Laser Performance of Nd-Doped Fiber Laser at 1120 nm

Zhiquan Lin, Yan Feng, Dijun Chen, and Weibiao Chen

***Abstract*—Compared with Yb, Nd has potential in 1120 nm fiber lasers, with the characteristics of larger emission cross section and four-level structure. In this work, Nd-doped fiber (NDF) oscillator and Nd-Raman fiber (NRF) oscillator were built using single-mode 5/125 NDF to study the lasing characteristics at 1120 nm, especially the suppression of amplified spontaneous emission at 1060 nm. Limited by the parasitic oscillation at 1060 nm, the NDF oscillator achieved 5 W output at 1120 nm. The NRF oscillator removed the limitation due to the Raman shift from 1064 nm to 1120 nm and obtained an output of 7.7 W at 1120 nm with a spectral peak-to-peak contrast of 36 dB. This work provides experimental basis for the application of NDF in 1.1 μm.**

***Index Terms*—Neodymium doped fiber, fiber lasers, 1120 nm fiber lasers, Raman fiber lasers.**

I. Introduction

FIBER lasers with wavelength at 1120 nm can be used to generate 1178 nm Raman fiber lasers, which have applications in sodium guide star [1], and also can be used to pump Tm-doped fiber lasers [2]. At present, kW-level 1120 nm fiber lasers have been realized by using Yb-Raman fiber amplifiers [3], [4]. However, amplifiers have the disadvantage of back-propagating light, and to solve this problem, high-power isolators are required. So 1120 nm fiber oscillators are favored in practical applications due to their robustness against backward lasing. Today, Raman fiber oscillators based on single-mode germanium-doped fiber are the common method to obtain 1120 nm fiber lasers, pumped by 1070 nm Yb-doped fiber lasers [5]. But this approach is challenged by the spectral broadening in Raman fiber laser.

In fact, Yb-doped fiber oscillator can directly lase the 1120 nm laser, which means the 1070 nm fiber lasers can be omitted. However, the emission cross section (ECS) of Yb decreases with wavelength, so the gain at 1120 nm is small, which causes the 1120 nm Yb-doped fiber lasers to suffer from amplified spontaneous emission (ASE) at shorter wavelength. Currently, single-mode 1120 nm Yb-doped fiber oscillators have output powers below 200 W [6], [7].

Recently, Nd emission wavelengths >1100 nm have attracted attention, and a kHz-linewidth single-frequency Nd-doped fiber (NDF) laser at 1120 nm with output power of 15 mW has been reported [8]. The 1120 nm emission of Nd comes from the transition from $^4F_{3/2}$ to $^4I_{11/2}$, which has a wavelength range of 1040 nm to 1160 nm. Compared with Yb, the emission of Nd at 1120 nm is a four-level structure, and the ECS of Nd at this wavelength is larger than that of Yb. More importantly, the emission intensity of Nd at 1120 nm is closely related to the glass composition of NDF [9], and a small ratio of Al:Nd or P:Nd benefits the 1120 nm emission [10]. With the current preform preparation technology, it is feasible to fabricate NDFs with small Al:Nd or P:Nd and high dispersity [11]. Interestingly, Nd was found to significantly improve photodarkening resistance of Yb [12]. Therefore, NDF may provide a new solution for the development of 1120 nm fiber lasers.

As a proof of principle experiment, we built a simple cladding-pumped 1120 nm NDF fiber oscillator using fiber Bragg grating (FBG) and found that its laser performance was severely affected by the 1060 nm ASE. The smaller ECS at 1120 nm compared to that of 1060 nm is the main reason. In this work, theoretical calculations based on 1120 nm NDF amplifier were first performed to understand the lasing properties of NDF at 1120 nm. Then, a NDF oscillator and a Nd-Raman fiber (NRF) oscillator were constructed by using single-mode 5/125 NDF to study the laser performance of NDF at 1120 nm, especially the suppression of 1060 nm ASE. Finally, 7.7 W at 1120 nm with a spectral peak-to-peak contrast of 36 dB was achieved in the NRF oscillator.

II. Simulations and Experimental Setup

In Ref. [13], Kelson *et al.* derived the rate equation for NDF. But for the 1120 nm NDF laser, the 1060 nm ASE needs to be considered additionally. Joes *et al.* demonstrated an ASE simulation method that takes into accont the emission bounded in fiber core [14]. Based on these two works, we applied a simplified 1120 nm NDF amplifier model to discuss the effects of 1060 nm ASE. The model has two considerations: i) neglecting the concentration quenching of Nd, so the laser power at 1120 nm is a theoretical reference value; ii) supposing the ASE is only generated at 1060 nm. In laser experiments, we observed the strongest ASE occurs at 1060 nm, which further generates parasitic oscillation. Therefore, the hypothesis is reasonable.

