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First Demonstration of Co-Pumped Single-Frequency Raman Fiber Amplifier With Spectral-Broadening-Free Property Enabled by Ultra-Low Noise Pumping

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ABSTRACT Single-frequency Raman fiber amplifier (RFA) has great potential applications in many regimes. Traditionally, counter-pumped manner is widely employed for its spectral linewidth broadening suppressing and maintaining single frequency property. In this paper, we propose the first demonstration of a co-pumped single-frequency RFA without linewidth broadening by applying the fiber laser with stable intensity as the pump source. The pump source with stable intensity is generated by cascaded power amplifying of a low noise, phase-modulated single-frequency seed laser. In this case, experimental results show that single frequency property of the RFA could be effectively maintained in the co-pumped manner. The contrast experiment is given with a conventional multi-longitudinal mode fiber oscillator as a pump source, and the linewidth is gradually broadened along with power scaling.

INDEX TERMS Fiber lasers, optical amplifiers, Raman scattering.

I. INTRODUCTION

As a result of their wavelength agility and power scalability, Raman fiber lasers (RFLs) have attracted intensive interests and have been widely investigated in recent years [1], [2]. It is well known that RFLs have great potential in many applications, such as frequency conversion [3]–[5], optical pumping [6], optical communications [7], supercontinuum generation [8], bio-medical detection [9], [10], and precisely spectral analysis [11]. Nowadays, several techniques have been proposed to enhance the output power, conversion efficiency and spectral purity of RFLs, including using filter fiber [12], cascaded Raman amplification [13], cladding pumped RFLs [14]–[16], and using rare-earth and Raman hybrid gains [17], [18]. Further, in some spectral-brightness-highlighted applications, single-frequency RFLs are strongly required. For example, in applications of second harmonic generation, single-frequency RFLs operating at 1.1$\sim$1.2 μm could be efficiently converted to yellow or orange light [19], which is widely used in medicine, astronomy and spectroscopy [1]. Especially, single-frequency RFLs operating at 1178 nm could be frequency-doubled to 589 nm, which has a particular application in sodium laser guide star adaptive optics [2], [20]–[24]. For the time being, single-frequency RFLs have been investigated by several groups and some impressive results have been achieved. In 2012, Vergien *et al.* realized one-stage, counter-pumped single-frequency RFA with an output power of 18 W at 1178 nm [22]. In the same year, by using two-stage, counter-pumped single-frequency RFAs operating at 1178 nm, Zhang *et al.* further scaled the output power to be 44 W [23]. In 2013, Dajani *et al.* achieved a 22 W single-frequency RFA by using special acoustic-tailed fiber for stimulated Brillouin scattering (SBS) suppression [24]. Notably that single-frequency RFA with output power of as high as 84 W has been realized quite recently [2].

It is to be noted that single-frequency RFAs above are all based on counter-pumped manner [1], [2], [22]–[24], which is often accepted and stated for spectral linewidth broadening suppressing in single-frequency RFAs. However, in counter-pumped RFAs, normally complex design should be made for protecting the backward pump power from injecting the pre-stage [22]–[24]. This issue will be more challenge for further power scaling to hundreds or even kilowatt levels. Compared with counter-pumped manner, co-pumped manner is an easier approach for higher output power scaling and the backward pump power isolation issue is automatically avoided. Besides, there is a necessity for maintaining the identical propagation directions of the pump and signal lasers in some specific styles of Raman amplification [17], [18]. In fact, the discrepancy of spectral broadening effect in co-pumped and counter-pumped manner is mainly attributed to the different pump noise transfer characteristics [25]–[27]. Specifically, linewidth broadening in co-pumped RFA is mainly caused by the strong intensity fluctuations transferred from the pump to the signal, while the pump fluctuations at high Fourier frequency would be effectively filtered in counter-pumped manner. The intrinsic physical mechanism above suggests that co-pumped single-frequency RFA may be also fulfilled by using pump source with quite stable intensity distribution.

