Stable 10 W Er:ZBLAN fiber laser operating at 2.71–2.88 μm

Shigeki Tokita,[1,2,]* Mayu Hirokane,[1,2] Masanao Murakami,[3] Seiji Shimizu,[3]
Masaki Hashida,[1,2] and Shuji Sakabe[1,2]

[1]*Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*
[2]*Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa, Sakyo, Kyoto 606-7501, Japan*
[3]*Mitsuboshi Diamond Industrial Company, Limited, 1-4-37 Minami-Kaneden, Suita, Osaka 564-0044, Japan*
**Corresponding author: tokita@laser.kuicr.kyoto-u.ac.jp*

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We have developed a diode-pumped tunable 3 μm fiber laser with a cw output power of the order of 10 W with the use of an erbium-doped ZBLAN fiber. A tunability range of 110 nm (2770 to 2880 nm) with an output power between 8 and 11 W was demonstrated. As the pump power was increased, the center of the wavelength range was shifted toward longer wavelengths, but the width of the wavelength range was largely unaffected. The total tunability range for various pump power levels was 170 nm (2710 to 2880 nm). To our knowledge, this is the highest performance (output power and tunability) obtained from a tunable 3 μm fiber laser.

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Er-doped and Er-Pr-codoped fluoride-glass fiber lasers have high average power in the mid-IR wavelength range (around 2.8 μm) and, consequently, are two of the most promising tunable laser sources for applications in medicine, spectroscopy, and IR-laser pumping [1]. In the past decade, mid-IR cw Er-doped and Er-Pr-codoped fluoride fiber lasers have been developed for obtaining higher power output [2–9]: our group recently developed a liquid-cooled 24 W Er-doped ZBLAN fiber laser with a free-running oscillator [10]. The wavelength tunability of Er-doped and Er-Pr-codoped fluoride fiber lasers has also been investigated [11–15]. For example, Zhu and Jain have obtained a broad tunability range of nearly 100 nm (2705 to 2805 nm) with a 2 W Er-doped ZBLAN fiber laser [13] at low pump intensities. However, the tunability range shrinks to about 60 nm (around 2770 to 2830 nm) at high pump intensities. In a 1 W Er-Pr-codoped ZBLAN fiber laser [14], shrinkage of the tunability range following the increase of the pump power has not been observed. Consequently, a constant tunability range wider than 100 nm (around 2700 to more than 2800 nm) has been maintained even while varying the pump power. This behavior is attributed to the residual populations of Er^{3+} ions at the lower laser level $^4I_{13/2}$. Furthermore, the generation of longer wavelengths with an Er-doped fluoride fiber has been demonstrated by Faucher *et al.* by using a fiber Bragg grating cavity with a fixed wavelength of 2940 nm and an output power of 5.2 W [16]. This result suggests that Er-doped fluoride fiber lasers have a potentially much broader tunability. However, laser operation in the wavelength range between 2830 and 2940 nm has not yet been demonstrated.

In this Letter, we report the highest output power and the broadest tunability range obtained with a wavelength-tunable 3 μm fiber laser. A maximum output power of 11 W with a high stability was obtained by the use of an Er-doped ZBLAN fiber with indirect water cooling that allowed for high-power pumping. The tunability range was extended up to 2880 nm, and a total tunability range of 170 nm was obtained.

A schematic diagram of a wavelength-tunable Er-doped ZBLAN fiber laser is shown in Fig. 1. A 3.8 m multimode-core double-clad fiber with ZBLAN-based fluoride-glass (fabricated by FiberLabs, Inc.) was used as the active medium. The specifications of the fiber core were as follows: a diameter of 25 μm, a NA of 0.12, and an ErF_3 concentration of 6 mol.%. The background loss of the core was measured to be <0.1 dB/m at 2780 nm. The inner D-shaped cladding of the fiber had a diameter of 350 μm and an NA of 0.51, while the outer polymer cladding of the fiber was 450 μm in diameter. The pump absorption in the inner cladding was measured to be ~3 db/m at 975 nm. The fiber was conductively cooled by placing it between aluminum plates that were maintained at a constant temperature of 20 °C by water cooling, and the ends of the fiber were held by fiber chuck holders with a U-shaped groove. To cool the ends conductively, the face of the output end was polished into a spherical shape and put in physical contact with one side of a sapphire plate with a thickness of 2 mm (see Fig. 1, inset). The other side of the sapphire plate had an antireflection (AR) coating (<0.5% reflectance at both 975 nm and 2.7–2.9 μm). Contact between the fiber and the sapphire plate was ensured by using a spring that pressed the plate against the fiber.

