Integrated ytterbium-Raman fiber amplifier

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An integrated ytterbium-Raman fiber amplifier architecture is proposed for power scaling of a Raman fiber laser. It is an ytterbium (Yb) fiber amplifier seeded with a double or multiple wavelength laser and followed by a passive Raman fiber. The bluest wavelength light gets amplified in the Yb fiber and the power is transferred to redder wavelengths in the following Raman fiber. A proof of principle experiment demonstrates a 300 W all-fiber linearly polarized single mode amplifier at 1120 nm with an optical efficiency of 70%, limited only by available pump power. The amplifier consists of 4 m of Yb-doped fiber and 20 m of germanium-doped fiber, and seeded with a laser emitting at 1070 and 1120 nm. The power evolution of the 1070 and 1120 nm light inside the amplifier is investigated, both numerically and experimentally. The possibility of power scaling to over kilowatt levels is discussed.

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Raman fiber lasers and amplifiers are well known for wavelength flexibility because Raman gain is available at arbitrary wavelengths across the transparency window of optical fibers [1]. In recent years, Raman fiber lasers have developed quickly in power scaling, now reaching a level of a few hundred watts [2–4]. Most recently, Supradeepa and Nicholson reported a 300 W high-efficiency cascade Raman fiber laser at 1.5 μm with a clever amplifier architecture, cored pumped by a high power ytterbium (Yb)-doped fiber (YDF) laser [5]. In their configuration, the most demanding fiber component is a wavelength division multiplexer (WDM), which combines the high power pump and seed lasers into a single mode Raman fiber. To further power scaling, this component could be the bottle neck.

The first Stokes Raman emission at 1120 nm of an YDF laser has an important application of pumping a Raman fiber amplifier at 1178 nm for a laser guide star [6]. Nevertheless, 1120 nm is within the emission spectrum of an YDF; therefore, much effort has been devoted to developing high power 1120 nm lasers with YDF directly, in order to simplify the laser system [7,8]. However, power scaling of the laser faces difficulty in suppressing amplified spontaneous emission (ASE) and, more seriously, parasitic lasing at ~1060 nm. Controlling the cavity loss between the laser wavelength and shorter wavelengths is effective, for example, by increasing the reflectivity of output fiber Bragg grating [7], but it is still highly sensitive to feedback at shorter wavelengths. To scale up the 1120 nm laser, an Yb-doped multimode fiber amplifier was studied [8], but the seed laser has to be over 50 W to efficiently suppress the parasitic lasing. The high seed power places greater demand on the combiner, especially for lasers with single mode and linearly polarized output.

In this Letter, we propose an integrated ytterbium-Raman fiber amplifier (YRFA) architecture, to solve the power scaling difficulty in a Raman fiber laser and/or long wavelength Yb fiber laser combination. The amplifier consists of a piece of YDF followed by a piece of Raman gain fiber, and seeded with lasers at the convenient Yb laser wavelength, λ_0, and Raman Stokes wavelengths, $\lambda_1, \lambda_2 \ldots$, simultaneously. Laser λ_0 gets amplified in the Yb-doped gain fiber, and then transfers power to $\lambda_1, \lambda_2 \ldots$ in the Raman gain fiber successively. Since λ_0 is at the center of the Yb gain spectrum, parasitic lasing and ASE are not the issues. Since the Raman seed lasers and pump laser propagate in the core of the same fiber, the demanding WDM is avoided.

Figure 1 illustrates the setup for a proof of principle experiment. The seed laser is a linearly polarized 1120 nm Raman fiber laser [9], which emits the residual 1070 nm pump laser as well. The power ratio of the two wavelengths varies with the total output power (details shown in Table 1). The seed light is coupled into the amplifier with a polarization maintaining (PM) $(6+1) \times 1$ pump and signal combiner. Other ends of the combiner (105/125 μm fiber) are connected to six 976 nm laser diodes. The measured available pump power is 390 W after the combiner. The gain fiber is 4 m of PM double clad YDF with a core diameter of 10 μm, a numerical aperture of 0.075, a cladding diameter of 125 μm, and a nominal cladding absorption of 4.8 dB/m at 976 nm. A piece of 20-m-long germanium-doped fiber (GDF) with matching parameters is spliced after the YDF as a Raman converter. A homemade cladding mode stripper (CMS) is used to remove the residual pump light. The output fiber is cleaved at an angle of 8° to suppress the parasitic oscillation. The output spectra are analyzed with an optical spectrum analyzer (AQ6370, YOKOGAWA).

