Bidirectional pumped high power Raman fiber laser

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Abstract: This paper presents a 3.89 kW 1123 nm Raman all-fiber laser with an overall optical-to-optical efficiency of 70.9%. The system consists of a single-wavelength (1070nm) seed and one-stage bidirectional 976 nm non-wavelength-stabilized laser diodes (LDs) pumped Yb-doped fiber amplifier. The unique part of this system is the application of non-wavelength-stabilized LDs in high power bidirectional pumping configuration fiber amplifier via refractive index valley fiber combiners. This approach not only increases the pump power, but also shortens the length of fiber by avoiding the usage of a multi-stage amplifier. Through both theoretical research and experiment, the bidirectional pumping configuration presented in this paper proves to be able to convert 976 nm pump laser to 1070 nm laser via Yb³⁺ transfer, which is then converted into 1123 nm Raman laser via the first-order Raman effect without the appearance of any higher-order Raman laser.

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1. Introduction

Lasers with wavelength ranging from 1120 to 1160 nm are attractive to applications involving the pumping of Raman fiber lasers (RFL), Tm-doped fiber lasers and Ho-doped lasers [1–3]. In 2009, Y. Feng et al. reported an 1120 nm all-fiber Raman laser with HI1060 fiber as the Raman gain material. The maximum output power was 153 W with 180 W of pumping power, reaching an optical-to-optical efficiency as high as 85% [4]. The record output power was increased to 200 W in 2012 by M. Rekas et al., employing a Raman amplifier configuration [5]. In 2013, V. R. Supradeepa et al. presented a five-stage cascade RFL pumped by a 1117nm Yb-doped fiber laser and achieved more than 200 W of power at the wavelength of 1480 nm [6]. Despite the five-stage Raman shift, the optical-to-optical efficiency still reached 65%. The power was then raised to 300 W in 2014 by themselves through refining the output of the seed laser and also increasing the pumping power [7]. However, all of the approaches mentioned above used Wavelength Division Multiplexing (WDM) as combiners of pump light and signal light, whose power tolerance confines the laser power to several hundreds of watts.

In 2014 Zhang et al. set out to further improve the output performance of RFL by proposing a Yb-Raman-mixed amplifier. This method, avoiding the usage of WDM, promises a kilowatt level output for RFL. Consequently, by adopting PM10/400 μm gain fibers, a 1120 nm 600 W RFL was accomplished [8]. Also, a 1.3 kW RFL was realized with 20/400 μm non-PM Yb-doped Raman gain fibers [9]. A further study carried out in 2014 by H. Zhang et al. reported a more compact Yb-Raman combined fiber amplifier, where the (Yb Doped Fiber)YDF serves as the Raman gain medium [10]. In the YDF, the Stokes wave is amplified by ion gain as well as the Raman gain, resulting in more efficient energy transfer, which allows a shorter fiber length in the amplifier stage than that reported in ref [9] and it is more conformable to amplify a single frequency laser in 1100-1150 nm range. Finally, a record power of 732 W of an 1120 nm laser was achieved with pump power launched at 890 W. In 2015, H. Zhang et al. reported 1.5-kW Yb-Raman Combined Nonlinear Fiber Amplifier at 1120 nm [11].

In order to further raise the power of the ~1120 nm RFL, the pumping power should be increased. The most direct solution to that includes enhancing the brightness of the pump source. The increase of forward pump laser power might easily act as a stimulus to second or even higher order Raman laser. Thus, the contradiction between raising pump power and avoiding high order Raman effect is the vital factor that limits the output power of Raman laser. The Raman effect is strongly influenced by the length of fiber and also the distribution of pump power along fiber. To be specific, higher order Raman effects will be more evident with longer fiber. In addition the Raman effect threshold of backward pumping configuration is higher than that of forward pumping configuration. Consequently, in order to solve the contradiction mentioned above, extremely high pump powers needs to be launched in a short fiber. Since the output power of single-end pumping is confined, the bidirectional-pumping configuration might be an alternative solution. Nevertheless, the non-wavelength-stabilized LDs is currently not capable of being applied to the high power bidirectional pumping since the pumping wavelength will shift with working current [12], leaving plenty of unabsorbed pump power endangering the laser diodes in the opposite direction.

