A 3.5 kW near single-mode oscillating-amplifying integrated fiber laser

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Abstract The fiber laser based on oscillating-amplifying integrated structure has the potential to take into account the advantages of fiber laser oscillator and amplifier with the characteristics of strong anti-back reflected light ability and high efficiency. Here, we achieved a 3.5 kW near single-mode (M^2~1.24) oscillating-amplifying integrated fiber laser with an active fiber length of 8 m in the oscillating section and 17.6 m in the amplifying section. While operating at the maximum power, the optical-to-optical conversion efficiency is 87.0%, and the intensity of stimulated Raman scattering is about 23.61 dB lower than the signal light. As far as we know, this is the highest output power of the oscillating-amplifying integrated fiber laser, accompanied with the best beam quality and the highest efficiency.

Key words: fiber laser, oscillating-amplifying integrated structure, Ytterbium-doped fiber

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I. INTRODUCTION

Benefits to advanced fiber fabricating process, fiber device manufacturing process and double-cladding pumping technology, high-power fiber lasers have been developed rapidly [1,2]. Since the discovery of transverse mode instability (TMI) ~~in high-power fiber lasers~~ in 2010, stimulated Raman scattering (SRS) and TMI ~~are~~ have been the most important factors ~~that~~ limiting the power scaling of the fiber lasers [3-8]. ~~In order to suppress SRS, i~~It is necessary to increase the core diameter and shorten the fiber length for the SRS suppression,~~. However,~~ but ~~–~~the suppression ~~measures~~ of TMI ~~are just the opposite~~needs to reduce the core diameter and increase the fiber length.~~,~~ ~~so~~ So it is difficult to ~~take care of~~balance ~~both~~ TMI and SRS at the same time. ~~For the purpose of~~In order to realize the simultaneous suppression of TMI and SRS, substantial~~many~~ research work~~s~~ has been carried out, including ~~improving~~ designing the new fiber structure [9-14], optimizing the laser system parameters and structure [15-18], and so on. From the perspective of laser structure, high-power fiber lasers are mainly divided into two types: the fiber amplifiers based on master oscillation power amplification (MOPA) structure and the fiber laser oscillators based on Fabry-Perot (FP) cavity structure. For the fiber amplifier, the simple structure with fewer fiber devices in the amplifying stage makes a higher optical-to-optical (O-O) efficiency. As early as 2009, IPG Photonics has realized a 10 kW near-single-mode fiber laser based on the MOPA structure [19]. However, the fiber amplifier is more sensitive to the back reflected light, and it is difficult for such lasers to be deployed in industrial applications such as laser cutting, with the presence of strong reflections from the target. In contrast, the fiber laser oscillator~~s~~ based on FP-fiber cavity ~~have~~ has better anti-~~capabilities of the~~ back reflected light ~~suppression~~ability, but the existence of the device insertion loss and output coupler grating loss makes ~~disadvantage is~~ a relative lower O-O efficiency~~, which is~~