According to the emission spectra of YDF, the gain at 1070 nm is much higher than 1120 nm and the 1070 nm laser will get amplified greater than the 1120 nm laser

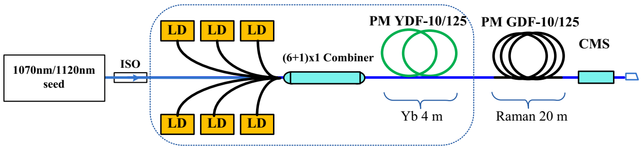

Fig. 1. Schematic diagram of the laser system.

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Table 1. Details of the Amplifier Results[a]

Seed power [W]	4.75	6	7.3	10	17	21.8	30.8	39.2
Seed 1120 nm ratio [%]	44.5	55.1	65.1	73	85.3	88.0	91.6	94.0
YDF 1120 nm ratio [%]	9.5	13.8	17.3	23.5	36.9	42.6	49.7	51.1
YRFA 1120 nm ratio [%]	78.5	84.3	87.3	90.7	94.6	95.6	96.8	98.5
Total output power [W]	259	259	260	262	266	269	275	301

[a] Seed and final amplifier output powers, 1120 nm ratio of the seed, the YDF part of the amplifier, and the final output are shown.

after the YDF. In the Raman fiber, the 1070 nm power would Raman-transfer to 1120 nm gradually.

A standard differential equation model is built to simulate the YRFA. The fiber amplifier is naturally divided into two parts: the 4-m-long YDF amplifier and the 20-m-long GDF Raman amplifier. In the first part, both Yb and Raman amplification exist. Considering a fiber amplifier with pump light going from the left, seeded by 1070 and 1120 nm lasers from the left, the following equations read in Eq. (1):

$$\begin{aligned}
\frac{dP_p}{dz} &= (N_2\sigma_p^e - N_1\sigma_p^a)\Gamma_p P_p - \alpha_p P_p,\\
\frac{dP_{s71}}{dz} &= (N_2\sigma_{s71}^e - N_1\sigma_{s71}^a)\Gamma_s P_{s71} - g_p P_{s71}P_{s121} - \alpha_{s71}P_{s71},\\
\frac{dP_{s121}}{dz} &= (N_2\sigma_{s121}^e - N_1\sigma_{s121}^a)\Gamma_s P_{s121} + g_s P_{s71}P_{s121} - \alpha_{s121}P_{s121},\\
\frac{dP_{si}}{dz} &= (N_2\sigma_{si}^e - N_1\sigma_{si}^a)\Gamma_s P_{si} - \alpha_{si}P_{si}\\
&\quad i = 1\cdots 131,\ \text{exclude}\ 71, 121,\\
\frac{dP_{si}}{dz} &= -(N_2\sigma_{si}^e - N_1\sigma_{si}^a)\Gamma_s P_{si} + \alpha_{si}P_{si} \quad i = 132\cdots 262.
\end{aligned} \tag{1}$$

In the simulation, forward and backward ASE have been included by dividing a continuous spectral region (1000–1130 nm) into discrete spectral channels with spectral width of 1 nm. P_p is the power of the 976 nm pump light and P_{si} is the power of the ith wave. N_1 and N_2 are the ground and excited state populations, respectively. P_{s71} and P_{s121} stand for the signal light at 1070 and 1120 nm, respectively. z is the location along the fiber. σ_p^e and σ_p^a are the emission and absorption emission cross sections for the 976 nm pump light. σ_{si}^e and σ_{si}^a are the absorption and emission cross sections for the ith channel signal light. Γ_p and Γ_s are the overlap factors between the light-field modes and the Yb^{3+} distribution, which are 6.4×10^{-3} and 0.69. α_p and α_{si} are loss coefficients of the pump and ith channel signal light in the YDF fiber, which are set to 0.09 and 0.0046 m^{-1}, respectively. g_p and g_s are Raman gain coefficients at 1070 and 1120 nm, which are set to 0.00071 and 0.00068 $\mathrm{m}^{-1}\,\mathrm{W}^{-1}$, respectively, in the simulation.

