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Review

Review of High-Power Continuous Wave Yb-Doped Fiber Lasers near 980 nm

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Abstract: In this paper, the development of a high-power continuous wave (CW) fiber laser near 980 nm is reviewed. This review is focused primary on the power evolution resulting from the designation of Yb-doped fibers, which is important in the suppression of the amplified spontaneous emission (ASE) around 1030 nm. Current studies on the in-band ASE as the power limitation of the Yb-doped fiber lasers near 980 nm are also summarized in this review.

Keywords: fiber laser; fiber amplifier; Yb-doped fiber; fiber laser near 980 nm; amplified spontaneous emission

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1. Introduction

The fiber laser is one sort of laser where the gain is in the optical fiber waveguide. It was presented as a promising laser configuration soon after the first well-known demonstration of the laser by Maiman [1–3]. In fiber lasers, the light is mainly generated and amplified by the stimulated emission of active ions in the rear-earth-doped fibers. Fiber lasers have certain advantages, such as high power, a good beam quality, high efficiency, compactness, portage, a low maintenance cost, and so on. With recent rapid developments in the last two decades, fiber lasers play a more and more important role in various application fields such as the industrial, medicine, communication, sensing, and material processing applications. The rapid development of fiber lasers has been presented in a number of excellent reviews [4–9].

Increasing the wavelength diversity is one important motivation driving the development of fiber lasers, because it can expand the applications of fiber lasers. Nowadays, various rear-earth-doped fibers are presented and studied to increase the wave-length diversity, e.g., Er-doped [10,11], Yb-doped [12,13], Nd-doped [14,15], Tm-doped [16,17], and Ho-doped [18,19] fibers, which extend the wavelength from the infrared to the mid-infrared region. The Yb-doped fiber laser near 980 nm is just one prospective topic among the pertinent studies.

The Yb-doped fiber laser, operating near 980 nm, has attracted much attention because of its significant potential application in two fields. The first one is an application as the high-brightness tandem pumping source near 980 nm. The source near 980 nm is widely needed to pump various rear-earth-doped fibers such as the Yb-doped, Er-doped, and Er/Yb-doped fibers. Nowadays, such a pump source is mainly provided by the laser diode (LD) with the advantages of a high electric–optical efficiency and low cost. However, the low brightness limits the LD application in the high-power fiber lasers [20–23]. Therefore, the Yb-doped fiber lasers near 980 nm can provide a high-brightness solution as the pumping source, the brightness of which can be 1~2 orders higher than the LD. Moreover, the fiber laser near 980 nm can also provide high-power single-mode lasing, which can be very useful for pumping the ultra-fast solid-state and fiber lasers [24,25].

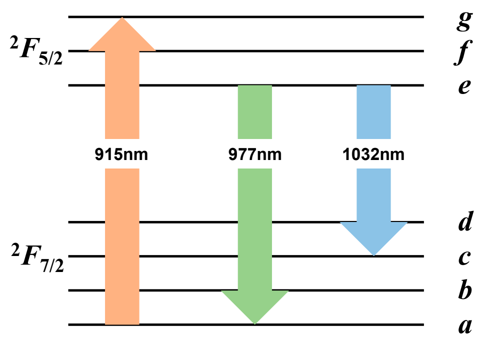
The second application of fiber lasers near 980 nm is to generate lasers at other wavelengths by non-linear frequency transferring, because the fiber lasers near 980 nm are promising candidates for the generation of a high-brightness laser with a high focused intensity, which is indispensable for the non-linear applications. For example, by frequency doubling, a blue-green light near 490 nm can be generated with the fiber laser near 980 nm [26–29], which can be applied in fields such as ocean exploration and underwater communication. Furthermore, with the fiber laser near 980 nm, a near-ultraviolet laser near 320 nm can also be produced by frequency tripling, which can be applied in fields such as materials, biology, medicine, spectroscopy, etc.

Fiber lasers near 980 nm can be divided into CW and pulsed lasers. In the early days, CW power was relatively low. In spite of that, some experimental demonstrations on its frequency doubling were conducted [28]. However, in recent years, with the development of fiber laser technology, the CW laser near 980 nm has experienced a rapid growth and a significant improvement in the power level, which can make a significant impact on the future applications of Yb-doped fiber lasers near 980 nm.

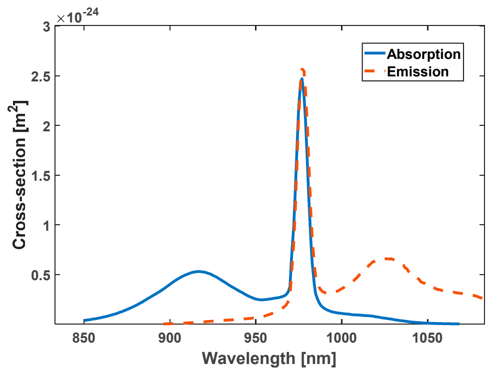
Therefore, this paper reviews the development of high-power CW Yb-doped fiber lasers near 980 nm. This paper is organized as follows. In Section 2, the challenge of high-power Yb-doped fiber lasers near 980 nm is analyzed. In Section 3, the development of high-power Yb-doped fiber lasers near 980 nm driven by the design of Yb-doped fibers is reviewed. Studies on the in-band ASE are also summarized. A summary and future prospects are set out in Section 4.

2. The Challenge of High-Power Yb-Doped Fiber Lasers near 980 nm

Nowadays, the 20 kW Yb-doped fiber laser has been demonstrated within the band around 1070 nm, but the achieved power of the Yb-doped fiber laser near 980 nm is much lower. The reason is that the power up-scaling of the fiber laser near 980 nm is very challenging. One obstacle is the unavoidable ASE around 1030 nm. Due to the energy level of the Yb-ions doped in silica fiber (see Figure 1a), light around 980 nm can be generated by the three-level transition of the Yb-ion, while the ASE around 1030 nm is generated by the four-level transition of the Yb-ion. As a result, because of the high population density on the ground level, a 50% population inversion is needed to amplify the light near 980 nm, while only a 5% population inversion is sufficient to amplify the ASE around 1030 nm. Thus, the pump threshold of the laser near 980 nm is much higher than that of the ASE around 1030 nm. It is implied that the ASE around 1030 nm can be generated more easily than the laser near 980 nm. Therefore, an ASE around 1030 nm is unavoidable in the Yb-doped fiber lasers near 980 nm, and the suppression of this is the issue that has to be solved.



(a)



(b)

Figure 1. (a) Energy-level diagram (a-g represent different states and a represents the ground state), and (b) typical absorption and emission cross-sections of Yb-ions.

However, the suppression of the ASE around 1030 nm is not easy because of not only its low pump threshold but also the strong absorption of Yb-ion near 980 nm. From Figure 1b, it can be found that the peak of the absorption cross-section of the Yb-ion is present near 980 nm. Then, if the population inversion cannot support the amplification of the light near 980 nm, the light near 980 nm will be rapidly absorbed by the Yb-ion. More severely, the absorbed light near 980 nm can also enhance the ASE around 1030 nm as the pump light (see Figure 1a). As a result, the light near 980 nm will be rapidly annihilated in the gain competition with the ASE around 1030 nm.

