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Abstract: We reported on a single stage 976 nm Yb-doped fiber amplifier(YDFA) and a double stage 1112 nm YDFA with commercially available Yb-doped fibers. In developing of two YDFAs of different wavelengths, we estimated upper limit of Yb-doped fiber length and output of signal and ASE by numerical simulation. The simulataion results showed good agreement with experimental results, and both YDFAs achieved stable several Watts continuous-wave(CW) outputs.

Todo list

1. Introduction

Rare-earth-doped fiber laser and amplifier systems are useful in a various fields. For example, the high-power and compact systems are used in laser processing, long-distance optical communication, and LiDAR systems. In physics, highly stable doped fiber systems are attractive as a light source for experiment [1, 2]. Although there are still some problems which are not fully understood such as photodarkening [3], remarkable progress has been made in their performance.

Single-frequency light sources at 976 nm and 1112 nm also such as spectroscopy of Yb atoms [4]. However, they are difficult to design because 976 nm is in the middle of the absorption band and 1112 nm is at the edge of the emission band of Yb-doped fiber. Therefore, numeraical simulation is indispensable. In this paper, we report on the development of YDFAs at 976 nm and 1112 nm and the comparison of experimental results with numerical simulations.

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2. Yb-doped fiber amplifier

In developing fiber amplifiers, it is important to keep the undesired gain as low as possible. The gain at ASE wavelength can be written as a function of gains at two other wavelengths [5]. In the cases of amplified signal at 976 nm with 915 nm pumping, and amplified signal 1112 nm with 976 nm pumping, ASE gains can be expressed using the cross section in Fig. 1 as follows

$$G_{ASE} = 0.29G_{976} + 0.96\beta A_{915} \tag{1}$$
$$G_{ASE} = 6.5G_{1112} + 0.027\beta A_{976}. \tag{2}$$

Here, The partial term scheme related this work shown in Fig. 1.

The steady-state rate equations to describe the pump, signal and ASE given by

$$\begin{aligned}
\frac{\mathrm{d}N_2}{\mathrm{d}t} &= \frac{\Gamma_p}{A_{core}}\frac{\lambda_p(P_p^+ + P_p^-)}{hc}(\sigma_a(\lambda_p)N_1 - \sigma_e(\lambda_p)N_2) \\
&+ \frac{\Gamma_s}{A_{core}}\frac{\lambda_s(P_s^+ + P_s^-)}{hc}(\sigma_a(\lambda_s)N_1 - \sigma_e(\lambda_s)N_2) \\
&+ \frac{\Gamma_a}{A_{core}}\frac{\lambda_a(P_a^+ + P_a^-)}{hc}(\sigma_a(\lambda_a)N_1 - \sigma_e(\lambda_a)N_2) - \frac{N_2}{\tau} \\
N &= N_1 + N_2,
\end{aligned} \tag{3}$$

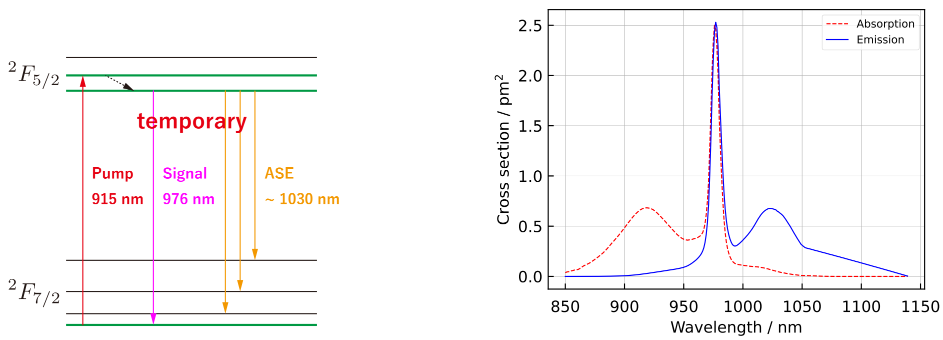


Fig. 1. Relevant energy level and cross sections of Yb-doped fiber.

