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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 simulation results showed good agreement with experimental results, and both YDFAs achieved stable several Watts continuous-wave(CW) outputs.

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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, numerical 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. 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

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

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

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 $\beta \approx 61$ in commercially available Yb-doped LMA fibers. Without consideration of the gain at 976 nm, the ASE gain increases ~ 59 dB for each 1 dB of 915 nm pump absorption. The above result indicates that it is important for 976 nm YDFA to control

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.

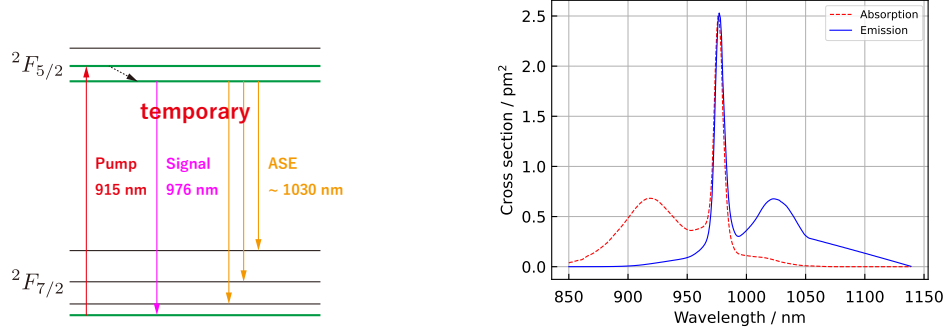


Fig. 1. Relevant energy level and cross sections of Yb-doped fiber.

For more detailed estimation for YDFA, numerical simulations 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

$$\begin{aligned}
 N &= N_1 + N_2 \\
 \frac{dN_2}{dt} &= \frac{1}{A_{core}} \frac{\lambda_p}{hc} \Gamma_p (P_p^+ + P_p^-) (\sigma_a(\lambda_p) N_1 - \sigma_e(\lambda_p) N_2) \\
 &\quad + \frac{1}{A_{core}} \frac{\lambda_s}{hc} \Gamma_s (P_s^+ + P_s^-) (\sigma_a(\lambda_s) N_1 - \sigma_e(\lambda_s) N_2) \\
 &\quad + \frac{1}{A_{core}} \frac{\lambda_a}{hc} \Gamma_a (P_a^+ + P_a^-) (\sigma_a(\lambda_a) N_1 - \sigma_e(\lambda_a) N_2) - \frac{N_2}{\tau},
 \end{aligned} \tag{3}$$

and propagation equations in fiber are described as

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

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

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

Here N is the Yb-ion concentration, N_1 and N_2 are the population densities of the ground and excited state, respectively. Γ_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 \pm corresponds to forward(+) and backward(-) propagation. 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.

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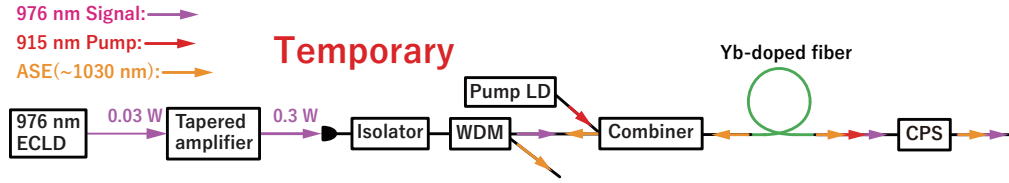


Fig. 2. 976 nm YDFA system.

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 pre-amplified by the TA up to nearly 1 W, and coupled to the YDFA input which is a polarization maintaining (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 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 measured by power meters, respectively.

3.2. 1112 nm amplifier system

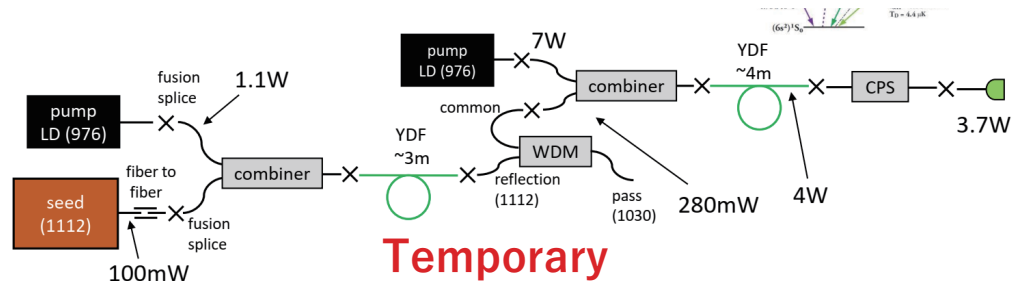


Fig. 3. 1112 nm YDFA system.