In order to suppress the ASE around 1030 nm, J. Nilsson et al. set out an important principle based on the theoretical claim that the core-to-cladding ratio of Yb-doped fibers should be large enough [30]. It was also argued that a high pump efficiency can be obtained only when an ASE around 1030 nm can be sufficiently suppressed. Furthermore, the requirement for a large core-to-cladding ratio makes the power up-scaling of the fiber laser near 980 nm very challenging, because the inner cladding cannot be too large, which limits the pump light coupling. In spite of that, this principle reveals the importance of the Yb-doped fiber design in the fiber laser near 980 nm. Therefore, the development of fiber lasers near 980 nm will be reviewed with the focus on an Yb-doped fiber designation.

3. Double-Cladding Yb-Doped Fiber Lasers near 980 nm

In the early stage, the Yb-doped fiber laser near 980 nm was generally fabricated with the single-cladding Yb-doped fiber, and the pump light was injected directly into the Yb-doped core. However, limited by the pump light coupling ability, the output power achieved by the single-cladding Yb-doped fiber is very low [31–34]. Although the Nd-doped fiber laser near 930 nm [33] and the Nd:YAG solid-state laser near 946 nm [32] were tried to increase the pump power, the achieved output power was also limited to the watt-level (about 2.1 W) [33]. Comparatively, the double-cladding Yb-doped fiber (DCYF) is more promising to achieve a high-power operation because more pump light can be coupled by the inner cladding designation. Thus, in this section, we will focus our review on the fiber lasers near 980 nm fabricated with DCYF.

Because of the requirement of a large core-to-cladding ratio for suppressing the ASE around 1030 nm, it is very hard to achieve the high-power, high-efficiency, and near diffraction-limited operations simultaneously by using the DCYF. Currently, the pertinent studies can be divided into two separate directions. The first one aims to produce high-power diffraction-limited lasing near 980 nm sacrificing pump efficiency, and the second one aims to achieve high-power, high-efficiency lasing near 980 nm sacrificing beam quality. The former one is studied for use in applications that need the pumping source of ultrafast solid-state and fiber lasers or for non-linear frequency transferring. The latter one is studied for applications that use the tandem pumping source for rare-earth-doped fiber lasers with the lower requirement of beam quality.

3.1. Power Up-Scaling with Optimization of Beam Quality

Limited by the small core diameter for the diffraction-limited beam quality, the inner cladding of the DCYF is firstly reduced to enlarge the core-to-cladding ratio for suppressing the ASE around 1030 nm. In 2001, L.A. Zenteno et al. reported a DCYF laser operating at 978 nm by utilizing the self-designed fiber with an elliptical inner cladding. The maximum output power of this laser was 1 W with a slope efficiency of 48% [35]. The beam quality was measured as well, and the M^2 factor was about 1.2. As shown in Figure 2a, the core diameter of this double-cladding Yb-doped fiber was 11 μm, and the inner cladding cross-section was elliptical with major and minor axis dimensions of 32×16 μm^2 [35]. In the same year, A.S. Kurkov et al. reported a single-mode fiber laser operating at 978 nm fabricated by DCYFs with the inner cladding diameters ranging from 25 to 50 μm and the core diameters ranging from 6 to 9 μm [36]. The maximum output power of 1.2 W was obtained with a slope efficiency of 60% [36].

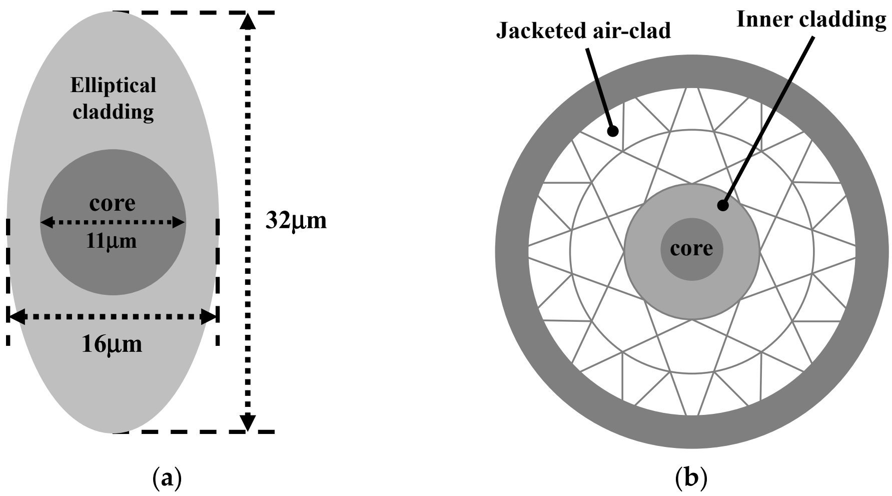


Figure 2. Schematic cross-sections of the elliptical inner cladding fiber (**a**) and JAC fiber (**b**).

Although the smaller inner cladding can be helpful for suppressing the ASE around 1030 nm, it limits the pump light coupling which does harm to the power up-scaling. Therefore, R. Selva et al. improved the DCYF by introducing the jacketed air-clad (JAC) fiber to enlarge the numerical aperture (NA) of the inner cladding to improve the pump light coupling [37]. The JAC was realized by a thin glass mesh with a wall thickness comparable to the wavelength (see Figure 2b). Then, the inner cladding NA can be enlarged to 0.7 [37]. Moreover, the Yb-ions were ring-doped in the active core to improve the suppression of the ASE around 1030 nm [30]. As a result, by using a 20 μm diameter inner cladding, the output power can be increased to around 4 W with an 11 W-launched 915 nm pump power [38]. In spite of that, the small inner cladding was still an obstacle for further up-scaling of the output power. Therefore, the issue of enlarging the inner cladding became more attractive.

Nevertheless, a larger inner cladding requires a larger core to ensure a core-to-cladding ratio that suppresses the ASE around 1030 nm. Thus, achieving a good beam quality with the large core became the key difficulty in the pertinent studies. In 2014, M. Leich et al. presented a long-tapered Yb-doped fiber with the inner cladding diameter from 1 mm to about 125 μm and the core diameter from 126 μm to about 15 μm [39]. The small end was spliced with a fiber Bragg grating (FBG) written in a passive single-mode fiber to form a resonator for single-mode operation. The pump light was launched directly into the core at the large end (see Figure 3). With such a designation, single-mode lasing at 976 nm was achieved with a maximum output power of 10 W and a slope efficiency of 31% [39].

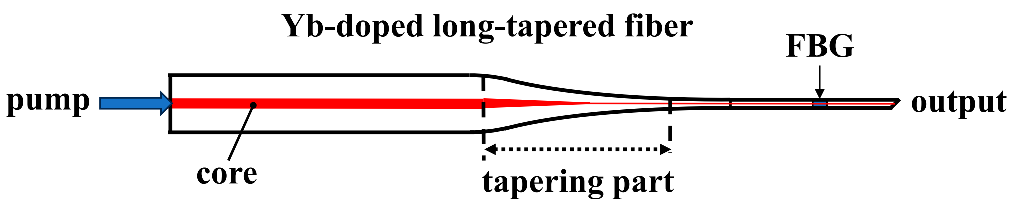


Figure 3. Schematic experimental setup of the long-tapered fiber laser in Ref. [33].