In this paper, we present an approach to achieve a high power RFL, which consists of a single-wavelength seed and one-stage bidirectional pumped amplifier. The seed is a 1070 nm fiber laser oscillator. The amplifier is pumped by 976 nm non-wavelength-stabilized LDs in
bidirectional pumping configuration with our developed refractive index valley (RIV) side-pump combiner which can suppress the backward coupling laser [13]. This ensures the bidirectional-pumping configuration can endure pumping power of over 5 kW with more than 2.5 kW in both forward and backward direction. Firstly, the amplifier magnifies the 1070 nm seed laser with the 976 nm pump laser. The 1070 nm laser is then converted into 1123 nm Raman laser via nonlinear effect. The conversion efficiency and output power is controlled by adjusting the distribution of pump power in the bidirectional pumping configuration and the length of gain fiber. As a result, with 976 nm pump power launched at 5487 W, the output power of the 1122.8 nm RFL reached 3889 W with the beam quality factor $M^2 = 1.49$, along with an optical-to-optical efficiency of 70.9%. To the best of our knowledge, this is the highest power reported.

2. Experiment setup

In the experiment, the RFL consists of two stages: a laser oscillator stage and an amplifier stage. All the components were connected by fusion splices. The experimental setup is shown in Fig. 1. The laser oscillator is composed of a double clad YDF, a 7 × 1 end-pumped combiner and a pair of fiber Bragg gratings with 1070 nm center wavelength. A core and inner clad diameter of the YDF was 20 μm (NA = 0.06) and 400 μm (NA = 0.46), respectively. A length of the YDF is 20 m. A cladding light stripper (CLS) is set between the oscillator and the amplifier to leak the residual pump light and signal light in the cladding. The power amplifier stage consists of a 30 m long double clad YDF (the same as that in the oscillator stage), two (6 + 1) × 1 RIV side-pumped combiners, a CLS and an end cap. The output facet of the end cap is coated with antireflection coating at 1070-1140 nm Raman wavelength where the reflection is lower than 0.5%. For the RIV combiner, the core and clad diameter of the pumping fiber is 200 μm (NA = 0.22) and 220 μm, respectively. The signal fiber of the combiner has an inner clad diameter of 400 μm (NA = 0.46), and a core diameter of 20 μm (NA = 0.06). The pumping LDs in the amplifier stage were divided into four groups, with three LDs in each group, labeled as Forward A, B and Backward A and B (Abbreviated as F-A, F-B, B-A, B-B, respectively). The sum of the pumping power of each group is approximately 1.2 kW.

The center fiber of 7 × 1 end-pumped combiner, instead of being spliced to any LD, was connected to a laser power meter to monitor the backward propagating laser power, which will be coupled into only the center signal fiber. The pump fiber of the RIV combiner was spliced to a pigtai fiber of the pump LD. In the oscillator, only six LDs each with an output power of 200 W were combined by the combiner, and among them merely two were launched. In the amplifier, each LD provides approximately 400 W of output power through a pigtai fiber of 200/240 μm (NA = 0.22). The LD is non-wavelength-stabilized, whose wavelength of output laser varies with the working wavelength, as depicted in Fig. 2, with the coolant temperature set at 21°C. The output power and central wavelength is 34 W and 968 nm at 1A, and 420 W and 976 nm at 10 A. As demonstrated in ref [14], free-running LDs are characterized by a pronounced wavelength shift, which depends on the output power and therefore on the diode current. Due to that, a significant amount of unabsorbed pump power at
medium power level will be observed, as shown in Fig. 3. When the driving current of the six laser diodes in forward pumping in the power amplifier stage (400 W output from each LD) rises from 1 to 10 A, the unabsorbed pump power first reaches its peak at 6 A of 395 W. Then, at 10A, the central wavelength of the pump laser matches the absorption peak of Yb$^{3+}$, resulting in an unabsorbed pump power of only 8 W. The 395 W pump laser left unabsorbed will put the LDs in the bidirectional pumping configuration at stake.

