Singlemode 1112 nm and few-mode 976 nm Yb-doped fiber amplifiers

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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

$$G_{1023} = 0.29 \cdot G_{976} + 0.96 \cdot \beta A_{915} \tag{1}$$
$$G_{1023} = 6.5 \cdot G_{1112} + 0.027 \cdot \beta A_{976}, \tag{2}$$

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 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.

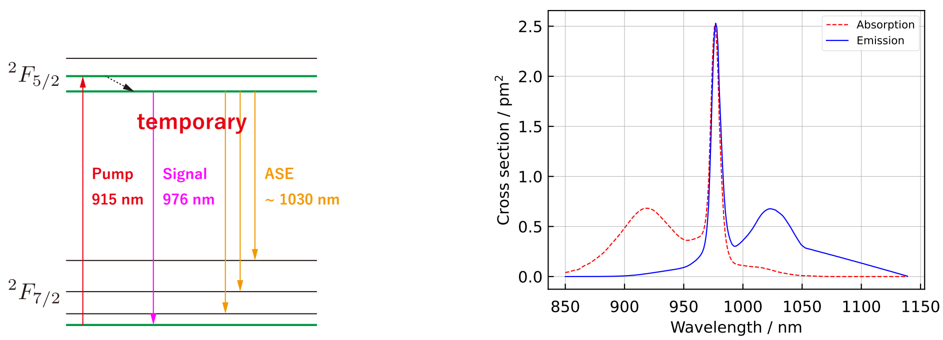

Fig. 1. Relevant energy level and cross sections of Yb-doped fiber.

Further estimation for amplifiers requires numerical simulation. For the estimation of 1112 nm, only the LP_{01} mode should be considered as the propagation mode, while a several higher modes include in the calculation for the 976 nm amplifier because the few-mode fiber is used for the gain fiber. From the normalizded frequency V_c of ASE, we included a few higher-order modes of LP_{01}, LP_{11}, LP_{21}, and LP_{02} for ASE calculation, while only LP_{01} mode was considered for signal calculation because the seed laser almost consisted of LP_{01} mode. In addition, they are assumed that coupling between the LP_{lm} modes is negligible, and that Yb dopant are uniformly distributed throughout the fiber core. Referring to [6], we developed the simulation code based on a model which has the cross section of the doped core devided into M layers in the radial direction. The rate equation and propagation equations for forward and backward propagating pump, signal, and ASE were given by

$$\begin{aligned} N_{1k} + N_{2k} &= 1 \\ \frac{\mathrm{d}N_{2k}}{\mathrm{d}t} &= \frac{\lambda_p \Gamma_{p,k}}{hcA_k}(\sigma_a(\lambda_p)N_{1k} - \sigma_e(\lambda_p)N_{2k})(P_p^+ + P_p^-) \\ &+ \frac{\lambda_s \Gamma_{s,k}}{hcA_k}(\sigma_a(\lambda_s)N_{1k} - \sigma_e(\lambda_s)N_{2k})(P_s^+ + P_s^-) \\ &+ \frac{\lambda_a \Gamma_{a,k}}{hcA_k}(\sigma_a(\lambda_a)N_{1k} - \sigma_e(\lambda_a)N_{2k})(P_a^+ + P_a^-) - \frac{N_{2k}}{\tau}, \end{aligned} \tag{3}$$

$$\frac{dP_p^{\pm}}{dz} = \pm \sum_k^M \Gamma_{p,k}(\sigma_e(\lambda_p)N_{2k} - \sigma_a(\lambda_p)N_{1k})NP_p^{\pm} \mp \alpha P_p^{\pm} \tag{4}$$

$$\frac{dP_s^{\pm}}{dz} = \pm \sum_k^M \Gamma_{s,k}(\sigma_e(\lambda_s)N_{2k} - \sigma_a(\lambda_s)N_{1k})NP_s^{\pm} \mp \alpha P_s^{\pm} \tag{5}$$

$$\frac{dP_{a,i}^{\pm}}{dz} = \pm \sum_k^M \Gamma_{a,k}(\sigma_e(\lambda_a)N_{2k} - \sigma_a(\lambda_a)N_{1k})NP_a^{\pm} \mp \alpha P_{a,i}^{\pm} \tag{6}$$

$$\pm \sum_k^M m\sigma_e(\lambda_a)\Gamma_{a,k,i}N_{2k}N\frac{hc^2}{\lambda_a^3}\Delta\lambda_a. \tag{7}$$

