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First Demonstration and Comparison of 5 kW Monolithic Fiber Laser Oscillator Pumped by 915 nm and 981 nm LDs

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Abstract: Fiber laser performances including transverse mode instability (TMI), stimulated Raman scattering (SRS) and optical-to-optical efficiency are in connection with the pump wavelength. Here we studied the output characteristics of a 5-kW ytterbium-doped fiber laser oscillator pumped with two different pump sources, i.e., 915 nm and 981 nm laser diodes (LDs). The output characteristics of fiber laser oscillators pumped by 915 nm and 981 nm have been compared strictly and directly with the same structure in a high-power situation. Experimental results show that both pump wavelengths can scale the power up to more than 5 kW by suppressing the TMI effect. While in the case of pumping by the 981 nm LDs, the laser oscillator has an optical-to-optical efficiency of 87%, which is 13% higher than that of the 915 nm pumped scheme. In addition, due to the higher backward pumping ratio and lower total pump power, the laser oscillator has a better SRS suppression ratio when pumped at 981 nm. Thus, it reveals a great potential to balance the limitations of TMI and SRS for scaling up to an even higher output while pumping at 981 nm. All the devices of the oscillator are commercial, and it will be helpful for the commercialization of high-power fiber laser oscillators.

Keywords: high-power fiber laser; ytterbium-doped fiber laser oscillator; transverse mode instability; stimulated Raman scattering; pump wavelength

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1. Introduction

Benefiting from the advantages of high conversion efficiency, outstanding beam quality, easy thermal management, and reliable stability, high-power fiber lasers have already been applied in many fields such as industrial manufacture, biomedical technology, fundamental research, and so on [1–4].

There are two kinds of structures to achieve high power fiber lasers in general. The first one is the master oscillator power amplifier (MOPA), and the second one is the fiber laser oscillator. Compared with the MOPA structure, the fiber laser oscillator has the advantages of compact structure, simple control logic, low cost, highly anti-reflection ability, and good stability. The output power of fiber lasers has boosted rapidly owing to the improvement of fiber manufacturing technology and LD pumping technology over the past decade. However, the TMI threshold of the oscillator is typically lower than that of the amplifier based on the same ytterbium-doped double-clad fiber (YDF). Thus, there are only a few near-single-mode fiber laser oscillators reaching 5 kW ever reported. In 2018, Shima K. from Fujikura Inc. reported a 5.05 kW fiber laser oscillator pumped by 970 nm LDs with a M^2 factor of 1.3 [5]. In the same year, Yang et al. reported a 915 nm LD pumped fiber laser oscillator with the output power of 5.2 kW and the beam quality of M^2 ~2.2 [6]. In 2019, Ye et al. improved the beam quality to M^2 ~1.6 at the maximum power of 5 kW [7]. In 2020, Krämer et. al. reported a 976 nm pumped fiber laser oscillator, which adopted Bragg gratings written on the 20/400 µm YDF by a femtosecond laser, and achieved 5 kW output with a M^2 factor ~1.3 at 4.8 kW [8]. In the present work, we can see that only a few fiber laser oscillators with an output power of more than 5 kW and a beam quality M^2 less than 1.4 are reported [5,8], or there is even the same report, but the author didn't give the details of the design of the laser, such as the fiber and pump parameters. High power fiber laser oscillators remain to be studied in detail.

Although these fiber lasers achieved a high-power output, the power scaling of fiber lasers based on commercial devices is still limited by both TMI and SRS effects. There are numerous methods for increasing the TMI threshold of fiber lasers, such as increasing high-order modes (HOMs) loss [9], optimizing fiber design [10,11], control mode excitation [12] and improving thermal management [13,14]. According to our previous research, the TMI threshold can be remarkably affected by the pump wavelength due to the difference of pump absorption [15]. Considering both the quantum defect and pump absorption, we optimized the pump wavelength from 976 nm to 981 nm and found 2.2 times the enhancement of the TMI threshold [16]. In 2021, our research group achieved a 6-kW single-mode fiber laser amplifier by using the optimized 981 nm pump LDs and the beam quality was excellent ($M^2 < 1.3$) [17]. However, some methods for suppressing TMI just conflict with those for suppressing SRS. As an example, for suppressing TMI, a smaller core diameter fiber is needed, while a larger core diameter fiber is needed to suppress SRS. Thus, it's difficult to suppress the TMI and SRS at the same time [18].

In this paper, we experimentally demonstrate two bidirectional pumped 5 kW fiber laser oscillators by using traditional 915 nm and 981 nm pumping, respectively. Using both pump wavelengths alone, a near-single-mode high-efficiency 5 kW output is achieved. The detailed output performance of the oscillator is investigated and compared. It was found that 981 nm pumping has a 13% efficiency higher than 915 nm pumping, and better suppression on SRS was also obtained under 981 nm pumping. In addition, long-term operations are in progress at full power, and the power fluctuations are less than 1%. To the best of our knowledge, this is the first report of a more than 5 kW all-fiber laser with a beam quality M^2 less than 1.4 and a detail description of all the design of the laser, including reflectivity of fiber Bragg gratings, 3 dB bandwidth, and so on.

