reported high-power fiber lasers have a unidirectional output structure. In research such as coherent beam combining and power beam combining, more than two lasers are usually required at the same time. If a unidirectional output fiber laser is used, more than two fiber lasers are required at the same time. However, the bidirectional output fiber laser can generate two laser beams from one laser, which can effectively reduce the system volume and cost when applied to beam combining. The bidirectional output fiber laser can theoretically overcome the power loss caused by the insufficient reflectivity of the high reflectivity fiber Bragg grating (HRFBG) in the traditional fiber laser oscillator and improve the optical-to-optical (O-O) efficiency\cite{17}. The most reported implementation methods for bidirectional output lasers are mainly space lens-based bidirectional output lasers\cite{18}, circulator-based ring lasers\cite{19-21}, and multi-core fiber-based bidirectional output lasers. However, none of the above methods can achieve high stability and high average power laser output. In 2022, Zhong et al. of our research group proposed a linear cavity all-fiber structure bidirectional output laser using two low reflectivity fiber Bragg gratings to form a resonant cavity\cite{17}. This method perfectly inherits the high-power output capability of traditional high-power fiber lasers and is an ideal solution for realizing high-power bidirectional output fiber lasers. However, due to the limited pump power and the appearance of stimulated Raman scattering (SRS), the current maximum output power is 2 kW level for two output ports at the same time.
As is the case with ordinary high-power fiber lasers, in bidirectional output fiber lasers based on conventional fibers are difficult to balance the transverse mode instability (TMI) and the SRS to achieve further power scaling. Vary core diameter active fibers (VCAF) represented by spindle-shaped fibers can achieve the purpose of balancing the TMI and SRS in lasers by changing the core diameters in different sections. At present, this type of fiber has been widely used in fiber lasers and shows good prospects. The length of the transition section of the VCAF is relatively long, and the diameter change in this section is very small. Under mature manufacturing conditions, it will not affect the efficiency of the laser. At the same time, we have theoretically and experimentally verified that the suppression ability of spindle-shaped fibers for SRS is similar to that of conventional fibers with a core diameter consistent with their equivalent core diameter. Compared with conventional fibers with the same core diameter as the small size section of spindle-shaped fibers, it has better SRS suppression ability while maintaining good beam quality.

In this work, for the first time, to the best of our knowledge, we apply a spindle-shaped ytterbium-doped fiber (SSYDF) with a total length of 24 m to a bidirectional output fiber laser. The core/cladding diameter is 25/400 μm at both ends and 37.5/600 μm in the middle. Using non-wavelength-stabilized 976-nm LDs as the pump source, a bidirectional 3 kW-level laser output fiber is obtained by measuring scattered light. The wavelength response range and bandwidth of the photodetector are 350–1100 nm and 12 MHz, respectively. Part of the scattered light is transmitted through fiber patch cords and enters an optical spectral analyzer with a wavelength response range of 600–1700 nm to measure the output spectra.

