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Demonstration of Yb-Doped Fiber Amplifier Operating near 980 nm with the Slope Efficiency Close to the Theoretical Limit

Zhaode Li [1,2,3,†], Shangde Zhou [1,2,3,†], Aimin Liu [1,2,3], Jianqiu Cao [1,2,3,*], Zhihe Huang [1,2,3] and Jinbao Chen [1,2,3]

[1] College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China
[2] State Key Laboratory of Pulsed Power Laser Technology, Changsha 410073, China
[3] Hunan Provincial Key Laboratory of High Energy Laser Technology, Changsha 410073, China
* Correspondence: caojianqiu@nudt.edu.cn
† These authors contributed equally to this work.

Abstract: In this paper, the scalability of slope efficiency of a Yb-doped fiber amplifier operating near 980 nm is studied with the core-pumping scheme. By means of numerical prediction, it is found that the theoretical limit of slope efficiency should be about 92.2%. Then, the experiment study is carried out. An 85.3% slope efficiency of emission around 980 nm is achieved with the seed light around 976.5 nm, and the strong in-band amplified spontaneous emission (ASE) is supposed to be a factor limiting the upscaling of slope efficiency. In order to suppress the in-band ASE, the double-wavelength fiber oscillator near 980 nm is fabricated and used as the seed source, with which the slope efficiency is elevated to 90.7%. Such slope efficiency is very close to the theoretical limit and sets a new record of slope efficiency for the Yb-doped fiber amplifier operating near 980 nm, to the best of our knowledge. It is also revealed that the suppression of in-band ASE should be of great importance to elevate the slope efficiency of a Yb-doped fiber amplifier operating near 980 nm.

Keywords: fiber amplifier; in-band ASE; Yb-doped fiber

Citation: Li, Z.; Zhou, S.; Liu, A.; Cao, J.; Huang, Z.; Chen, J. Demonstration of Yb-Doped Fiber Amplifier Operating near 980 nm with the Slope Efficiency Close to the Theoretical Limit. *Photonics* **2022**, *9*, 571. https://doi.org/10.3390/photonics9080571

Received: 30 June 2022
Accepted: 7 August 2022
Published: 12 August 2022

1. Introduction

Yb-doped fiber lasers operating near 980 nm are attractive for their potential applications, such as the high-brightness pump sources for the high-power Yb/Er-doped fiber lasers and amplifiers [1,2] or the optical parameter amplification to generate blue-green and ultraviolet emissions [3,4]. One important parameter of the fiber laser operating near 980 nm is pump efficiency, which evaluates the conversion efficiency of pump light to signal light (or the emission near 980 nm) in the active fiber. Currently, a majority of studies on the Yb-doped fiber lasers are focused on the band larger than 1000 nm (corresponding to the four-level transmission of Yb-ions, typically ranging from 1020 nm to 1100 nm), where high pump efficiency (larger than 80%) can be achieved [1,2,5–8]. However, it is not easy to realize high pump efficiency for the Yb-doped fiber laser operating near 980 nm because the emission around 980 nm is generated by the three-level transmission of Yb-ions and has to suffer from the gain competition with the ASE around 1030 nm generated by the four-level transmission of Yb-ions [2,5,8,9]. In order to suppress the ASE around 1030 nm, the active fiber has to be short enough (determined by the absorption and emission cross sections of Yb ions [1,2,5,8,10]), which will result in insufficient absorption of pump light and thus not be a benefit to high pump efficiency.

Currently, the majority of studies on the fiber lasers near 980 nm are focused on the design of double-clad Yb-doped fiber (DCYF) because [10] revealed that enlarging the ratio of filling factors of pump to signal light in the doped area (approximately equal to the core-to-cladding area ratio) is an effective way for elevating pump efficiency. There are several demonstrations of fiber lasers operating near 980 nm with more than 60% slope efficiency with respect to the launched pump power [11–13]. For example, by using the double-clad, Yb-doped photonic crystal fiber (PCF) or the photonic bandgap fiber (PBGF), hundred-Watt-level fiber lasers operating near 980 nm have been demonstrated with a slope efficiency of more than 60%. By using the large-core DCYF, the kW-level fiber laser was also demonstrated with a slope efficiency of 65%. There were still studies on other sorts of DCYFs, such as W-profile fiber [14–16], saddle-shaped fiber [17], multicore fiber [18], jacketed-air-clad (JAC) fiber [19,20], and so on. However, their reported values of slope efficiency were even lower. There were also some studies reporting the slope efficiency with respect to the absorbed pump light [20,21]. It should be noted that such efficiency does not take into account the unabsorbed pump light (or the insufficient pump absorption related to the 1030-nm ASE suppression) and thus can be much larger than that with respect to the launched pump power. Therefore, only the slope efficiency with respect to the launched pump power is considered in this paper, and the slope efficiency mentioned in the following parts is all with respect to the launched pump power. Then, to the best of our knowledge, the state-of-art slope efficiency achieved by the DCYF is no larger than 70% in the fiber lasers operating near 980 nm.

One obstacle to higher pump efficiency is the configuration of DCYF because, as mentioned above, the core-to-cladding ratio of DCYF will affect the pump slope efficiency. In fact, the core-to-cladding diameter ratios of DCYFs used in these literatures mentioned above were all smaller than 0.76, which limited the upscalability of slope efficiency. Moreover, there is still a problem, i.e., how much slope efficiency can be achieved if the maximum core-to-cladding area ratio can be adopted. This problem is of great importance because it will reveal the scalability of pump efficiency of Yb-doped fiber lasers operating near 980 nm.