In this manuscript, by using pump source with stable intensity distribution, we experimentally investigate and validate the linewidth-maintaining effect of the co-pumped RFA operating at $\sim$ 1120 nm as an example. The stable intensity pump source is generated by cascaded amplifying of a low noise, phase-modulated single-frequency seed laser. It is demonstrated that single-frequency RFA can be successfully realized in this case. For comparison, conventional pump source constructed by Yb-doped fiber oscillator is employed and obvious spectral broadening is observed. To the best of our knowledge, this is the first demonstration of co-pumped single-frequency RFA by optimizing the intensity stability of the pump source.

II. EXPERIMENTAL SETUP

The schematic of the single-frequency RFA in co-pumped structure is shown in Fig. 1. The seed laser (Seed1) is a single frequency one with central wavelength of $\sim$ 1120 nm and output power of 90 mW. The seed laser is firstly injected into

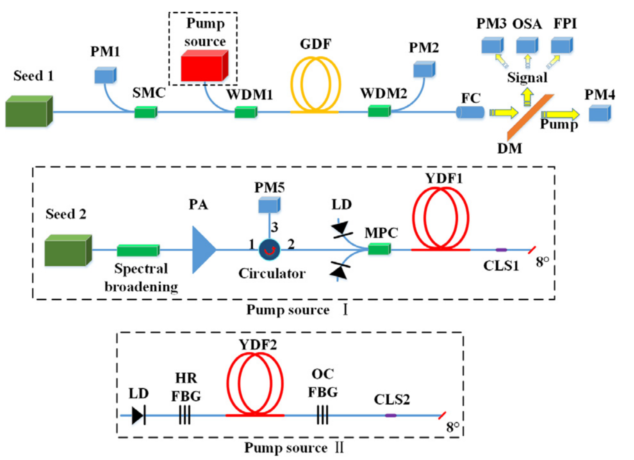

FIGURE 1. Schematic of the single-frequency RFA in co-pumped structure.

a single mode standard coupler (SMC) and then delivered into the co-pumped RFA. The output port coupling ratios of SMC to injected signal port and detector port are 99% and 1%, respectively. 1% port (PM1) is employed to detect the backward power and monitor the SBS effect. The co-pumped RFA is consisted by two wavelength division multiplexing (WDM1, WDM2), the pump source, and as long as 80 m passive fiber (GDF). The passive fiber used is a standard non-polarization-maintained single mode fiber with a core diameter of 6 μm and a cladding diameter of 125 μm, whose core attenuation at 1060 nm is less than 0.015 dB/m. The pump power is coupled into passive fiber through WDM1 for generating effective Raman amplification. The role of WDM2 is to strip out the residual pump laser at the rear end, which is collected by a power meter (PM2). The core and inner cladding diameters of signal and pump coupled ports of WDM1 and WDM2 are 10 μm and 125 μm, respectively. The mismatch of fiber types between WDMs and GDF will seriously impact the optical to optical conversion efficiency of the RFA while fortunately it is not the main focus point in this work. The output port of co-pumped RFA is spliced with a fiber collimator (FC) for beam delivery. After FC, a dichroic mirror (DM) is used for further strip out the residual pump laser. After DM, the signal laser is reflected and detected by the power meter (PM3), the optical spectrum analyzer (OSA) and the Fabry-Perot interferometer (FPI). The residual pump laser is transmitted and collected by PM4.