Based on the results in Ref. [17], the simultaneous suppression of the SRS and the TMI was considered when making device selection. The gratings with a 3 dB bandwidth of ~3 nm can effectively improve the SRS threshold of the laser, while the use of non-wavelength-stabilized 976-nm LDs can help to improve the TMI threshold. In addition, combined with our self-designed SSYDF, a better balance of the SRS and the TMI can be achieved. The longitudinal structure of the SSYDF used is consistent with the fiber in Ref. [23], and the longitudinally gradient fiber size is achieved by varying the drawing speed during the fabrication process. Based on our previous experimental experience and to ensure sufficient absorption of the pump light, the total length of the fiber is designed to be 24 m. As shown in Fig. 2, the two small size sections at both ends have core/cladding diameters of 25/400 μm with lengths of 3 and 5 m, respectively. The corresponding parameters of the middle large size section are 37.5/600 μm and 5 m. The diameters of the output fiber are 135/155 and 25/250 μm, respectively. Thirty-six non-wavelength-stabilized 976-nm LDs with an output power of about 250 W are divided into two groups as the pump sources of the laser (18 LDs for the A-end and 18 LDs for the B-end). According to the conclusions of Ref. [30], benefit from the deviation of the pump wavelength and the absorption peak of the active fiber, the TMI threshold of the fiber laser pumped with non-wavelength-stabilized 976-nm LDs can be increased to about 2 times that of the laser pumped with the wavelength-stabilized 976-nm LDs. The signal output fibers of the two BPSCs are, respectively, spliced with a pair of low reflectivity fiber Bragg gratings with core/cladding diameters of 25/400 μm to provide feedback for signal generation. The center wavelength and 3 dB bandwidth of the gratings are 1080.03 and 3.04 nm, respectively, with a reflectivity of 10.2%. The resonant cavity of the laser consists of fiber Bragg gratings, BPSCs, and active fibers. The signal passes through CLS (1/2) and End cap (1/2) and then enters the two measuring systems to simultaneously measure the power, spectra, and beam quality (M² factor). In the measuring system, the output laser is collimated and expanded before being directly incident on the target surface of the power meter. The power meter has a range of 10 kW and is cooled by a water-cooled mechanism. The time-domain signal and spectra of the output laser are obtained by measuring scattered light. The wavelength response range and bandwidth of the photodetector are 350–1100 nm and 12 MHz, respectively. Part of the scattered light is transmitted through fiber patch cords and enters an optical spectral analyzer with a wavelength response range of 600–1700 nm to measure the output spectra.

2. Experimental Setup

Figure 1 shows the structure of a bidirectional output fiber laser based on an SSYDF. The laser applies a bidirectional pump configuration. The two ends of the active fiber are respectively spliced with the two (18 + 1) × 1 backward pump and signal combiners (BPSC). The core and cladding diameters of the signal input fiber of the BPSC are matched to the sizes of both ends of the active fiber, which are 25 and 400 μm, respectively. The core/cladding diameters of the pump input fiber and signal photodetector; OSA, optical spectrum analyzer; PM, power meter.
two transition sections match the size of the large and small size sections, with lengths of 4 and 7 m, respectively. Compared to the fiber in Ref. [23], this fiber increases the length ratio of the small size sections and optimizes the pump absorption coefficient to achieve a higher TMI threshold. Compared with the conventional fibers with core/cladding diameters of 20/400 μm in Ref. [17], the current SSYDF can achieve very good SRS suppression. The cladding pump absorption coefficient of the active fiber is 2.419 dB/m@976 nm.

3. Results and Discussion

First, the performance of the laser under the condition of the unidirectional pump was tested, and the results were compared with the unidirectional output structure. The results are shown in Fig. 3. For comparison, the unidirectional output oscillator is realized by replacing FBG1 in Fig. 1 with a high-reflectivity fiber Bragg grating (HRFBG) with a core/cladding diameter of 25/400 μm. The center wavelength and 3 dB bandwidth of this HRFBG are 1080.00 and 3.00 nm, respectively with a reflectivity of 99.2%. The pump source of the A-end in the bidirectional output oscillator is changed to the co-pump source in the unidirectional output oscillator. This adjustment can ensure that the structure of the unidirectional output oscillator and the bidirectional output oscillator used for comparison are completely consistent, including gain fiber, loss, and bending. When applying the A-end pump configuration, the output power of the unidirectional output oscillator reaches 2922 W at a pump power of 4175 W, and the O-O efficiency is 70.0%. Under the same conditions, the total output power of the bidirectional output oscillator is 3206 W (1650 W at the A-end and 1556 W at the B-end), and the total O-O efficiency is 76.8%. The results show that the bidirectional output oscillator has higher O-O efficiency than the unidirectional output oscillator, which is also verified by the results when applying the B-end pump configuration. The reason is that the bidirectional output oscillator can overcome the backward loss of the unidirectional output oscillator due to insufficient reflectivity of the HRFBG. Figures 3(c) and 3(d) show the comparison of the output spectra of the two lasers under the same conditions. The spectral broadening of the unidirectional output oscillators is more pronounced than that from B-end, and it is between the two in the unidirectional output oscillator. In the above experiments, no TMI appeared in either the bidirectional output oscillator or the unidirectional output oscillator.

