Untitled

Yasutaka Imai,[1, *], Hideaki Hara,[1, *]

[1] *Reserch Institute for Interdisciplinary Science, Okayama University, Okayama, Japan*
[*] *imai1117@okayama-u.ac.jp*

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.

incomplete sentence

2. Yb-doped fiber amplifier

In developing fiber amplifiers, it is important to keep the undesired gain as low as possible. 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, gain of ASE which has center wavelength of 1023 nm can be expressed using the cross section in Fig. 1 as follows

$$G_{1023} = 0.29 \cdot G_{976} + 0.96 \cdot \beta A_{915} \tag{1}$$

$$G_{1023} = 6.5 \cdot G_{1112} + 0.027 \cdot \beta A_{976}, \tag{2}$$

where G_λ is gain at wavelength λ, A_λ is absorption of the pump at λ, and β is the ratio of pump propagation area to effective modal field area of 1023 nm ASE. For the 976 nm YDFA, as shown in Eq. (1), a smaller value of β is necessary to suppress the ASE gain. In our 976 nm system, we use Yb-doped fiber with core and cladding diameters of 20 µm and 125 µm, respectively, which has a relatively small $\beta \simeq 61$ in commercially available Yb-doped LMA fibers. Without considereation of the gain at 976 nm, the ASE gain increases $\sim$ 59 dB for each 1 dB of 915 nm pump absorption. The above result indicates that it is important for 976 nm YDFA to controll 915 nm pump absorption by using relative short Yb-doped fiber and to reduce input components to amplifier near ASE wavelength. On the other hand, for the 1112 nm system, pump absorption has less contribution to the ASE gain G_{1023}. Therefore, we use Yb-doped LMA fiber with a core diameter of 10 µm and a cladding diameter of 125 µm, which has a more single-mode characteristic than that used for 976 nm system.

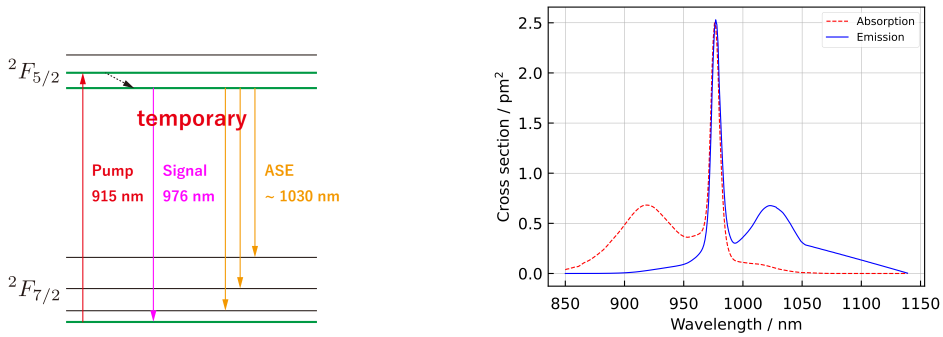


Fig. 1. Relevant energy level and cross sections of Yb-doped fiber.

For more detailed estimation for YDFA, numerical simultaions are required. We developed the simulation code based on the model in [6]. The simulations for forward and backward propagating pump, signal, and ASE were conducted according to the rate equation given by

$$
\begin{aligned}
N &= N_1 + N_2 \\
\frac{\mathrm{d}N_2}{\mathrm{d}t} &= \frac{1}{A_{core}}\frac{\lambda_p}{hc}\Gamma_p(P_p^+ + P_p^-)(\sigma_a(\lambda_p)N_1 - \sigma_e(\lambda_p)N_2) \\
&+ \frac{1}{A_{core}}\frac{\lambda_s}{hc}\Gamma_s(P_s^+ + P_s^-)(\sigma_a(\lambda_s)N_1 - \sigma_e(\lambda_s)N_2) \\
&+ \frac{1}{A_{core}}\frac{\lambda_a}{hc}\Gamma_a(P_a^+ + P_a^-)(\sigma_a(\lambda_a)N_1 - \sigma_e(\lambda_a)N_2) - \frac{N_2}{\tau},
\end{aligned}
\tag{3}
$$

and propagation equations in fiber are described as

rewrite equations later

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

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

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

Here N is the Yb-ion concentration, N_1 and N_2 are the population densities of the ground and excited state, respectively. $\Gamma_i(i = p, s, a)$ is the overlapping factors for pump, signal, and ASE relative to the doped area, A_{core} is the area of the doped area, $P_i^\pm(i = p, s, a)$ is the pump, signal, and ASE power, whose symbol ± corresponds to forward(+) and backward(-) propagations. σ_e, σ_a are the emission and absorption cross sections of Yb ions, and τ is the spontaneous lifetime of Yb ion in the excited state. Comparison of simulation and experimental results will be discussed in a later Section 5.