mainly caused by the device insertion loss and output coupler grating loss. Currently, the highest output power of the all-fiber laser oscillator is 8 kW with an O-O efficiency of 81%, and the beam quality BPP (beam parameter product) value is 0.5 mm-mrad [20]. In order to increase the TMI threshold of fiber laser oscillator, K. Hejaz and others proposed a new laser structure and successfully, which increased the TMI threshold of the oscillator by ~26% (an increase of ~200 W) under the same conditions in 2018 [21]. This new structure contains an oscillating section (consists of a resonant cavity composed of a relatively shortshorter active fiber, two fiber Bragg gratings and series of co-pumping source) and an amplifying section (consists of a longer active fiber and series of counter pumping source). Figure 1 shows a schematic diagram of this new structure and another 2 traditional all-fiber laser structures (FP-fiber cavity and MOPA). The most significant difference between this new structure and the traditional fiber laser amplifier based on MOPA is that there is no isolator and cladding light stripper (CLS) between the oscillating section and the amplifying section, . so Therefore, the unabsorbed forward and backward pump light can enter the amplifying section and the oscillating section respectively, and be reused. The unabsorbed backward pump light can also enter the oscillating section and be reused. TThe laser of this new structure has the functions of an oscillator and an amplifier at the same time, and we call it oscillating-amplifying integrated fiber laser (OAIFL). Compared with the fiber laser amplifier based on the MOPA, the reduction of fiber devices makes the system structure simpler, which is beneficial to shorten the fiber length of passive fiber of the system., and And the total length of the active fiber length is also shorter than that in the traditional fiber laser amplifier. The shortening of the fiber length is beneficial to suppress SRS. Compared with the fiber laser oscillator, thanks to the lack of output coupler grating loss at the output end and the fuller utilization of pump, it has higher efficiency than fiber laser oscillator. At the same time, the backward light reflected into the laser can be reflected by the HR-FBG as laser output, making~~es~~ it have the same anti-back reflected light ability as the oscillator. Therefore, this laser has the potential to take ~~into account~~ the advantages of fiber laser amplifiers and oscillators into account. In 2018, Q. Shu et al. realized a 2 kW fiber laser output based on an OAIFL, with an O-O efficiency of 81.6%, and a beam quality M^2 of 1.4, and verified its good anti-back reflected light characteristics [22]. In addition to the above-mentioned advantages, OAIFL can allow a more flexible arrangement of pump energy between the oscillating section and the amplifying section. A~~It can also carry out flexible matching of active fibers, that is, a~~ctive fibers with different characteristics can be~~are~~ used in the oscillating section and the amplifying section to jointly achieve better output results. In 2019, J. Tian et al. realized a 1018 nm fiber laser with an output power of 300 W and a beam quality M^2 factor of 1.19 based on this structure [23]. By adopting ytterbium-doped fibers with different characteristics in the oscillating section and the amplifying section, ~~both~~ high conversion efficiency, good ASE suppression effect and high beam quality are taken into consideration. At present, the highest power of OAIFL is 2.19 kW of a narrow linewidth laser achieved by Y. Huang et al. in 2019. The 3 dB bandwidth is 86.5 pm with an O-O efficiency of 78.3% and a beam quality M^2 of ~1.46 [24].

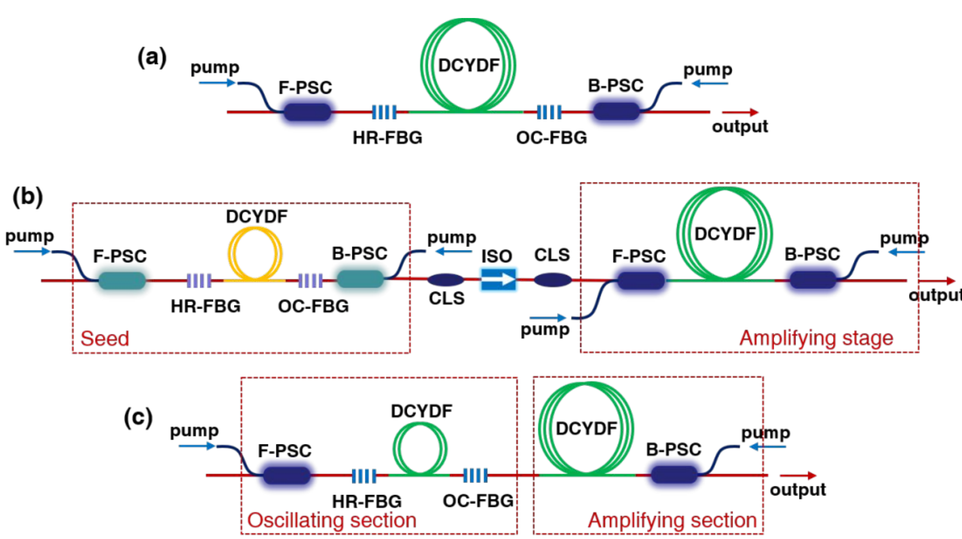


Figure 1. Schematic diagram of the three structures of fiber lasers. (a) The Fiberfiber laser oscillator based on the FP-fiber cavity; (b) The Fiber fiber laser amplifier based on the MOPA structure; (c) The OAIFL

In this paper, we designed and realized an OAIFL. Two double-clad Ytterbium-doped fibers (DCYDF) with a core/cladding diameter of 22/400 µm are used as the gain medium, and the length of the active fiber in the oscillating section and the amplifying section is 8 m and 22 m, respectively. By reducing the length of the active fiber in the amplifying section, a 3.5 kW near single-mode (M^2~1.24) all-fiber laser is realized with an O-O efficiency of 87.0% under the condition of co-/counter pump power of 256 W/3,787 W.