In the experiment, two types of pump sources are used to pump the GDF, one is narrow-linewidth, Yb-doped fiber amplifiers (YDFAs) (Pump source I shown in Fig. 1) and the other is a conventional Yb-doped fiber oscillator (Pump source II shown in Fig. 1). Pump source I is based on master oscillator power amplification configuration, which is seeded by using a low noise, single-frequency seed laser (Seed 2) with central wavelength of 1064.4 nm and output power of 40 mW [28]. Output power of Seed 2 is power amplified by two cascaded all-fiberized amplifiers. The first amplifier (PA) is a commercial one with maximal output power of 0.8 W. After pre-amplified by PA, the $\sim$ 1064 nm pump laser is further amplified by the second fiber amplifier. Two laser diodes (LDs) with individually maximal output power of 25 W and central wavelength of 976 nm are pumped the Yb-doped active fiber (YDF1) through a multi-mode pump-combiner (MPC). The core and inner cladding diameters of the YDF1 are also 10 μm and 125 μm, respectively. The cladding absorption coefficient of the YDF is about of 3.8 dB/m at 976 nm and 4 m long active fiber is used. In order to suppress SBS effect in the Raman amplification process, the spectral linewidth of the pump laser is broadened to be $\sim$ 30 GHz by using white-noise phase modulation technique [29]. Besides, an optical fiber circulator is inserted between the PA and the next fiber amplifier to monitor the SBS effect and protect Seed 2 from the backward power. Pump source II is made up of a LD, a pair of fiber Bragg gratings (HR FBG, OC FBG), and 6 m long active fiber (YDF2). The active fiber type of YDF2 is identical with

YDF1 and the LD with maximal output power of 90 W and central wavelength of 976 nm is employed to pump the active fiber for laser emission in Pump source II. Cladding light strippers (CLS1, CLS2) are used to strip the residual cladding and 976 nm pump light both in the two pump sources.

III. EXPERIMENTAL RESULTS

Firstly, the RFA is co-pumped by using Pump source I, and the output and backward power properties are shown in Fig. 2. Overall, the output signal power increases nonlinearly with the increase of injected pump power. Effective Raman power transfer could be found when the pump power is beyond 9 W, which indicates that the pump power has been well above the Raman threshold and the pump light has begun to convert to the signal light rapidly. When the pump power reaches 16 W, the output signal power is measured to be 564 mW with an optical to optical efficiency of 3.5%. From Fig. 2, it is also observed that the backward power of the co-pumped RFA is increased with the scaling of pump power. When the pump power is reached to be 16 W, the backward power ratio, which is defined as the ratio of backward power to output signal power, is just calculated to be $\sim 0.18\%$. Besides, by calculation, the backward power ratio is not increase non-linearly along with power scaling process, which indicates that the co-pumped RFA operates without suffering from SBS effect.

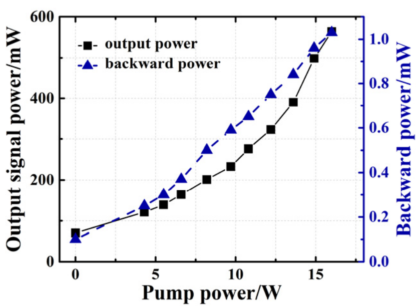

FIGURE 2. The output and backward power properties of the RFA pumped by Pump source I.

The long wavelength range output spectrum from 1050 nm to 1140 nm at 564 mW is shown in Fig. 3(a), which is measured by OSA. It is concluded that the extinction ratio (ER) between the signal power and the pump power is typically $\sim$27 dB compared to the 1064 nm pump laser. Besides, as a result of the dual functions of WDM2 and DM, the ERs of the $\sim$ 1120 nm signals detected by PM3 are all > 25 dB at different pump powers. However, because the spectral resolution of the OSA is just limited to 0.02 nm, it is difficult to measure the linewidth of the output signal light by OSA. Thus, the finite optical spectra of the $\sim$ 1120 nm signal laser at different output powers are further measured by FPI with free spectral range of 4 GHz and stated resolution of $\sim$ 10 MHz, which is shown in Fig. 3(b). From Fig. 3(b), it is shown that the spectral linewidth of the Raman amplified signal laser is broadened little along with power scaling.

