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Research of Transverse Mode Instability in High-Power Bidirectional Output Yb-Doped Fiber Laser Oscillators

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Abstract: Bidirectional output fiber laser oscillators can realize two high-power laser outputs employing only a single-laser resonant cavity and hold the advantages of being low cost and of compact size. However, like other fiber lasers, their power improvement is limited by transverse mode instability (TMI). To achieve higher power output, in this paper, the characteristics and corresponding suppression method of the TMI in bidirectional output fiber laser oscillators were investigated for the first time. Firstly, the TMI threshold was obtained when the fiber laser oscillator was pumped by 976 nm LDs and 981 nm LDs, separately, and the difference between the two pumping conditions was researched in detail. After that, a comparison study between the bidirectional and unidirectional output fiber laser oscillators pumped by 981 nm LDs was carried out. In the experiment, the effect of pump distribution on the TMI threshold was also considered. The results show that the TMI threshold of the bidirectional-output laser pumped by 981 nm LDs is much higher than that pump by 976 nm LDs, which means that the effective TMI suppression methods in the unidirectional output laser are also applicable in the bidirectional output laser. In addition, it is found that the TMI threshold of a bidirectional output fiber laser is much lower than that of a unidirectional output fiber laser.

Keywords: fiber laser; ytterbium-doped fiber laser oscillator; transverse mode instability; bidirectional output laser; pump wavelength

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1. Introduction

Fiber lasers are widely used in the field of material processing, communication equipment, medical devices, scientific research, and so on, because of their advantages such as high conversion efficiency, convenient thermal management, good beam quality, and flexible transmission [1–3]. Compared with the fiber laser amplifier, the fiber laser oscillator has a simpler and more compact structure, simple control logic, excellent anti-reflection ability, and is easier to operate and use, which has gained wider attention in industrial application [4,5], but at the same time, due to the direct output of the high-power laser, the fiber laser oscillator has a higher requirement on the withstanding power of the fiber grating, fiber combiner, and other devices. In recent years, the development of fiber device fabrication technology has greatly risen the output power of fiber laser oscillators [6,7]. Fujikura has made significant progress in the field of all-fiber laser oscillators and has reported 2 kW [8], 3 kW [9], and 5 kW [10] all-fiber single-mode fiber laser oscillators since 2016. In 2020, Fujikura increased the output power of all-fiber laser oscillators to 8 kW, with a BPP of 0.50 mm-mrad [6]. The increase in the output power of fiber laser oscillators has greatly facilitated their use in industry. For industrial applications, however, a high power output is not the only requirement for a laser system; cost savings and size compression are also critical.

The bidirectional output fiber laser oscillator is a novel type of fiber laser oscillator that can achieve double-end output employing one single-laser resonant cavity [11]. This new structure of laser achieves bidirectional laser output by replacing the high-reflectivity fiber Bragg grating (HR FBG) in the ordinary laser resonant cavity with a low-reflectivity (LR) FBG. Compared to two unidirectional output laser oscillators of the same power, the bidirectional output fiber laser oscillator reduces the number of fiber gratings and gain fibers, resulting in system cost savings, as well as a simplification of the laser's cooling system, power supply module, and control system, and a reduction in the size and weight of the system while accomplishing the same amount of work as the two unidirectional output laser oscillators, resulting in a significant increase in work efficiency. The average cost of industrial massive production can be further reduced by adopting this new structured laser. Reports on bidirectional output lasers are relatively few and mostly focus on ring lasers [12–14], which have low output power. However, as early as 2004, researchers at the University of Michigan proposed a bidirectional output fiber laser oscillator in which a resonant cavity was formed by 3.5% Fresnel reflections from each straight-cleaved fiber end [15]. The gain medium is a 30 m long, double-cladding, ytterbium-doped fiber (DCYDF) with a core/cladding diameter of 20/400 μm. In this system, two equal-power lasers emitted from both ends with a total signal power of 810 W, a slope efficiency of 70%, and a beam quality factor of ~1.27. In 2022, our team achieved a 2×2 kW near-single-mode bidirectional output fiber laser oscillator based on a DCYDF with 20/400 μm core/cladding diameter [16]. A pair of LR FBGs with 10% reflectivity was adopted. By means of bidirectionally pumping with 976 nm laser diodes (LDs), about 2025 W and 1948 W output powers were eventually obtained, respectively. Further increases in power are limited by pumping power. In 2023, Liu reported a bidirectional output oscillating-amplifying integrated fiber laser achieving a near-single mode laser output of 2×2 kW [17]. The TMI limits the further output power scaling.