2. Experimental Setup

The schematic diagram of the high-power fiber laser oscillator is shown in Figure 1. A total of 12 groups of LDs are bidirectionally injected into the laser cavity through the forward/backward pump& signal combiners (FPSC/BPSC). The cavity is composed of a piece of YDF and a pair of fiber Bragg gratings (FBG) with a center wavelength of 1080 nm. The high reflection fiber Bragg grating (HR FBG) has a reflectivity of 99.8%, a 3 dB bandwidth of 3.92 nm, and the output coupler fiber Bragg grating (OC FBG) has a reflectivity of 8.2%, a 3 dB bandwidth of 0.97 nm. The length of the YDF is ~30 m. Its core and cladding diameter are 25 µm and 400 µm (25/400 for abbreviation), respectively. The numerical aperture (*NA*) of the core is 0.065. Its cladding pump absorption at 915 nm is 0.57 dB/m and 0.86 dB/m at 981 nm. In order to control the high order mode excitation and obtain a good beam quality, the YDF was coiled with a minimized radius of 42.5 mm. Therefore, we can achieve a better beam quality than our previous work. The laser excited in the cavity is output by a quartz beam head (QBH) after passing through a cladding light stripper (CLS). The unabsorbed pump light and high-order modes are filtered by the CLS, and the signal arm of the FPSC is angle cleaved to prevent feedback light. After collimation, the output beam measured the power meter (PM), optical spectrum analyzer (OSA), photodetector (PD), and the beam quality measurement system through the splitting system to get the output data. All the parts mentioned above are commercial.

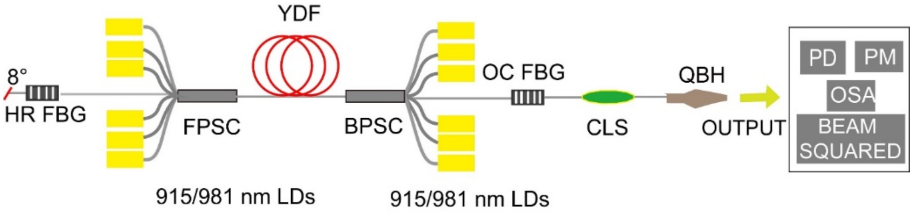


Figure 1. Schematic diagram of fiber laser oscillator (LD: laser diode, PSC: pump/signal combiner, CLS: cladding light stripper, HR FBG: high reflection fiber Bragg grating, OC FBG: output coupler fiber Bragg grating, YDF: ytterbium-doped fiber).

3. Results and Discussion

In 2020, Krämer from Jena University reported that the oscillator achieved 5 kW by using 20/400 YDF and a 976 nm pumped source [8]. But if the YDF was changed to 25/400, the TMI threshold of the oscillator dropped to 3203 W, according to the report by Wan et al. in 2022 [19]. According to these results, it is difficult to achieve 5 kW output using 25/400 YDF and employing a 976 nm pump source with common commercial fibers. Based on our previous work, we optimized the pump wavelength to 915 nm and 981 nm for comparison. In this experiment, the output characteristics of the fiber laser oscillator under 915 nm and 981 nm pumping conditions were researched and compared in detail. To ensure the reliability of the comparison results, the experimental structure and optical devices are kept unchanged except for the pump LDs.

3.1. Laser Output Performance Pumped with 915 nm LDs

Figure 2 demonstrated the output performance of the oscillator pumped by 915 nm LDs. As we can see from Figure 2a, the output power increase linearly and the optical-to-optical conversion efficiency (O-O efficiency) ranged from 71.1% at 307 W to 77.6% at 4790 W. The fiber laser oscillator achieved the highest output of 5070 W with a total pump power of 6558 W, which consists of 1766 W of forward pumping and 4792 W of backward pumping. The temporal characteristics were stable at the highest power shown in Figure 2b, and it can be seen from the figure that the TMI has not appeared. Benefiting from the small bending radius of YDF, the oscillator kept good beam quality. The beam quality factor M^2 was superior to 1.4. Furthermore, SRS can be observed through the output spectrum in Figure 2c. The peak Raman light is about 28.3 dB lower than that of the signal light.

Then in the stability test, the fiber laser oscillator was continuously operated at the maximum output power for 100 min and the fluctuation of output power was below 0.5% with an average power of 5085 W. The beam quality M^2 factors fluctuate between 1.3 and 1.4 without deterioration, where Figure 2d shows.