In the second part, only stimulated Raman scattering takes place, where α_{s71} and α_{s121} are the loss coefficients for the 1070 and 1120 nm laser in the GDF fiber, which are set to 0.0018 m^{-1} and 0.0015 m^{-1}, respectively, and the Raman gain coefficients are considered to be the same as that of the YDF, since the GDF fiber has matching parameters.

$$\begin{aligned}
\frac{dP_{s71}}{dz} &= -g_p P_{s71}P_{s121} - \alpha_{s71}P_{s71},\\
\frac{dP_{s121}}{dz} &= g_s P_{s71}P_{s121} - \alpha_{s121}P_{s121}.
\end{aligned} \tag{2}$$

First, the YDF part of the amplifier is simulated with different seed lasers: a single wavelength laser at 1120 nm with a power of 40 W, and a dual wavelength laser at 1070 and 1120 nm with powers of 2 and 38 W, respectively. As is depicted in Fig. 2, at a pump power of 375 W, for the first case, the forward and backward ASE intensities are only 31 and 22 dB lower than the signal light. For the second case, the forward and backward ASE intensities are 55 and 42 dB lower than the signal light, which means that the ASE was effectively suppressed by dual wavelength seeding. In the corresponding experiments, with single wavelength seed, only a 70 W 1120 nm laser could be achieved before the onset of parasitic lasing. Further increase of pump power leads to damage to the amplifier. With the dual wavelength seed, the amplifier can be raised to full power without a problem.

The output from the YDF part of the amplifier is the input for the Raman part of the amplifier. The signal and pump power distributions along the fiber are then calculated for understanding the laser power evolution inside the YRFA. As shown in Fig. 3(a), with a dual wavelength seed laser at 1070 and 1120 nm (2 and 38 W, respectively), at full pump power, in the first 2.7 m of the YDF, both the 1070 and 1120 nm lasers are amplified. Then, the 1070 nm laser reaches a maximum and starts to roll over, because the Raman conversion from 1070 to 1120 nm becomes significant. At the end of the YDF, the power of the 1070 and 1120 nm lasers are 111 and 196 W, respectively. When the dual-wavelength laser propagates along the 20 m GDF, Raman shift continues. At the output end, the power ratio of the 1120 nm laser is

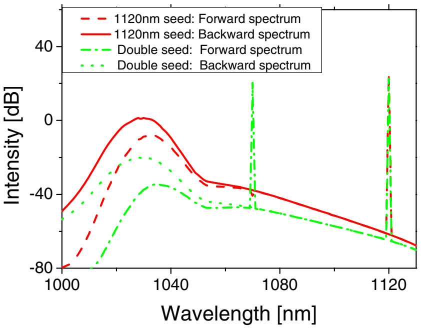

Fig. 2. Simulated forward and backward output spectra of a YDF amplifier with a 1120 nm only seed and a 1070 and 1120 nm dual-wavelength seed.

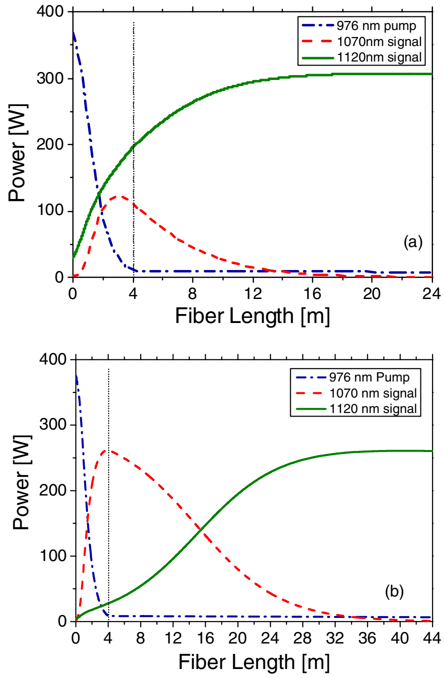

Fig. 3. Simulated 976, 1070, and 1120 nm laser power distribution along the fiber within a YRFA with (a) 38 W 1120 nm and 2 W 1070 nm seed and (b) 4 W 1120 nm and 2 W 1070 nm seed.

calculated to be over 99%. When the seed laser consists of only 4 W 1120 nm and 2 W 1070 nm lasers, they are amplified to be 28 and 262 W, respectively, in the YDF part of the amplifier, as shown in Fig. 3(b). The fraction of the 1120 nm laser is reduced to be only 9.6%. Raman conversion from 1070 to 1120 nm happens in the following GDF. After 20 m, the ratio of the 1120 nm increases to 84%. If one doubles the length of the GDF to 40 m, the 1120 nm ratio reaches well over 99% at the end of the amplifier.