The output power and brightness enhancement of high-power fiber laser oscillators are not only limited to the device fabrication process but are also restricted to many physical effects [1–3]. In 2010, researchers from the University of Jena reported the discovery of TMI in fiber lasers for the first time [18]. Since then, TMI has become a hot spot in the research field of high-power fiber lasers. Numerous experimental and theoretical studies have been conducted to explore the causes and suppression methods of TMI. At present, it is widely believed that the physical root of TMI is mode coupling due to thermal effects such as quantum defects [19–21]. Therefore, it has been proven that reducing the quantum defect by changing the wavelength of the pump light or signal light is able to suppress the TMI [22,23]. In addition, reducing the number of modes supported by the gain fiber by decreasing the gain fiber's core diameter or numerical aperture can also increase the TMI threshold [24,25]. Furthermore, the numerical simulation results of the fiber laser show the benefits from the gain saturation effect, and the counter-pump scheme can obtain a higher TMI threshold than the co-pump scheme [26]. A new study shows that the thermal effect which affects the TMI mainly comes from pump absorption rather than quantum defects by comparing and studying TMI threshold characteristics of the laser when 915 nm LDs, 940 nm LDs, and 976 nm LDs are pumped, respectively [27].

However, all the above TMI studies are based on unidirectional output fiber lasers, and none of them are related to bidirectional output fiber lasers. In this paper, the characteristics and suppression method of TMI in bidirectional fiber lasers are researched and discussed for the first time. A high-power fiber laser oscillator is established and able to realize unidirectional or bidirectional output by changing the FBGs. The effect of pump wavelength and pump distribution on the TMI threshold of bidirectional output fiber laser oscillator is investigated, and it is found that the fiber laser has a higher TMI threshold when it is bidirectionally pumped by 981 nm LDs. In addition, the difference in the TMI threshold between unidirectional and bidirectional output fiber lasers is also studied. The TMI threshold of the unidirectional output fiber laser oscillator reached 4000 W bidirectionally pumped by 981 nm LDs, which is much higher than the bidirectional output fiber laser oscillator under the same pumping conditions.

2. Experimental Setup

The structure of the unidirectional output fiber laser oscillator used in the experiment is shown in Figure 1.

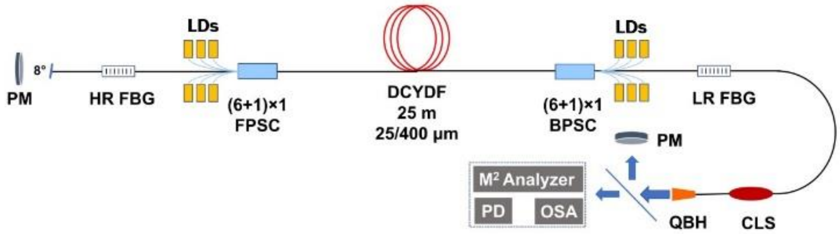

Figure 1. Schematic diagram of unidirectional output fiber laser oscillator.

The resonator cavity consists of an HR FBG, a DCYDF, and an LR FBG fused sequentially. The central wavelength of two FBGs is 1070 nm, and the core/cladding diameter of the fiber is 25/400 µm. The reflectivity of the LR FBG is 9.3%, and its 3 dB bandwidth is about 1 nm. The reflectivity of the HR FBG is 99.3%, and its 3 dB bandwidth is about 3 nm. In order to avoid the effect of end-face feedback, the fiber end-face of the outer part of the resonator cavity of the HR FBG is cut at an angle of 8°. For the detailed study of the TMI effect, the DCYDF shown in Figure 1 was used, which has a core/cladding diameter of 25/400 µm and supports a relatively low TMI threshold. The absorption coefficient of the DCYDF at 915 nm is about 0.56 dB/m. The length of the DCYDF in the experiment is about 25 m to ensure that the pump light can be fully absorbed. The ends of the DCYDF are fused to the output fibers of the forward pump and signal combiner (FPSC) and the backward pump and signal combiner (BPSC), respectively. The pump LDs are injected into the cavity via FPSC and BPSC. The pumping efficiency and insertion loss of the two beam combiners are basically the same, the signal insertion loss of the beam combiner is 0.2 dB, and the pumping efficiency is higher than 97%, which can meet the requirements of high-power operation of the laser. By placing the combiners inside the resonator, on the one hand, the pump light does not pass through the FBGs during the transmission process, which can reduce the thermal load of the FBGs. On the other hand, when replacing the HR FBG with an LR FBG, the structure does not need to disconnect the fusion point between the DCYDF and the beam combiner, so the state of the DCYDF remains stable, which reduces the impact of introducing other variables on the experimental results. The laser output from the resonator cavity is expanded by the Quartz Block Head (QBH) after the cladding light stripper (CLS) strips out the leaked signal power and the remaining pump power. Finally, the output laser is collimated into a test system consisting of a power meter (PM), a photodetector (PD), an optical spectrum analyzer (OSA), and a beam quality (M^2) analyzer, which are used to measure and record the power of the output laser, the time-domain signals, the spectrum, and the beam quality, respectively. The time-domain signals collected by the PD are transmitted to an oscilloscope for display. The stability of the time-domain signals and the corresponding spectral information can be used to monitor whether the TMI is occurring in real-time [28].