3.2. Laser Output Performance Pumped with 981 nm LDs

The output power and O-O efficiency are displayed in Figure 3a. As shown in Figure 3a, with the increase in pump power, the output power grows linearly. Using a total pump power of 5883 W, which consists of 1523 W of forward pumping and 4360 W of backward pumping, the fiber laser oscillator obtained the highest output of 5120 W with beam quality $M^2 < 1.4$. The optical-to-optical efficiency grew from 80% at 186.7 W to 87% at 5120 W. Even though the highest output power had exceeded 5 kW, there was no TMI observed, and the temporal characteristics were still stable as shown in Figure 3b. Figure 3c shows the spectrum at 5120 W output, and the Raman light is ~32.5 dB lower than the signal light. According to our previous work, an oscillator with a similar structure pumped by 976 nm LDs has a TMI threshold of 3203 W [19], while the 981 nm pumped one has a threshold of more than 5120 W, which has a 1.6 times enhancement. Thus, the TMI threshold of the oscillator has been improved, and the SRS can be suppressed at lower levels.

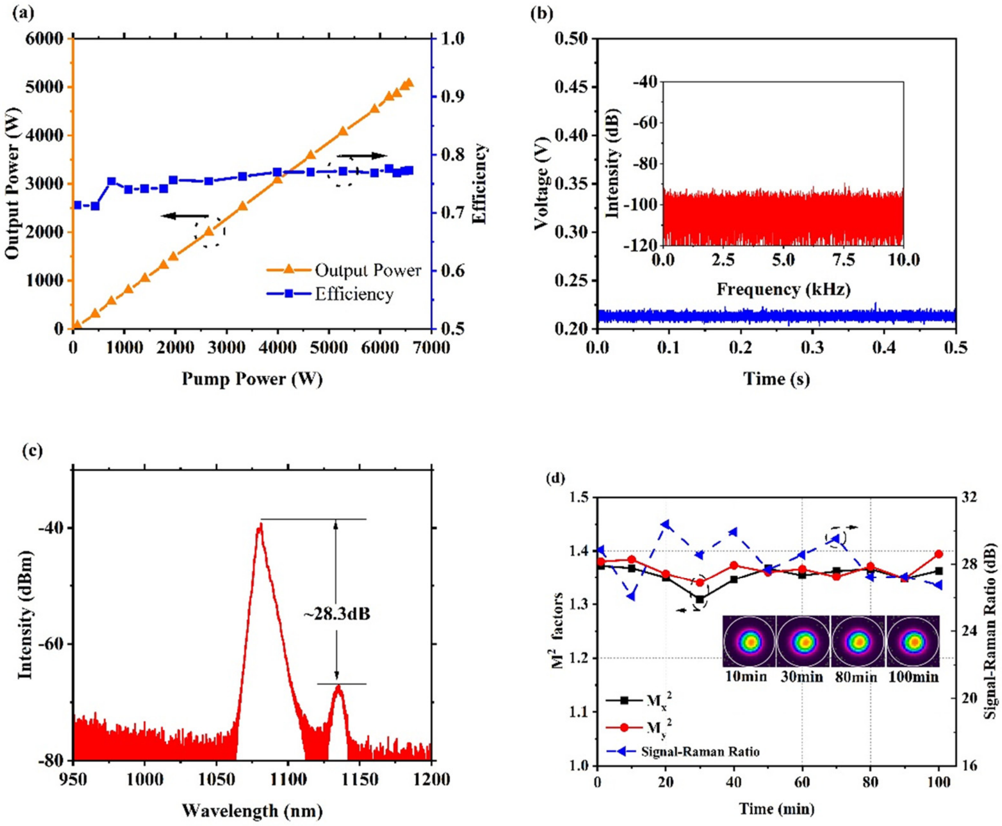


Figure 2. Output performance of the fiber laser oscillator pumped at 915 nm. (**a**) Output power and O-O efficiency. (**b**) Temporal trace and corresponding Fourier spectra (inset) at 5070 W. (**c**) Output spectrum at 5070 W. (**d**) M^2 factors with beam profile (inset).

In order to test the power stability, the fiber laser oscillator was continuously operated at the maximum output power for 120 min, and the results are shown in Figure 4. During the long-term test, the average output power is 5175 W with the power fluctuation of less than 1%. The beam quality of the output is also steady. As can be seen from Figure 4b, the M^2 factors fluctuate between 1.3 and 1.4. The SRS has been observed through the spectrum. The Raman light mentioned above is ~32.5 dB lower than the signal light. The intensity of Raman light fluctuated through time, and the signal-Raman ratio kept fluctuating around 30 dB, as we can see in Figure 4b. According to the results above, it can be easily drawn that the 981 nm pumped fiber laser oscillator still has the potential for power improvement.

3.3. Discussion

According to the experimental results above, our laser structure can achieve a stable 5 kW output at two different pump wavelengths, respectively. Compared to the two experiments above, the oscillator pumped by 981 nm LDs has a 13% O-O efficiency higher than the 915 nm LDs pumped one. Also, comparing the signal-Raman ratio of two experiments, the 981 nm LDs pumped oscillator has better suppression of Raman light.