The tapered idea for controlling the beam quality was also used in the saddle-shaped fiber laser proposed by S. Aleshkina et al. [40]. The saddle-shaped fiber was obtained by tapering a DCYF with a core/cladding diameter of 20/80 μm. The inner cladding was tapered to around 49 μm with core diameters of about 12 μm for the single-mode operation. In this designation, the taper was not only used for the single-mode operation but also used to improve the pump light coupling, because the pump light was injected into the end with a larger inner cladding (see Figure 4). By using the saddle-shaped Yb-doped fiber, the maximum output power of 10.6 W with a slope efficiency of 18.4% was obtained from the monolithic Yb-doped fiber laser at 976 nm [40]. A similar taper design was also used in some later studies to improve the pump light coupling into the DCYF with a small inner cladding. In Ref. [41], the inner cladding of a HI1060 commercial fiber was tapered down to 45 µm for the light pump coupling into the DCYF with a square inner cladding of 40 µm and a core diameter of 14 µm (see Figure 5). The maximum output power of 13 W was achieved with a slope efficiency of 31% [41]. In Ref. [42], the inner cladding of a 20/125 µm commercially available DCYF was etched to around 40 µm by hydrogen fluoride (HF), and a taper structure was also used for coupling the pump light (see Figure 6). The 10.3 W output power was achieved with a slope efficiency of 25.4% [42]. In summary, by using the tapered DCYF, a 10 W-level output power can be achieved with a slope efficiency of about 20%~30%. The main limitation is the small inner cladding that limits the pump power. Moreover, the efficiency is also poor, because of the loss induced by the taper structure.

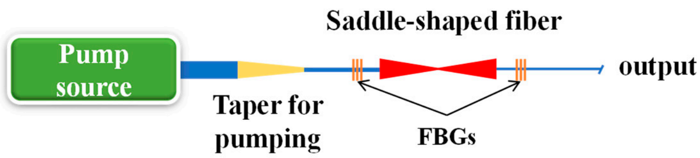


Figure 4. Schematic experimental setup of saddle-shaped Yb-doped fiber laser near 980 nm.

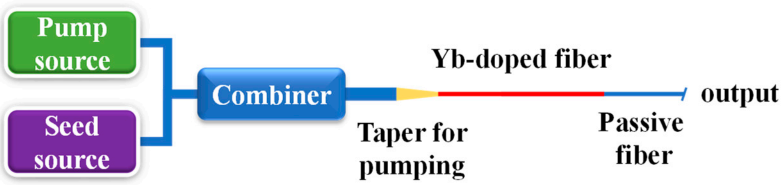


Figure 5. Schematic experimental setup of Yb-doped fiber amplifier in Ref. [35].

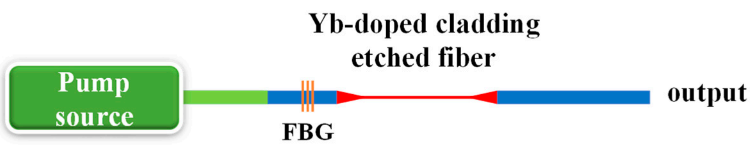


Figure 6. Schematic experimental setup of Yb-doped fiber laser in Ref. [36].

Some studies enlarged the core diameter instead of reducing the inner cladding. In 2016, a DCYF with a 28 µm core was used to generate the lasing near 980 nm [43]. The inner cladding of this DCYF was square-shaped with a side-to-side distance of 80 µm. In order to achieve the single-mode operation, a low NA (~0.038) was used, and a Wprofile design was also introduced to resist the bend loss (see Figure 7a). With the DCYF, a 5.5 W fiber laser near 980 nm was demonstrated with a slope efficiency of 25% [43]. In 2020, a DCYF with a 35 µm core and 125 µm inner cladding was presented [44]. In this fiber, the core NA was about 0.07, and the confined Yb-doped core was used for the single-mode operation (the diameter of the Yb-doped region was about 20 µm, see Figure 7b). With this fiber, a 39 W narrow-band fiber laser near 980 nm was demonstrated with a slope efficiency of 19% [44].

Later, some studies were carried out to investigate the performance of the 20/125 µm DCYF in the fiber lasers near 980 nm. In 2021, M. Chen et al. reported an all-fiber oscillator operating at 978 nm with 15 W of output power and a 13% slope efficiency [45]. The beam quality was measured, and the M^2 factor was about 2 with a core NA of about 0.08. After that, by improving the suppression of optical feedback and the ability of the cladding light stripper (CLS), the output power was further increased to 50.8 W with a slope efficiency of 15.6%, while the beam quality was worsened to 2.5 M^2 factor, because of the higher gain of the higher-order transverse modes (HOMs) [46]. In 2022, a 100 W-level fiber laser near 980 nm was demonstrated with the same fiber by using the master oscillator power amplifier (MOPA) configuration [47]. The maximum output power of the laser was 109 W, with a slope efficiency of 13% corresponding to the total pump power. The M^2 factor was about 1.9 at the maximum output power [47]. The above studies imply that the single-mode 100 W-level fiber laser near 980 nm should be possible by optimizing the design of the DCYF. The study findings of DCYF lasers near 980 nm with optimization of beam quality are presented in Table 1.

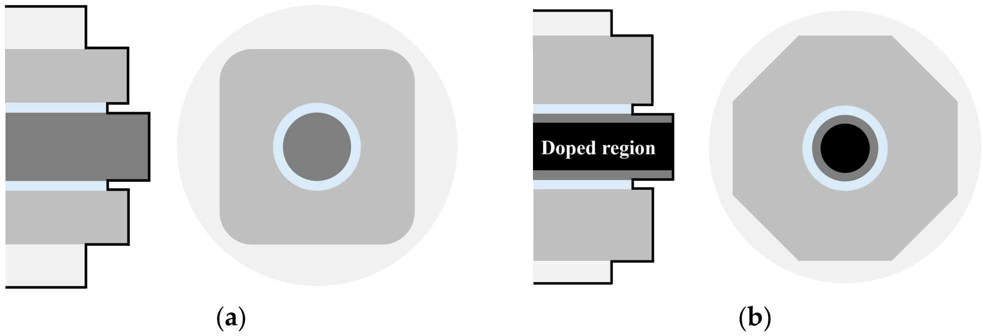


Figure 7. Schematic refractive index profiles and cross-sections of the W-profile Yb-doped fiber in Ref. [43] (**a**), and the confined Yb-doped fiber in Ref. [44] (**b**).

Table 1. DCYF lasers near 980 nm with optimization of beam quality.

Fiber Types	Details	Output Power (W)	Slope Efficiency *	Beam Quality	Year
Reduced inner cladding	11 μm core and 32 × 16 μm^2 elliptical cladding [35].	1	48%	$M^2 < 1.2$	2001
	6~9 μm core and 25~50 μm inner cladding [36].	1.2	60%	Not mentioned	2001
	Jacketed air-clad around 20 μm cladding [38].	4.3	About 40%	$M^2 \approx 1.14$	2004
Tapered fiber	Long-tapered Yb-doped fiber [39].	10.4	31%	Single mode	2014
	Saddle-shaped Yb-doped fiber [40].	10.6	18.4%	$M^2 \approx 1.16$	2018
	Tapered passive fiber for coupling into active fiber [41].	13	31%	$M^2 \approx 1.1$	2020
	Cladding-etched Yb-doped fiber [42].	10.3	25.4%	Not mentioned	2023
W-profile fiber	28/80 × 80 μm Yb-doped fiber with 0.038 core NA [43].	5.5	25%	Single mode	2016
	35/125 μm Yb-doped fiber with 20 μm doped region [44].	39	19%	Not mentioned	2020
Commercially available fiber	20/125 μm all-fiber oscillator [45].	15	13%	$M^2 \approx 2$	2021
	20/125 μm all-fiber oscillator [46].	50.8	15.6%	$M^2 \approx 2.5$	2021
	20/125 μm MOPA configuration [47].	109	13%	$M^2 \approx 1.9$	2022

* Slope efficiency relative to launched pump power.