3. Experimental setup

3.1. 976 nm amplifier system

A schematic of the 976 nm YDFA system is shown in Fig. 2. An external-cavity laser diode(ECLD) at 976 nm followed a tapered amplifier(TA) is used as a seed laser. The output of seed laser is

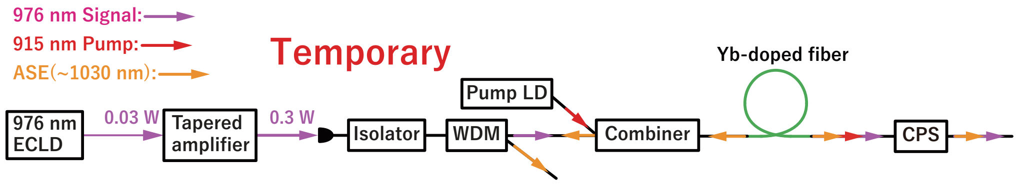


Fig. 2. 976 nm YDFA system.

pre-amplified by the TA up to nearly 1 W, and coupled to the YDFA input which is a polarization maintining(PM) fiber with a FPC/AC connector. Owing to the spatial-mode mismatch of the output from TA, the power coupled to the input is only 300 mW. The input of YDFA is fusion-spliced to an inline isolator and a wavelength division multiplexing(WDM) filter, which protect the seed laser from backward propagation light generated in a gain fiber. The WDM which has three ports: a common port, a pass port, and a reflection port separates ASE around 1020 nm from signal path(common-pass) to the reflection port. A fiber end of the reflection port is cleaved so that it is angled at least 8° in order to prevent ASE from returning from the end to a gain fiber. A 915 nm pump radiation is generated from fiber-coupled laser diode with output power of up to 70 W. The pump laser is fixed on a water-cooled heatsink for stable operation. A signal pump combiner, which has a signal port with PM fiber of 6/125 µm, two pump ports with multimode fibers of 105/125 µm, and a common port with double-cladding PM fiber of 20/125 µm, combines the seed laser and the pump laser into the common port fiber. The Yb-doped fiber fusion-spliced from the common port fiber of the combiner is rolled to approximately 100 mm in diameter and fixed on a water-cooled heatsink with a thermal conductive sheet. For safe operation of the YDFA, all the bare glass cladding around the fusion-spliced points are recoated with low-refractive index polymer. A residual pump power in the output of the Yb-doped fiber is removed by a cladding power stripper(CPS). Amplified signal and ASE are collimated by pigtailed collimator, separated by a filter, and measaured by power meters, respectively.

3.2. 1112 nm amplifier system

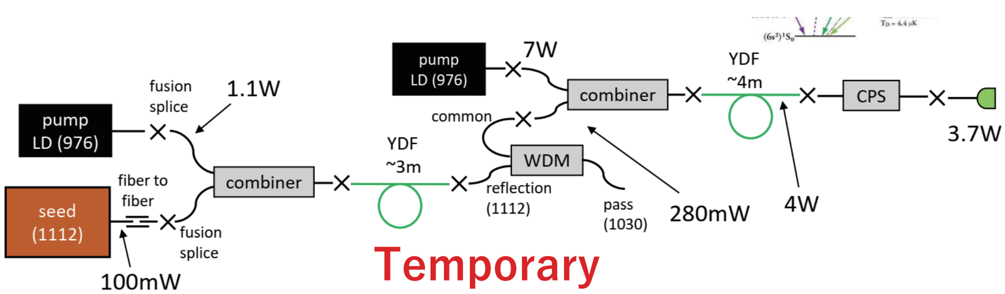


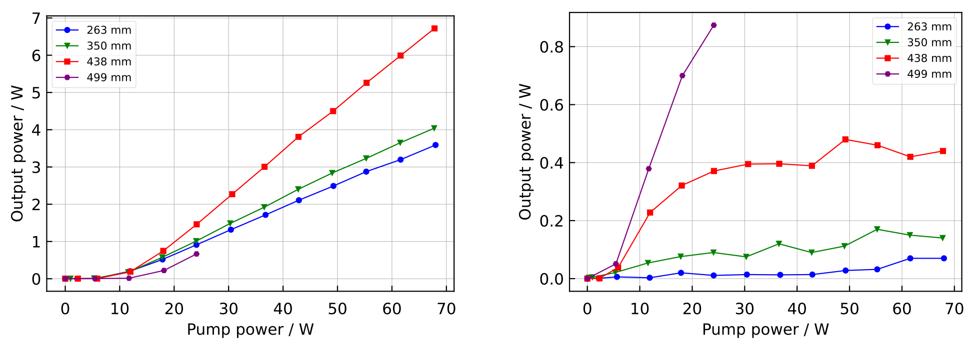
Fig. 3. 1112 nm YDFA system.