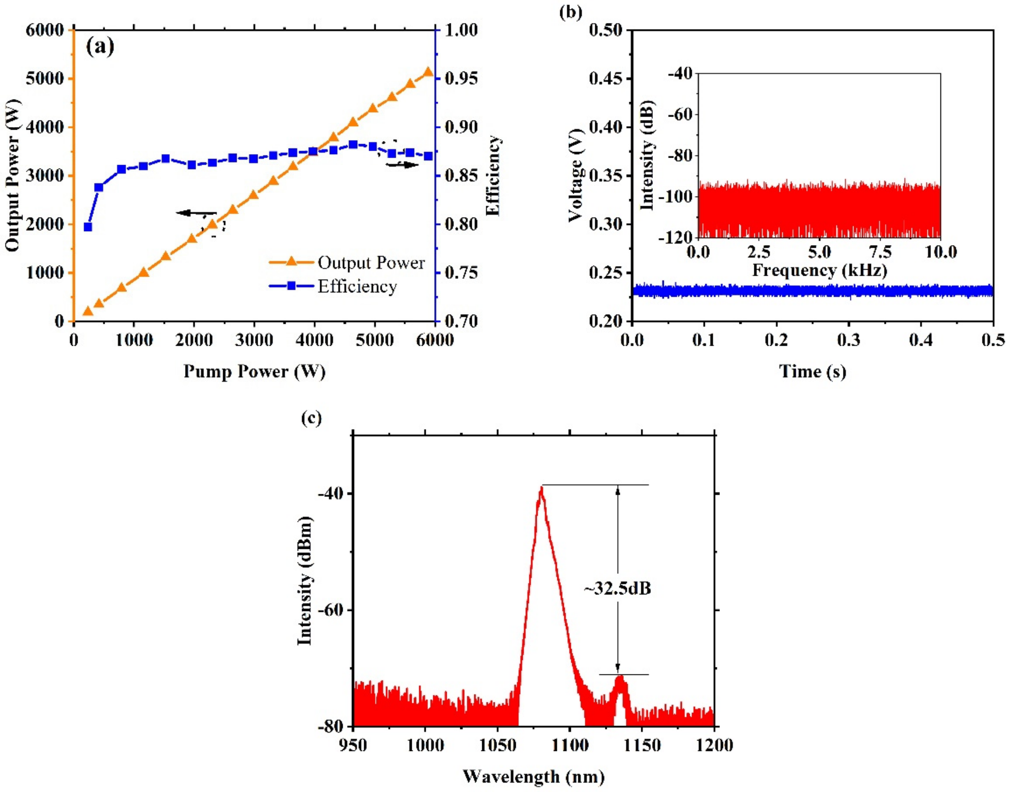


Figure 3. Output performance of the 981 nm pumped oscillator. (**a**) Output power and optical-to-optical efficiency. (**b**) Temporal trace and corresponding Fourier spectra (inset) at 5120 W. (**c**) Output spectrum at 5120 W.

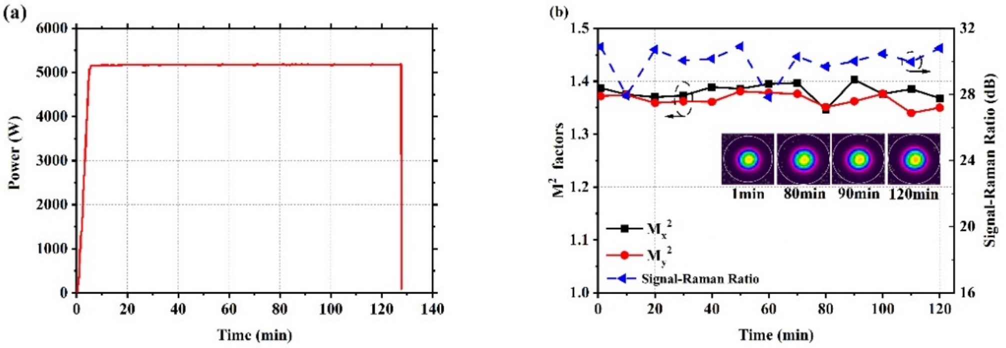


Figure 4. Output performance of stability test. (**a**) Output power. (**b**) M^2 factors with beam profile (inset).