According to the results under the unidirectional pump configuration, the current bidirectional output oscillator can achieve a power output of ~1500 W at both ends under the unidirectional pump. Therefore, it can be predicted that the bidirectional pump configuration has the potential to achieve a bidirectional 3 kW level laser output. A bidirectional pump configuration was applied to the laser, and the results are shown in Fig. 4. When the total pump power is 8343 W (among which the A-end pump is 4175 W and the B-end pump is 4168 W), the output powers of the A-end and B-end are 3265 and 2840 W respectively, and the total O-O efficiency is 73.2%. With the
increase of the output power, the efficiency of the laser gradually increases. The reason is that the wavelength of the pump light is closer to 976 nm when the output power is higher, which is more fully absorbed by the active fiber. Figures 4(b)–4(d) show the spectra, photodetector signal, and beam quality measurements of the output lasers at the two ends under the condition of the maximum output power. These results show that no TMI and SRS occur at the maximum output power, and the beam qualities of the output lasers from the A-end and B-end are $M_{xA}^2 = 2.06$, $M_{yA}^2 = 1.90$ and $M_{xB}^2 = 2.36$, $M_{yB}^2 = 2.40$, respectively.

Compared with the unidirectional output oscillator, the bidirectional output oscillator has a higher O-O efficiency, but from the experimental results of the publicly reported fiber laser oscillator, the efficiency of the current laser is general. On the one hand, the BPSC placed in the resonator will introduce the insertion loss of the BPSC and affect the efficiency. On the other hand, insufficient absorption of the pump light is an important factor for poor laser efficiency. The pump source currently used is the non-wavelength-stabilized 976-nm LDs, and the wavelength of the pump light is affected by various factors such as operating current and temperature. In addition, we also notice that the beam quality of the output laser of the bidirectional output laser is poor, and the beam profile is quite different from that of the publicly reported spindle-shaped fiber-based lasers. It can be seen from the results in Fig. 5 that the beam profile at the beam waist of the output laser presents a perfect annular profile. We believe that the fiber, the structure of the oscillator, and the fiber devices all play a role in it.

First, the maximum core diameter of the fiber used is 37.5 μm, which can be called a multimode fiber. In Ref. [23], a fiber amplifier with a beam quality below 2.0 based on a spindle-shaped fiber with the core/cladding diameter distributions of 25/400 μm–37.5/600 μm–25/400 μm was achieved. For fiber amplifiers, the degradation of the beam quality can be minimized by controlling the beam quality of the seed laser. But this is difficult for fiber laser oscillators because of the lack of effective mode control measures. Second, in order to change the laser to a unidirectional output structure and compare the output characteristics, two BPSCs are placed in the resonator, and the number of splicing points in the cavity is also increased. High-order modes will be excited when the laser passes through the splicing point and the device. But the current output laser with a perfect annular profile has a better effect than the Gaussian profile in laser cutting, laser welding, and other fields.

4. Conclusion

In conclusion, we apply a spindle-shaped ytterbium-doped fiber to a bidirectional output laser oscillator for the first time, to the best of our knowledge. The total length of the spindle-shaped ytterbium-doped fiber used is 24 m, and its core/cladding diameter distribution in the longitudinal direction is 25/400 μm–37.5/600 μm–25/400 μm (the corresponding length distribution is 3 m–4 m–5 m–7 m–5 m). Combined with non-wavelength-stabilized 976-nm LDs and low-reflectivity fiber gratings with a bandwidth of 3 nm, the SRS and the TMI are well suppressed. Under the bidirectional pumping condition, we realized the bidirectional 3 kW level laser output for the first time without SRS and TMI. The beam profile of the output laser presents a perfect annular shape, which has great potential in practical applications.

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References


Fig. 5. Beam profiles at the beam waist of the output lasers from the A-end and B-end.