and propagation equations in fiber are described as

$$\frac{\mathrm{d}P_p^{\pm}}{\mathrm{d}z} = \pm\Gamma_p P_p^{\pm}(\sigma_e(\lambda_p)N_2 - \sigma_a(\lambda_p)N_1) \mp \alpha P_p^{\pm} \tag{4}$$

$$\frac{\mathrm{d}P_s^{\pm}}{\mathrm{d}z} = \pm\Gamma_s P_s^{\pm}(\sigma_e(\lambda_s)N_2 - \sigma_a(\lambda_s)N_1) \mp \alpha P_s^{\pm} \tag{5}$$

$$\frac{\mathrm{d}P_a^{\pm}}{\mathrm{d}z} = \pm\Gamma_a P_a^{\pm}(\sigma_e(\lambda_a)N_2 - \sigma_a(\lambda_a)N_1) \mp \alpha P_a^{\pm} \pm 2\sigma_e(\lambda_a)N_2\frac{hc^2}{\lambda_a^3}\Delta\lambda_a^3. \tag{6}$$

3. Experimental setup

3.1. 976 nm amplifier system

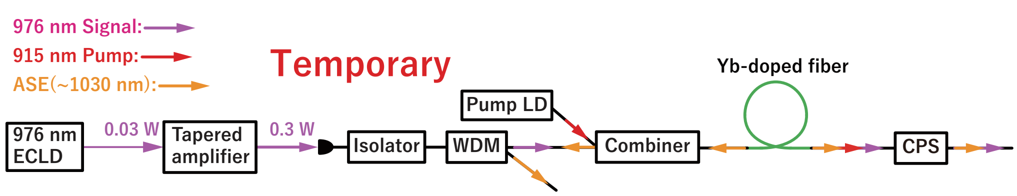


Fig. 2. 976 nm YDFA system.

A schematic of the 976 nm YDFA system is shown in Fig. 2. An external-cavity laser diode(ECLD) at 976 nm is used for the seed laser. The seed laser is pre-amplified by tapered amplifier from 30 mW to 900 mW, and coupled to the YDFA input fiber which is a polarization maintining(PM) fiber with a FPC/AC connector. The seed input of the YDFA is connected to an isolator and a wavelength division multiplexing(WDM) filter, which are used to block return light to the seed laser such as backward ASE. The seed and pump are combined into a double cladding PM fiber, which has a core diameter of 20 µm and a cladding diameter of 125 µm by a pump and signal combiner. The 915 nm radiation for pumping the Yb-doped fiber is generated from fiber-coupled laser diode with an output power of up to 70 W. The combiner output is spliced to the Yb-doped fiber. The Yb-doped fiber nLIGHT Yb1200-25/125DC-PM is used as the gain fiber. The fiber is fixed on top of the water-cooled heatsink with a thermal conductive sheet. The cladding power stripper(CPS) is connected after Yb-doped fiber to remove a residual pump power in the output of Yb-doped fiber. The output of YDFA system collimated by pigtailed collimator is separated into the ASE around 1030 nm and other wavelengths by a filter.