Changing wavelengths results in an obvious performance improvement. To figure out the differences between those two pump wavelengths brought to the oscillator, we simulated the output performance of the fiber laser oscillator pumped by 915 nm and 981 nm, respectively. The signal light transmission over fibers can be expressed as:

$$\pm\frac{\mathrm{d}P_n^{s\pm}(\lambda_n^s,z)}{dz}=\Gamma_s[\sigma_n^{es}(\lambda_n^s)N_2(z)-\sigma_n^{as}(\lambda_n^s)N_1(z)]P_n^{s\pm}(\lambda_n^s,z)-\alpha_n^s(\lambda_n^s)P_n^{s\pm}(\lambda_n^s,z)$$
$$+2\sigma_n^{es}(\lambda_n^s)N_2(z)\frac{hc^2}{(\lambda_n^s)^3}\Delta\lambda+\Gamma_n^s(\lambda_n^s)P_n^{s\pm}(\lambda_n^s,z)\sum_{i=1}^{N}\frac{1}{A_{eff}^{i,n}}g_R(\omega_i-\omega_n)[P_i^{s+}(\lambda_i^s,z)+P_i^{s-}(\lambda_i^s,z)] \quad (1)$$

The distribution of pump light over fibers can be expressed as:

$$\pm\frac{\mathrm{d}P_m^{p\pm}(\lambda_m^p,z)}{dz}=\Gamma_p[\sigma_m^{ep}(\lambda_m^p)N_2(z)-\sigma_m^{ap}(\lambda_m^p)N_1(z)]P_m^{p\pm}(\lambda_m^p,z)-\alpha_m^p(\lambda_m^p)P_m^{p\pm}(\lambda_m^p,z)] \tag{2}$$

And the heat equation of gain fiber can be expressed as:

$$Q(r,z)=\frac{v_p-v_s}{v_p}[N_d\sigma_{ap}-(\sigma_{ep}+\sigma_{ap})N_2(r,z)]\frac{P_p(r,z)}{A_p}+\alpha_s(r)I_s(r,z)] \tag{3}$$

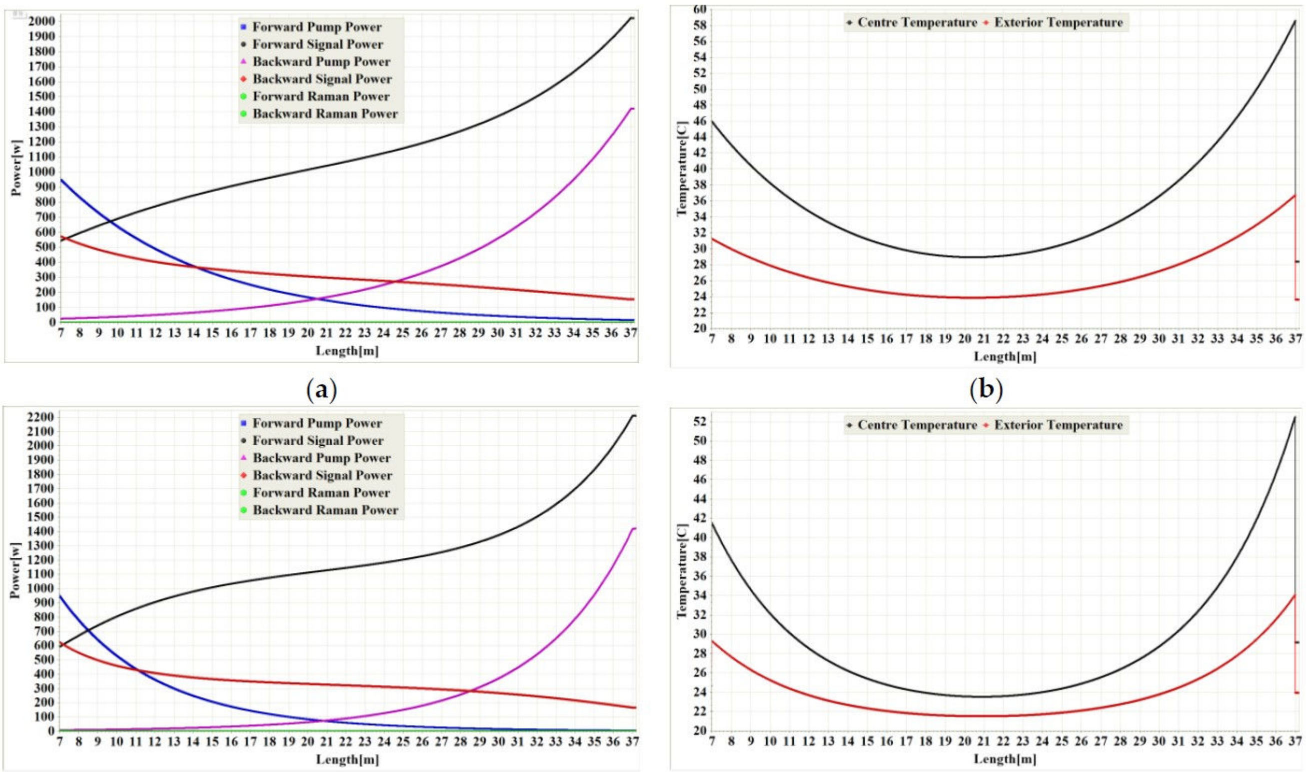
The physical meaning of symbols of those equations are listed in Table 1. And the parameters of the symbols are listed in the Appendix A.

Table 1. The physical meaning of symbols in rate equation.