One proper scheme to study the problem is to use the core-pumped, Yb-doped fiber, which can provide the maximum core-to-cladding area ratio (close to 1). Although the core-pumping scheme limits the output power to only Watt level [22], it is still attractive in the applications as the seed source or to generate the blue-green light [3,23–26]. In fact, as early as 1989, pumped by a 900-nm dye laser, a single-mode, single-clad, Yb-doped fiber with the core-pumping scheme has been used to generate the emission near 980 nm [27]. In 2005, by using a single-mode, Yb-doped fiber core-pumped with a 914-nm Nd: YVO4 pump laser, 2-W output power at 978 nm was obtained with 72% slope efficiency [25]. In 2008, by using a 946-nm Nd: YAG laser as the pump source, 1.32-W total output power at 980 nm was obtained with 75.3% slope efficiency [26]. In 2011, with the pump light at 930 nm provided by an Nd-doped fiber laser, the largest slope efficiency was achieved, which was about 81% [22]. In these schemes, the solid or fiber lasers were used as the tandem pumping source in order to increase the launched pump power. Moreover, the longer pump wavelength was also helpful to lower the quantum defect and thus helpful in increasing the slope efficiency. However, there are still some problems. For example, can the slope efficiency be further enlarged, and what is the key issue limiting the slope efficiency in the core-pumping scheme? These problems are still not so clear and need to be further investigated.

In this paper, a single-mode Yb-doped fiber amplifier core-pumped with the laser diode (LD) around 912 nm is studied in order to reveal the scalability of its pump slope efficiency. Here, the LD is utilized as the pump source, because although the LD cannot provide so large pump power as the solid or fiber laser [22,25,26], it owns advantages such as high electro-optical efficiency, portability, robustness, etc., and has been widely used as the pump source of fiber lasers. By means of numerical calculation with the rate-equation model, it is revealed that as much as 92.2% slope efficiency can be achieved with the optimized active fiber length. Then, the experimental study is carried out. With the seed source at 976.5 nm, only 85.3% slope efficiency was obtained by optimizing the active fiber length. Besides, the in-band ASE was also observed in the experiment. In order to study the effect of in-band ASE on the efficiency, a double-wavelength fiber oscillator was fabricated and used as the seed source instead of the 976.5-nm LD seed. With the double-wavelength seed light provided by the oscillator, the in-band ASE in the amplifier is better suppressed and the slope efficiency of the fiber amplifier is further enlarged to 90.7%, which is very close to the theoretical limit (i.e., 92.2%). It is revealed that the suppression of in-band ASE is of great importance for improving pump efficiency.

2. Numerical Prediction of Theoretical Limit of Slope Efficiency

The slope efficiency of a Yb-doped fiber amplifier operating near 980 nm should be determined by three factors, i.e., the quantum defect, cavity loss and pump absorption, and its theoretical limit can be predicted with the help of a well-known steady-state rate-equation model, given as follows [27,28].

$$\frac{N_2(z)}{N} = \frac{\frac{\left[P_p^+(z)+P_p^-(z)\right]\Gamma_p\sigma_{ap}\lambda_p}{hcA} + \frac{\Gamma_s}{hcA}\int \sigma_a(\lambda)\cdot[P^+(z,\lambda)+P^-(z,\lambda)]\lambda d\lambda}{\frac{\left[P_p^+(z)+P_p^-(z)\right]\left(\sigma_{ap}+\sigma_{ep}\right)\Gamma_p\lambda_p}{hcA} + \frac{1}{\tau} + \frac{\Gamma_s}{hcA}\int (\sigma_a(\lambda)+\sigma_e(\lambda))\cdot[P^+(z,\lambda)+P^-(z,\lambda)]\lambda d\lambda}, \tag{1}$$

$$\pm\frac{dP^{\pm}(z,\lambda)}{dz} = \Gamma_s\{[(\sigma_a(\lambda)+\sigma_e(\lambda)]N_2(z)-\sigma_a(\lambda)N\}\cdot P^{\pm}(z,\lambda) + \Gamma_s\sigma_a(\lambda)N_2(z)P_0(\lambda) - \alpha(z,\lambda)P^{\pm}(z,\lambda), \tag{2}$$

$$\pm\frac{dP_p^{\pm}(z)}{dz} = -\Gamma_p\left\{\sigma_{ap}(N-N_2(z))-\sigma_{ep}\right\}\cdot P_p^{\pm}(z) - \alpha\left(z,\lambda_p\right)P_p^{\pm}(z). \tag{3}$$

Here, N and N_2 are the dopant concentration and upper-state population density, respectively. P and P_p present the power density of the ASE and pump light, respectively. z presents the position along the active fiber, and the plus and minus signs indicate the positive and negative propagation along the z-direction, respectively. $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are absorption and emission cross sections at wavelength λ, respectively. Particularly, σ_{ap} and σ_{ep} represent absorption and emission cross sections at pump wavelength λ_p, respectively. Γ_p and Γ_s refer to the pump and signal-filling factors, respectively. Because the core-pumped single-mode fiber amplifier is considered here, Γ_p should be approximately equal to Γ_s, and the value is assumed as 0.9. $\alpha(z,\lambda)$ is the scattering loss, and A is the doping area of the active fiber core. τ and h are the spontaneous emission lifetime and Planck's constant, respectively, and c is light velocity in vacuum. $P_0(\lambda)$ is the spectral energy density of spontaneous emission given as [29]

$$P_0(\lambda) = \frac{2hc^2}{\lambda^3}. \tag{4}$$

Equations can be solved with the constraints of boundary conditions, given as

$$P^-(L,\lambda) = P^+(L,\lambda)R, \tag{5}$$

$$P^+(0,\lambda) = \begin{cases} P^-(0,\lambda)R, & \lambda \neq \lambda_s \\ P_{s0} + P^-(0,\lambda)R, & \lambda = \lambda_s \end{cases}, \tag{6}$$

$$P_p^+(0) = P_{p0}^+,\ P_p^-(L) = 0 \tag{7}$$

where L is the active fiber length, and R represents the reflectivity of the angle-cleaving facet. P_{s0} is the input seed power at the wavelength λ_s. P_{p0}^+ and P_{p0}^- are the injected co-pumping power and counter-pumping power, respectively. In this paper, we only consider the case of co-pumping, and thus $P_{p0}^- = 0$. The model is solved numerically with the parameter values given in Table 1.