Here $P_j^{\pm}(j = p, s, a)$ is the pump, signal, and ASE power, whose symbol of $\pm$ indicates to forward(+) and backward(-) propagation. λ_j is the wavelength of the pump, signal and ASE, $\sigma_a(\lambda_j)$ and $\sigma_e(\lambda_j)$ are the absorption and emission cross-sections of Yb ions at the wavelength λ_j, respectively. $A_k = \pi(r_{k+1}^2 - r_k^2), (k = 0, 1, \cdots M - 1))$ is the k^{th} layer area of the doped core, N is the Yb-ion dopant density, N_{1k} and N_{2k} are the population of the ground and excited states at the k^{th} layer, respectively. $\Gamma_{(p,s),k}$ is the overlapping factors for pump and signal, and $\Gamma_{a,k,i}$ is the overlapping factor of i^{th} transverse mode of the ASE relative to the k^{th} layer. τ is the spontaneous lifetime of Yb ion in the excited state, and α_j and $\alpha_{j,i}$ are loss factors during fiber propagation. h is the plamck constant and c is the speed of light in vacuum.

In this experiment, we set the boundary conditions for the above equations as following:

$$\begin{aligned} P_{p,s}^{+}(0) &= P_{p,s} + R1P_{p,s}^{-}(0) \\ P_{p,s}^{-}(L) &= P_{p,s} + R2P_{p,s}^{+}(L) \\ P_{a,i}^{+}(0) &= R1P_{a,i}^{-}(0) \\ P_{a,i}^{-}(L) &= R2P_{a,i}^{+}(0), \end{aligned} \tag{8}$$

where L is length of the doped fiber, and $R1$ and $R2$ are the equivalent reflectance at $z = 0$ and $z = L$ which includes reflections from outside the amplifier. Comparison of simulation and experimental results will be discussed in a later Section 5.

3. Experimental setup

3.1. 976 nm amplifier system

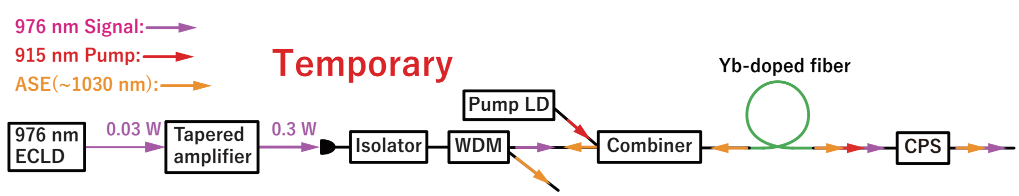

Fig. 2. 976 nm YDFA system.

A schematic of the 976 nm YDFA system is shown in Fig. 2. An external-cavity laser diode(ECLD) at 976 nm 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 FC/APC connector. Owing to the spatial-mode

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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 measured by power meters, respectively.

3.2. 1112 nm amplifier system

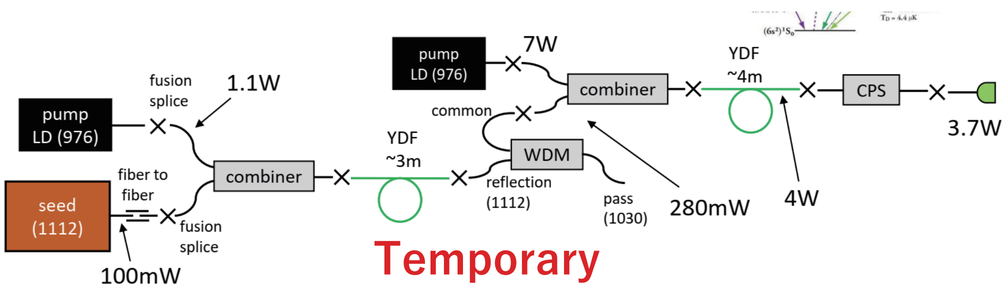
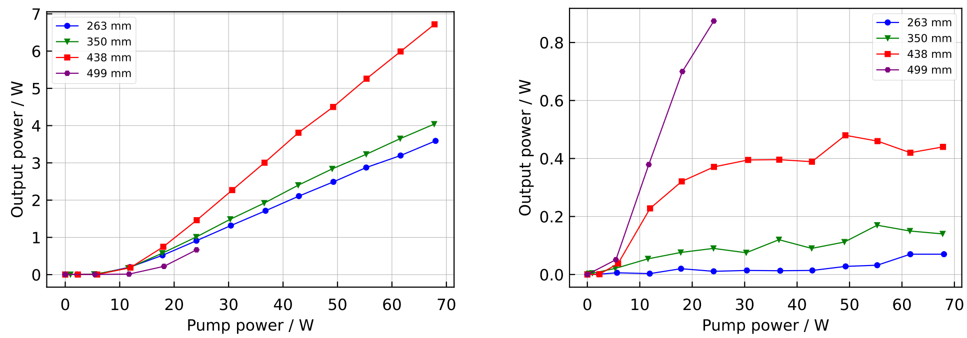