Symbol	Physical Quantity	Symbol	Physical Quantity
N	Numbers of signal light wavelengths	A_{eff}	Effective mode area
n	Ordinal number of signal light wavelengths	m	Ordinal number of pump light wavelengths
σ_n^{es}	Emission cross section of the nth signal light	σ_m^{ep}	Emission cross section of the mth pump light
σ_n^{as}	Absorption cross section of the nth signal light	σ_m^{ap}	Absorption cross section of the mth pump light
α_n^s	Loss coefficient of signal light	α_m^p	Loss coefficient of pump light
N_1	Number of ground state particles	N_2	Number of excited particles
λ^s	Signal light wavelength	λ^p	Pump wavelength
Γ_p	Pump light filling factor	Γ_s	Signal light filling factor
h	Planck constant	c	Light speed
v_p	Frequency of pump light	v_s	Frequency of signal light
A_p	Inner cladding area for transmitting pump light	N_d	Dopant concentration of ytterbium ion
I_s	Luminous intensity of signal light		

A fiber laser oscillator is numerical simulated and its performances is shown in Figure 5. The output power reaches 1989 W when the co- and count-pump power are 1000 W and 1500 W, respectively. Both forward and backward pump power are not absorbed sufficiently in the gain fiber. As shown in Figure 5b, the maximum temperature at the fiber core is about 59 °C when pumped at 915 nm. The corresponding performance of the oscillator pumped at 981 nm is depicted in Figure 5c,d. Compared with the previous case, the absorption of pump power is sufficient and the maximum output power reaches 2170 W. The maximum temperature of the fiber core is 6 °C lower than that of pumped at 915 nm.

Numerical results fitted well with the experimental results. As the 981 nm pump source has a higher absorption coefficient and lower quantum defect, 981 nm pump power can be absorbed completely in the fiber laser oscillator while that of the 915 nm pump has more residual pump light. This results in the increasement of O-O efficiency. The higher absorption and quantum efficiency lead to a lower maximum temperature but a stronger temperature gradient. Although there is no obvious difference in TMI threshold for those two pump wavelengths. However, to achieve the same absorption, choosing a 981 nm pump source can make the gain fiber shorter, which leads to a better SRS suppression ability. To suppress SRS and TMI comprehensively, the 981 nm pump source is the better choice. By optimizing the structure of the oscillator, there is a great potential to achieve a higher output by employing the 981 nm pump source.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Numerical simulation results. (**a**) Power distribution with fiber length of the oscillator pumped by 915 nm LDs. (**b**) Temperature distribution with fiber length of the oscillator pumped by 915 nm LDs. (**c**) Power distribution with fiber length of the oscillator pumped by 981 nm LDs. (**d**) Temperature distribution with fiber length of the oscillator pumped by 981 nm LDs.

Moreover, although the output power of the oscillator we demonstrated in this paper is not the highest compared to previous reports, it still has its advantage at high brightness. In order to better show the advantages of the oscillators in this paper, we found high power oscillators with similar pump wavelength reported in recent years for comparison as shown in Table 2. All the oscillators in the table reveal great improvement of the TMI threshold compared to 976 nm pumped one [19]. The main differences between the oscillators in Table 1 come from the brightness, efficiency, and Raman suppression ability. For the application of fiber lasers, output power is not the sole indicator, beam quality also plays an important role. In order to simultaneously reflect the output power and beam quality, the brightness of fiber lasers becomes an important parameter [20].

The brightness of fiber lasers can be calculated by the brightness formula [21]. To show the difference in oscillator brightness more visually, the relative brightness has been defined as follows [1]:

$$B_{relative} = \frac{P}{100(\lambda M^2)^2} \tag{4}$$

where the λ is in micron. Assume a fiber laser with an output power of 10 kW, M^2 = 10 at 1 µm as the reference. The relative brightness is calculated and demonstrated in Table 2. As can be seen from Table 1, the two oscillators in this paper are brighter, more efficient, and maintain better Raman suppression ability without special operation. The two oscillators reported in this paper are advanced to the previous oscillator for the following reasons:

Firstly, we employ a commercial YDF with a high absorption compared to the 6 kW one, and do not need the tapered YDF to keep beam quality, so that the oscillator in this paper has a higher O-O efficiency. Also, as 981 nm has higher absorption and advanced quantum efficiency but still has a lower temperature gradient in the center of YDF, and it has a higher O-O efficiency compared to the 915 nm LDs pumped one. Secondly, the oscillator maintained good beam quality by reducing the minimized bending diameter of the YDF, which can lead to more high-order modes leaking into the cladding at the beginning. This is an effective way to improve both beam quality and O-O efficiency. Finally, suppression of SRS benefits from a reasonable pumping ratio. Due to the higher O-O efficiency, a lower total pump power and a higher ratio of counter-pumping enhanced the SRS suppression ability of the fiber laser oscillator in this paper.