II. EXPERIMENTAL SETUP

The experimental structure of the OAIFL is shown in Figure 2(a). The active fiber used is a DCYDF with a core/cladding diameter of 22/400 µm, and the absorption coefficient for 915 nm pump light is about 0.54 dB/m. The oscillating section of the laser consists of a piece of DCYDF (DCYDF1) with a length of 8 m, a high reflection fiber Bragg grating (HR-FBG), an output coupler fiber Bragg grating (OC-FBG) and a set of co-pumping sources. The HR-FBG, the OC-FBG and the active fiber (DCYDF1) together form a resonant cavity to generate signal. The pump source used for the co-pumping of the oscillating section are 5 groups of laser diodes (LDs) with a center wavelength around 976 nm and the maximum output power of each group is about 900 W. All the LDs are combined through a (6+1) ×1 forward pump/signal combiner (F-PSC). Both the HR-FBG and the OC-FBG are with a core/cladding diameter of 22/400 µm and a center wavelength of 1080 nm. The reflectivity of the HR-FBG and the OC-FBG is 99.5% and 9.7% with a 3 dB bandwidth of 3.11 nm and 1.00 nm, respectively. After the OC-FBG is the amplifying section of the laser composed of a piece of DCYDF (DCYDF2) with a length of 22 m and a set of counter pumping sources. The pump sources used for the counter pumping of the amplifying section are 5 groups of LDs same as the LDs used in the oscillating section, and are combined through a (6+1) ×1 backward pump/signal combiner (B-PSC). The laser applies the bidirectional pump scheme shown in Figure 2(a) with the co-pumping of the oscillating section and the counter pumping of the amplifying section. The core/cladding diameters of the output signal fiber and input signal fiber of F-PSC and B-PSC are both 22/400 μm and 25/250 μm, respectively. Since there is no CLS between the oscillating section and the amplifying section, the residual forward pump light passing through the resonant cavity can be directly injected into the DCYDF2 and the residual backward pump light can also enter the oscillating section. The output laser passes through a CLS and a passive fiber with a length of about 3 m and a core/cladding diameter of 25/400 μm, and then enters the measuring system. The power, the spectrum, the beam quality and the time domain characteristics of the output laser are measured. The DCYDF1 and the DCYDF2 are coiled on the same water-cooled plate with a figure- ‘8’ fiber groove as shown in Figure 2(b), and the coiling diameters at both ends of the DCYDF1 (DCYDF2) are 8.5 cm (8.5 cm) and 11.5 cm (12.3 cm), respectively. The smaller coiling diameter of the fiber in the oscillating section causes the large loss of the higher-order mode, and the signal generated in the oscillating section is mainly the fundamental mode. The smaller coiling diameter at both ends of the DCYDF2 also ensures a large enough high-order mode loss in the amplification process, so that the laser has the ability to realize a near-single-mode laser.