Bidirectional output fiber laser oscillators and unidirectional output fiber laser oscillators have a high similarity in structure, and the differences in the structure of the two types of lasers will be highlighted here. As shown in Figure 2, the bidirectional output fiber laser oscillator can be divided into three parts: the DCYDF, the A-end, and the B-end.

The HR FBG in the unidirectional output fiber laser oscillator was replaced by another LR FBG (FBG1) with the same parameters as the original LR FBG (now FBG2), i.e., a reflectivity of 9.3%, a 3 dB bandwidth of about 1 nm, and a center wavelength of 1070 nm. The resonator cavity consists of FBG1, DCYDF, and FBG2. The fiber outside the cavity of the FBG1 is fused to the pigtail of the other QBH, and the CLS is performed at a suitable location on the fused energy-transmitting fiber. The rest of the laser is kept unchanged. Laser is output from QBH1 (named output A) and QBH2 (named output B), respectively. The bidirectional output fiber laser oscillator has symmetry, and theoretically, the device parameters contained in the A-end and B-end should be identical.

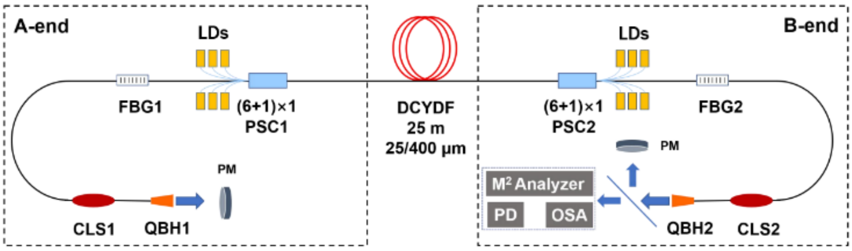

Figure 2. Schematic diagram of bidirectional output fiber laser oscillator.

Based on the position of the pump source in this oscillator, the pump distributions are categorized in this paper as A-pump, B-pump, and Bi-pump. A-pump means that the pump source is injected into the resonant cavity through the PSC1 located at the A-end, which is the same set of pump sources used for the co-pump in a unidirectional output fiber laser oscillator. Similarly, B-pump means that the pump source is injected into the resonant cavity through the PSC2 located at the B-end, which is the same set of pump sources used for the counter-pump in a unidirectional output fiber laser oscillator. Therefore, A-pump and B-pump are collectively referred to as unidirectional pumping. Bi-pump refers to the simultaneous use of A-pump and B-pump, where the ratio of pump power between the A-end and B-end is always 1:1 in a bidirectional output fiber laser oscillator.

Two groups of LDs with different working wavelengths are adopted to study the effect of pump wavelength on the TMI threshold, one located at 976 nm and the other located at 981 nm. It is worth mentioning that the fiber laser oscillator uses two QBHs with 6.4 m of transmission fiber to output the laser light. In addition, the CLS is performed on the QBH pigtail to ensure good beam quality of the output laser.

3. Results and Discussion

3.1. TMI Characteristics of the Bidirectional Output Fiber Laser Oscillator Pumped by 976 nm LDs

Firstly, the TMI thresholds of the bidirectional output fiber laser oscillator pumped by 976 nm LDs with different pump distributions is studied. Considering the structural symmetry of the bidirectional output laser, the following comparison will focus on the output characteristics of the B-end. The TMI threshold is measured under the following three types of pump distributions: A-pump, B-pump, and Bi-pump. The specific results are shown in Table 1 below.