Table 1. Parameters used in the simulation.

Parameter	Value	Parameter	Value
λ_p	912 nm	n	1.45
λ_s	976 nm	Core diameter	6 μm
τ	0.84 ms	N	$9.91 \times 10^{24}/\mathrm{m}^3$
σ_a	See Ref. [30]	L	0.3∼2.5 m
σ_e	See Ref. [30]	P_{s0}	160 mW
α_p	0.0013	R	10^{-6}
$\alpha(\lambda)$	0.0013		
Γ_p	0.9		
Γ_s	0.9		

The variation of slope efficiency with the active fiber length is given in Figure 1a. Here, in order to compare with the experimental data, the slope efficiency is calculated with the output power of emission around 980 nm (i.e., the total output power of signal light plus in-band ASE around 980 nm). The reason is that the in-band ASE is the ASE within the same band of signal light near 980 nm (see Figure 1b,d), and its spectral band is within the range from 972 nm to 985 nm [9,31]. Similar to the signal light, it is also generated by the three-level transmission of Yb ions [32,33], which is distinguished from the ASE around 1030 nm generated by the four-level transmission of Yb ions. Hence, the in-band ASE is just around the signal light and cannot be simply separated from the signal light in the experiment. Therefore, the experimentally measured output power of the fiber amplifier around 980 nm generally includes the in-band ASE. In spite of that, from the calculated spectrum given in Figure 1b, it can be found that the in-band ASE is much weaker than the signal light.

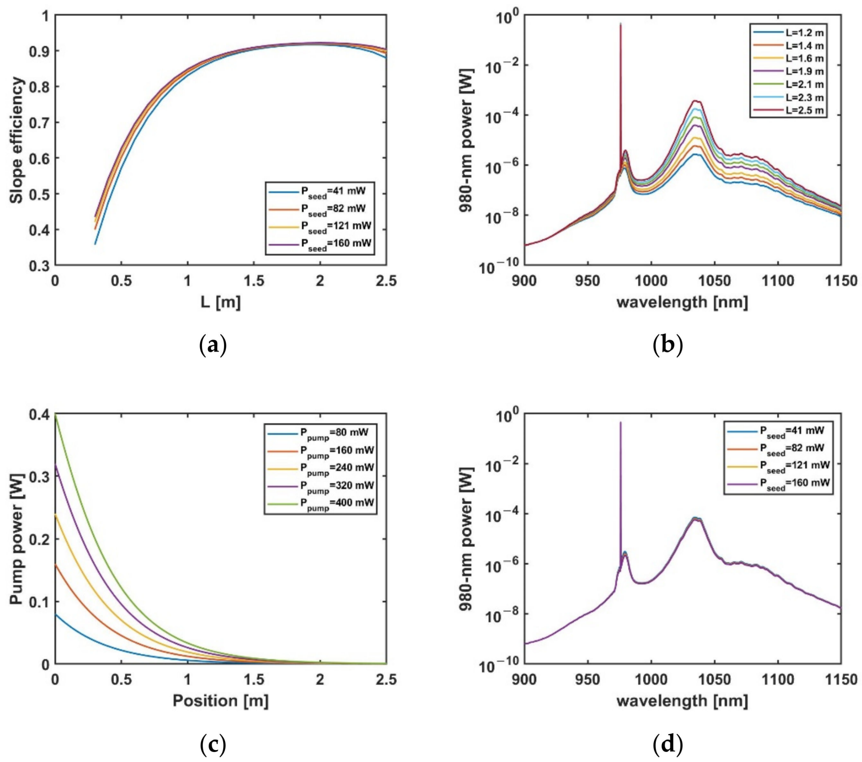


Figure 1. (**a**) The variations of slope efficiency with active fiber length. (**b**) The variation of output spectrum with active fiber length. The pump and seed power are 400 mW and 160 mW, respectively. (**c**) The variations of pump power along the active fiber. (**d**) The variation of spectrum with seed power. The active fiber length and pump power are 2.0 m and 160 mW, respectively.

From Figure 1a, it can be found that when the active fiber is shorter than 1.3 m, the slope efficiency grows rapidly with lengthening the active fiber. Such improvement of slope efficiency is mainly induced by the enhancement of pump absorption with the active fiber lengthening. The explanation can be verified by Figure 1c, which shows that the residual pump light decreases rapidly with lengthening the active fiber.

Figure 1a also shows that when the active fiber is longer than 1.3 m, the variation of slope efficiency becomes much slower because the pump absorption is too sufficient to obviously affect the slope efficiency (see Figure 1c). It is also revealed that the maximum slope efficiency can be obtained with the 2.0-m active fiber. With further lengthening the active fiber, the slope efficiency will be slightly lowered because of the enhancement of the ASE around 1030 nm (see Figure 1b). In fact, from spectra given in Figure 1b, it can be found that the ASE around 1030 nm is obviously stronger than the in-band ASE around 980 nm, and thus, its effect on the slope efficiency should be dominant.

