High-Power Single-Frequency 1336 nm Raman Fiber Amplifier

Lei Zhang, Huawei Jiang, Xuezong Yang, Xijia Gu, and Yan Feng

***Abstract*—A high power, single frequency, quasi-continuous-wave 1336 nm laser is achieved by Raman amplification of an external cavity diode laser in a variably strained polarization maintaining silica fiber. The pump laser is a 1256 nm Ytterbium-Raman integrated fiber amplifier with a maximum output peak power of 235 W. The 1336 nm amplifier produces square-shaped pulses with tunable repetition rate and duration. The peak power is as high as 53 W, which remains constant during the tuning. A polarization extinction ratio of >25 dB is achieved due to the all polarization maintaining fiber configuration. The laser is locked precisely at 1336.63 nm for future application in laser cooling of $^{27}Al^{+}$ after 8^{th} harmonic generation.**

***Index Terms*—Raman fiber amplifier, single frequency.**

I. Introduction

RAMAN fiber lasers have found various applications for its wavelength flexibility as Raman gain is available at arbitrary wavelength across the transparency window of optical fiber [1]. In recent years, Raman fiber laser development has been very successful in power scaling, now reaching a level of kilowatts [2]–[5]. However for single frequency Raman fiber amplifiers, the power scaling is still limited by the stimulated Brillouin scattering (SBS) effect − the highest reported output power is up to 120 W peak power at 1178 nm with pulsewidth in hundreds of microseconds range [6]. For laser wavelength beyond 1200 nm, the reported single frequency Raman fiber laser is confined to only several watts, which severely restricts its applications. For examples, in the laser absorption spectroscopy measurements of atmospheric oxygen, J. A. Nagel reported 3 W single frequency 1260 nm laser with phosphorus-doped fiber (PDF) [7]. R. Bauer *et al*. used a 1550 nm Er-doped laser to pump a single frequency Raman amplifier and achieved 1.1 W single frequency lasing at 1651 nm [8].

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A narrow linewidth tunable 167.079 nm laser is required for direct cooling of $^{27}Al^{+}$ ions for optical frequency standard [9]. Harmonic generation in KBBF crystal is potentially a solution to obtain the 167 nm laser [10]. However, there is no efficient gain medium at fundamental wavelengths of 334, 668 or 1336 nm. Although 1336 nm is close to one of laser transitions of Nd ions, tuning a Nd-doped solid-state laser to the exact wavelength of 1336.63 nm is challenging and low efficient, especially for continuous wave or quasi continuous wave (QCW) single frequency generation which is usually required for laser cooling experiments. Attempts have been made with Nd:YVO_4 [11] and Nd: GYSGG crystals [12]. However, the linewidth, pulse width and frequency characteristics of the all solid-state lasers are hard to meet the atom cooling requirement. Given the recent development in the high power Raman fiber lasers and amplifiers [3]–[4], [6], a single frequency diode laser amplified by a Raman fiber amplifier is proposed to generate high power single frequency and diffraction-limited laser at 1336 nm. In addition, the spectral characteristic and pulse parameters can be easily controlled for the atom cooling application.

In this paper, a high power 1336 nm single frequency Raman fiber laser system is developed. The laser produces square-shaped pulses with a tunable repetition rate from 1 to 10 Hz and pulsewidth from 1 to 10 ms. The peak power is as high as 53 W. The laser wavelength can be tuned and locked from 1336.60 to 1336.66 nm with a wavelength meter. To the best of our knowledge, this is the first report of high power single frequency fiber amplifier at 1336 nm. And its output power higher than any reported narrow linewidth Raman fiber amplifiers at wavelength beyond 1.2 μm.

II. Experimental Setup

Fig. 1 illustrates the schematic diagram of the 1336 nm laser system. Fig. 1(a) is a 1256 nm integrated Yb-Raman fiber amplifier seeded with a 1077/1256 nm dual-wavelength laser, which is used as a pump source for the 1336 nm Raman fiber amplifier shown in Fig. 1(b). The seed laser of the 1256 nm amplifier is a linearly polarized 1256 nm PDF Raman laser pumped at 1077 nm, which emits the residual 1077 nm pump laser as well. The power ratio of the two wavelengths can be adjusted. The seed laser is coupled into a Yb-doped fiber amplifier with a polarization maintaining (PM) $(6 + 1) \times 1$ pump and signal combiner. The other input ends of the combiner are connected to six 90 W 976 nm laser diodes. The measured available pump power is 500 W after the combiner. The gain fiber is a piece of 4 m-long PM double clad Yb-doped fiber 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

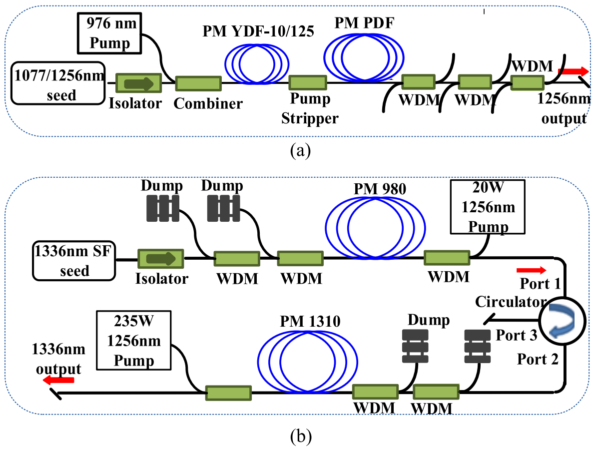

Fig. 1. (a) Schematic diagram of the integrated Yb-Raman 1256 nm Raman laser, which is the pump source for the (b) single frequency 1336 nm Raman amplifier.