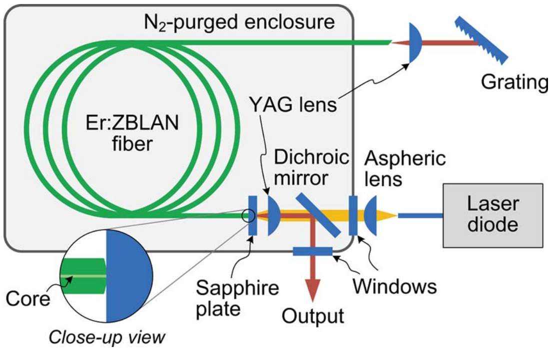

Fig. 1. (Color online) Schematic diagram of the wavelength-tunable Er-doped ZBLAN fiber laser pumped by a laser diode. The inset shows how the spherical polishing of the fiber end ensures contact between the fiber core and the sapphire plate.

To prevent moisture in the air from inducing optical damage at the face of the output end of the fiber [17], the end was placed in a nitrogen-purged enclosure. The other end of the fiber was polished at an angle of 15° to avoid parasitic lasing. Because of the lower laser intensity, optical damage was not caused at this end of the fiber, although it was exposed to the air. A laser cavity in the Littrow configuration was formed between a gold-coated diffraction grating and the face of the output end of the fiber. The groove number and the diffraction efficiency of the grating were 600 grooves/mm and >90% in the 2.7–2.9 μm range, respectively. Two AR-coated YAG lenses (>99% transmittance at both 975 nm and 2.7–2.9 μm) with a focal length of 8 mm were used as collimating lenses. A fiber-coupled laser diode was used as a cw pump source and was operated at a wavelength of around 975 nm with a maximal output power of 93 W (at the fiber end of the laser diode). The output fiber of the laser diode had a core diameter of 200 μm and an NA of 0.22. The pump beam was sent into the inner cladding of the fiber through an aspherical lens with a focal length of 7.5 mm, an airtight window, a dichroic mirror, the YAG lens and the sapphire plate. The total transmission loss of the pumping optics without the sapphire plate was measured to be ~5%. Including this loss, the fiber-to-fiber coupling efficiency was estimated to be ~80% through a cutback experiment. The output beam of the gain fiber was reflected by the dichroic mirror (>99% reflectance at 2.7–2.9 μm) and passed through a sapphire window (>99% transmittance at 2.7–2.9 μm) and then was measured using a power meter [30(150)A, Ophir-Spiricon, Inc.] and a scanning spectrometer with a focal length of 110 mm (CM110, Spectral Products).

Figure 2 shows the tuning curves for the output when the laser was pumped at nine different pump power levels. The center of the tunability range shifted toward longer wavelengths as the pump power increased. Although the tunability range tends to decrease as the pump power is increased, the range was wider than 100 nm at all pump power levels. It should be noted that tunability ranges of 130 nm (2710 to 2840 nm) and 110 nm (2770 to 2880 nm) were obtained at the lowest and highest pump power levels (5 and 93 W), respectively, and the highest output power of 11 W was obtained at around 2820 nm at the maximum of the pump power.

The output power as a function of the incident pump power is shown in Fig. 3, where the grating angle was fixed in order to maximize the output power at the maximal pump power. The output power increased linearly as the pump power was increased, and the slope efficiency was 12.2%. The inset of Fig. 3 shows a typical laser spectrum for a center wavelength of 2817 nm, where the spectrum width (FWHM of <1 nm) was limited by the resolution of the spectrometer. Note that the output power was limited by the available pump power. No damage to the fiber ends was observed, even when it was operated at maximal power. Figure 4 shows the temporal dependence of the output power for the maximal pump power of 93 W, which was measured using a power meter with a response time of 1 s. No significant fluctuations were observed during the 60 min of operation at maximal power, resulting in an rms fluctuation of 14 mW (0.13% of the average power). Power fluctuations were also monitored with an InAs photodetector with a response time of 10 μs and, in this case, too, no significant fluctuations were observed for short periods of time. A typical signal waveform acquired with an oscilloscope is shown in the inset of Fig. 4.