The variations of slope efficiency corresponding to various values of seed power are also given in Figure 1a. It can be found that the slope efficiency is increased monotonously with the increment of seed power. Such improvement should also be induced by the suppression of ASE. From Figure 1d, it can be found that both the in-band and 1030-nm ASEs become weaker with the stronger seed light, which is more dominant in the gain competition with ASE. In spite of that, it can be also found that the improvement is very weak, and the maximum slope efficiency changes only from 91.7% to 92.2% when the seed power increases from 41 mW to 160 mW. Thus, the theoretical limit of slope efficiency should be around 92.2%, which is very close to the value determined uniquely by the quantum defect (about 93.4%).

3. Experimental Study

In the above section, it was numerically predicted that the theoretical limit of slope efficiency of the 912-nm core-pumped Yb-doped fiber amplifier operating near 980 nm should be about 92.2%, which is much larger than the largest reported value (about 72% [22]) demonstrated with the pump wavelength around 914 nm. Therefore, the experimental study is indispensable to demonstrating whether the slope efficiency close to the theoretical limit can be achieved.

3.1. Experimental Setup

The experimental setup is shown in Figure 2. A single-clad Yb-doped fiber with an 825-µm cutoff wavelength is utilized as the active fiber, and thus all the emissions generated in the active fiber are single-mode. The core of the Yb-doped fiber owns the diameter of about 6 µm, and its absorption is about 26 dB/m at 915 nm.

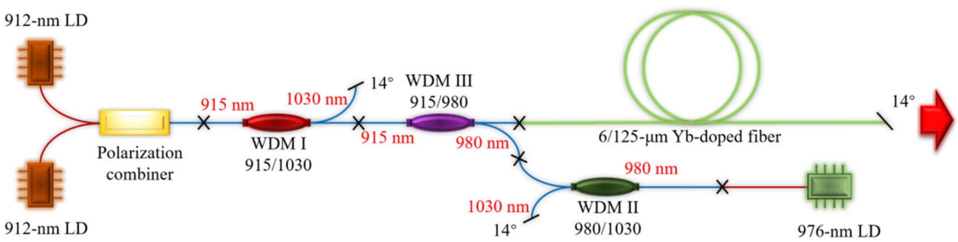


Figure 2. The experimental setup.

The pig-tailed, single-mode LDs are utilized as the pump sources, which can provide pump light at the wavelength around 912 nm with a 20-dB bandwidth of 1.2 nm. A pig-tailed, single-mode LD with the wavelength centered at 976.5-nm is utilized as the seed source, and its 3-dB bandwidth is about 0.14 nm. The 915-nm/980-nm wavelength division multiplexer (WDM, see WDM III in Figure 2) as the core-pumped combiner couples the pump and signal light into the active fiber core. WDM III owns the pass band ranging from

910 nm to 920 nm and the reflection band ranging from 975 nm to 985 nm with 0.59-dB and 0.36-dB insertion losses, respectively.

In order to protect these LDs, WDM I and WDM II are used to filter out the counter-propagating 1030-nm ASE generated in the active fiber. The pass and reflection bands of the WDM I are from 905 nm to 925 nm and from 1020 nm to 1080 nm with 0.3-dB and 0.29-dB insertion losses, respectively, whereas those two bands of WDM II range from 960 nm to 990 nm and from 1020 nm to 1080 nm with 0.27-dB and 0.49-dB insertion losses, respectively.

All the passive fibers used in the experiment are adopted to match the configuration of the active fiber. In order to suppress the optical feedback, all unoccupied fiber ends are angle-cleaved. Here, the co-pumping scheme is used in our experiment in order to measure the emission directly output from the active fiber with no other fiber component affecting the output power and spectrum.

3.2. Results and Discussions

With the experimental setup, the output power and spectrum are measured and given in Figures 3 and 4. Here, the 2.3-m active fiber is used in the fiber amplifier. Figure 3a gives the variation of output spectrum with pump power where the seed power is 41 mW. It can be found that the ASE around 1030 nm is well suppressed, and its peak-to-peak suppression reaches to 44.1 dB at 298.1-mW pump power. Although some residual pump light can still be observed, its peak-to-peak suppression is about 22.5 dB (lower than 1.7 mW, estimated by spectral integration), which means that the pump light should be fully absorbed. The zoom-in spectra around 980 nm are also given in Figure 3a. It can be found that both the signal light and in-band ASE are enhanced by increasing the pump power.