A schematic of the 1112 nm YDFA system is shown in Fig. 3. The 1112 nm laser system is composed of a seed laser and two-stage YDFA. A fiber laser at 1112 nm(Menlo systems Orange one-2) is used as the seed laser. The output singlemode fiber with a FPC/AC connector is contacted to the input singlemode fiber of the first YDFA stage with a mating sleeve. A coupled power into the input is about 100? mW. As pump lasers, two 976 nm fiber-coupled diode lasers based on an air-cooled heatsink with maximum outputs of 7 W are used. The configuration of the first stage of 1112 nm YDFA is similar to the 976 nm system except for an isolator and fiber type.

The seed laser and the pump laser are combined into a double-cladding fiber of 10/125 µm by a pump-signal combiner, and launched into the first Yb-doped fiber. Before a second pump-signal combiner, the ASE around 1020 nm generated in first Yb-doped fiber is removed by a WDM. The 1112 nm signal after WDM is 300? mW. The second Yb-doped fiber is rolled in a diameter of 100? mm, and fixed inside an aluminum enclosure with thermal conductive sheet. Temperature of the aluminum enclosure is controlled by peltier devices. Similar to 976 nm system, the output of the second Yb-doped fiber is removed by CPS and collimated by pigtailed collimator. The output power of the 1112 nm signal and the ASE near 1020 nm are obtained by measuring the output powers through long-pass filters with cut-on wavelengths at 1100? nm.

4. Experimental results

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 YDFA with Yb-doped aluminosilicate fiber(nLIGHT, Yb1200-20/125DC-PM). We tested 263 mm, 350 mm, 438 mm, and 499 mm long of the 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 499 mm fiber, we applied the pump power less than 25 W because the ASE power significantly increased.

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. Figure 7 shows 976 nm output stability of the 172 mm Yb-doped fiber.

4.2. 1112 nm YDFA

5. Discussion

6. Conclusion

Funding. JSPS KAKENHI Grant Number JP21K13944

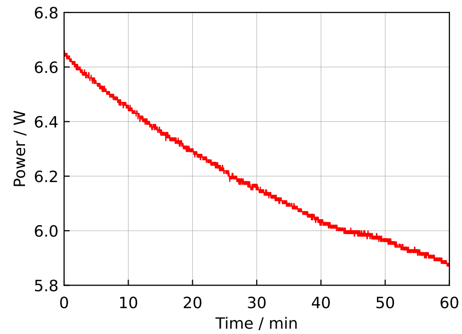
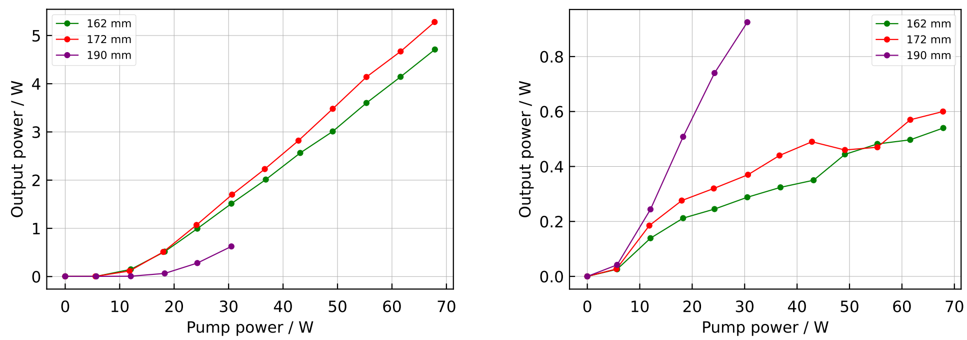


Fig. 5. Measured output power of the 976 nm fiber amplifier as a function of the launched 915 nm pump power and results of the simulation.



(a) (b)

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

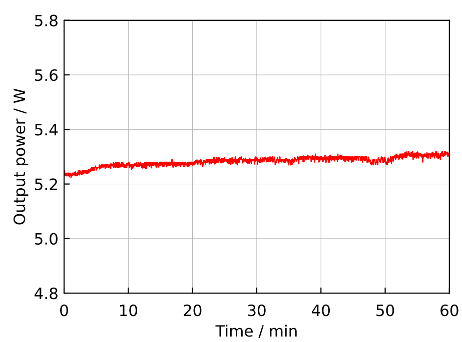


Fig. 7. Measured output power of the 976 nm fiber amplifier as a function of the launched 915 nm pump power and results of the simulation.

Acknowledgments.

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).
6. F. Roeser, C. Jauregui, J. Limpert, and A. Tünnermann, "94 W 980 nm high brightness Yb-doped fiber laser," Opt. Express **16**, 17310 (2008).