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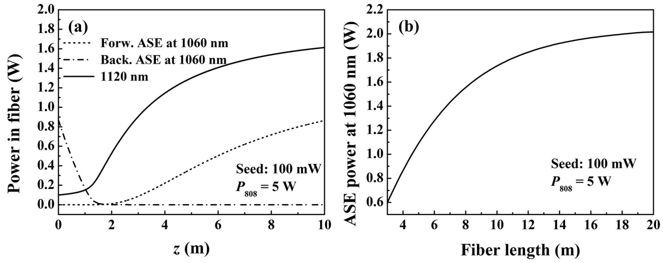

Fig. 1. Evolution of signal power and ASE power along the NDF fiber (z direction) (a) and effect of fiber length on ASE suppression (b) in 1120 nm NDF amplifier. P_{808}: pump power at 808 nm.

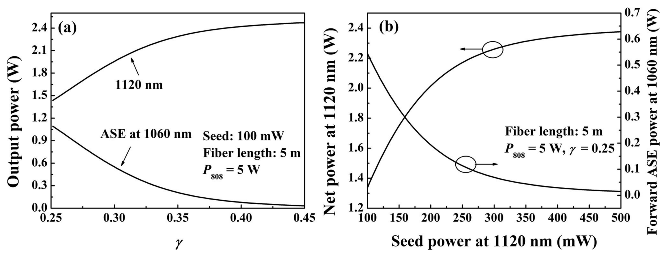

Fig. 2. Effects of γ (a) and seed power (b) on ASE suppression in 1120 nm NDF amplifier. Parameter of γ is defined as the ratio of emission cross section at 1120 nm to 1060 nm ($\sigma_{em\_1120}/\sigma_{em\_1060}$).

A single-mode 5/125 NDF fiber with cladding pump absorption coefficient of 1 dB/m at 808 nm and with core numerical aperture (NA) of 0.14 (Coherent, PM-NDF-5/125) was used in the following calculations. The main spectral parameters are $\sigma_{abs\_808} = 1.12\times10^{-20}$ cm^2, $\sigma_{em\_1120} = 0.43\times10^{-20}$ cm^2, $\sigma_{em\_1060} = 1.71\times10^{-20}$ cm^2, and $\tau = 0.37$ ms, all from a Nd-doped silica glass with Al:Nd ratio of 20:1 [15].

Fig. 1(a) shows the distribution of signal power and ASE power in a 10-m-long NDF fiber with 5 W pump power at 808 nm (P_{808}) and with a 100 mW seed laser at 1120 nm. It is a forward-pumped amplifier. The seed laser achieves gain in the amplifier and its power increases to 1.6 W after passing through the 10 m NDF, while the forward and backward 1060 nm ASE power also increase. The backward ASE grows rapidly in $z <$ 2 m range. The total ASE power is 1.7 W, which is comparable to the 1120 nm power. In a real amplifier, the 1060 nm ASE already causes parasitic oscillation. To reduce the ASE power, the fiber length needs to be shortened because the gain of ASE is positively related to fiber length. Fig. 1(b) plots the total ASE power at 1060 nm as a function of fiber length. As expected, shortening fiber length helps to reduce the ASE power. But on the other hand, a shorter NDF also means less amplifying gain at 1120 nm. Nonetheless, it provides a viable method to suppress the 1060 nm ASE for real NDF fibers.

Then, we considered the influence of γ, defined as the ratio of $\sigma_{em\_1120}/\sigma_{em\_1060}$, on ASE suppression. This parameter is related to the composition of fiber core. The calculation results are depicted in Fig. 2(a). In the calculation, the σ_{em_1060} is a fixed value (of 1.71×10^{-20} cm^2). For the 5/125 NDF fiber, its γ is 0.25. As shown in Fig. 2(a), the total ASE power decreases with increasing γ, while the 1120 nm power increases. Both of them tend to saturate when γ is > 0.4. The value of γ represents the magnitude of the difference between 1120 nm and 1064 nm in ECS. So a larger γ corresponds to a larger 1120 nm power. It is feasible to achieve γ values lager than 0.4 by adjusting the Al:Nd or P:Nd ratio of NDF fiber [10].

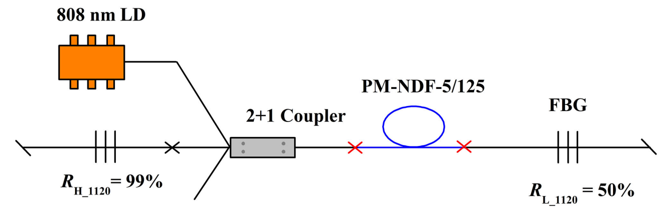

Fig. 3. Schematic representation of the single-mode 1120 nm NDF oscillator. LD: laser diode; FBG: fiber Bragg grating.