Table 1. Measured TMI thresholds of bidirectional output fiber laser oscillator pumped by 976 nm LDs with different pump distribution.

Pump Distribution	A-End		B-End	
	Pump Power (W)	TMI Threshold (W)	Pump Power (W)	TMI Threshold (W)
A-pump	583	184	583	276
B-pump	760	321	711	262
Bi-pump	2248	842	2347	1016

As mentioned above, A-pump and B-pump are unidirectional pumping, and theoretically, the parameters of the A-end and B-end of the bidirectional output fiber laser oscillator are strictly equal. The pump power and output power at which the TMI effect occurs should be very close for the A-pump and B-pump. However, in practice, when TMI occurs, the pump power and total output power of the B-pump are higher than those of the A-pump. The pumping power is 583 W when TMI occurs in the A-pump and over 700 W when TMI occurs in B-pump. The difference should be due to the actual reflectivity of the FBGs at both ends. Meanwhile, the output power of the B-end is higher in the condition of A-pump, while the output power of the A-end is higher in the condition of B-pump. The distribution of the pump power of the LDs may change the laser power distribution in the resonant cavity, even if the cavity is symmetric.

Finally, for a bidirectional output fiber laser oscillator, under the same pump wavelength, the bidirectional pump can significantly increase the TMI threshold compared with the unidirectional pump. Compared with the A-pump, the TMI threshold of the B-end increases from 276 W to 1016 W when the bidirectional output fiber laser oscillator is bidirectionally pumped. Separating the two output lasers, for the A-end output, the A-pump is equivalent to counter-pump and the B-pump is equivalent to co-pump; similarly, for the B-end output, the A-pump is equivalent to co-pump and the B-pump is equivalent to counter-pump. Under unidirectional pumping (A-pump or B-pump), since one of the lasers has a lower threshold due to co-pump, and the two lasers share a resonant cavity, the laser also has a lower threshold overall. Under Bi-pump conditions, a 1:1 ratio of co-pump and counter-pump power for both output lasers results in a higher TMI threshold compared to co-pump alone.

Figure 3 shows the bidirectional output fiber laser performance when bidirectionally pumped by 976 nm LDs. In experiments, the maximum output power of the B-end is 1040 W, and the corresponding optical-to-optical (O−O) conversion efficiency is about 80%. The pump power is not further increased due to the appearance of the TMI. The time-domain signal and its fast Fourier transform (FFT) analysis, as shown in Figure 3b, reveal that the TMI appears when the B-end output power is 1016 W. The measured laser spectrum when the output power reaches 1040 W is shown in Figure 3c, and no obvious stimulated Raman scattering (SRS) is observed. The measured beam quality (M^2) factors in the X and Y directions were 1.49 and 1.62, respectively.