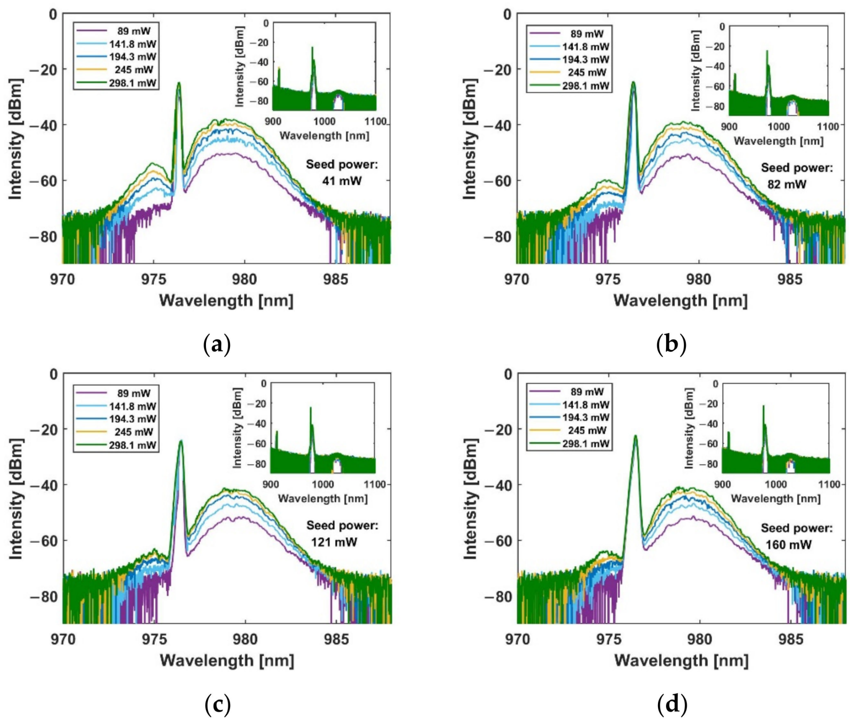
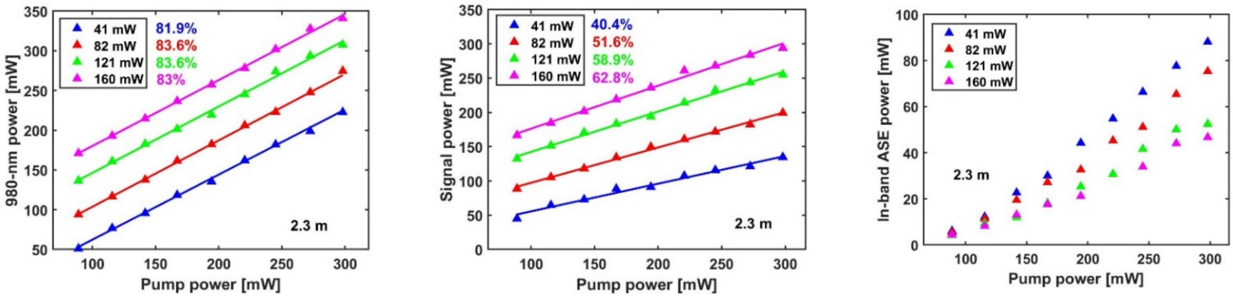


Figure 3. Four figures of output spectra via pump power corresponding to four seed power values corresponding to 41 mW, 82 mW, 121 mW, 160 mW (**a**–**d**).



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

Figure 4. Output power of (**a**) emission around 980 nm and (**b**) signal light and (**c**) in-band ASE with 2.3-m active fiber.

All of these results can be expected with the numerical calculation given above except one thing, i.e., the strong in-band ASE. From Figure 3, it can be seen that the in-band ASE can be stronger than the ASE around 1030 nm, which is different from the numerical prediction (see Figure 1b,d).

A similar phenomenon was also reported in [31], which indicates that the in-band ASE can be more dominant in the gain competition than the numerical prediction. The reason is not so clear currently and needs to be further investigated. In spite of that, its impact on the slope efficiency of the fiber amplifier will be investigated in the following part.

The variations of output spectra corresponding to various seed power are also given in Figure 3. It can be found that the suppressions of both the in-band and 1030-nm ASEs are slightly improved with the stronger seed light. The peak-to-peak suppression of in-band ASE is increased from 13.2 dB to 18.4 dB, whereas that of 1030-nm ASE is increased from 44.1 dB to 47.4 dB, with the seed power varied from 41 mW to 160 mW at the maximum pump power.

In order to calculate the slope efficiency, the output power of emission around 980 nm (consisting of the signal light and in-band ASE) is estimated by spectral integration and is given in Figure 4a. It can be found that with the increment of seed power, the slope efficiency only varies within the range from 81.9% to 83.6%, and the dependence of slope efficiency on the seed power predicted by the numerical results given in Figure 1a cannot be observed in the experimental results. The reason should be that the effect of seed power on slope efficiency is too weak (also see the numerical prediction given in Figure 1a) to be measured in our experiment.

However, the effect of seed power on the output power of signal light (without the in-band ASE) is stronger (see Figure 4b). It can be found that the slope efficiency of signal light increases monotonously from 40.4% to 62.8%, with the seed power varied from 41 mW to 160 mW. The reason owes to the effect of seed power on the in-band ASE. From Figures 3 and 4c, it can be seen that the in-band ASE is obviously weakened with the increment of seed power. Then, more gain is abstracted by the signal light, which makes the efficiency of signal light increased.

Then, we gradually shortened the active fiber length and measured output power and spectrum at each active fiber length. The slope efficiency of output emission around 980 nm is given in Figure 5. It can be found that the largest slope efficiency is obtained with the 1.9-m active fiber, and its value is about 85.3% (also see Figure 6c). When the active fiber is shortened to 1.3 m, a slope efficiency of 82% can also be achieved (also see Figure 6b). However, when the active fiber is shorter than 1.3 m, the slope efficiency is rapidly lowered with shortening of the active fiber. This means that the variation of slope efficiency with the active fiber length should become slow when the active fiber is long enough to sufficiently absorb the pump light, which also agrees well with the numerical prediction given in Figure 1a.

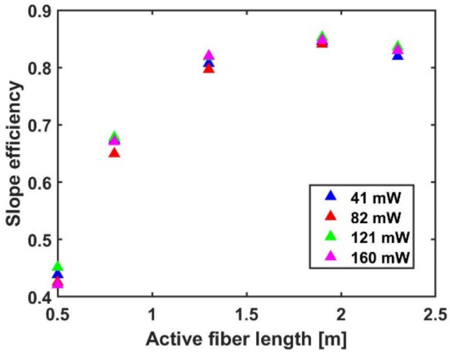


Figure 5. The slope efficiency of output emission around 980 nm via active fiber length.