3.2. High-Power, High-Efficiency Fiber Lasers near 980 nm with Large-Core DCYF

A high-power fiber laser near 980 nm with a high efficiency is also an attractive topic for the applications that have low requirements for the beam quality. In the pertinent study, the large-core DCYF is generally used in order to enlarge the core-to-cladding ratio for the suppression of the ASE around 1030 nm, which is of great importance to elevate the pump efficiency. Simultaneously, the large-enough inner cladding can also be used for the pump light coupling. Such large-core DCYFs are generally used in the amplifier of the MOPA fiber laser to amplify the power of the signal light near 980 nm.

In 2017, a fiber amplifier operating near 980 nm was demonstrated with a 95/125 µm core/cladding diameter Yb-doped fiber. With the 5.5 W seed power, a 34 W output power was achieved, and the slope efficiency was about 66% [48]. In 2021, the performance of a DCYF with 300/400 µm core/cladding diameter was also investigated in a fiber laser near 980 nm. With the large-core DCYF, a 38 W fiber oscillator and 77 W fiber amplifier near 980 nm were demonstrated [49]. The slope efficiencies were 84% and 75% with respect to the absorbed pump power, respectively.

In 2021, some other attractive studies on the large-core Yb-doped fiber amplifier near 980 nm were also reported. In Ref. [50], a 100 W-level fiber amplifier near 980 nm was demonstrated with a DCYF that had a 60/125 µm core/cladding diameter. About 110 W of output power was achieved with a 10 W-level seed power, and the slope efficiency was about 35% with respect to the launched pump power [50].

In order to further up-scale the output power, the inner cladding diameter was enlarged to 250 µm, and, correspondingly, the core diameter was enlarged to 105 µm to suppress the ASE around 1030 nm. With the help of this fiber, the output power of the fiber amplifier near 980 nm was rapidly developed. In Ref. [51], the first 500 W-level fiber amplifier near 980 nm was demonstrated, and the slope efficiency was more than 50%. Although a strong in-band ASE was observed in the spectrum, the potential power scalability of this fiber was revealed. Later, the first kW-level fiber amplifier near 980 nm was demonstrated with this large-core DCYF in Ref. [52]. About 1.11 kW of output power was achieved with a 11 W seed light at 978 nm, and the slope efficiency was about 65.3%. The study findings of high-power, high-efficiency fiber lasers near 980 nm with a large-core DCYF are presented in Table 2.

Table 2. High-power, high-efficiency fiber lasers near 980 nm with a large-core DCYF.

Core/Cladding Diameter of Yb-Doped Fiber	Output Power (W)	Slope Efficiency	Beam Quality	Year
95/125 µm [48]	34	66%	Not mentioned	2017
300/400 µm [49]	38 [1] 77 [2]	84% [1,3] 75% [2,3]	$M^2 \approx 41$ [2]	2021
60/125 µm [50]	110	35%	Not mentioned	2021
105/250 µm [51]	556	50.5%	$M^2 \approx 23.6$	2021
105/250 µm [52]	1110	65.3%	$M^2 \approx 16.2$	2021

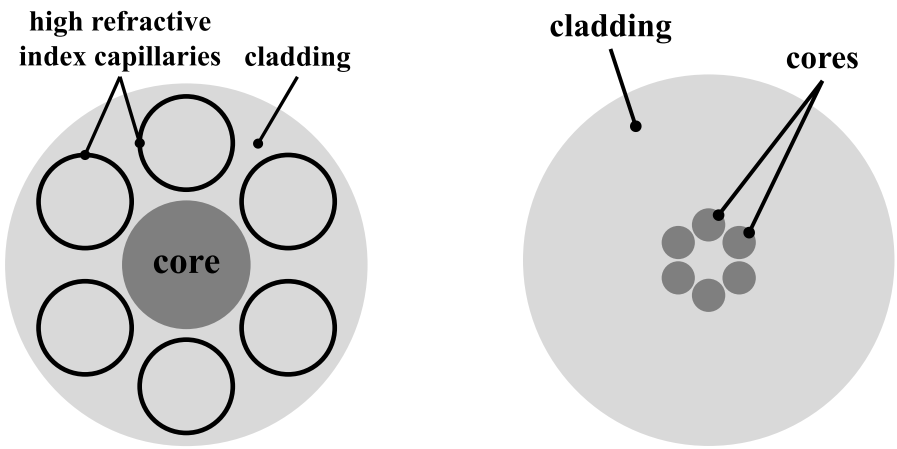
[1] For fiber oscillator. [2] For fiber amplifier. [3] Relative to absorbed pump power.

3.3. Micro-Structured Yb-Doped Fiber Lasers near 980 nm

Prior to the DCYF, the micro-structured Yb-doped fiber provided better optical characteristics by optimizing its micro-structure. Different from the DCYF, where the optical field is confined by the total reflection on the boundary between the core and inner cladding, the micro-structured fibers confine the optical field with the periodically (generally) arranged micro-elements surrounding the core. Nowadays, some micro-structured fibers have been designed and tested to achieve high-power, high-efficiency Yb-doped fiber lasers near 980 nm with a diffraction-limited beam quality.

In 2008, a rod-type Yb-doped photonic crystal fiber (PCF) was presented to generate lasing near 980 nm [53,54]. In this PCF, a core with a diameter as large as 80 µm was designed with an inner cladding of 200 µm diameter, in order to enlarge the core-to-cladding ratio to suppress the ASE around 1030 nm. The periodically arranged micro-air-holes was designed for the diffraction-limited beam quality [55]. A circle of air-holes was also used to define the inner cladding with a high NA. With this PCF, the first hundred Watt-level fiber laser near 980 nm was demonstrated with a diffraction-limited beam quality. An output power of 94 W was achieved with an M^2 factor of 1.2 [53]. The slope efficiency was about 50%. By recycling the residual pump light, the slope efficiency can be enlarged to more than 60%.

In 2022, an all-solid Yb-doped anti-resonant fiber (YbARF) was also designed in order to enlarge the fundamental mode diameter (and thus enlarge the equivalent core-to-cladding ratio) to suppress the ASE around 1030 nm (see Figure 8a), and its performance for lasing near 980 nm was numerically studied. It was predicted that the near diffraction-limited lasing at 976 nm with a slope efficiency of 85% could be achieved with the fundamental mode diameter enlarged to 68 μm [56].



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

Figure 8. Schematic cross-sections of the YbARF [56] (**a**), and the Yb-doped 6-core fiber [57] (**b**).

The Yb-doped multi-core fiber was also studied. The super-mode supported by the multi-core can also enlarge the mode area to suppress the ASE around 1030 nm. In 2021, a fiber laser operating around 980 nm was demonstrated with the Yb-doped 6-core fiber (see Figure 8b). With the mode area enlarged to 1432 μm^2, an output power of 25 W was achieved with a slope efficiency of 46% [57].