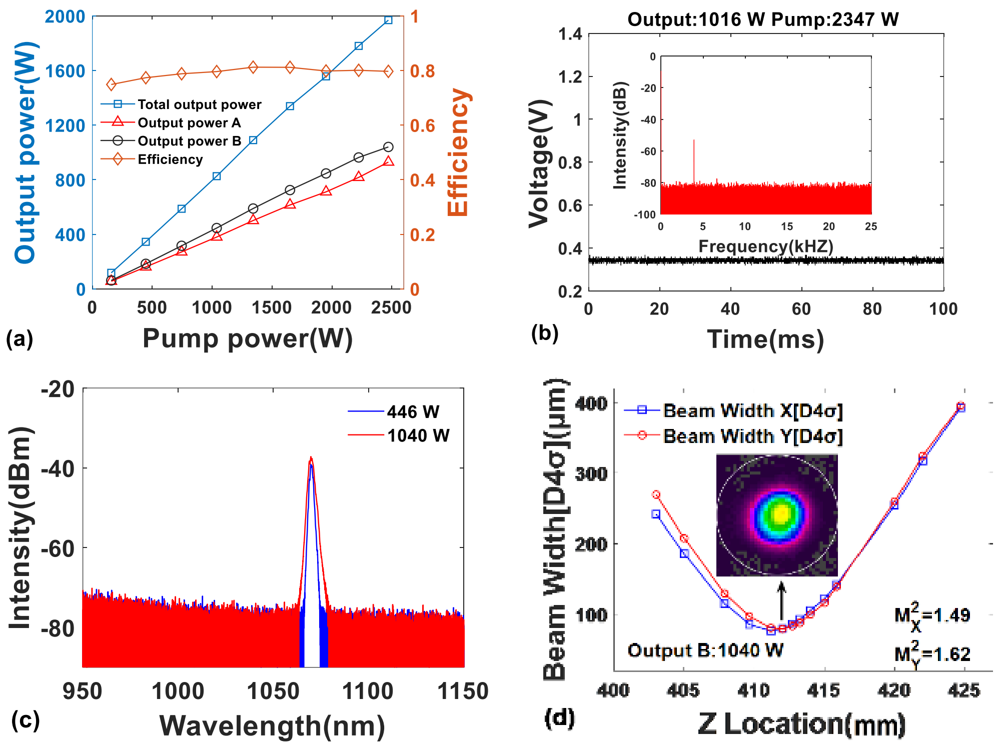

Figure 3. Bidirectional output laser performance when bidirectionally pumped by 976 nm LDs. (**a**) Output power and O−O conversion efficiency. (**b**) Time-domain signal and its FFT analysis when TMI appears at B-end. (**c**) Laser spectrum at different output powers at B-end. (**d**) Beam quality when the B-end output is 1040 W.

3.2. TMI Threshold of the Bidirectional Output Fiber Laser Oscillator Improvement Employing 981 nm LDs

It has been proven that compared with 976 nm LDs, 981 nm LDs can significantly increase the TMI threshold of the unidirectional output fiber laser. In 2021, Wan [29] increased the TMI threshold of the unidirectional fiber laser oscillator from 208 W to 448 W by optimizing the pump wavelength, and the TMI threshold was increased by a factor of about 2.2. To verify the applicability of this method in the bidirectional output fiber laser, the 976 nm LDs in Figure 2 are replaced by 981 nm LDs, and the output characteristics of the bidirectional output fiber laser oscillator are measured again. The specific results can be seen in Table 2.

Table 2. Measured TMI thresholds of bidirectional output fiber laser oscillator pumped by 981 nm LDs with different pump distributions.

Pump Distribution	A-End		B-End	
	Pump Power (W)	TMI Threshold (W)	Pump Power (W)	TMI Threshold (W)
A-pump	1247	385	1224	584
B-pump	1908	805	1886	692
Bi-pump	3596	1046	3646	1443

In Table 2, similar conclusions to those in Table 1 can be obtained. A comparison of Tables 1 and 2 reveals the effect of different pump wavelengths on the TMI threshold of the bidirectional output fiber laser oscillator. Taking B-pump for example, the TMI threshold of the B-end in bidirectional output laser enhanced from 262 W to 692 W by replacing 976 nm LDs with 981 nm LDs. It obviously reveals that, compared with 976 nm LDs, the 981 nm LDs can also significantly increase the TMI threshold of the bidirectional output fiber laser oscillator, not only because the quantum defect under 976 nm pumping is more severe than 981 nm pumping, but also because the absorption coefficient of the DCYDF at 981 nm is only about half of that at 976 nm, which greatly reduces the average heat load due to quantum defect. The lower absorption coefficient of the pump absorption means a lower temperature inside the active fiber and a smaller temperature gradient, which helps to inhibit the formation of thermally induced refractive index gratings, thus increasing the TMI threshold.

Figure 4 shows the bidirectional output laser's performance under the 981 nm Bi-pump condition. Figure 4a reveals that the output power is basically linearly increased with the pump power. The total output power reaches 2469 W when the pump power is 3138 W, and the corresponding O−O conversion efficiency is calculated to be 79%. However, obvious power stagflation appears when the pump power further increases to 3395 W and the conversion efficiency drops to 71%. But no time-domain fluctuation and characteristic frequency peak were observed, indicating the absence of TMI. It is analyzed that in the case of all-fiber lasers with CLS, the output power may stop growing or even drop due to the filtering of higher-order modes. When the pump power continuously increases to 3646 W, the conversion efficiency drops to 69% and the output power at the B-end is 1443 W. The measured time-domain signal and its FFT analysis are shown in Figure 4b, and it can be found that the TMI appears. The output spectrum is shown in Figure 4c, and no SRS is observed. The measured beam quality factors in the X and Y directions were 1.40 and 1.48, respectively.