The slope efficiency was relatively low compared to what has been reported [8,17]. Intracavity losses cannot be the sole reason for the low efficiency, because these losses are estimated to be only 30%–50% for a round trip. A significant loss of the pump power was found to be caused by a low concentration of Er^{3+} ions, which are contained in the inner cladding; this loss was estimated from a fluorescence measurement to be >30% of absorbed pump power. This problem was caused by the fabrication process of the fiber. Thus, it is expected that more efficient laser operation can be obtained by optimizing the fabrication conditions.

The tunability ranges obtained in the present experiment are significantly broader on the longer wavelength side than those in other reports describing singly Er-doped ZBLAN fiber lasers [11–13]. In the other reports, the mechanism that limits the tunability range on the longer wavelength side (at around 2830 nm) is still not completely understood. One possible reason for this limiting is that the OH absorption peak in ZBLAN glass suppresses the lasing effect for longer wavelengths.

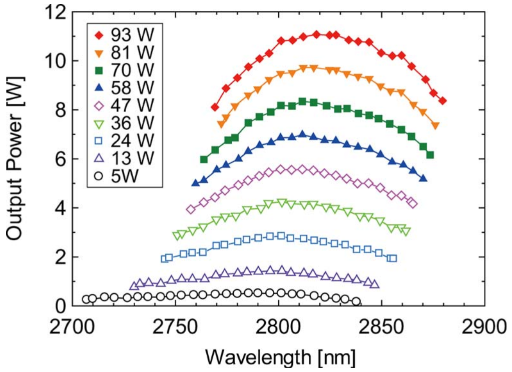

Fig. 2. (Color online) Tuning curves of the diode-pumped cw Er-doped ZBLAN fiber laser for different pump-power levels.

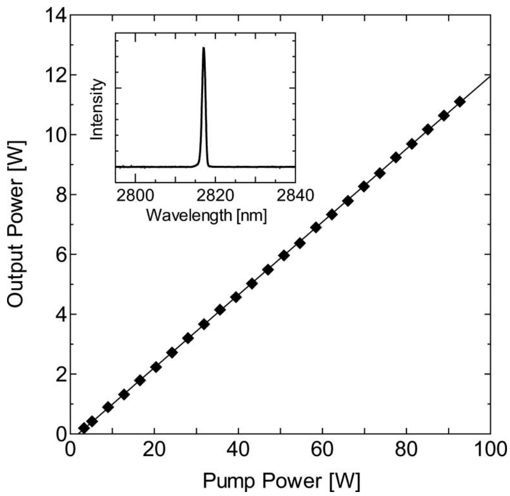

Fig. 3. Continuous wave output power as a function of incident pump power at a wavelength of 2817 nm. Inset, a typical laser spectrum.

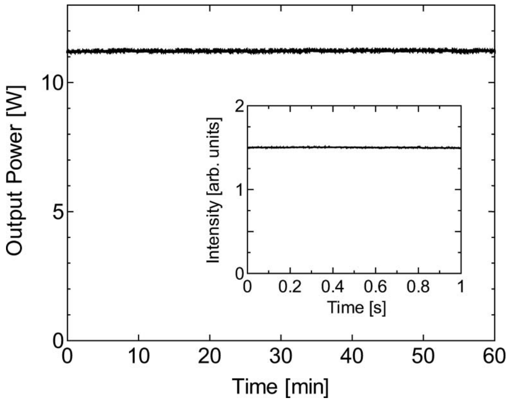

Fig. 4. Temporal stability of the output power over a 1 h time span, as measured with a power meter with a response time of 1 s. Inset, a typical signal obtained with an InAs photodetector with a response time of 10 μs.