A schematic of the 1112 nm YDFA system is shown in Fig. 3. The 1112 nm YDFA system is composed of a seed laser and two amplifiers. 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 stage amplifier with a mating sleeve. A coupled power into the input is about 80 mW. As pump lasers, a 976 nm fiber-coupled diode laser installed on an air-cooled heatsink with maximum output of 7 W is used for the first and second stage, respectively. The configuration of the first stage amplifier is similar to the 976 nm system except 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. The first Yb-doped fiber is under no temperature control because the pump power is limited to less than 1 W. 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 the second combiner is 220 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

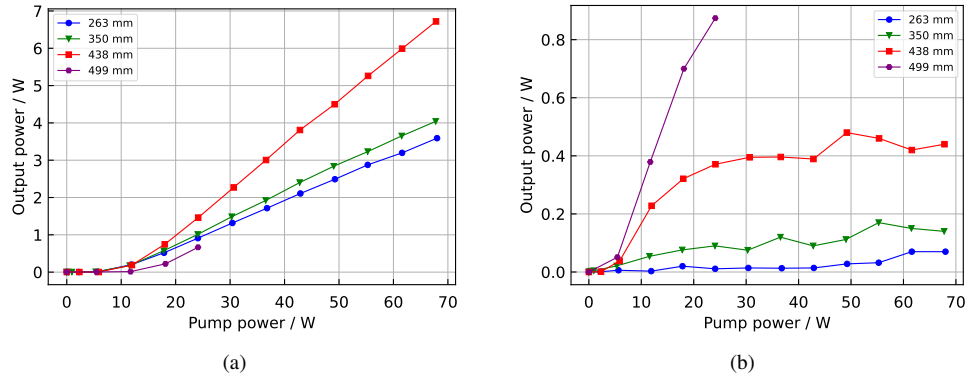


Fig. 4. Measured 976 nm and ASE around 1020 nm power as a function of the launched 915 nm pump power.

The 976 nm and ASE near 1020 nm output power of the YDFA are shown in Fig. 4. In this measurement, we used a Yb-doped aluminosilicate fiber (nLIGHT, Yb1200-20/125DC-PM) as a gain fiber. 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. As increasing the length of the Yb-doped fiber, the 976 nm output power increases, and reaches maximum at the 438 mm long fiber. In the test of 438 mm long fiber, the 976 nm gain 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. The reason for the lower slope efficiency compared to YDFAs which has operating wavelength above 1 μm is that the 976 nm transition occurs between the lowest sublevel of the ground state and the lowest sublevel of the excited state in Yb ion. In the test of 499 mm fiber, we applied the pump power less than 25 W because the ASE power significantly increased.

To measure the output stability of the 976 nm YDFA, we logged the maximum output of the 438 mm long fiber during 60 min. As the result shown in Fig. 5, the output of YDFA decayed in time to decrease by about 88% of its original power after 60 min. This is mainly due to photodarkening caused by the high-inversion distribution of Yb ion [3]. Although

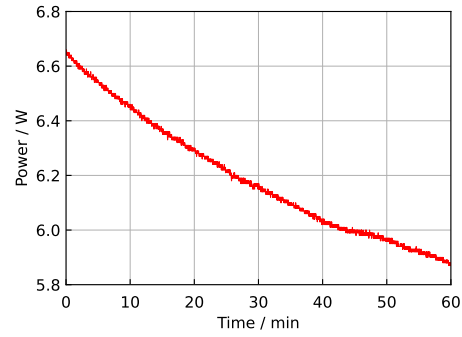


Fig. 5. The output power of the 976 nm YDFA with during 60 min.

the photodarkening is not fully understood, there are many proposals to mitigate the effect [7–9]. We developed another 976 nm YDFA using a Yb-doped fiber with phosphosilicate-glass core (Coractive, DCF-YB-20/128P-FAC). The output powers of YDFA with the 162 mm, 172 mm,