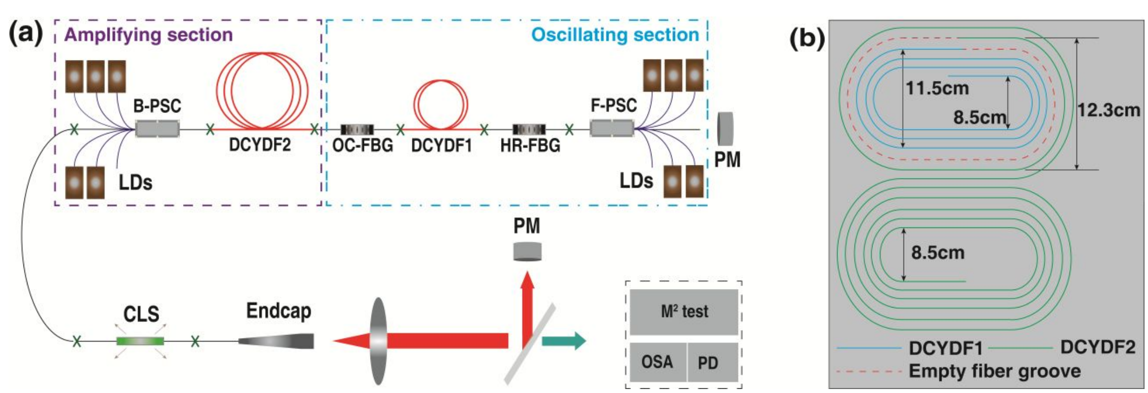
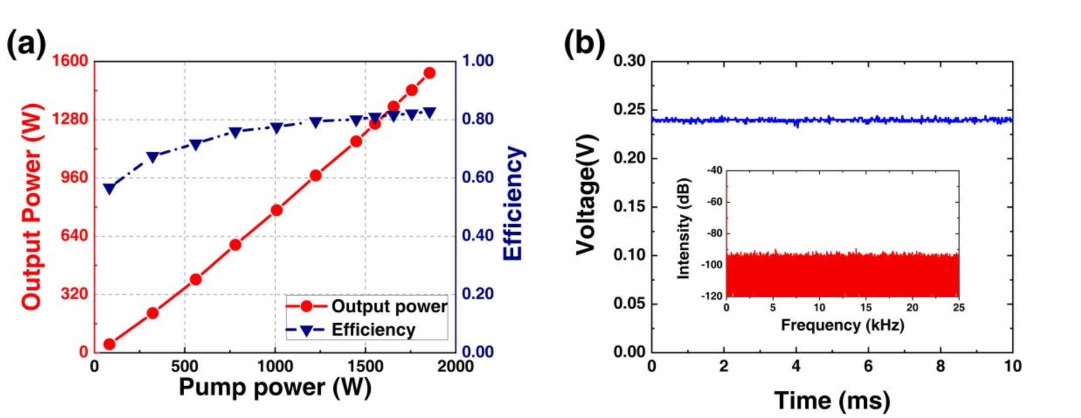


Figure 2. Schematic of the bidirectionally pumped OAIFL. (a) The ~~E~~experimental structure; (b) The ~~S~~schematic diagram of the fiber groove.

III. RESULTS AND DISCUSSION

3.1 Experiment results of co-pumping

Firstly, we only turned on the co-pumping of the oscillating section and the experimental results are shown in Figure 3. From the results in Figure 3~~-~~(a), we can see a good linear relationship between the output power and the pump power with a gradually increasing O-O efficiency. An output power of 1,537 W is achieved with an O-O efficiency of about 82.9% when the pump power is 1,855 W. At this time, no TMI characteristics was observed in the signal of the photodetector and its corresponding Fast Fourier Transform (FFT) results, as shown in Figure 3 (b). The beam quality of the laser at the maximum power shown in Figure 3~~–~~(c) is $M_x^2 = 1.14, M_y^2 = 1.16$, without beam quality degradation. Figure 3~~-~~(d) shows that obvious SRS has been observed at the power of 1,352 W. And the SRS intensity is only 21.07 dB lower than the signal light at the maximum power with a 3 dB bandwidth of 4.68 nm. So, the power scaling of the laser when only turning on the co-pumping of the oscillating section is limited by the SRS.