![Fig. 2. Wavelength shift in non-wavelength-stabilized LD.](image)

![Fig. 3. Variation of unabsorbed pump power depending on the diode current.](image)

This also explains why most experiments that use non-wavelength-stabilized LD employ single directional pumping configuration. Nevertheless, the $(6 + 1) \times 1$ side pump combiner used in this paper was developed by ourselves, with the RIV configuration. The schematic of the side-pumped coupler which consists of a double clad(DC) fiber and a multimode(MM) pump fiber with a silica-clad doped with fluorine and a tapered section [13]. The silica-clad doped with fluorine is between the core of MM pump fiber and the inner-clad of DC fiber. The refractive index of silica-clad doped with fluorine is smaller slightly than that of MM fiber core and DC fiber inner-clad, so the cladding of MM pump fiber forms a RIV between the core of MM pump fiber and the inner-clad of DC fiber. The whole length of tapered MM pump fiber is converged with the inner-clad of DC fiber, forming the coupling region. When the light in the DC fiber transmits through the coupling region, and the transmission direction is opposite to the pumping direction, the light with small propagation angle may be resisted by the RIV, and cannot be coupled into the pump fiber. Therefore, the $(6 + 1) \times 1$ side pump combiner is able to restrain backward lasing, providing protection for the pumping LDs, thus making it suitable to high power bidirectional pumping configuration of fiber lasers and also keeps the system operating properly with residual pump power.
3. Numerical simulations

The Raman laser amplification feature in the bidirectional pumping configuration is analyzed based on the theoretical model presented in ref [10], and we upgraded the model by taking second-order Raman effect into consideration.

\[
\frac{N(z)}{N} = \frac{\left[ P_p(z) + P_s(z) \right] \sigma_{r1} P_p(z) + \left[ P_p(z) + P_s(z) \right] \sigma_{r2} \left( P_p(z) + P_s(z) \right) + \Gamma_{s,1} \sigma_{s1} \left( P_p(z) + P_s(z) \right) + \Gamma_{s,2} \sigma_{s2} \left( P_p(z) + P_s(z) \right)}{\nu A} \left( \left[ P_p(z) + P_s(z) \right] \sigma_{r1} P_p(z) + \left[ P_p(z) + P_s(z) \right] \sigma_{r2} \left( P_p(z) + P_s(z) \right) \right) + \Gamma_{s,1} \sigma_{s1} \left( P_p(z) + P_s(z) \right) + \Gamma_{s,2} \sigma_{s2} \left( P_p(z) + P_s(z) \right)}{\nu A} 
\]

(1)

\[
\pm \frac{dP_p(z,v_s)}{dz} = -\Gamma_{p} \left[ \sigma_{r1} N - \left( \sigma_{s1} + \sigma_{s2} \right) N_s(z) \right] P_p(z) - \alpha_{p} P_p(z) + 2\Gamma_{p} \sigma_{s1} N_s(z) \frac{h c^2}{\lambda_p} \Delta \lambda
\]

(2)

\[
\pm \frac{dP_s(z,v_s)}{dz} = -\Gamma_{s1} \left[ \sigma_{s1} N - \left( \sigma_{s1} + \sigma_{s2} \right) N_s(z) \right] P_s(z) - \alpha_{s1} P_s(z) + \frac{\lambda_{s1} \Delta \lambda}{\lambda_{s1} A_{\text{eff}}} \left[ P_{s1}^p(z,v_{s1}) + P_{s2}^p(z,v_{s1}) \right] \frac{h c^2}{\lambda_{s1}} \Delta \lambda
\]

(3)

\[
\pm \frac{dP_{s2}(z,v_{s1})}{dz} = -\Gamma_{s2} \left[ \sigma_{s2} N - \left( \sigma_{s1} + \sigma_{s2} \right) N_s(z) \right] P_{s2}(z,v_{s1}) - \alpha_{s2} P_{s2}(z,v_{s1}) + \frac{\lambda_{s2} \Delta \lambda}{\lambda_{s2} A_{\text{eff}}} \left[ P_{s1}^p(z,v_{s1}) + P_{s2}^p(z,v_{s1}) \right] \frac{h c^2}{\lambda_{s2}} \Delta \lambda
\]

(4)

\[
\pm \frac{dP_{s3}(z,v_{s1})}{dz} = -\Gamma_{s3} \left[ \sigma_{s3} N - \left( \sigma_{s1} + \sigma_{s2} \right) N_s(z) \right] P_{s3}(z,v_{s1}) - \alpha_{s3} P_{s3}(z,v_{s1}) + \frac{\lambda_{s3} \Delta \lambda}{\lambda_{s3} A_{\text{eff}}} \left[ P_{s1}^p(z,v_{s1}) + P_{s2}^p(z,v_{s1}) \right] \frac{h c^2}{\lambda_{s3}} \Delta \lambda
\]

(5)

Here, subscript p, s, R1 and R2 stand for the parameters of pumping laser, signal laser, first-order 1123 nm Raman laser and second-order 1181.2 nm Raman laser, respectively.