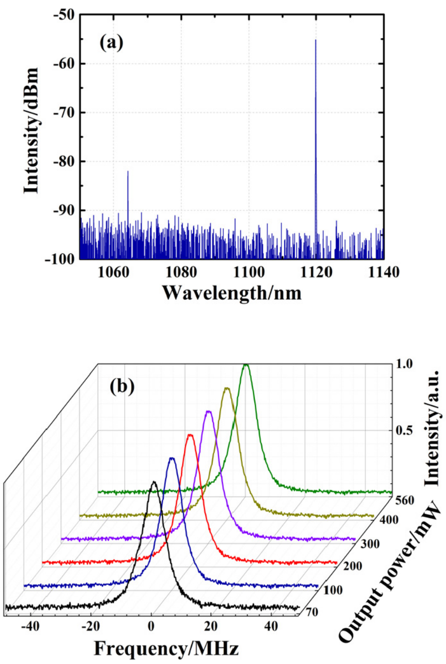

FIGURE 3. Output spectra of the RFA pumped by Pump source I: (a) long wavelength range spectrum at 564 mW measured by OSA; (b) finite spectra at different output powers measured by FPI.

By calculating, the full widths at half maximum (FWHM) of the spectra at different output powers are all about $\sim$ 9 MHz, which has been a little narrower than the stated resolution of the FPI. Thus, it could be concluded that single frequency property could be effectively maintained in co-pumped RFA by using intensity stable YDFAs seeded by phase-modulated, single-frequency fiber laser as the pump source.

In this section, the co-pumped RFA is pumped by Pump source II for comparing the differences of the output properties by using different types of pump source. In this case, the output and backward power properties of the RFA along with pump power increase is shown in Fig. 4. With the scaling of the pump power from 4 W to 17 W, the output power grows nonlinearly from 70 mW to 930 mW. At maximal output power, the optical to optical conversion efficiency is calculated to be 5.3%, which is obviously higher than

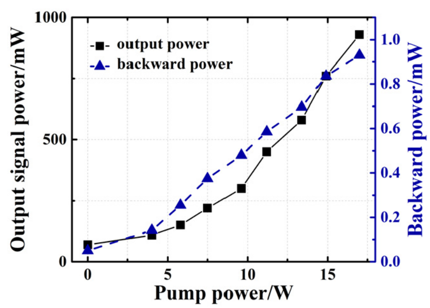

FIGURE 4. The output and backward power properties of the RFA pumped by Pump source II.

that in the RFA pumped by Pump source I. In fact, when effective Raman power transfer occurs, with near the same injected pump power, the optical to optical conversion efficiency shown below is all higher than that shown in Fig. 2. The physical origin of the difference of optical to optical conversion efficiency in co-pumped RFA is mainly caused by the different intensity fluctuations of different pump sources [25], [30]. The intensity fluctuations of pump lasers could be transferred into the Raman amplified signal completely in co-pumped manner, so the effective gain coefficient of Raman amplification would be higher when pump source with stronger intensity fluctuation is applied. The backward power of the co-pumped RFA is also increased with the increase of pump power and the backward power ratio is calculated to be $\sim 0.1\%$ when the pump power reaches to be 17 W.

By using Pump source II, in order to investigate the spectral linewidth evolution process, FPI is firstly employed for diagnosing the spectral properties. The typical normalized results at different output powers are shown in Fig. 5(a). From Fig. 5(a), it could be found that obvious spectral broadening, especially the broadening of sideband wings, are occurred along with power scaling. Compared with the spectral distribution without pump power injection ($\sim$ 70 mW), the base floor of the normalized spectra intensity at near 100 mW, 200 mW, 300 mW and 400 mW are increased to $\sim$ 0.08, 0.12, 0.20 and 0.41, respectively. Besides, the FWHM is also broadened from 9 MHz to 11.3 MHz when the output power scales from 70 mW to 300 mW. Further increase of the output power, the spectrum is broadened beyond the free spectral range of the FPI and the FWHM is difficult to precisely confirm. For further investigating the spectral broadening effect, OSA with spectral resolution of 0.02 nm is used to diagnose the detailed spectrum. The measured results are shown in Fig. 5(b). From Fig. 5(b), it could also be seen that obvious spectral broadening effect is generated along with power scaling. When the output power is below 300 mW, spectral broadening is mainly occurred at sideband wings. Further output power scaling, both the FWHM and the sideband wings are obviously broadened. At the output power of $\sim$900 mW, the FWHM is broadened to be 27 GHz.