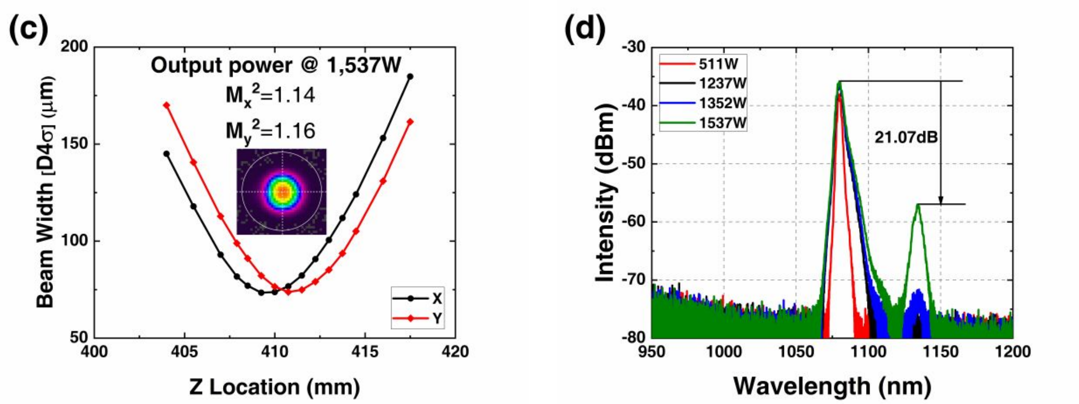


Figure 3. Experimental results of co-pumping. (a) The ~~V~~variation curves of the output laser power and the O-O efficiency with the pump power; (b) The signal of the PD at the maximum output power and their FFT results (inset); (c) The result of the beam quality M^2 factor at the power of 1,537 W. Inset: the beam profile; (d) The results of the spectra of several different output powers.

3.2 Experiment results of bidirectional pumping

In order to suppress the SRS, we increased the counter pump power of the amplifying section, and the experimental results are shown in Figure 4. Limited by the strong SRS (29.92 dB lower than the signal light), the maximum output power is 3,124 W under a total pump power of 3,572 W (256 W for the co-pumping of the oscillating section and 3,316 W for the counter pumping of the amplifying section), which corresponds to an O-O efficiency of 87.5%. Figure 4(b) shows the signal of the PD and its corresponding FFT results at the maximum power, and no TMI characteristics~~feature~~ is observed. Throughout the experiment, the spectrum bandwidth of the output laser gradually broadened which maintains a good linear relationship with the output power. The 3 dB bandwidth is 1.6 nm at the output power of 188 W, and this value reaches 5.10 nm with a broadening rate of about 0.119 nm/100 W when the output power reaches 3,124 W.