Different to enlarging the mode diameter, another sort of micro-structed fiber was tried in the Yb-doped fiber laser near 980 nm, i.e., the Yb-doped solid-core photonic bandgap fiber (PBGF). In this fiber, the optical field is confined by the photonic bandgap effect that is induced by the scattering of periodically arranged high-refraction index micro-columns surrounding the core [58]. The feature of the PBGF is that its loss of transmission band can be controlled by designing the micro-structure. Then, by increasing the loss of the band around 1030 nm while keeping the low loss of the band near 980 nm, the ASE around 1030 nm can be filtered with a well-transmitted or amplified signal light, which is very helpful for suppressing the ASE around 1030 nm in fiber lasers near 980 nm. As a result, the ASE around 1030 nm can be sufficiently suppressed with a smaller core diameter that can bring convenience for the control of the beam quality.

Thus, an Yb-doped solid-core PBGF was presented and tested in a laser oscillating near 980 nm. With this fiber, a slope efficiency of 65% was achieved, but the output power was only 130 mW [59]. The low output power was mainly caused by the core pumping scheme used in the oscillator, because the high-refraction index micro-columns bring difficulty in designing the inner cladding for the pump light coupling.

This issue of the inner cladding was solved later, which resulted in the presence of a double-cladding (DC) PBGF [60]. The DC design can dramatically improve the pump light coupling of PBGF, and thus it is very helpful for the power up-scaling of fiber lasers near 980 nm. In 2019, a 150 W-level diffraction-limited fiber laser near 980 nm was demonstrated with the DC-PBGF [61]. An output power of 151 W was achieved with an M^2 factor of 1.25, which still keeps the power record of the diffraction-limited fiber laser near 980 nm to date. The ASE around 1030 nm was well-suppressed with a core diameter of about 25 μm. The slope efficiency was about 63% with respect to the launched pump power [61]. The study findings of micro-structured Yb-doped fiber lasers near 980 nm are presented in Table 3.

Table 3. Micro-structured Yb-doped fiber lasers near 980 nm.

Yb-Doped Fiber Types	Output Power (W)	Slope Efficiency	Beam Quality	Year
Rod-type PCF [53]	94	50%	$M^2 \approx 1.2$	2008
Single-cladding solid-core PBGF [59]	0.13	65%	Not mentioned	2008
DC solid-core PBGF [61]	151	63%	$M^2 \approx 1.25$	2019
Six-core fiber [57]	25	46% [1]	Not mentioned	2021
All-solid YbARF [56]	Not mentioned	85% [2]	Not mentioned	2022

[1] Residual pump light is re-used. [2] Simulation results only.

3.4. Issue of in-Band ASE near 980 nm

Different from the ASE around 1030 nm, the in-band ASE near 980 nm is located in the same band of signal light, and thus named the "in-band" ASE. Similar to the signal light near 980 nm, the in-band ASE is also generated by the three-level transition of the Yb-ions. The strong in-band ASE is a unique phenomenon in the Yb-doped fiber near 980 nm. In fact, the in-band ASE is not a newly discovered phenomenon in the Yb-doped fiber lasers near 980 nm. As early as 2004, the in-band ASE near 980 nm had been shown in the experimental spectra reported in Ref. [38]. Moreover, in the experimental spectra reported in subsequent studies [39,43,62], the presence of an in-band ASE can also be observed. However, because the in-band ASE observed in these experiments was so weak, almost no attention was paid to it, and the in-band ASE was not mentioned in this literature either.

In 2015, Y. Yu et al. observed a strong in-band ASE (with a central wavelength of approximately 985 nm) in the experimental study of Yb-doped fiber amplifiers near 980 nm and stated that the in-band ASE near 980 nm needed to be considered in future studies on the Yb-doped fiber amplifiers near 980 nm [63]. In 2016, Y. Wang et al. conducted an experimental study on Yb-doped fiber amplifiers near 980 nm and found that the thresholds of the in-band ASE near 980 were related to the signal wavelength [64]. However, no further study was carried out, because the observed in-band ASE was still so weak that the ASE around 1030 nm was still considered as the key issue of the Yb-doped fiber lasers near 980 nm.

However, with the power up-scaling of the Yb-doped fiber lasers near 980 nm, the in-band ASE became increasingly attractive. In 2018, T. Matniyaz et al. conducted an experimental study on an Yb-doped all-solid PBGF oscillator near 980 nm [65]. By observing the spectrum at the output power of 84 W, it was found that the oscillator could generate oscillation peaks over a wide spectral range (from 975 nm to 980 nm). The team believed that it was the in-band ASE near 980 nm that caused the broad spectrum and that the in-band ASE was caused by the inhomogeneous broadening of the gain spectral lines in the Yb-doped fibers. The team also pointed out that such a gain characteristic of the Yb-doped fibers should become a challenge to achieve a narrow bandwidth and a high-power laser output, whether for oscillators or amplifiers [65].

Later, the serious effect of the in-band ASE was revealed in 2021 by studying a 500 W-level Yb-doped fiber amplifier near 980 nm [51]. It was found that with an increase in the increments of the pump power, the in-band ASE near 980 nm was strengthened rapidly, which resulted in the parasitic laser oscillation being much stronger than the signal light. It was first demonstrated, to the best of our knowledge, that the in-band ASE can be dominant in the gain competition with the signal light and thus can limit the power up-scalability of the Yb-doped fiber amplifier near 980 nm.

Following that, some studies were carried out to study the in-band ASE in an Yb-doped fiber amplifier near 980 nm. By suppressing the in-band ASE with enlarged seed power, the first kilowatt Yb-doped fiber amplifier was demonstrated, which showed once more the importance of the in-band ASE suppression in high-power Yb-doped fiber amplifiers near 980 nm [52]. In 2022, the characteristics of the in-band ASE in the low-power core-pumping single-mode Yb-doped fiber amplifier were preliminary studied experimentally, and a slope efficiency close to the theoretical limit was achieved by suppressing the in-band ASE [66,67]. The comparison between the in-band and 1030 nm ASEs was also discussed in brief in Ref. [66]. However, the pertinent study is still in the infancy stage, and the origin of a strong in-band ASE is still unclear. Many more studies on the in-band ASE are still needed because of the important role of in-band ASE suppression in the high-power Yb-doped fiber lasers and amplifiers near 980 nm.

4. Summary and Future Prospects

In this paper, the development of high-power CW Yb-doped fiber lasers near 980 nm is reviewed. The first obstacle to the power scalability of the Yb-doped fiber lasers near 980 nm is an ASE around 1030 nm that strongly limits the pump efficiency. The suppression of the ASE around 1030 nm requires a large core-to-cladding ratio of the DCYF which makes a high-power, high-efficiency operation with a good beam quality very challenging. Currently, the output power is limited to a level of tens-of-Watts with an M^2 factor smaller than 1.5. This can be limited to 100 W with an M^2 factor of about 2 by optimizing the DCYF [47]. The pertinent slope efficiency generally ranges from 10% to 30% with respect to the launched pump power. How to improve the slope efficiency with diffraction-limited beam quality by using the DCYF is an interesting but very challenging topic. For the applications that have no strict requirements for the beam quality, the large-core DCYF is a solution to improve the slope efficiency but sacrificing the beam quality. To date, the large-core DCYF has greatly up-scaled the output power to the kilowatt level with a slope efficiency larger than 60% [52]. How to achieve the theoretical limit of the slope efficiency by using the large-core fiber is also an attractive topic that needs to be studied in the future.