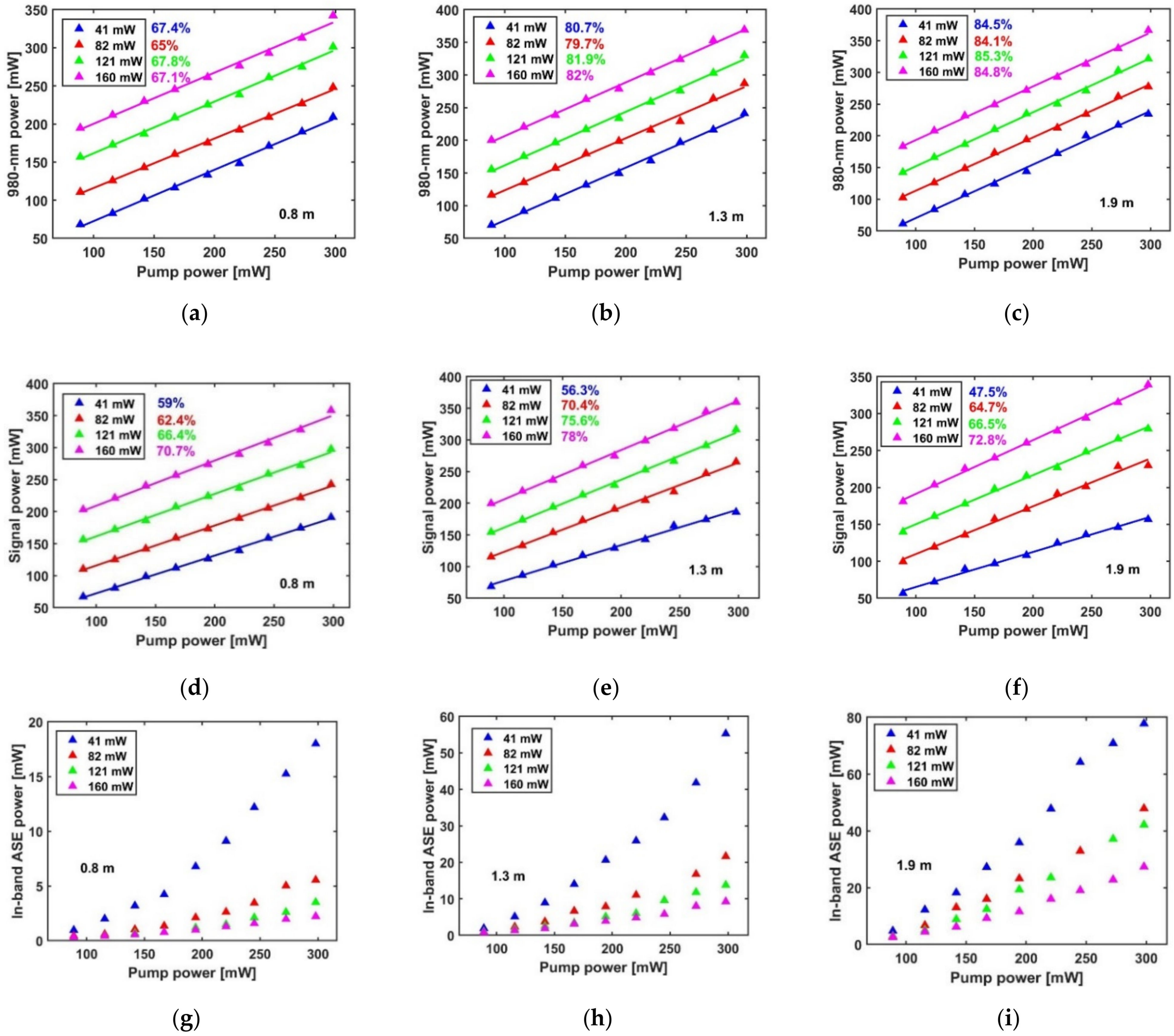
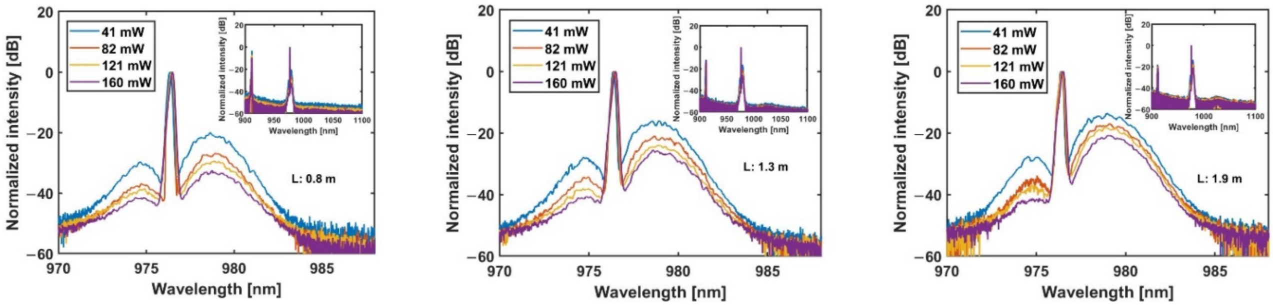


Figure 6. Output power of (**a**–**c**) emission around 980 nm and (**d**–**f**) signal light and (**g**–**i**) in-band ASE with 0.8-m, 1.3-m, and 1.9-m active fibers, respectively.

The variations of output spectrum and power corresponding to 0.8-m, 1.3-m, and 1.9-m active fibers are also given in Figures 6 and 7. Figure 7 gives the variations of output spectrum with various seed power. It can be found that the in-band ASE is weakened with shortening the active fiber (also see Figure 6g–i), and thus its effect on the signal gain is also weakened. Then, the slope efficiency of signal light with the 1.3-m active fiber is larger than that with the 1.9-m active fiber (see Figure 6e,f). However, because of the insufficient pump absorption with the 0.8-m active fiber (see Figure 7a), the slope efficiency values of emission around 980 nm and signal light are still lower, even with the weaker in-band ASE (see Figure 6a,d,g).