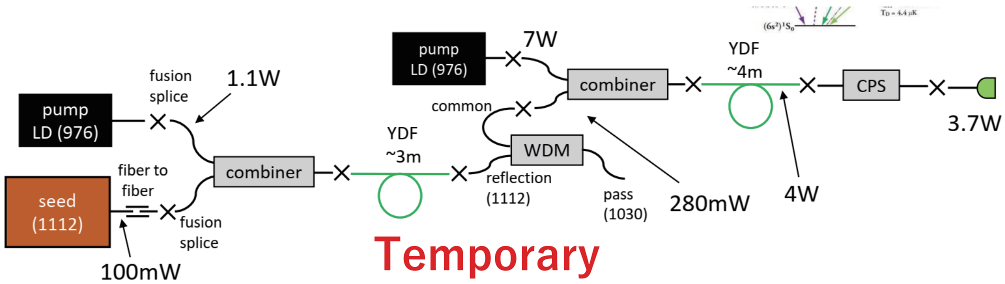


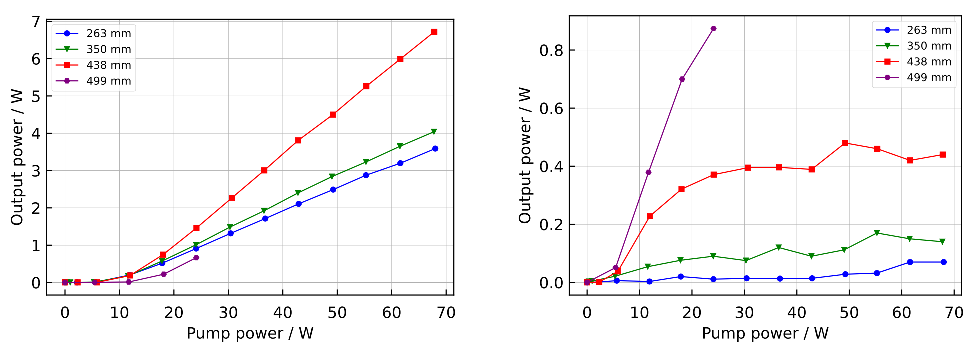
Fig. 3. 1112 nm YDFA system.

3.2. 1112 nm amplifier system

The configuration of the 1112 nm YDFA system is shown in Fig. 3. The 1112 nm YDFA system consists of a two-stage amplifier. The fiber laser at 1112 nm(Menlo systems Orange one-2) is used as the seed laser. In the first stage, the seed laser and the pump laser, which is generated by fiber-coupled laser diode at 976 nm with a maximum output of 7 W, are mixed with the first combiner. The first combiner has a signal port, two pump ports, and a common port, which are a single-mode fiber of 5.8/125 µm, multi-mode fibers of 105/125 µm, and a double-cladding fiber 10/125 µm. The seed power at the common port of the first combiner is 80? mW. The Yb-doped fiber(nLIGHT Yb1200-10/125DC) is used as a gain fiber. The length of the Yb-doped fiber is about 1? m. The output from Yb-doped fiber is separated into 1112 nm signal component and ASE component around 1030 nm by WDM, and only the 1112 nm signal component is coupled to the the second amplifier stage. The second Yb-doped fiber is the same one of the first Yb-doped fiber. The about 3? m long doped fiber is coiled to a diameter of 10 cm and fixed inside an aluminum enclosure with thermal conductive sheet. Temperature of the aluminum enclosure is controlled by peltier devices. Output of the second Yb-doped fiber is removed by CPS and collimated by pigtailed collimator.

4. Results and discussion

4.1. 976 nm YDFA



(a) (b)

Fig. 4. Measured 976 nm and ASE around 1030 nm power as a function of the launched 915 nm pump power.

We measured the output of YDFAs with the 263 mm, 350 mm, 438 mm, and 499 mm length of Yb-doped fibers at pump powers up to about 70 W. The output powers are shown in Fig. 4. As increasing the length of Yb-doped fiber, the 976 nm output power increases, reaching maximum at length of 438 mm. For the 438 mm fiber, the gain of 976 nm began to exceed 1 at the pump power of 12 W, and 6.7 W output of 976 nm was achieved with a slope efficiency of 0.12. The maximum 976 nm gain corresponds to 14.5 dB. In the test of 976 nmm fiber, we applied the pump power less than 25 W because the ASE power significantly increased.