In the simulation, due to the output facet of the end cap coated with antireflection coating, the power of the backward propagating laser is so little that the feedback of the output end can be neglected. The output power of the fiber laser oscillator is 290 W and the central wavelength is 1070 nm with a bandwidth of 1 nm@3 dB. The spontaneous Raman scattering at 1123 nm, i.e. the raman noise, generated from the oscillator serves as the seed of Raman amplification. The raman noise takes up a small fraction (typically $10^{-6}$) [15]. So the raman noise power is about $290 \times 10^{-6} = 0.29\text{ mW}$, which is used in the calculation as the seed power for RFL. The parameters for the fiber and pumping lasers are shown in Fig. 1. The 20/400 μm Yb-doped double-clad fiber employed in the amplifier stage has an absorption coefficient of 1.26 dB/m@975nm, and the length of the fiber is chosen as 30 m. The pumping
LD, whose central wavelength is 976 nm, has a bandwidth of 4 nm@3 dB. The Raman gain coefficient is set to be $0.5 \times 10^{-13}$ m/W.

Figure 4 presents results with 2.4 kW of pump power in both directions. The laser power variation with fiber length can be divided into three sections. The first one is from 0 to 17 m, namely the below-Raman-threshold section, where the 1070 nm laser power is lower than the Raman threshold and therefore there is almost no 1123 nm Raman laser generated. The second section, from 17 to 18 m, is named the threshold section, during which the 1070 nm laser power rises slightly above the threshold, causing a slow growth in the 1123 nm Raman laser. The last section, or the amplifying section, begins at 18 m. In this section, the 1123 nm Raman laser power is rapidly amplified and eventually outruns the 1070 nm laser power, the ratio of the 1123 nm laser power to the total output power is approaching 100%. The second-order 1181.2 nm Raman laser is calculated to be 41 μW, which can be neglected compared to the total output power.

![Figure 4](image1.png)

**Fig. 4.** The calculated power distribution of the 1070 nm, 1123 nm and 1181.2 nm lasers along the fiber (2.4 kW of pump power in both directions).

In order to determine whether the 1070 nm Yb$^{3+}$ energy transfer or the stimulated Raman effect has acted as the main pump source for the 1123 nm laser, the absorption and emission cross section are set to 0 @1123 nm, with 2.4 kW pump power in both forward and backward pumping. The result of this calculation is depicted in Fig. 5. Compared to Fig. 4, it is clear that with the Yb$^{3+}$ energy transfer neglected, the 1123 nm laser output power is 4310 W, only 122 W less the original situation.

![Figure 5](image2.png)

**Fig. 5.** The calculated power distributions of 1070 nm, 1123 nm and 1181.2 nm laser along the fiber. (The absorption and emission cross section are set to 0@1123nm).
If the Raman gain is set to 0, the 1123 nm laser in the seed laser is set to noise power level and 1070 nm laser powers is set to 290 W, then after the amplification of 30 m gain fiber, the 1070 nm laser power will arrive at 4500 W, while the 1123 nm laser will be hardly effected, as shown in Fig. 6(a). If both 1123 nm and 1070 nm laser powers in the seed laser are 290 W, then most of the pump power will be distributed to the 1070 nm laser, resulting in an 1070 nm laser power of 3800 W and an 1123 nm laser power of 965 W, as presented in Fig. 6(b). Comparing Fig. 5 and Fig. 6(b), it is safe to conclude that the majority of the 1070 nm laser is converted into 1123 nm laser through stimulated Raman effect, while direct pumping form the 976 nm and 1070 nm only participate in part of the total output. According to the theoretical analysis above, the 1123 nm SRS laser output can reach higher than 4 kW with 2.4 kW pump power in both forward and backward pumping using the structure in Fig. 1.