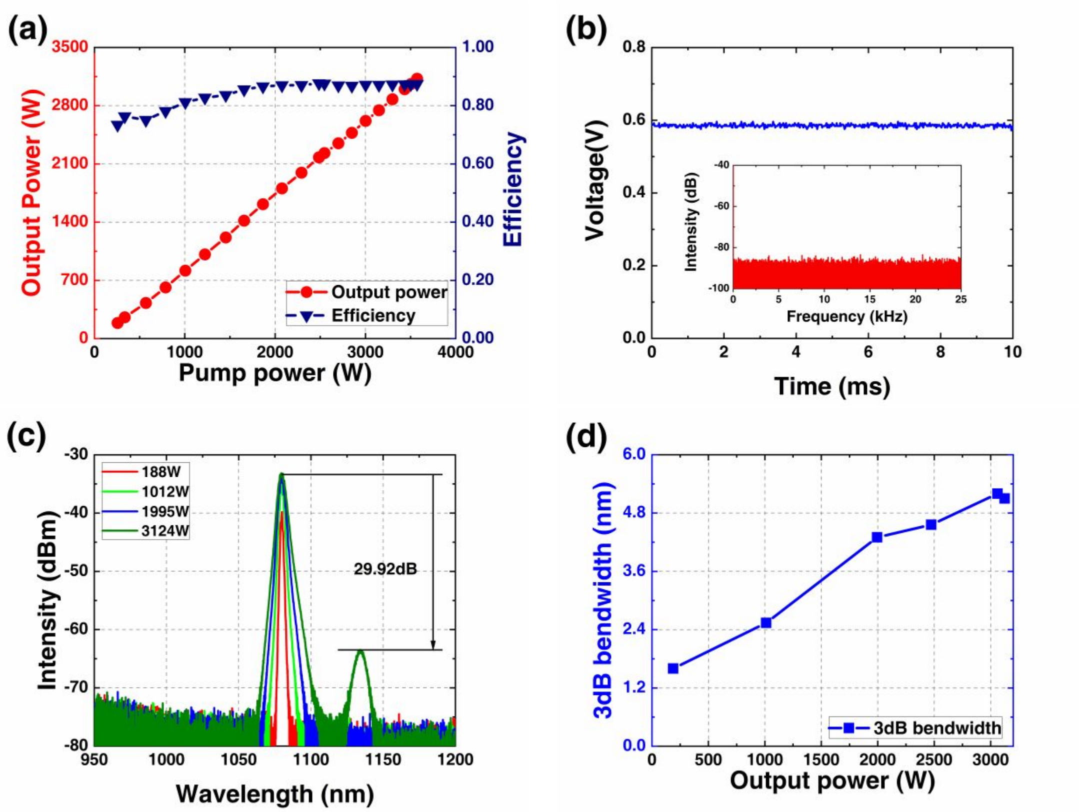


Figure 4. Experimental results of bidirectional pumping. (a) The ~~V~~variation curves of the output laser power and the O-O efficiency with the pump power; (b) The signal of the PD at the highest output power and their FFT results (inset); (c) The results of the spectra of several different output powers; (d) The measured 3 dB bandwidth at the different output powers.

The emergence of the SRS severely inhibited the ~~increase~~ scaling of~~in~~ the power. From the analysis of the above results, it can be found that the laser has a high efficiency and no pump light component was observed in the output spectrum. Therefore, the fiber length of the current amplifying section is sufficient. Considering the influence of the fiber length on the SRS, we can reduce the length of the active fiber in the amplifying section to suppress the SRS and achieve a better result. Based on this, after shortening the active fiber of the amplifying section by about 4.4 m, an output of 3,517 W with an O-O efficiency of 87.0% is obtained under the condition of a total pump power of 4,043 W (256 W for the co-pumping of the oscillating section and 3,787 W for the counter pumping of the amplifying section). Table 1 shows the main experimental parameters before and after the shortening of the fiber in the amplifying section. We can see that the shortening of the fiber caused a slight decrease in the efficiency. And at the same power level (~3,100 W), the SRS intensity is reduced by approximately 4.80 dB. The spectrum comparison shown in Figure 5(a) more clearly shows the improvement of the SRS suppression after the shortening of the fiber. It can be found that the SRS intensity is about 23.61 dB lower than the signal light at the maximum power and the 3 dB bandwidth is 5.62 nm. At present. The highest O-O efficiency of an all-fiber laser oscillator based on a common fiber is publicly reported about 81% [20], and the efficiency of this laser is obviously higher than that of a common fiber-based laser oscillator. The main reason is that there is no CLS between the oscillating section and the amplifying section, and the forward and backward pump light can be fully utilized. The measured M^2 factor of $M_x^2 = 1.24, M_y^2 = 1.24$ shown in Figure 5(b) indicates that we have obtained a near-single-mode laser output. In the literature [25], a 15 m-long YDF with a core/cladding diameter of 25/400 μm is used as the amplification stage of an all-fiber laser amplifier. Under the condition of a seed laser of about 400 W, a significant SRS is observed when the output laser is 2 kW and the difference in intensity between the signal light and the SRS is less than 30 dB. In comparison, the SRS intensity of this OAIFL is about 34.72 dB lower than the signal light when the output is 3,115 W, and it shows a stronger SRS suppression capability.

Table1. The main experimental parameters and results before and after the shortening of the active fiber in the amplifying section

Length of the DCYDF1(m)	Length of the DCYDF2(m)	Output power(W)	Efficiency	SRS intensity(dB)
8.0	22.0	3,124	87.5%	29.92
8.0	17.6	3,115	87.2%	34.72
8.0	17.6	3,517	87.0%	23.61