For more intuitively comparing the discrepancy of intensity stability of the two different types of pump sources, Figs. 6(a) and (b) give the normalized temporal traces of the output intensities of Pump source I and Pump source II when the 1120 nm signal powers are set to 100 mW (trace A), 300 mW (trace B), $\sim$ 550 mW (trace C), respectively. The temporal traces shown in Fig. 6 are measured by using a high-speed, InGaAs photoelectric detector with electro-optic bandwidth of 5 GHz. The normalized intensity characteristics in a time window of 10 μs with a time resolution of 0.2 ns are displayed. As for pump source I, the intensity stability is not deteriorated along with power scaling process. The normalized standard deviations (NSDs) are calculated to be 2.97%, 2.50%, and 2.93% when the output signal powers are 100 mW, 300 mW and 550 mW, respectively. As for pump source II, the NSDs are calculated to be 8.93%, 7.64%, and 6.03% when the output signal powers are 100 mW, 300 mW and 550 mW, respectively. By comparison, the intensity fluctuations in Pump source II are obviously stronger than that in Pump source I.

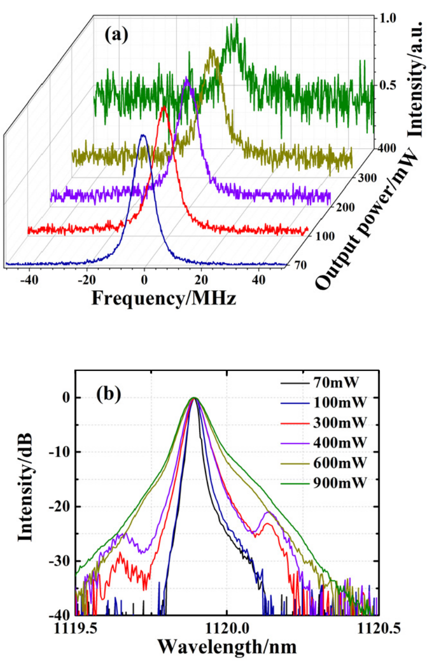

FIGURE 5. Output spectra of the RFA pumped by Pump source II: (a) output spectra measured by the FPI; (b) output spectra measured by the OSA.

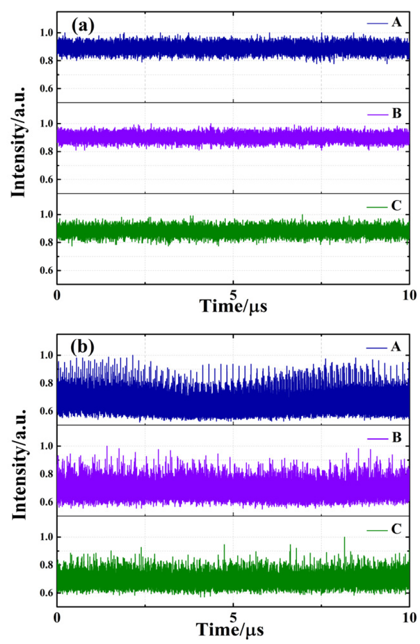

FIGURE 6. The normalized temporal distributions: (a) Pump source I; (b) Pump source II.

IV. CONCLUSION

In conclusion, the dependences of output power and spectral broadening properties of co-pumped RFA on two different pump sources with different intensity stabilities are carefully investigated and compared. Experimental results prove that co-pumped single-frequency RFA could be successfully fulfilled by using intensity stable pump source. In practice, this type of intensity stable pump source could be implemented by cascaded power scaling of a low-noise phase-modulated, single-frequency seed laser. The technique for achieving co-pumped single-frequency RFA presented could be simply extended to other wavelength and other types of RFLs with the strong requirements for simultaneously high output power and narrow linewidth spectral property.

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