![Fig. 6. The calculated power distributions of the 1070 nm, 1123 nm and 1181.2 nm lasers along the fiber (the Raman gain is set to 0, (a)1123 nm and 1181.2 nm laser in the seed laser is set to noise power level, (b)1123 nm laser powers in the seed laser are 290 W, 1181.2 nm laser in the seed laser is set to noise power level).](image)

4. Experiment result

Experimental work, as shown in Fig. 1, was performed in order to verify the theoretical calculations. In the experiment, the LDs were used to pump at a power of 5487 W in both the oscillator and amplifier stage resulting in an output power of 4035 W. This includes 3889 W from the Raman laser and thus accounts for 96.4% of the total power as well as the residual unconverted 1070 nm laser, as shown in Fig. 7. The curve doesn't show any signs of saturation, indicating potential for further power scaling. The overall optical-to-optical efficiency of the all-fiber laser was 70.9%. Also, the maximum backward laser power was measured to be 7.8 W when the output Raman laser power reached 4 kW, which was negligible compared to the total output power.
A 1070 nm laser power of 290 W was obtained from the oscillator with pump power of 425 W, corresponding to an optical efficiency of 68.2%. In the amplifier stage, the output power increased by 3745 W with the pump power of 5062 W, leading to an extraction efficiency in the amplifier stage of 74.0%.

The output spectrum of the RFL is depicted in Fig. 8. The spectrum includes two peak wavelengths, which originate from the signal laser and the first-order Raman laser. No second or higher order Raman laser was shown, suggesting that the majority of the signal laser was transformed into the first-order Raman laser. The central wavelength of the remaining signal laser and Raman laser is 1070.0 nm and 1122.8 nm, with 3 dB bandwidth of 3.6 nm and 10.6 nm, respectively. Integration of the spectral data allows the Raman laser power to be calculated and is found to make up 96.4% of the total output power. Accordingly, the 1122.8 nm Raman laser power was 3889 W. Since this CLS could not withstand the full power, the data shown in Fig. 4 is measured without CLS. That is why significant amount of 1070 nm laser exists in the total laser output.

The 3dB bandwidth of the Raman laser spectrum starts at 1117.5 nm and ends at 1128.1 nm. The frequency shifts of Raman laser compared to 1070 nm signal laser range from 11.91 THz to 14.43 THz with a center frequency shift of 13.18 THz which matches the Raman gain spectrum. Therefore, the 1123 nm laser generated in this experiment is transferred through Raman effect from 1070 nm. The reason for the relatively wide output spectrum is mainly due to the structure of the RFL. In the experiment, the RFL consists of two stages: a laser
oscillator stage and an amplifier stage. The seed fiber laser oscillator provided 1070 nm signal laser, and also spontaneous Raman scattering at 1123 nm, i.e. Raman noise, both of which were injected into the amplifier. In this experiment, no high power 1120 nm Raman seed laser was employed. Instead, the Raman noise served as the seed for the RFL amplifier stage with power of about 0.29 mW. The low Raman seed laser power limited the ability of controlling the output wavelength of RFL.

In addition, we compared the output spectrums of different pumping power distributions. With 290 W of seed laser from the oscillator stage, the output spectrums of the system in different pumping power distributions were compared in Fig. 9. Figure 9(a) presents the spectrum of the output laser from the amplifier with seed power of 290 W and no pump power in the amplifier stage. The output is found to consist of a pure 1070 nm signal laser with 3 dB width of 1.1 nm. Figure 9(b) depicts the result with the same seed power and 1.2 kW of pump power from F-A. It can be shown from the spectrum that part of the signal laser was Raman shifted to the first-order Raman laser, although it only makes up 0.4% of the total power. However, as Fig. 9(c) indicates, the Raman effect did not occur in the backward pumping configuration with the same pump power. In fact, it was not until the backward pump power reached 2.4 kW that the Raman laser appeared, with a signal peak power of 871 times that of the Raman laser, as shown in Fig. 9(d). If the amplifier is pumped by both F-A and B-A, each with 1.2 kW, the Raman effect becomes obvious, as depicted in Fig. 9(e). Despite the fact that the peak power of the signal laser was still 60% higher than that of the Raman laser; the percentage of Raman power rises to 60.1% of the output power. This results from the bandwidth of Raman laser at 3 dB of 7.2 nm, which is 2.8 nm wider than that of the 1070 nm laser. Figure 9(f) depicts the output spectrum when raising the backward pumping power to 2.4 kW while maintaining the forward pumping power. The difference between the peak powers diminished to 0.1 dB. The bandwidth at 3 dB of signal and Raman laser was 2.8 nm and 7.0 nm respectively whilst the power percentage of the Raman laser was 70.1%.