Compared with the DCYF, the micro-structured Yb-doped fibers have more potential to improve the performance of the fiber lasers near 980 nm, because of their advantages in optical transmission characteristics. The first advantage is enlarging the fundamental mode area (or, equivalently, the core-to-cladding ratio) with single-mode operation. Currently, with the rod-type PCF of an 80 μm core diameter, an output power of 94 W was achieved with an M^2 factor of 1.2 and slope efficiency close to 50% [53]. The second one is controlling the passbands and lossbands of the optical transmission to suppress the ASE around 1030 nm. By using the all-solid Yb-doped PBGF with a core diameter of about 25 μm, a record 151 W output power was achieved with an M^2 factor of 1.25 and slope efficiency larger than 60% [61]. However, although the micro-structured fibers provide better solutions for the fiber lasers near 980 nm, their shortcoming is the difficulty of fabrication, which limits the cost control and popularization of the pertinent studies. Moreover, studies on fiber components that match the micro-structured fibers are also needed to achieve the compactable and portable all-fiberization of the micro-structured fiber lasers near 980 nm.

With the power up-scaling of the fiber lasers near 980 nm, the in-band ASE becomes another obstacle because it can be very strong with a high pump power. Although some preliminary studies have been conducted, our understanding of the in-band ASE is still very limited. There are two topics that urgently need to be studied, i.e., the origin and the suppression of the in-band ASE, which can be of great importance for the further development of high-power fiber lasers near 980 nm. In summary, the high-power fiber laser near 980 nm is a field full of vitality where new exciting results can be expected in the near future.

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References

1. Maiman, T.H. Stimulated Optical Radiation in Ruby. *Nature* **1960**, *187*, 493–494. [CrossRef]
2. Snitzer, E. Proposed Fiber Cavities for Optical Masers. *J. Appl. Phys.* **1961**, *32*, 36–39. [CrossRef]
3. Koester, C.J.; Snitzer, E. Amplification in a Fiber Laser. *Appl. Opt.* **1964**, *3*, 1182–1186. [CrossRef]
4. Kurkov, A.S. Oscillation spectral range of Yb-doped fiber lasers. *Laser Phys. Lett.* **2007**, *4*, 93–102. [CrossRef]
5. Richardson, D.J.; Nilsson, J.; Clarkson, W.A. High power fiber lasers: Current status and future perspectives. *J. Opt. Soc. Am. B-Opt. Phys.* **2010**, *27*, B63–B92. [CrossRef]
6. Tünnermann, A.; Schreiber, T.; Limpert, J. Fiber lasers and amplifiers: An ultrafast performance evolution. *Appl. Opt.* **2010**, *49*, F71–F78. [CrossRef] [PubMed]
7. Nilsson, J.; Payne, D.N. High-Power Fiber Lasers. *Science* **2011**, *332*, 921–922. [CrossRef]
8. Jauregui, C.; Limpert, J.; Tuennermann, A. High-power fibre lasers. *Nat. Photon.* **2013**, *7*, 861–867. [CrossRef]
9. Zervas, M.N.; Codemard, C.A. High Power Fiber Lasers: A Review. *IEEE J. Sel. Top. Quantum Electron.* **2014**, *20*, 219–241. [CrossRef]
10. Mears, R.J.; Reekie, L.; Poole, S.B.; Payne, D.N. Low-threshold tunable CW and Q-switched fibre laser operating at 1.55 µm. *Electron. Lett.* **1986**, *22*, 159–160. [CrossRef]
11. Bing, F.; Xuefang, Z.; Zengyang, L.; Yu, Z.; Tianshu, W. Experimental research on an L-band multi-wavelength erbium-doped fiber laser based on a cascaded Sagnac loop and M–Z filters. *Laser Phys.* **2019**, *29*, 065102. [CrossRef]
12. Hanna, D.C.; Percival, R.M.; Perry, I.R.; Smart, R.G.; Suni, P.J.; Tropper, A.C. An ytterbium-doped monomode fibre laser: Broadly tunable operation from 1.010 µm to 1.162 µm and three-level operation at 974 nm. *J. Mod. Opt.* **1990**, *37*, 517–525. [CrossRef]
13. 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*, 075106. [CrossRef]
14. Mears, R.J.; Reekie, L.; Poole, S.B.; Payne, D.N. Neodymium-doped silica single-mode fibre lasers. *Electron. Lett.* **1985**, *21*, 738–740. [CrossRef]
15. Florentin, R.; Corre, K.L.; Robin, T.; Barnini, A.; Prakash, R.; Santarelli, G.; Gilles, H.; Girard, S.; Laroche, M. Optimization of Nd-Doped LMA Fibers for High-Power Laser Emission Near 915 nm. *IEEE Photon. J.* **2024**, *16*, 1500706. [CrossRef]
16. Sincore, A.; Bradford, J.D.; Cook, J.; Shah, L.; Richardson, M.C. High Average Power Thulium-Doped Silica Fiber Lasers: Review of Systems and Concepts. *IEEE J. Sel. Top. Quantum Electron.* **2018**, *24*, 0901808. [CrossRef]
17. Zhong, C.; Zou, J.; Wang, H.; Chen, T.; Ruan, Q.; Lan, L.; Dong, Z.; Luo, Z. 816 nm All-Fiber Mode-Locked Tm-Doped Laser in Noise-Like Pulse Regime. *IEEE Photon. Technol. Lett.* **2024**, *36*, 195–198. [CrossRef]
18. Hemming, A.; Simakov, N.; Haub, J.; Carter, A. A review of recent progress in holmium-doped silica fibre sources. *Opt. Fiber Technol.* **2014**, *20*, 621–630. [CrossRef]
19. Hu, P.; Mao, J.; Zhou, X.; Feng, T.; Nie, H.; Zhang, B.; Li, T.; He, J.; Yang, K. 603 MHz harmonic mode-locked femtosecond Ho-doped fiber laser. *J. Light. Technol.* **2024**, 1–7. [CrossRef]
20. Dawson, J.W.; Messerly, M.J.; Beach, R.J.; Shverdin, M.Y.; Stappaerts, E.A.; Sridharan, A.K.; Pax, P.H.; Heebner, J.E.; Siders, C.W.; Barty, C.P.J. Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power. *Opt. Express* **2008**, *16*, 13240–13266. [CrossRef]
21. Cao, J.; Guo, S.; Xu, X.; Chen, J.; Lu, Q. Investigation on Power Scalability of Diffraction-Limited Yb-Doped Fiber Lasers. *IEEE J. Sel. Top. Quantum Electron.* **2014**, *20*, 373–383. [CrossRef]
22. Dong, L.; Ballato, J.; Kolis, J. Power scaling limits of diffraction-limited fiber amplifiers considering transverse mode instability. *Opt. Express* **2023**, *31*, 6690–6703. [CrossRef] [PubMed]
23. Cao, J.; Chen, M.; Huang, Z.; Wang, Z.; Chen, J. Requirements on double-cladding Yb-doped fiber for power scaling of diffraction-limited fiber amplifiers. *Opt. Express* **2024**, *32*, 12892–12910. [CrossRef] [PubMed]
24. Machinet, G.; Andriukaitis, G.; Sévillano, P.; Lhermite, J.; Descamps, D.; Pugžlys, A.; Baltuška, A.; Cormier, E. High-gain amplification in Yb:CaF2 crystals pumped by a high-brightness Yb-doped 976 nm fiber laser. *Appl. Phys. B* **2013**, *111*, 495–500. [CrossRef]
25. Sévillano, P.; Georges, P.; Druon, F.; Descamps, D.; Cormier, E. 32-fs Kerr-lens mode-locked Yb:CaGdAlO4 oscillator optically pumped by a bright fiber laser. *Opt. Lett.* **2014**, *39*, 6001–6004. [CrossRef] [PubMed]
26. Soh, D.B.S.; Codemard, C.; Wang, S.; Nilsson, J.; Sahu, J.K.; Laurell, F.; Philippov, V.; Jeong, Y.; Alegria, C.; Baek, S. A 980-nm YB-doped fiber MOPA source and its frequency doubling. *IEEE Photon. Technol. Lett.* **2005**, *16*, 1032–1034. [CrossRef]
27. Zou, S.; Li, P.; Wang, L.; Chen, M.; Li, G. 980 nm Yb-doped single-mode fiber laser and its frequency-doubling with BIBO. *Appl. Phys. B* **2009**, *95*, 685–690. [CrossRef]
28. Laroche, M.; Bartolacci, C.; Cadier, B.; Gilles, H.; Girard, S.; Lablonde, L.; Robin, T. Generation of 520 mW pulsed blue light by frequency doubling of an all-fiberized 978 nm Yb-doped fiber laser source. *Opt. Lett.* **2011**, *36*, 3909–3911. [CrossRef] [PubMed]