3.3. Comparison of TMI Effect in Bidirectional and Unidirectional Output Fiber Laser Oscillators

At last, the comparison of the TMI threshold of bidirectional and unidirectional output fiber lasers is carefully researched. The unidirectional output fiber laser oscillator is transformed from the bidirectional one by replacing the FBG1 with an HR FBG and keeping the other parameters of the laser system unchanged. Figure 5 shows the output performance of the unidirectional laser bidirectionally pumped by 981 nm LDs.

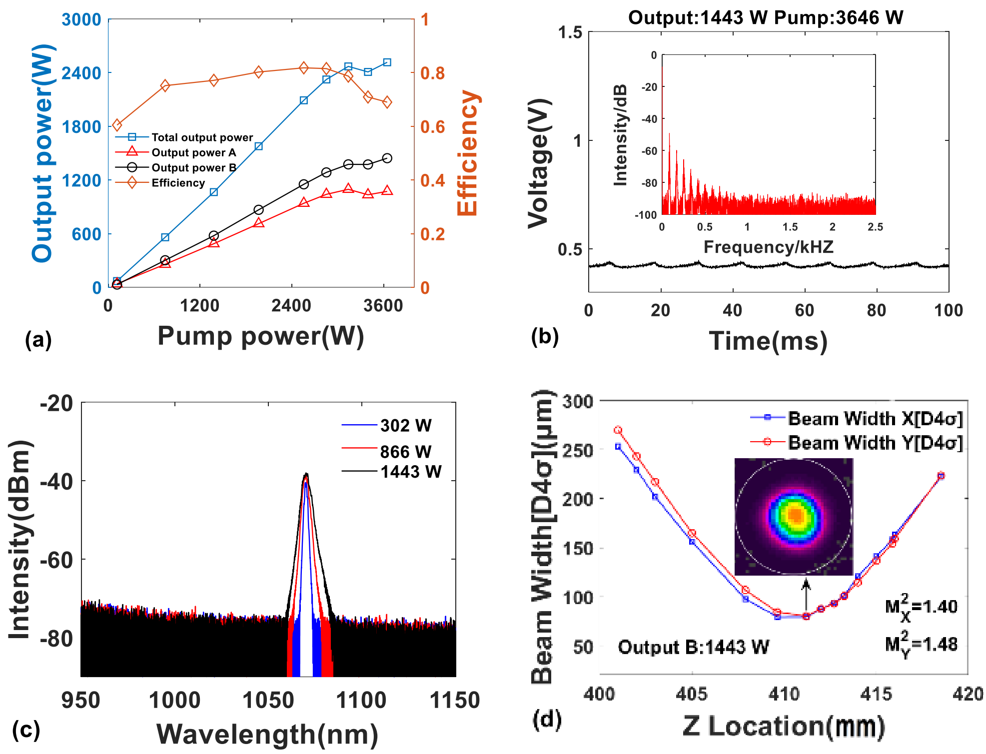

Figure 4. Bidirectional output laser performance when bidirectionally pumped by 981 nm LDs. (**a**) Output power and O–O conversion efficiency. (**b**) Time-domain signal and its FFT analysis when TMI appears at B-end. (**c**) Laser spectrum of B-end at different output powers at B-end. (**d**) Beam quality when the B-end output is 1443 W.