Nevertheless, if the backward pumping power was maintained at 1.2 kW whilst increasing the forward pumping power to 2.4 kW, the Raman laser was significantly magnified by the Raman shifting from the 1070 nm laser, as shown in Fig. 9(g). The peak power of the Raman laser was 4.79 times as high as that of signal laser. With the bandwidth at 3 dB of 1070 nm laser and Raman laser being 2.9 nm and 7.6 nm, the power of the Raman laser accounted for 95.1% of the total power. Finally, all of the pumping LDs in the amplifier stage were put to use, providing a sum of 4.8 kW pumping power. The output spectrum is presented in Fig. 9(h) and Fig. 8.

We also managed to measure the beam quality factor $M^2$ of the output laser at different power levels, as depicted in Fig. 10. The measurement was carried out via a PRIMES High-Power-LaserQualityMonitor. Since there are two wavelength components in the output spectrum, the working wavelength was set to the wavelength that occupies the majority of the output power to minimize measurement error. When the output power reached 4 kW, the beam quality arrived at $M^2 = 1.49$. This fine beam quality at high power level was mainly attributed to the excellent beam quality of the fiber oscillator and the precise alignment of fiber cores in the fusion splicing process, preventing high-order mode excitation. As for the amplifier, high-order modes were suppressed through lowering the fiber temperature to moderate thermal-induced refractive index change. The temperature was brought down through bidirectional pumping configuration and elaborate design of heat dissipation.
The beam quality remained fine at low power level as the $M^2$ factor stayed below 1.3. However, once the output power exceeded 3.3 kW, a deterioration of the beam quality was observed while the $M^2$ factor suddenly rose to 1.48 and was measured to be 1.49 when the output power reached its peak. This abrupt degeneration might be due to the active fiber that has a core diameter of 20 μm and NA of 0.06 and is capable of containing one fundamental mode and two differently polarized high-order modes. The majority of the output laser resided in fundamental mode of excellent beam quality at low power level and in high-order modes when the power grew high. In addition, this phenomenon might also be caused by mode instability. However, limited by the lack of measurement instruments, e.g. high speed camera, we were unable to make a thorough investigation. Further researches will be focused.
on this issue. Besides, the RFL adopts the bidirectional pumping configuration where the high power pumping laser was injected into the active fiber through two opposite ends. Compared to single directional pumping configuration where the active fiber temperature grows high near the single pump end, it disperses the temperature rise into two ends and thus effectively lower the generated heat per unit length along the active fiber, contributing to the suppression of the onset of mode instability [16]. Therefore, whether this sudden deterioration in beam quality originated from mode instability requires further investigation.

![Graph](image-url)

Fig. 10. The beam quality factor of the output laser at different output power.

5. Conclusion

In summary, we have demonstrated a 3.89 kW, 1123 nm RFL pumped by 976 nm non-wavelength-stabilized LDs, which consists of a single-wavelength seed and one-stage bidirectional pumped YDF amplifier. In the experiment, the \((6 + 1) \times 1\) side pump combiner with RIV has the functionality of preventing the backward pump laser from entering LDs, ensuring that the bidirectional pumping configuration can withstand pumping power of in excess of 5 kW and more than 2.5 kW in both forward and backward pumping. Theoretical analysis shows that the amplifier magnified the 1070 nm seed laser with the 976 nm pump laser. The 1070 nm laser is converted into 1123 nm Raman laser via nonlinear effect and Yb\(^{3+}\) energy transfer. It is our conclusion that the majority of the 1070 nm laser is converted into 1123 nm laser through stimulated Raman effect, whilst the 976 nm and 1070 nm direct pumping only participates in part of the total output. Future work will concentrate on the further power scaling of RFL.

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