29. Li, P.; Zhong, G.; Liu, Z.; Chi, J.; Zhang, X.; Yang, C.; Zhao, Z.; Li, Y.; Wang, X.; Zhao, H.; et al. 980 nm Yb-doped double-clad photonic crystal fiber amplifier and its frequency doubling. *Opt. Laser Technol.* **2012**, *44*, 2202–2205. [CrossRef]
30. Nilsson, J.; Minelly, J.D.; Paschotta, R.; Tropper, A.C.; Hanna, D.C. Ring-doped cladding-pumped single-mode three-level fiber laser. *Opt. Lett.* **1998**, *23*, 355–357. [CrossRef]
31. Hanna, D.C.; Percival, R.M.; Perry, I.R.; Smart, R.G.; Suni, P.J.; Tropper, A.C. Continuous-Wave Tunable and Superfluorescent Operation of a Monomode Ytterbium-Doped Fiber Laser. In Proceedings of the Advanced Solid State Lasers, Cape Cod, MA, USA, 1 May 1989.
32. Zenteno, L.A.; Minelly, J.D.; Dejneka, M.; Crigler, S. 0.65 W single-mode Yb-fiber laser at 980 nm pumped by 1.1 W Nd:YAG. In Proceedings of the Advanced Solid State Lasers 2000, Davos, Switzerland, 13 February 2000.
33. Bartolacci, C.; Laroche, M.; Gilles, H.; Girard, S.; Robin, T.; Cadier, B. All-fiber Yb-doped CW and pulsed laser sources operating near 980 nm. In Proceedings of the Advances in Optical Materials, Istanbul, Turkey, 13 February 2011.
34. Bouchier, A.; Lucas-Leclin, G.; Georges, P. Frequency doubling of an efficient continuous wave single-mode Yb-doped fiber laser at 978 nm in a periodically-poled MgO:$LiNbO_3$ waveguide. *Opt. Express* **2005**, *13*, 6974–6979. [CrossRef] [PubMed]
35. Zenteno, L.A.; Minelly, J.D.; Liu, A.; Ellison, A.J.G.; Crigler, S.G.; Walton, D.T.; Kuksenkov, D.V.; Dejneka, M.J. 1 W single-transverse-mode Yb-doped double-clad fibre laser at 978 nm. *Electron. Lett.* **2001**, *37*, 819–820. [CrossRef]
36. Kurkov, A.S.; Medvedkov, O.I.; Paramonov, V.M.; Vasiliev, S.A.; Dianov, E.M.; Solodovnikov, V.; Zhilin, V.; Guryanov, A.N.; Laptev, A.Y.; Umnikov, A.A. High-power Yb-doped double-clad fiber lasers for a range of 0.98–1.04 µm. In Proceedings of the Optical Amplifiers and Their Applications, Stresa Italy, 1 July 2001.
37. Selvas, R.; Sahu, J.K.; Fu, L.B.; Jang, J.N.; Nilsson, J.; Grudinin, A.B.; Ylä-Jarkko, K.H.; Alam, S.A.; Turner, P.W.; Moore, J. High-power, low-noise, Yb-doped, cladding-pumped, three-level fiber sources at 980 nm. *Opt. Lett.* **2003**, *28*, 1093–1095. [CrossRef] [PubMed]
38. Soh, D.B.S.; Codemard, C.; Sahu, J.K.; Nilsson, J.; Philippov, V.; Alegria, C.; Jeong, Y. A 4.3 W 977 nm Ytterbium-doped Jacketed-Air-Clad Fiber Amplifier. In Proceedings of the Advanced Solid-State Photonics, Santa Fe, Mexico, 1 February 2004.
39. Leich, M.; Jäger, M.; Grimm, S.; Hoh, D.; Jetschke, S.; Becker, M.; Hartung, A.; Bartelt, H. Tapered large-core 976 nm Yb-doped fiber laser with 10 W output power. *Laser Phys. Lett.* **2014**, *11*, 045102. [CrossRef]
40. Aleshkina, S.S.; Levchenko, A.E.; Medvedkov, O.I.; Bobkov, K.K.; Bubnov, M.M.; Lipatov, D.S.; Guryanov, A.N.; Likhachev, M.E. Photodarkening-Free Yb-Doped Saddle-Shaped Fiber for High Power Single-Mode 976-nm Laser. *IEEE Photon. Technol. Lett.* **2018**, *30*, 127–130. [CrossRef]
41. Kotov, L.; Temyanko, V.; Aleshkina, S.; Bubnov, M.; Lipatov, D.; Likhachev, M. Efficient single-mode 976 nm amplifier based on a 45 micron outer diameter Yb-doped fiber. *Opt. Lett.* **2020**, *45*, 4292–4295. [CrossRef] [PubMed]
42. Tsai, T.Y.; Song, Y.C.; Lee, Z.C.; Lin, S.T.; Tang, Y.C. Realization of a compact 10-W 976-nm ytterbium-doped all-fiber laser. *Opt. Lett.* **2023**, *48*, 5667–5670. [CrossRef] [PubMed]
43. Aleshkina, S.S.; Likhachev, M.E.; Lipatov, D.S.; Medvedkov, O.I.; Bobkov, K.K.; Bubnov, M.M.; Guryanov, A.N. 5.5 W monolithic single-mode fiber laser and amplifier operating near 976 nm. In Proceedings of the Conference on Fiber Lasers XIII: Technology, Systems, and Applications, San Francisco, CA, USA, 15–18 February 2016.
44. Valero, N.; Feral, C.; Lhermite, J.; Petit, S.; Royon, R.; Bardin, Y.V.; Goeppner, M.; Dixneuf, C.; Guiraud, G.; Proulx, A.; et al. 39 W narrow spectral linewidth monolithic ytterbium-doped fiber MOPA system operating at 976 nm. *Opt. Lett.* **2020**, *45*, 1495–1498. [CrossRef] [PubMed]
45. Chen, M.; Li, Z.; Cao, J.; Liu, A.; Huang, Z.; Chen, J. Study on tens-of-Watt all-fiber oscillator operating near 980 nm with commercially-available double-cladding ytterbium-doped fiber. *Optik* **2021**, *228*, 166131. [CrossRef]
46. Chen, M.; Liu, A.; Cao, J.; Huang, Z.; Chen, J. Demonstration of 50-W-level all-fiber oscillator operating near 980 nm with the 20-µm core-diameter double-cladding Yb-doped fiber. *Opt. Fiber Technol.* **2021**, *65*, 102609. [CrossRef]
47. Li, Z.; Chen, M.; Liu, A.; Tian, Y.; Huang, Z.; Cao, J.; Chen, J. Experimental investigation on a hundred-Watt monolithic fiber laser operating near 980 nm with 20/125-µm double-cladding Yb-doped fiber. *Opt. Fiber Technol.* **2022**, *72*, 103004. [CrossRef]
48. Aleshkina, S.S.; Bardina, T.L.; Lipatov, D.S.; Bobkov, K.K.; Bubnov, M.M.; Gur'yanov, A.N.; Likhachev, M.E. Factors reducing the efficiency of ytterbium fibre lasers and amplifiers operating near 0.98 µm. *Quantum Electron.* **2017**, *47*, 1109–1114. [CrossRef]
49. Kim, J.P.; Park, J.S.; Oh, Y.J.; Han, E.H.; Kim, J.W.; Park, E.J.; Jeong, H.; Jung, Y.; Lee, K.; Lee, Y.; et al. High-power extra-large-mode-area Yb-doped fiber laser and amplifier at 978 nm. *J. Korean Phys. Soc.* **2021**, *78*, 1062–1066. [CrossRef]
50. Chen, M.; Du, H.; Cao, J.; Liu, A.; Pan, Z.; Huang, Z.; Chen, J. Experimental study of a 100-W all-fibre amplifier operating near 980 nm. *Quantum Electron.* **2021**, *51*, 976–982. [CrossRef]
51. Chen, M.; Cao, J.; Liu, A.; Huang, Z.; Pan, Z.; Chen, Z.; Chen, J. Experimental study on the 500-W-level all-fiber amplifier operating near 980 nm. *Results Phys.* **2021**, *29*, 104784. [CrossRef]
52. Chen, M.N.; Cao, J.Q.; Liu, A.M.; Huang, Z.H.; Pan, Z.Y.; Chen, Z.L.; Chen, J.B. Demonstration of kilowatt monolithic Yb-doped fiber laser operation near 980 nm. *Opt. Lett.* **2021**, *46*, 5340–5343. [CrossRef] [PubMed]
53. Boullet, J.; Zaouter, Y.; Desmarchelier, R.; Cazaux, M.; Salin, F.; Saby, J.; Bello-Doua, R.; Cormier, E. High power ytterbium-doped rod-type three-level photonic crystal fiber laser. *Opt. Express* **2008**, *16*, 17891–17902. [CrossRef] [PubMed]
54. Röser, F.; Jauregui, C.; Limpert, J.; Tünnermann, A. 94 W 980 nm high brightness Yb-doped fiber laser. *Opt. Express* **2008**, *16*, 17310–17318. [CrossRef] [PubMed]