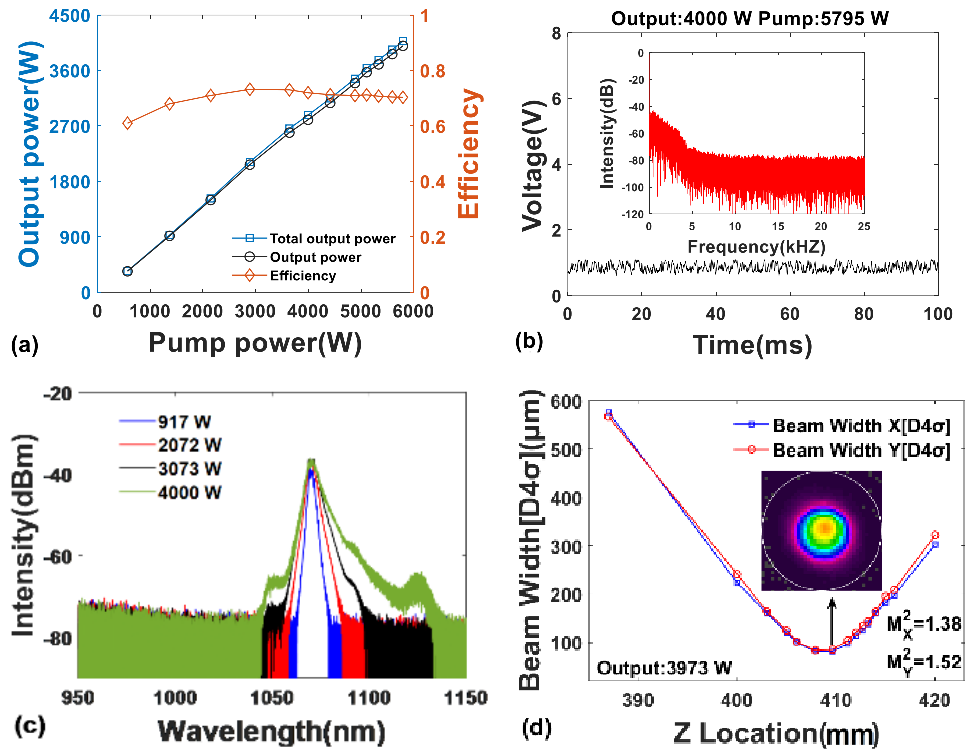

Figure 5. Unidirectional output fiber laser oscillator performance when bidirectionally pumped by 981 nm LDs. (**a**) Output power and O–O efficiency. (**b**) Time-domain signal and its FFT analysis when TMI appears. (**c**) Laser spectrum at different output power. (**d**) Beam quality when the output power is 3973 W.

In Figure 5a, the total output power represents the sum of the forward output power from the QBH and the backward signal power from the free port of the HR FBG, and the efficiency is the ratio of the total output power to pump power. The output power grows linearly with the scaling of the pump power, and the O−O conversion efficiency stabilizes at about 69% before the TMI occurs. The max O−O conversion efficiency of the unidirectional output laser is about 71%. As shown in Figure 5b, the apparent TMI appears when the output power reaches 4 kW. At this point, many burrs appear on the spectrum of the output laser. Figure 5c demonstrates the output spectrum at different output power points, and obvious four-wave mixing and SRS can be found. When the output laser power is 3973 W, the beam profile is not perfectly symmetrical, and the beam quality factor is $M_X^2 = 1.38$, $M_Y^2 = 1.52$.

Table 3 shows the comparison of the TMI threshold of the two fiber lasers. The TMI threshold of the unidirectional output fiber laser oscillator with forward, backward, and bidirectional 981 nm LDs pump is 1037 W, 2628 W, and 4 kW, respectively. However, with the same pump wavelength and bidirectional pump scheme, the TMI threshold of the bidirectional output fiber laser oscillator is only about 2.5 kW, 37.5% lower than that of the unidirectional output fiber laser oscillator. Under the same pump power and pump distribution of the LDs, the laser power distribution in the resonant cavity is changed by replacing the FBG1 with an HR FBG, which is the biggest difference between the two fiber lasers. The difference in resonant cavities leads to the difference in laser output results between the unidirectional and bidirectional output fiber laser oscillators.

Table 3. Comparison of the TMI threshold of bidirectional and unidirectional output fiber laser oscillators.

Structure	Pump Distribution	Pump Power(W)	TMI Threshold (W)
Unidirectional output	Co-pump	1508	1037
	Counter-pump	3907	2628
	Bidirectional pump	5795	4000
Bidirectional output	Bidirectional pump	3646	2515

4. Conclusions

In this paper, the TMI suppression method in bidirectional output fiber laser oscillators is studied and discussed for the first time. Although the physical structures of bidirectional and unidirectional output fiber laser oscillators are different, the origin of the TMI effect in them is completely the same. Therefore, the design of high-power bidirectional output lasers can be refined and inspired by referring to the traditional TMI suppression methods. The experimental results show that TMI suppression methods such as reducing quantum defects, enhancing the gain saturation effect, and optimizing pump wavelength have been proven to be equally effective in bidirectional output fiber laser oscillators. Meanwhile, it is also worth noting that bidirectional output lasers change the distribution of the pump power and signal power within the resonator. Thus, bidirectional output fiber laser oscillators have a lower TMI threshold compared to unidirectional output fiber laser oscillators.

Author Contributions: P.W., B.Y., X.X., H.Z., X.W. and J.C. contributed to the conception and design of the study. X.D. and P.W. organized the database. F.L. performed the statistical analysis. F.L. wrote the first draft of the manuscript. H.Z., X.D., B.Y. 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.

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