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

Figure 7. The variations of output spectrum with various seed power corresponding to 0.8-m, 1.3-m, and 1.9-m active fibers (**a**–**c**).

3.3. Further Improving the Slope Efficiency

From the above experiment, as much as 85.3% slope efficiency of emission around 980 nm was obtained. Here, it should be stated that the total power of emission around 980 nm can give the total power abstracted from the active fiber within the band near 980 nm, and it is more comparable with the numerical prediction because the effect of in-band ASE difference in the numerical and experimental results on the comparison can be suppressed. In spite of that, the value 85.3% is still not so close to the theoretical limit, 92.2%. One possible reason is that the in-band ASE observed in our experiment is stronger than that of numerical prediction.

The in-band ASE is considered to be induced by the inhomogeneous broadening of the Yb-ion gain spectrum, which makes the signal light abstract the Yb gain predominantly around the signal wavelength [34,35]. As a result, the emission around the signal wavelength will be affected much more seriously than the emission at other wavelengths [34,35] (also see Figures 3 and 6 for examples), and then, the in-band ASE will be present. Based on this consideration, [35] pointed out that the in-band ASE can be better suppressed by using the broadband signal light. Here, in order to reveal the effect of in-band ASE on the slope efficiency, a double-wavelength fiber oscillator is fabricated and utilized as the broadband seed source, with the purpose of suppressing the in-band ASE in the fiber amplifier [35].

The experimental setup of the double-wavelength fiber oscillator is given in Figure 8. The same single-mode, Yb-doped fiber is also utilized here with 2.1-m length, which can ensure the sufficient pump absorption mentioned above. The pump configuration is similar to that of the amplifier, and the only difference is the 915-nm/980-nm WDM used to filter out the counter-propagating laser around 980 nm to protect pump LDs. One pair of high-reflectivity and low-reflectivity fiber Bragg gratings (HR-FBG and LR-FBG, respectively, see Figure 8) are utilized to define the cavity of the fiber oscillator, and their transmission spectra are given in Figure 9. The double-wavelength operation is achieved by using the LR-FBG. The 980-nm/1030-mn WDM spliced behind the LR-FBG is used to filter out the 1030-nm ASE generated in the oscillator. All unoccupied ports of WDMs are also angle-cleaved to suppress the optical feedback.

Then, the fiber oscillator is used as the seed source instead of the 976.5-nm LD. About 160-mW seed light is injected into the core of the active fiber, and the pertinent seed spectrum (measured behind WDM III, see Figure 1) is given in Figure 10. It can be seen that two peaks of signal light are located around 976.6 nm and 977.4 nm, respectively, which agree well with the transmission spectrum of LR-FBG given in Figure 9. The 3-dB bandwidths of two peaks are both about 0.14 nm. The signal light around 977.4 nm is 18 dB higher than that around 976.6 nm, which means that the 977.4-nm peak should be more dominant in the gain competition. The in-band ASE in the seed light is also well suppressed (only about 0.22 mW estimated by spectral integration). No residual pump light is observed because it is well filtered out by the WDM III (see Figure 1).

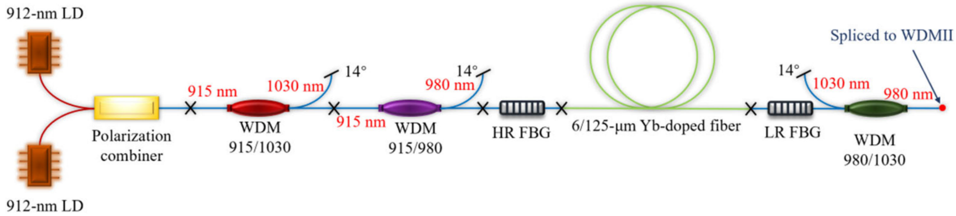


Figure 8. The experimental setup of the double-wavelength fiber oscillator.

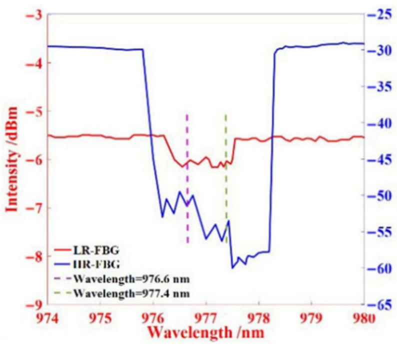


Figure 9. The transmission spectra of HR-FBG and LR-FBG.

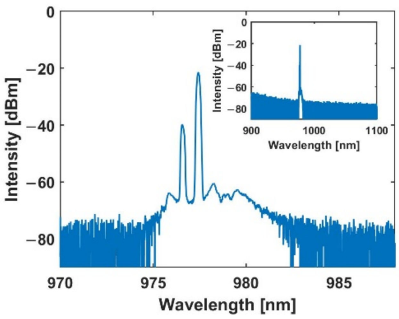
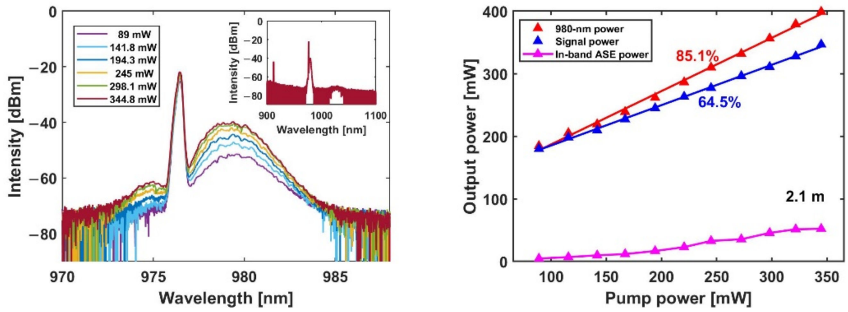


Figure 10. The output spectrum of the double-wavelength fiber oscillator with 160-mW output power.