Fig. 3. 1112 nm YDFA system.

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 FC/APC 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



(a) (b)

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 the 263 mm, 350 mm, 438 mm, and 499 mm long 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. The 976 nm output increased with pump power to exceed the gain of 1 dB at 12 W pump power, and 6.7 W was achieved at 68 W pump power 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. The ASE also increased with pump power above 6 W, but remained almost constant of 0.4 W above 30 W pump power. In the test of 499 mm fiber, we applied the pump power less than 25 W because the ASE power significantly increased.

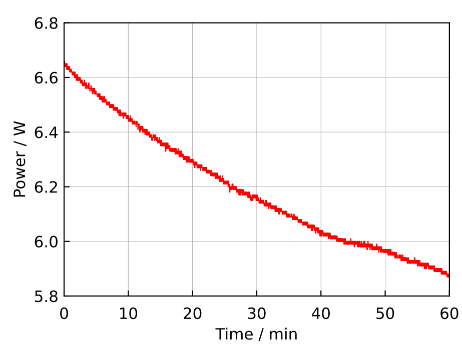
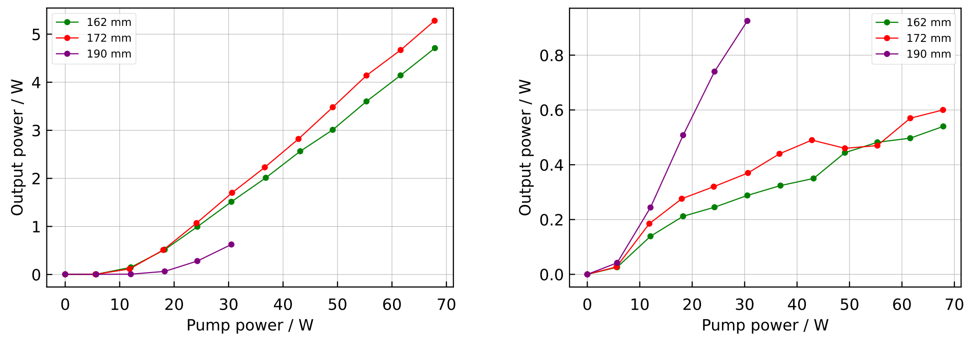


Fig. 5. The output power of the 976 nm YDFA with during 60 min.

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 12% of its original power after 60 min. This is mainly due to photodarkening caused by the high-inversion distribution of Yb ion [3]. Although 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 with the 162 mm, 172 mm, and 190 mm long phosphosilicate fibers



(a) (b)

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

are shown in the Fig. 6. Both the 976 nm amplified signal and the ASE increased with pump power and reached a maximum of 5.3 W and 0.6 W at pump power of 68 W with the 172 mm long fiber, respectively. 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.