In conclusion, the fiber laser oscillator schemes we reported in this manuscript reveal great performance at high power output. After strictly comparison of the output characteristics under different pump wavelengths, the 981 nm LDs pumped oscillator shows a strong capability to suppress both TMI and SRS. It has great potential to balance the limitations of TMI and SRS suppression to achieve a higher output.

Table 2. Comparison of output performances among different oscillators.

YDF	Pump Wavelength	Output	Efficiency	M^2	Relative Brightness	Signal-Raman Ratio	
25/400	981 nm	5120 W	87%	<1.4	22.40	32.5 dB	This work
25/400	915 nm	5070 W	77.3%	<1.4	22.18	28.3 dB	This work
25/400	915 nm	5070 W	60.7%	1.62	16.56	35 dB	Ref. [7]
30/600	915 nm	6070 W	65.8%	2.6	7.70	21.6 dB	Ref. [22]

4. Conclusions

In summary, an all-fiber laser oscillator bidirectionally pumped by 981 nm and 915 nm LDs separately was demonstrated and their output characteristics have been compared strictly. Compared to earlier reports, the oscillator has a considerable improvement in terms of beam quality and efficiency. As a similar structure oscillator pumped by 976 nm LDs has a TMI threshold of 3203 W, both schemes in this manuscript are unaffected by TMI with a 5-kW level output and keep great beam quality. Benefiting from higher quantum efficiency and absorption, the optical-to-optical efficiency of the 981 nm pumped scheme is 13% higher than the 915 nm pumped scheme. In addition, it has a better performance on SRS suppression when the oscillator is pumped by 981 nm LDs. The main reason is that the 981 nm pumped scheme has a lower total pump power and a higher percentage of backward pumping. The oscillator pumped with 915 nm and 981 nm LDs individually tested for the stability by a long-term operation, and the power fluctuations of both wavelengths were less than 1%. Results show that the 981 nm pumped fiber laser oscillator has great potential to balance the limitations of TMI and SRS to gain a higher output. By employing commercial devices for all the parts of the fiber laser oscillator, the result will be helpful for the higher power fiber laser design and commercialized.

Author Contributions: P.W., B.Y., H.Z., X.X. (Xiaoming Xi), X.W. and X.X. (Xiaojun Xu) contributed to conception and design of the study. P.W. and B.Y. organized the database. Y.W. performed the statistical analysis. Y.W. wrote the first draft of the manuscript. Y.W., P.W., X.X. (Xiaoming Xi) and X.W. wrote sections of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Parameters entering in Equations (1)–(3):

$$\begin{gathered}\alpha_n^s = 0.005,\ \alpha_m^p = 0.003,\ h = 6.626068096 \times 10^{-34},\ c = 2.99792458 \times 10^8,\\ \sigma_m^{ep}@915\ \text{nm} = 1.9256 \times 10^{-26},\ \sigma_m^{ap}@915\text{nm} = 5.6932 \times 10^{-25},\\ \sigma_m^{ep}@981\ \text{nm} = 1.0735 \times 10^{-24},\ \sigma_m^{ap}@981\text{nm} = 8.5664 \times 10^{-25}\\ \sigma_n^{es}@1080\ \text{nm} = 2.8219 \times 10^{-25},\ \sigma_n^{as}@1080\ \text{nm} = 2.2850 \times 10^{-27}\end{gathered}$$