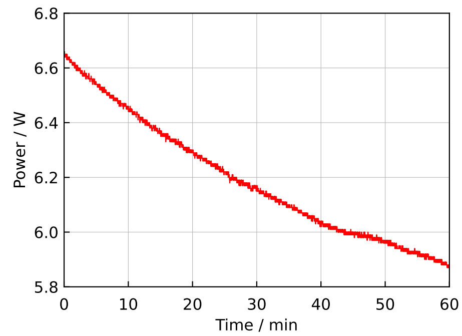
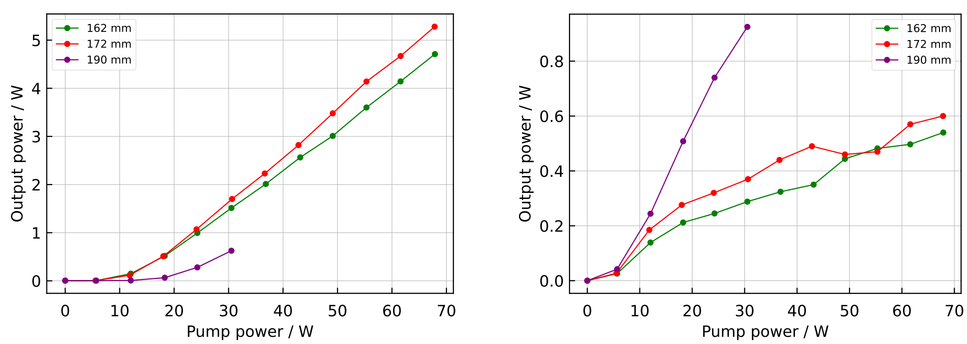


Fig. 5. Measured output power of the 976 nm fiber amplifier as a function of the launched 915 nm pump power and results of the simulation.

Figure 5 shows 976 nm output stability of the 438 mm Yb-doped fiber. The output decays in time to decrease by about 12% of its original power after 60 min. This is mainly due to photodarkening caused by the high-inversion distribution of Yb ion [3]. To avoid power decay by photodarkening, we tested Yb-doped phosphosilicate fiber(Coractive, DCF-YB-20/128P-FAC). We measured the output of the Yb-doped fiber by changing the fiber length, and obtained the results shown in the Fig. 6. The 976 nm output power reached a maximum of 5.3 W at the 172 mm length fiber.



(a) (b)

Fig. 6. Measured 976 nm and ASE around 1030 nm power as a function of the launched 915 nm pump power.

4.2. 1112 nm YDFA

5. Discussion

6. Conclusion

Funding. Content in the funding section will be generated entirely from details submitted to Prism Authors may add placeholder text in the manuscript to assess length, but any text added to this section

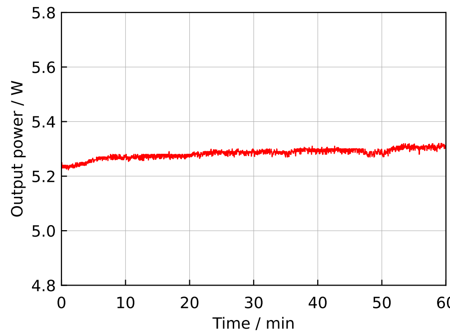


Fig. 7. Measured output power of the 976 nm fiber amplifier as a function of the launched 915 nm pump power and results of the simulation.

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References

1. Z. Burkley, C. Rasor, S. F. Cooper, A. D. Brandt, and D. C. Yost, "Yb fiber amplifier at 972.5 nm with frequency quadrupling to 243.1 nm," Appl. Phys. B **123**, 5 (2017).
2. N. Coluccelli, M. Cassinerio, B. Redding, H. Cao, P. Laporta, and G. Galzerano, "The optical frequency comb fibre spectrometer," Nat Commun **7**, 12995 (2016).
3. R. Paschotta, J. Nilsson, P. R. Barber, J. E. Caplen, A. C. Tropper, and D. C. Hanna, "Lifetime quenching in Yb-doped fibres," Opt. Commun. **136**, 375–378 (1997).
4. T. Franzen, B. Pollklesener, and A. Görlitz, "A single-stage 1112 nm fiber amplifier with large gain for laser cooling of ytterbium," Appl. Phys. B **124**, 234 (2018).
5. J. Nilsson, J. D. Minelly, R. Paschotta, A. C. Tropper, and D. C. Hanna, "Ring-doped cladding-pumped single-mode three-level fiber laser," Opt. Lett. **23**, 355 (1998).