Because the emission cross section steeply decreases at wavelengths longer than about 2800 nm [18], the loss in the cavity must be low in order to obtain lasing at long wavelengths. On the other hand, OH absorption increases at wavelengths longer than about 2750 nm and has a peak at around 2870 nm [19]. In the present result, the tunability range extended beyond the OH peak. Thus, if the OH absorption was the limiting factor at the other reports, there is a possibility that the tunability range of the present system can be further extended to longer wavelengths by increasing the pump power (increasing the gain). On the shorter wavelength side, the mechanism for the shrinkage of the tunability range is likely to be explained by the reabsorption of the laser emission, because the fact that the lifetime of the lower laser level ($^4I_{13/2}$) is longer than that of the upper laser level ($^4I_{11/2}$) leads to a large population at the $^4I_{13/2}$ level under cw laser operation [20] and, consequently, leads to a strong and broad absorption peak ($^4I_{11/2} \leftarrow {}^4I_{13/2}$) at around 2730 nm [18].

In summary, we have demonstrated the highly stable cw operation of a diode-pumped wavelength-tunable Er-doped ZBLAN fiber laser with an output power of the order of 10 W in the wavelength range between 2770 and 2880 nm. High-power single-end pumping of the order of 100 W was possible without direct liquid cooling of the fiber. Consequently, a highly stable output power with a maximum of 11 W was obtained with an rms power fluctuation of 0.13% over a 1 h time span. By using a higher power pump source or a fiber with a smaller core, it might be possible to shift the tunability range toward longer wavelengths and extend it up to around 2950 nm because Er-doped fluoride glasses have sufficiently high gain even at longer wavelengths [16,18].

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References

1. X. Zhu and N. Peyghambarian Adv. OptoElectron. **2010**, 501956 (2010).
2. B. Srinivasan, E. Poppe, J. Tafoya, and R. K. Jain, Electron. Lett. **35**, 1338 (1999).
3. B. Srinivasan, J. Tafoya, and R. Jain, Opt. Express **4**, 490 (1999).
4. S. D. Jackson, T. A. King, and M. Pollnau, Opt. Lett. **24**, 1133 (1999).
5. S. D. Jackson, T. A. King, and M. Pollnau, Electron. Lett. **36**, 223 (2000).
6. X. Zhu and R. Jain, in *IEEE/LEOS 2004 Annual Meeting Conference Proceedings* (IEEE, 2004), paper ThP5.
7. X. Zhu and R. Jain, Appl. Opt. **45**, 7118 (2006).
8. X. Zhu and R. Jain, Opt. Lett. **32**, 26 (2007).
9. S. D. Jackson, Electron. Lett. **45**, 830 (2009).
10. S. Tokita, M. Murakami, S. Shimizu, M. Hashida, and S. Sakabe, Opt. Lett. **34**, 3062 (2009).
11. L. Wetenkamp, Ch. Frerichs, G. F. West, and H. Többen, J. Non-Cryst. Solids **140**, 19 (1992).
12. N. J. C. Libatique, J. Tafoya, N. K. Viswanathan, R. K. Jain, and A. Cable, Electron. Lett. **36**, 791 (2000).
13. X. Zhu and R. Jain, Opt. Lett. **32**, 2381 (2007).
14. X. Zhu and R. Jain, IEEE Photon. Technol. Lett. **20**, 156 (2008).
15. X. Zhu and R. Jain, Opt. Lett. **33**, 1578 (2008).
16. D. Faucher, M. Bernier, N. Caron, and R. Vallée, Opt. Lett. **34**, 3313 (2009).
17. M. Bernier, D. Faucher, N. Caron, and R. Vallée, Opt. Express **17**, 16941 (2009).
18. B. Wang, L. Cheng, H. Zhong, J. Sun, Y. Tian, X. Zhang, and B. Chen, Opt. Mater. **31**, 1658 (2009).
19. C. R. Day, P. W. France, S. F. Carter, M. W. Moore, and J. R. Williams, Opt. Quantum Electron. **22**, 259 (1990).
20. M. Pollnau and S. D. Jackson, IEEE J. Quantum Electron. **38**, 162 (2002).