References

1. Zervas, M.N.; Codemard, C.A. High power fiber lasers: A review. *IEEE J. Sel. Top. Quantum Electron.* **2014**, *20*, 219–241. [CrossRef]
2. Richardson, D.J.; Nilsson, J.; Clarkson, W.A. High power fiber lasers: Current status and future perspectives. *J. Opt. Soc. Am. B* **2010**, *27*, B63–B92. [CrossRef]
3. Zervas, M.N. High power ytterbium-doped fiber lasers—Fundamentals and applications. *Int. J. Mod. Phys. B* **2014**, *28*, 1442009. [CrossRef]
4. Jauregui, C.; Limpert, J.; Tünnermann, A. High-power fibre lasers. *Nat. Photonics* **2013**, *7*, 861–867. [CrossRef]
5. Shima, K.; Ikoma, S.; Uchiyama, K.; Takubo, Y.; Kashiwagi, M.; Tanaka, D. 5-KW single stage all-fiber Yb-doped single-mode fiber laser for materials processing. In Proceedings of the Fiber Lasers XV: Technology and Systems, San Francisco, CA, USA, 27 January–1 February 2018. [CrossRef]
6. Yang, B.; Shi, C.; Zhang, H.; Ye, Q.; Pi, H.; Tao, R.; Wang, X.; Ma, P.; Leng, J.; Chen, Z.; et al. Monolithic fiber laser oscillator with record high power. *Laser Phys. Lett.* **2018**, *15*, 75106. [CrossRef]
7. Ye, Y.; Xi, X.; Shi, C.; Zhang, H.; Yang, B.; Wang, X.; Zhou, P.; Xu, X. Experimental study of 5-kW High-Stability monolithic fiber laser oscillator with or without external feedback. *IEEE Photonics J.* **2019**, *11*, 1503508. [CrossRef]
8. Krämer, R.G.; Möller, F.; Matzdorf, C.; Goebel, T.A.; Strecker, M.; Heck, M.; Richter, D.; Plötner, M.; Schreiber, T.; Tünnermann, A.; et al. Extremely robust femtosecond written fiber Bragg gratings for an ytterbium-doped fiber oscillator with 5 kW output power. *Opt. Lett.* **2020**, *45*, 1447–1450. [CrossRef] [PubMed]
9. Yan, D.; Guo, C.; Zhao, P.; Tao, R.; Shu, Q.; Lin, H.; Wang, J.; Liao, R. A simple O-shaped cylinder fiber laser without inter-cladding-power-strippers. In Proceedings of the Advanced Lasers, High-Power Lasers, and Applications XII, Nantong, China, 10–20 October 2021. [CrossRef]
10. Leidner, J.P.; Marciante, J.R. Three fiber designs for mitigating thermal mode instability in high-power fiber amplifiers. *Opt. Express* **2020**, *28*, 28502. [CrossRef] [PubMed]
11. Naderi, S.; Dajani, I.; Madden, T.; Robin, C. Investigations of modal instabilities in fiber amplifiers through detailed numerical simulations. *Opt. Express* **2013**, *21*, 16111. [CrossRef] [PubMed]
12. Chu, Q.; Tao, R.; Li, C.; Lin, H.; Wang, Y.; Guo, C.; Wang, J.; Jing, F.; Tang, C. Experimental study of the influence of mode excitation on mode instability in high power fiber amplifier. *Sci. Rep.* **2019**, *9*, 9396. [CrossRef] [PubMed]
13. Jauregui, C.; Stihler, C.; Limpert, J. Transverse mode instability. *Adv. Opt. Photonics* **2020**, *12*, 429–484. [CrossRef]
14. Jianjun, W.; Yu, L.; Min, L.; Xi, F.; Qiuhui, C.; Chun, Z.; Cong, G.; Rumao, T.; Honghuan, L.; Feng, J. Ten-year review and prospect on mode instability research of fiber lasers. *High Power Laser Part. Beams* **2020**, *32*, 49–60. [CrossRef]
15. Khush, B.; Matthias, S.; Jason, H.; Sean, C.; Christian, D.; Robert, A.; Eric, H. Threshold power and fiber degradation induced modal instabilities in high-power fiber amplifiers based on large mode area fibers. In Proceedings of the Fiber Lasers XI: Technology, Systems, and Applications, San Francisco, CA, USA, 1–6 February 2014.
16. Wan, Y.; Xi, X.; Yang, B.; Zhang, H.; Wang, X. Enhancement of TMI threshold in Yb-Doped fiber laser by optimizing pump wavelength. *IEEE Photonics Technol. Lett.* **2021**, *33*, 656–659. [CrossRef]
17. Yang, B.; Wang, P.; Zhang, H.; Xi, X.; Shi, C.; Wang, X.; Xu, X. 6 kW single mode monolithic fiber laser enabled by effective mitigation of the transverse mode instability. *Opt. Express* **2021**, *29*, 26366. [CrossRef] [PubMed]
18. Hejaz, K.; Shayganmanesh, M.; Rezaei-Nasirabad, R.; Roohforouz, A.; Azizi, S.; Abedinajafi, A.; Vatani, V. Modal instability induced by stimulated Raman scattering in high-power Yb-doped fiber amplifiers. *Opt. Lett.* **2017**, *42*, 5274–5277. [CrossRef] [PubMed]
19. Wan, Y.; Yang, B.; Xi, X.; Zhang, H.; Wang, P.; Wang, X.; Xu, X. Comparison and Optimization on Transverse Mode Instability of Fiber Laser Amplifier Pumped by Wavelength-Stabilized and Non-Wavelength-Stabilized 976 nm Laser Diode. *IEEE Photonics J.* **2022**, *14*, 1503905. [CrossRef]
20. Wallace, J. High-Power Fiber Lasers Techniques and Accessories. Available online: https://www.ipgphotonics.com/cn/619/Widget/High-power+fiber+lasers%3A+techniques+and+accessories.pdf (accessed on 20 September 2022).
21. Fan, T.Y. Laser beam combining for high-power, high-radiance sources. *IEEE J. Sel. Top. Quantum Electron.* **2005**, *11*, 567–577. [CrossRef]
22. Ye, Y.; Yang, B.; Wang, P.; Zeng, L.; Xi, X.; Shi, C.; Zhang, H.; Wang, X.; Zhou, P.; Xu, X. Industrial 6 kW high-stability single-stage all-fiber laser oscillator based on conventional large mode area ytterbium-doped fiber. *Laser Phys.* **2021**, *31*, 35104. [CrossRef]