In the experiment, the maximum seed laser power is 39.2 W and the spectrum is shown in Fig. 4. The 1120 nm power ratio is calculated to be 94%. The YDF part of the amplifier is studied at first. A 1 m GDF is spliced to the end of the YDF as the delivery fiber. The YDF amplifier has higher gain at 1070 nm than at 1120 nm; therefore, the ratio of the 1120 nm laser decreases to 51.1%, as deduced from the spectra in Fig. 4.

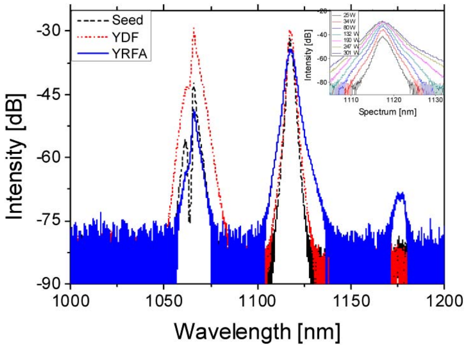

Fig. 4. Spectra of the dual wavelength seed laser, the YDF part of the amplifier, and the YRFA. Inset is the zoom-in view of laser spectra at 1120 nm at different output powers (from the bottom to the top, the output power increases).

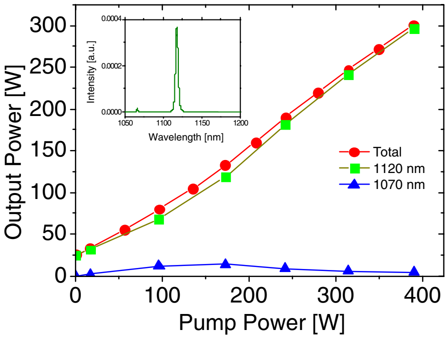

Fig. 5. 1070 nm, 1120 nm, and total output power from the YRFA as a function of the pump power. Inset: the output spectrum in a linear scale at the maximum output power.

After that, the 1 m GDF delivery fiber is replaced by a 20 m GDF to construct an YRFA. A maximum output of 301 W is achieved, as shown in Fig. 5, and that is limited by the available pump power. According to the spectra depicted in Fig. 4 (in dB scale) and in the inset of Fig. 5 (in linear scale), the 1120 nm power ratio is calculated to be 98.5%. The second order Raman Stokes at 1180 nm is observed and, however, remains trivial (<0.05%). Note that when the wavelength conversion is over several Stokes components the higher order Stokes could cause incomplete conversion between the pump light and the final Stokes, but it can be mitigated by optimizing the power of seed lasers at different Stokes wavelengths and Raman gain fiber length, or even using filter fiber [5]. The optical efficiency reaches 70%, which is much higher than the reported 1120 nm oscillator [7]. The 1120 nm laser spectra under different output power are shown in the inset of Fig. 4. The linewidth of the 1120 nm laser broadens from 1.6 nm (seed linewidth) to 3.3 nm (amplifier linewidth at an output power of 300 W) and the spectral broadening is mainly due to the four-wave-mixing between numerous longitudinal modes associated with a long fiber [10]. The polarization extinction ratio of the laser is measured to be 18 dB at an output power of 50 W. Measurement at higher power is limited by the power handling of the setup. The time domain characteristic of the laser is examined with a high speed oscilloscope (1 GHz bandwidth) and no sign of self-pulsing is observed.

It is interesting to know how the power ratio of the 1120 and 1070 nm lasers evolves in the YRFA. Therefore, the YRFA is studied with different seed laser power, which have different power ratios of the two wavelengths as well (Table 1). Figure 6 shows the 1120 nm power ratio after the YDF part of the amplifier as a function of the pump power at different seed levels. When the pump power is low, the Yb gain dominates the amplification process. The 1070 nm laser will grow faster for higher gain than the 1120 nm laser. The fraction of the 1120 nm laser decreases quickly. When the pump power increases the 1070 nm laser power increases, as well as the Raman gain for 1120 nm. As a result, the 1070 nm laser is partly Raman-shifted to 1120 nm through the YDF and the 1 m GDF, so the 1120 nm ratio keeps almost constant. Figure 7 shows the 1120 nm power ratio as a function of the pump power for the complete YRFA. When the pump power is lower than 100 W, the 1120 nm laser ratio