In order to make a comparison, the fiber amplifier is firstly tested with the 160-mW 976.5-nm LD seed used in former sections. Here, 2.1-m active fiber is used in the amplifier. From Figure 11, it can be found that at the maximum pump power, the in-band ASE is about 17.9-dB peak-to-peak suppressed, and its output power can reach to 52.2 mW (approximately equal to 15.1% of signal power, estimated by spectral integration). It is also shown that the slope efficiency of the emission around 980 nm is about 85.1%, and the slope efficiency of the signal light is about 64.5%.

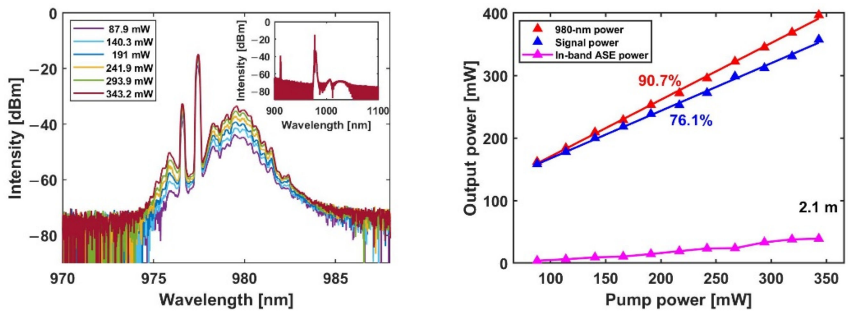
Then, the double-wavelength fiber oscillator is used instead of the 976.5-nm LD as the seed source, and the output power and spectrum of the fiber amplifier are given in Figure 12. From Figure 12, it can be found that at the maximum pump power, the peak-to-peak suppression of in-band ASE is about 18.6 dB, and the output power is lower than 39 mW (approximately equal to 11.0% signal power, estimated by spectral integration). Then, compared with the results related to the in-band ASE given in Figure 11 (17.9-dB suppression and 52.2-mW output power), it can be found that the in-band ASE is better suppressed by the double-wavelength seed light. Then, Figure 12b also shows that the slope efficiency of emission around 980 nm is elevated to 90.7%, which is closer to the theoretical limit (i.e., 92.2%). Such slope efficiency should be the largest one ever achieved by the emission around 980 nm in the Yb-doped fiber amplifier, to the best of our knowledge.

It is also revealed that the slope efficiency can be improved by suppressing the in-band ASE. In addition, the slope efficiency of signal light is also elevated to 76.1% because of the suppression of the in-band ASE (see Figure 12b).



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

Figure 11. (**a**) The variation of output spectrum with pump power; (**b**) the variations of output power with pump power by using the 976.5-nm LD seed source.



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

Figure 12. (**a**) The variation of output spectra with pump power. (**b**) The variation of output power with pump power by using the double-wavelength seed source.

4. Conclusions

In this paper, a core-pumped single-mode Yb-doped fiber amplifier operating near 980 nm is investigated in order to reveal the scalability of slope efficiency of a Yb-doped fiber amplifier operating near 980 nm. The numerical study is firstly carried out with the rate-equation model. It is predicted that as much as 92.2% slope efficiency can be obtained by optimizing the length of the active fiber. Then, the experimental study is carried out. By using the single-wavelength seed light provided by a 976.5-nm LD seed, about 85.3% slope efficiency is obtained by means of optimizing the active fiber length. However, the slope efficiency is still a little lower than the numerical prediction. One possible reason is the in-band ASE observed in experiment, which is much stronger than the numerical prediction.

In order to reveal the effect of in-band ASE on the slope efficiency, the double-wavelength, all-fiber oscillator is fabricated and used as the broadband seed source instead of the 976.5-nm LD. It is found that the in-band ASE in the fiber amplifier can be better suppressed with the double-wavelength seed light. As a result, about 90.7% slope efficiency is realized, which is closer to the theoretical limit (i.e., 92.2%). It should be the first demonstration of emission around 980 nm generated with more than 90% slope efficiency in an Yb-doped fiber amplifier, to the best of our knowledge. The slope efficiency of the signal light is also elevated to 76.1% with the double-wavelength seed light. Then, compared with the results obtained with the 976.5-nm signal light (85.1% and 64.5% slope efficiency of emission around 980 nm and signal light, respectively), it is revealed that the slope efficiency of a fiber amplifier operating near 980 nm can be improved by suppressing the in-band ASE. The results and conclusion can provide significant guidance for studying the

Yb-doped fiber lasers and amplifiers operating near 980 nm or other sorts of three-level fiber sources.

Author Contributions: Methodology, J.C. (Jianqiu Cao); validation, J.C. (Jianqiu Cao); formal analysis, Z.L. and S.Z.; investigation, Z.L., S.Z., A.L. and Z.H.; resources, J.C. (Jianqiu Cao); data curation, Z.L., S.Z. and A.L.; writing—original draft preparation, Z.L. and S.Z.; writing—review and editing, J.C. (Jianqiu Cao) and Z.H.; visualization, Z.L. and S.Z.; supervision, J.C. (Jianqiu Cao) and J.C. (Jinbao Chen); project administration, J.C. (Jianqiu Cao) and J.C. (Jinbao Chen); funding acquisition, J.C. (Jinbao Chen). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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

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