Fig. 2(b) shows the effect of seed power on ASE suppression (with $\gamma = 0.25$). It is similar to that in Fig. 2(a). The increase of seed power results in the decrease of 1060 nm ASE power, as well as the saturation of 1060 nm ASE power and net power at 1120 nm. The 1120 nm net power is the difference between output power and seed power. The increase in seed power enhances the stimulated emission at 1120 nm, which provides ideas for 1120 nm NDF oscillators to suppress 1060 nm ASE by using high reflectivity FBGs.

According to the simulation results above, a single-mode 1120 nm fiber oscillator was built by using the 5/125 NDF fiber with a length of 5 m to study the laser properties of NDF at 1120 nm. The laser setup is depicted in Fig. 3. The 808 nm LD is an 80 W output multimode laser (BWT Beijing Ltd.) with NA and pigtailed fiber of 0.22 and 105/125, respectively. The pump arm of the (2+1)×1 pump combiner is the same 105/125 fiber, and its signal input/output fiber is the matched passive PM-GDF-5/130 fiber (for 5/125 NDF fiber). The high-reflection FBG has a reflectivity of 99% ($R_{H\_1120} = 99\%$) with a bandwidth of 0.4 nm, while the low-refection FBG has a reflectivity of 50% ($R_{L\_1120} = 50\%$) with a bandwidth of 0.07 nm. Both of them are inscribed on the PM980 fiber. At the junction of the 5/125 NDF fiber and the PM980 (low-refection FBG), there is a homemade cladding pump stripper (CPS) by curing high refractive index glue, which is not shown in Fig. 3. In the laser experiment, 5/125 NDF was coiled on metal plate with a diameter of 10 cm for cooling. To avoid the free-running of 1060 nm laser caused by end-face feedback, both end-faces were angle-cleaved at 8°.

In the experiment, the output power, P_{out}, and laser spectrum were measured by a power meter (Thorlabs, S442C) and an spectrum analyzer (Yokogawa, AQ6370D), respectively. Besides, an integrating sphere (Labsphere, 3P-GPS-020-SL) was used in the spectral measurement to eliminate the spatial inhomogeneity of the output laser.

III. Results and Discussion

Fig. 4(a) shows the output power of the 5/125 NDF oscillator versus the launched pump power. A maximum laser power of 5.3 W is achieved at 33 W pump, corresponding to a slope efficiency of 16.8%. Fig. 4(b) plots the laser spectrum at each output power in Fig. 4(a). A parasitic oscillation peak at 1060 nm is observed at the output of 5.3 W. The occurrence of the parasitic laser limits

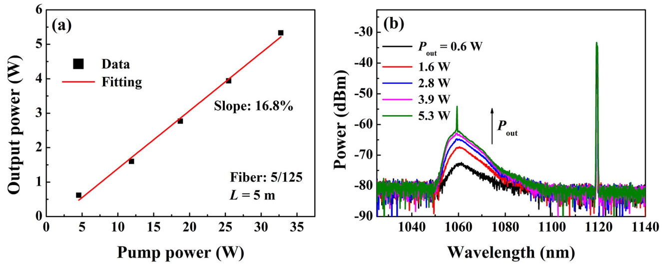

Fig. 4. Laser performance of the single-mode 1120 nm NDF oscillator: (a) output power; (b) laser spectrum.

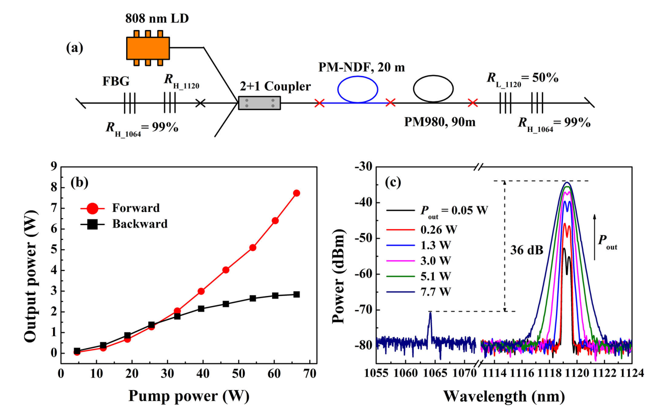

Fig. 5. Schematic diagram of the 1120 nm Nd-Raman fiber oscillator (a), output power (b) and laser spectrum (c).

the maximum output power of the 1120 nm NDF oscillator. According to the fiber length under test and pump absorption coefficient, the absorbed pump power at 808 nm is calculated to be 22.6W, so the absorbed pump-to-laser conversion efficiency is 23.5%, which is well below the theoretical quantum efficiency of 72% (808 nm to 1120 nm). The concentration quenching of Nd is the main cause because of the heavy doping concentration of 5/125 NDF (with $Nd^{3+} > 1.0$ wt.% [16]). A spectral integration calculation was carried out based on the data in Fig. 4(b). The energy ratio of the 1120 nm laser peak at each output power was the same, about 96.5%.