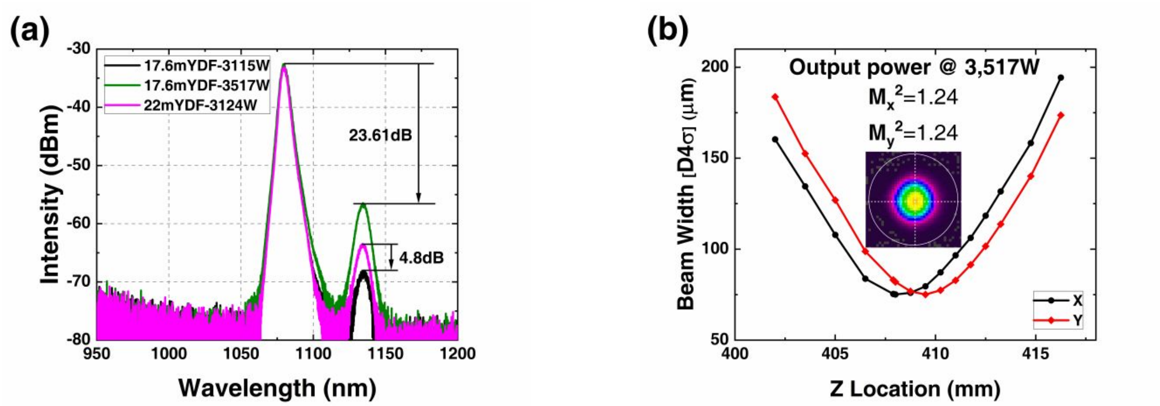


Figure 5. Experimental results of bidirectional pumping after shortening the active fiber of the amplifying section. (a) The Sspectral comparison before and after the shortening of the fiber; (b) The result of the beam quality M^2 factor at the power of 3,517 W. Inset: a beam profile of the output laser.

Table2. A comparison of the main parameters and results of the existing OAIFL

Core/cladding diameter of the oscillating (amplifying) section (μm)	Fiber length of the oscillating (amplifying) section(m)	Output power(W)	M^2	Efficiency	Experimental purpose	Reference
20/400(20/400)	1.5(22.5)	1,570	1.36	71.4%	Increase the TMI threshold of the fiber oscillator	[21]
20/400(25/400)	10.0(14.5)	2,190	1.46	78.3%	Narrow linewidth laser	[24]
20/400(20/400)	2.0(15.0)	2,031	1.40	83.6%	Verification of anti-back reflected lightanti-reflection ability	[22]
10/130(20/130)	1.3(1.3)	300	1.19	79.3%	1018 nm fiber laser	[23]
22/400(22/400)	8.0(17.6)	3,517	1.23	87.0%	High power, high beam quality laser	This work

Table 2 lists the main experimental parameters and results of the existing researches of the OAIFL which shows the potential application fields of the OAIFL. It can be seen from the table that the choice of the type and the length of the active fiber for the oscillating section and the amplifying section is very flexible, and can be matched and adjusted according to actual needs and experimental results. Our laser has currently the maximum power with the best beam quality and the highest O-O efficiency. The active fiber with a core diameter of 22 μm can achieve the better SRS suppression than those with a core diameter of 20 μm. Under a proper coiling diameter, it can also increase the loss of higher order modes and increase the TMI threshold. For current lasers, the SRS is the main factor limiting the power scaling, and many potential works can be done for the purpose of the SRS suppression. Before and after the shortening of the fiber in the amplifying section, the O-O efficiency of the laser remained at a relatively high level, indicating that the final fiber length can still ensure sufficient pump absorption. Therefore, the length of the active fiber in the amplifying section can still be reduced for further SRS suppression. In addition, according to the conclusion in the literature [26], a better SRS suppression can be achieved with shorter fiber in the resonant cavity. The length of the fiber in the current resonant cavity of oscillating section is 8 m, and there is still more room for optimization. We can try to shorten the active fiber length in the resonant cavity to suppress the SRS. Finally, the use of the fibers with larger core diameters or the fibers with new structure such as spindle-shaped YDF with gradual core diameters is also an experimental program with great potential for achieving even higher power levels [27].

IV. CONCLUSION

An OAIFL was successfully achieved, and the output characteristics of the laser were studied in detail. By turning on the co-pumping of the oscillating section and the counter pumping of the amplifying section at the same time, a 3.5 kW near-single-mode laser output is realized with an O-O efficiency of 87.0%, which is the highest output power of the OAIFL, accompanied with the best beam quality and the highest O-O efficiency. This experiment verifies the good power amplification capability of the OAIFL, which has the better SRS suppression capability than the amplifier and the higher O-O efficiency than the oscillator under the same conditions. On the basis of this experiment, the fiber length and parameters can be optimized to achieve a higher power laser while ensuring high beam quality and high efficiency.

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