55. Limpert, J.; Schmidt, O.; Rothhardt, J.; Röser, F.; Schreiber, T.; Tünnermann, A.; Ermeneux, S.; Yvernault, P.; Salin, F. Extended single-mode photonic crystal fiber lasers. *Opt. Express* **2006**, *14*, 2715–2720. [CrossRef]
56. Goel, C.; Yoo, S. All-solid antiresonant fiber design for high-efficiency three-level lasing in ytterbium-doped fiber lasers. *Opt. Lett.* **2022**, *47*, 1045–1048. [CrossRef]
57. Li, H.Z.; Zang, J.C.; Raghuraman, S.; Chen, S.X.; Goel, C.R.; Xia, N.; Ishaaya, A.; Yoo, S. Large-mode-area multicore Yb-doped fiber for an efficient high power 976 nm laser. *Opt. Express* **2021**, *29*, 21992–22000. [CrossRef]
58. White, T.P.; McPhedran, R.C.; de Sterke, C.M.; Litchinitser, N.M.; Eggleton, B.J. Resonance and scattering in microstructured optical fibers. *Opt. Lett.* **2002**, *27*, 1977–1979. [CrossRef] [PubMed]
59. Pureur, V.; Bigot, L.; Bouwmans, G.; Quiquempois, Y.; Douay, M.; Jaouen, Y. Ytterbium-doped solid core photonic bandgap fiber for laser operation around 980 nm. *Appl. Phys. Lett.* **2008**, *92*, 061113. [CrossRef]
60. Gu, G.; Kong, F.; Hawkins, T.W.; Jones, M.; Dong, L. Extending mode areas of single-mode all-solid photonic bandgap fibers. *Opt. Express* **2015**, *23*, 9147–9156. [CrossRef] [PubMed]
61. Li, W.S.; Matniyaz, T.; Gafsi, S.; Kalichevsky-Dong, M.T.; Hawkins, T.W.; Parsons, J.; Gu, G.C.; Dong, L. 151W monolithic diffraction-limited Yb-doped photonic bandgap fiber laser at ~978 nm. *Opt. Express* **2019**, *27*, 24972–24977. [CrossRef] [PubMed]
62. Jelger, P.; Engholm, M.; Norin, L.; Laurell, F. Degradation-resistant lasing at 980 nm in a Yb/Ce/Al-doped silica fiber. *J. Opt. Soc. Am. B* **2010**, *27*, 338–342. [CrossRef]
63. Yu, Y.; An, Y.; Cao, J.; Guo, S.; Xu, X. Experimental Study on All-Fiberized Continuous-Wave Yb-Doped Fiber Amplifier Operating Near 980 nm. *IEEE Photon. Technol. Lett.* **2016**, *28*, 398–401. [CrossRef]
64. Yanshan, W.; Weiwei, K.; Yi, M.; Yinhong, S.; Yujun, F. Theoretical and experimental research on the ~980-nm Yb-doped fiber laser. *Opt. Eng.* **2016**, *55*, 076113. [CrossRef]
65. Matniyaz, T.; Li, W.S.; Kalichevsky-Dong, M.; Hawkins, T.W.; Parsons, J.; Gu, G.C.; Dong, L. Highly efficient cladding-pumped single-mode three-level Yb all-solid photonic bandgap fiber lasers. *Opt. Lett.* **2019**, *44*, 807–810. [CrossRef]
66. Li, Z.; Zhou, S.; Liu, A.; Cao, J.; Huang, Z.; Chen, J. Experimental Study on the In-Band Amplified Spontaneous Emission in the Single-Mode Continuous-Wave Yb-Doped Fiber Amplifier Operating near 980 nm. *Photonics* **2022**, *9*, 377. [CrossRef]
67. 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. [CrossRef]