To further improve the laser performance of the 1120 nm NDF laser, an efficient way is to reduce the gain difference between 1120 nm and 1060 nm, as shown in Fig. 2(a). We note that the 1060 nm parasitic oscillation and the 1120 nm laser satisfy the Raman shift of silica glass fiber in wavelength. Drawing on the achievements of Yb-Raman fiber lasers, we believe that NRF oscillator is a feasible way to solve the problem of 1060 nm ASE in the 1120 nm NDF oscillator. To test this method, we modified the laser setup in Fig. 3 to construct a NRF oscillator, which is shown in Fig. 5(a). Two high-reflection FBGs at 1064 nm ($R_{\mathrm{H\_1064}} = 99\%$) with bandwidth of 0.5 nm were used to form a low-output 1064 nm oscillator, which can significantly promote the Raman laser shift from 1064 nm to 1120 nm. In order to fully absorb the pump power at 808 nm, a 20-m-long 5/125 NDF was used. In addition, a PM980 fiber with fiber length of 90 m was spliced between the NDF and the low-reflection 1120 nm FBG as Raman gain fiber.

Fig. 5(b) plots the output power of NRF oscillator in the forward and backward directions as a function of the launched pump power. We have checked by OSA that almost all forward output is 1120 nm laser and most of the backward output is 1064 nm laser. As shown in Fig. 5(b), initially, the output power at 1120 nm is slight less than that at 1064 nm. However, when the pump power is > 25 W, the 1120 nm power increases rapidly, while the 1064 nm power becomes slowly and tends to saturate. Finally, a maximum 7.7 W 1120 nm laser with single-mode output is obtained at a pump power of 66.3 W.

Fig. 5(c) depicts the laser spectrum of the 1120 nm NRF oscillator with output power increasing from 0.05 W to 7.7 W. The line with $P_{\mathrm{out}} = 1.3$ W corresponds to the pump power of 25 W in Fig. 5(b), and its laser peak is broadened compared to the lines with smaller P_{out}. Moreover, with the increase of P_{out}, the phenomenon of spectral broadening intensifies, and even the spectral gap in laser peak (the slow axis and fast axis of PM980 fiber have different reflection wavelengths) disappears gradually. As observed in Ref. [5], in Raman fiber oscillators, the increase of output power is generally accompanied by obvious spectral broadening. In our 1120 nm NRF experiment, the spectral broadening is consistent with the increase of 1120 nm power, and the line with $P_{\mathrm{out}} = 1.3$ W can be regarded as the onset of the Raman shift from 1064 nm to 1120 nm. The peak-to-peak contrast between 1120 nm and 1064 nm is 36 dB at the maximum output, which is a significant improvement compared with that in Fig. 4(b). Theoretical simulations are being conducted to explore the power evolution process and influence factors of NRF oscillators.

As expected, the Nd-Raman fiber oscillation increases in both output power and spectral contrast compared to the NDF oscillator. Because NRF oscillator does not have the problem of parasitic oscillation and a longer NDF is used. But the 11.6% optical-to-optical efficiency achieved in the NRF oscillator does not meet our expectation. Efforts of such as optimizing the fiber length of 5/125 NDF and increasing the reflection bandwidth of 1064 nm FBG may help improve the laser efficiency. Overall, the NRF oscillator scheme provides the possibility to increase the output power of 1120 nm laser.

IV. Conclusion

In this work, laser properties of 1120 nm NDF laser were theoretically and experimentally explored based on a single-mode 5/125 NDF. In theory, an amplifier rate model was applied to discuss the strategies to suppress the ASE at 1060 nm. For a real NDF, reducing fiber length and increasing signal power at 1120 nm are the practical and effective methods to control the 1060 nm ASE. Of cause, adjusting the core composition of the NDF to increase γ value is another important approach. Based on simulation results, a 5-m-long NDF and a 50% low-reflection FBG were used to construct a single-mode 1120 nm NDF oscillator. Limited by the parasitic oscillation at 1060 nm, the NDF oscillator achieved 5 W output at 1120 nm with a slope efficiency of 16.8%. Further, the Raman shift from 1064 nm to 1120 nm was applied to build a Nd-Raman fiber oscillator to overcome the limitation of parasitic oscillation. As expected, the hybrid oscillator was ASE-free at 1060 nm. Finally, a spectral peak-to-peak contrast of 36 dB was achieved at maximum 7.7 W output.

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