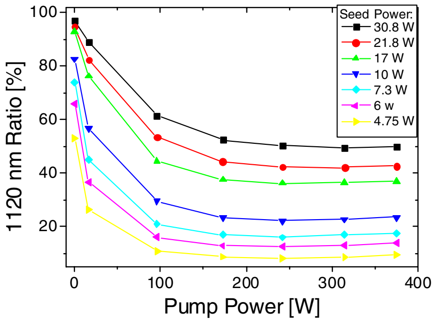

Fig. 6. 1120 nm power ratio as a function of the pump power at different seed powers for the YDF part of the amplifier (1 m GDF fiber is spliced as the delivery fiber).

drops rapidly as in the case of the YDF part of the amplifier. However, when the pump power increases to above 100 W, the Raman shift between the two wavelengths becomes significant and, as a result, the 1120 nm ratio increases. When the injected seed power is 30.8 W, the 1120 nm ratio at the highest output power reaches 96.8%. For the lower injected seeds, the 1120 nm ratio of the final output is lower, but it can be improved by increasing the length of Raman fiber as seen in the numerical simulation. The detailed output results are listed in Table 1. In the case of the highest seed power of 39.2 W, the total output power is measured at a pump power of 390 W, while the others are measured at a pump power of 375 W.

Here, we have demonstrated a 300 W level YRFA, which is limited by the available pump power. Since Yb fiber master oscillator power amplifiers (MOPAs) can now produce kilowatts or even tens of kilowatts output [11], power scaling of the proposed YRFA to more than kilowatt level is rather straightforward by replacing the master oscillator with a dual wavelength laser. Compared with the architecture used in ref. [5], the demanding single mode WDM component is avoided and the pump and signal are combined with a multimode fiber component. Such devices allowing input of more than a kilowatt of diode laser are commercially available. The proposed YRFA architecture can also be used for cascade Raman fiber laser generation, by using a multi-wavelength seed laser whose wavelengths are separated by the Raman shift of the fiber.

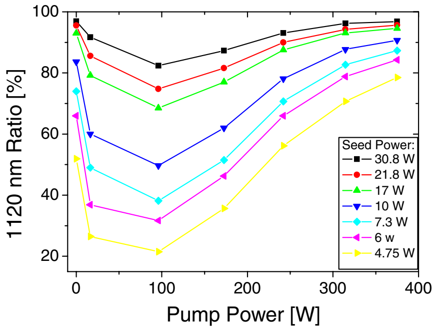

Fig. 7. 1120 nm power ratio as a function of the pump power at different seed powers for the complete YRFA.

In summary, we have proposed an integrated YRFA architecture for the power scaling of Raman fiber lasers. In a proof of principle experiment, we have demonstrated a 300 W level all-fiber linearly polarized single-mode YRFA at 1120 nm, limited only by the available pump power. In view of the current state of high power Yb fiber laser and amplifier, power scaling of a Raman fiber laser into kilowatt level can be done with the proposed architecture.

References

1. E. M. Dianov, J. Lightwave Technol. **20**, 1457 (2002).
2. Y. Feng, L. R. Taylor, and D. B. Calia, Opt. Express **17**, 23678 (2009).
3. M. Rekas, O. Schmidt, H. Zimer, T. Schreiber, R. Eberhardt, and A. Tünnermann, Appl. Phys. B **107**, 711 (2012).
4. C. A. Codemard, J. Ji, J. K. Sahu, and J. Nilsson, Proc. SPIE **7580**, 75801N (2010).
5. V. R. Supradeepa and J. W. Nicholson, Opt. Lett. **38**, 2538 (2013).
6. L. Zhang, J. Hu, J. Wang, and Y. Feng, Opt. Lett. **37**, 4796 (2012).
7. J. Wang, J. Hu, L. Zhang, X. Gu, J. Chen, and Y. Feng, Opt. Express **20**, 28373 (2012).
8. H. Zhang, H. Xiao, P. Zhou, X. Wang, and X. Xu, IEEE Photon. Technol. Lett. **25**, 2093 (2013).
9. J. Wang, L. Zhang, J. Zhou, L. Si, J. Chen, and Y. Feng, Chin. Opt. Lett. **10**, 021406 (2012).
10. P. Suret and S. Randoux, Opt. Commun. **237**, 201 (2004).
11. D. J. Richardson, J. Nilsson, and W. A. Clarkson, J. Opt. Soc. Am. B **27**, B63 (2010).