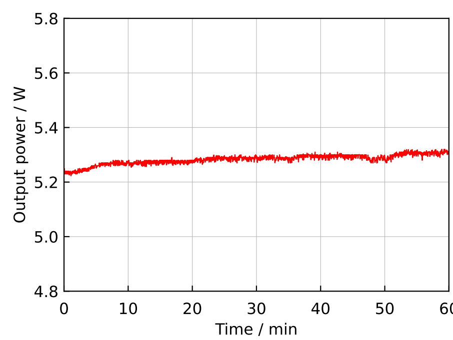
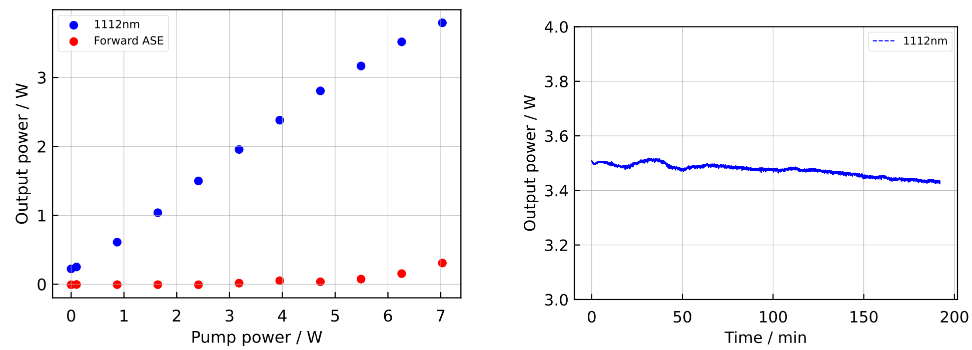


Fig. 7. The output power stability of the 976 nm YDFA during 60 min.

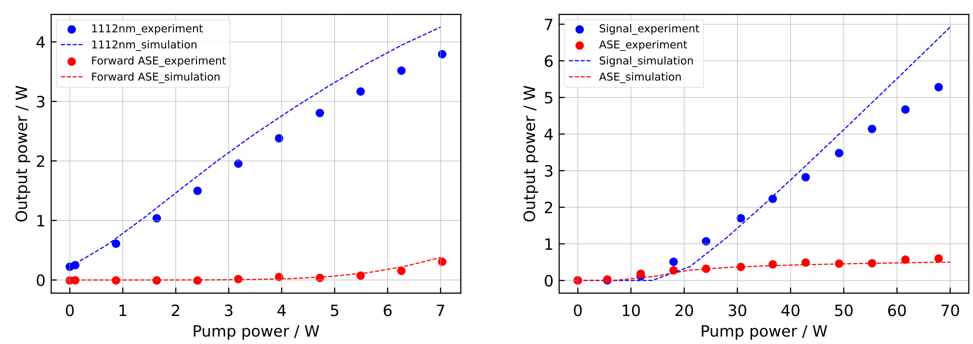
4.2. 1112 nm YDFA

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%.



(a) (b)

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.



(a) (b)

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

5. Comparison between numerical simulations and experimental results

We evaluated the experimental results by numerical simulations using eqs. (3) to (5) and (7) as the model. Simulation parameters are shown in table 1. Comparison between the simulation results and experimental results of 1112 nm YDFA shown in Fig. 9a indicates good consistency. The slightly larger experimental result in the forward ASE comparison is probably due to the ASE input at the second stage amplifier caused by residual forward ASE from the first stage amplifier, and re-injection of backward ASE resulting from reflection in upper stream of the 1112 nm system. Figure fig. 9b shows the result of comparison of 976 nm YDFA. While the simulated 976 nm output is overestimated relative to its experimental results, the ASE is conversely underestimated. This may be caused by the fact that the higher-order modes of the ASE were not taken into account in the simulations. Since the 976 nm seed light is mainly composed of a fundamental mode while the spontaneous emission includes all allowed higher-order modes. Therefore, the simulation without considering the higher-order modes resulted in large errors in the prediction of the ASE.

Table 1. Simulation parameters.

Parameter	1112YDFA	976YDFA
Yb ion concentration N	$7.3 \times 10^{25}/\mathrm{m}^{-3}$	$43 \times 10^{25}/\mathrm{m}^{-3}$
Core diameter	10 µm	19.8 µm
Cladding diameter	125 µm	128∗ µm
Core numerical aperture	0.076	0.086
Pump wavelength λ_p	976 nm	915 nm
Signal wavelength λ_s	1112 nm	976 nm
ASE wavelength λ_a	$1000 - 1100$ nm	$1000 - 1100$ nm
R1	10^{-6}	10^{-6}
R2	10^{-6}	10^{-6}

6. Conclusion

In this paper, we demonstrated the 1112 nm singlemode YDFA and 976 nm few-mode YDFA using only commercial fibers. By using the Yb-doped fiber with phosphosilicate glass, the power attenuation caused by photodarkening in the 976 nm amplifier which requires a high inversion distribution was suppressed to the same level as that of the 1112 nm amplifier.

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