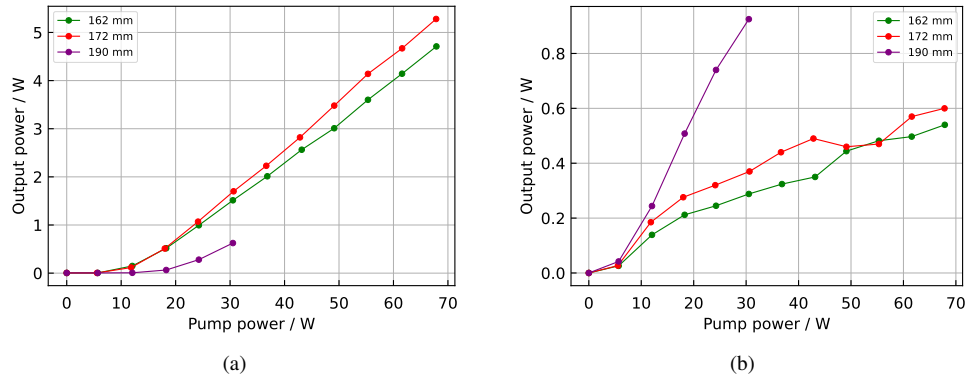


Fig. 6. Measured 976 nm and ASE around 1020 nm power as a function of the launched 915 nm pump power.

and 190 mm long doped-phosphosilicate fiber are shown in the Fig. 6. The 976 nm output power reached a maximum of 5.3 W at the 172 mm length fiber. As with the case of the aluminosilicate fiber, the 976 nm output power was recorded with a duration of 60 min. The fluctuation of output was less than 1.5% as shown in Fig. 7, which indicates that photo darkening is significantly reduced.

4.2. 1112 nm YDFA

In the 1112 nm YDFA, we used a Yb-doped fiber with a core based on aluminosilicate glass (nLIGHT, Yb1200-10/125DC) as a gain fiber. The 3 m and 4 m long gain fiber are embedded in the first-stage and second-stage amplifiers, respectively. Plots of the amplified 1112 nm and forward ASE as a function of pump power applied to the second-stage amplifier are shown in Fig. 8a. The maximum generation of 1112 nm is 3.8 W at applied pump power of 7 W, which corresponds to the gain of 12.3 dB. As shown in Fig. 8b, the variation of 1112 nm is less than 2.4%.

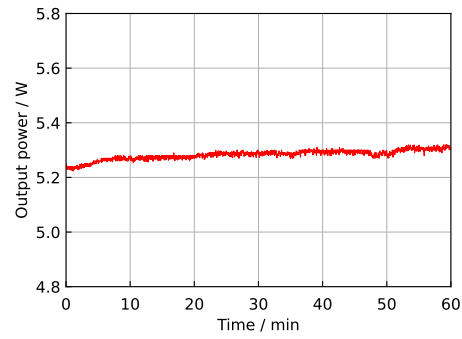


Fig. 7. The output power of the 976 nm YDFA during 60 min.

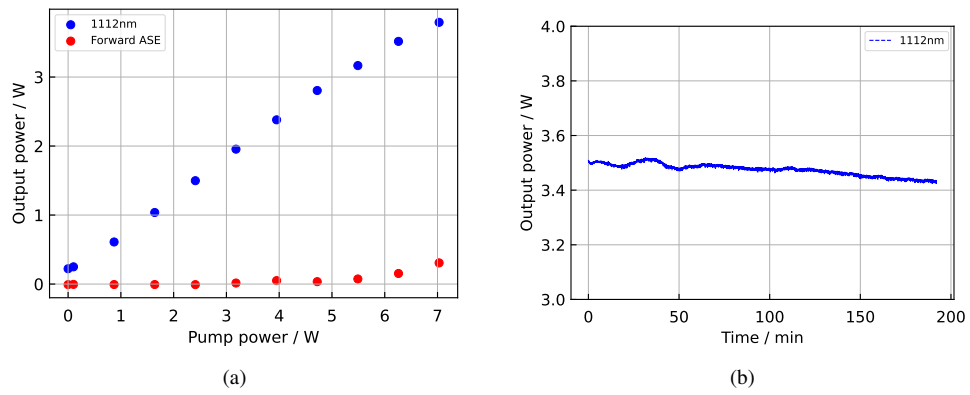


Fig. 8. The output of 1112 nm YDFA. (a) The 1112 nm and forward ASE as a function of the 976 nm pump power applied to the second stage amplifier. (b) The 1112 nm output stability in duration over 3 h.

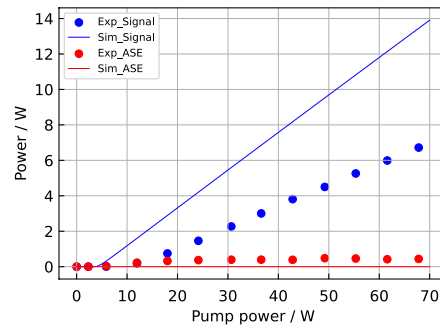


Fig. 9. Comparison between numerical simulation and experimental results of the 976 nm YDFA.

125 5. Comparison between numerical simulations and experimental results

126 6. Conclusion

127 **Funding.** JSPS KAKENHI Grant Number JP21K13944

128 **Acknowledgments.**

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