at 976 nm. A pump stripper fabricated with matched passive fiber is spliced with the output end of the Yb-doped gain fiber to remove the undepleted 976 nm pump light. A piece of 12 m-long PDF with core diameter of 4.5 μm are spliced after that as a Raman converter. The PDF has a peak Raman gain at a frequency shift of 1330 cm^{-1} (approximately 3 times of the 440 cm^{-1} frequency shift of typical Ge-doped silica fiber) from the pump wavelength. Although there is a mode field diameter mismatch between the pump stripper fiber and PDF, the splice between them is optimized to have a loss of less than 0.5 dB.

For the 1336 nm Raman fiber amplifier (RFA), an external cavity diode laser at 1336 nm is used as seed source. The fiber-coupled seed power is about 30 mW, which is amplified by two RFA stages. As depicted in Fig. 1, two RFAs have the same configuration, both are backward pumped by the 1256 nm Raman fiber lasers via wavelength division multiplexers (WDM). The power of the 1256 nm linearly polarized pump sources are 20 W and 235 W for the 1st and 2nd 1336 nm Raman amplifiers, respectively. The unused pump power is coupled out of the amplifiers with two WDMs. The preamplifier delivers up to 1.5 W at 1336 nm, limited by the damage threshold of the fiber pigtailed circulator between the two amplifier stages. The fiber used in the first amplifier is a piece of 200 m long PM980 fiber, on which, 8 strain steps are applied to suppress the SBS. The second amplifier uses 38 m of PM1310 fiber with a 25-step strain distribution as the Raman gain fiber [13], [14]. The backward propagating light from the amplifier, including possible SBS light, residual pump light, and amplified spontaneous Raman scattering, is analyzed at the port 3 of the circulator. Please note, for germanosilicate gain fiber (PM980 and PM1310) used in the RFA, the optimum pump laser wavelength is at 1262 nm. The choice of the 1256 nm wavelength is due to the availability of FBGs at the time of the study.

III. Results and Discussion

The high power 1256 nm pump laser uses an integrated Yb-Raman fiber amplifier architecture [4]. The dual-wavelength seed laser emits a total of 20 W, of which 54% is at 1256 nm.

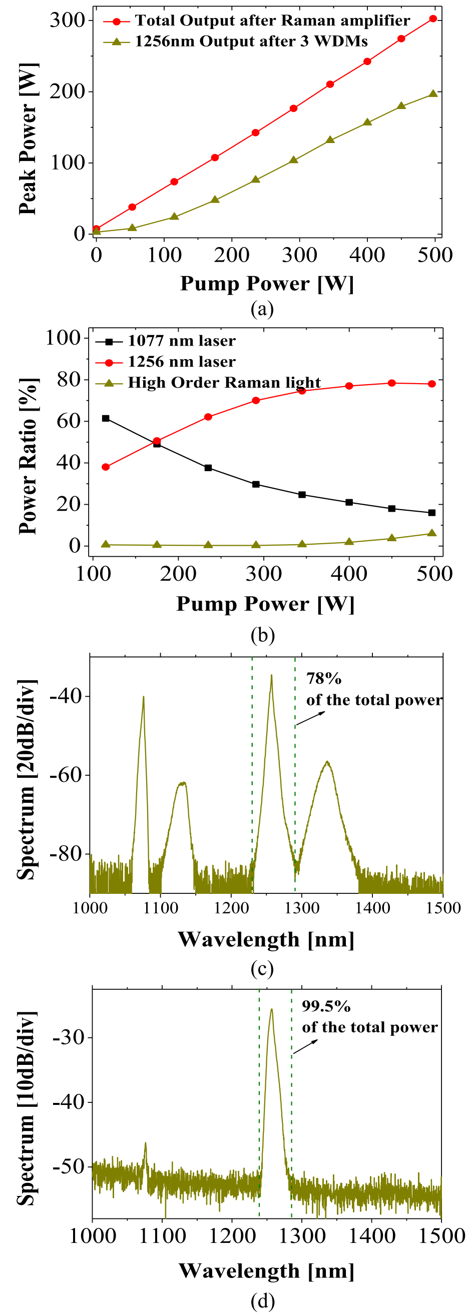

Fig. 2. (a) 1256 nm output power after the Raman amplifier and three WDMs, (b) Power ratio of 1077 nm, 1256 nm and high order Raman light as a function of the pump laser, (c) 1256 nm output spectrum after the Raman amplifier, (d) 1256 nm output spectrum after 3 WDMs.

The amplifier operates in the required QCW format by modulating the drive current of the laser diodes. The Yb-doped fiber amplifier (YFA) part of the main amplifier is studied first. The maximum peak power after the YFA reaches over 381 W, which is limited by the available diode pump power. The power ratio of the 1256 nm laser decreases to be only 1%. Then, 12 m PDF is spliced after the YFA to convert the 1077 nm light to 1256 nm. A maximum output of 301 W is achieved, as shown in Fig. 2(a). Fig. 2(b) shows the power ratios of 1077, 1256 nm and high order

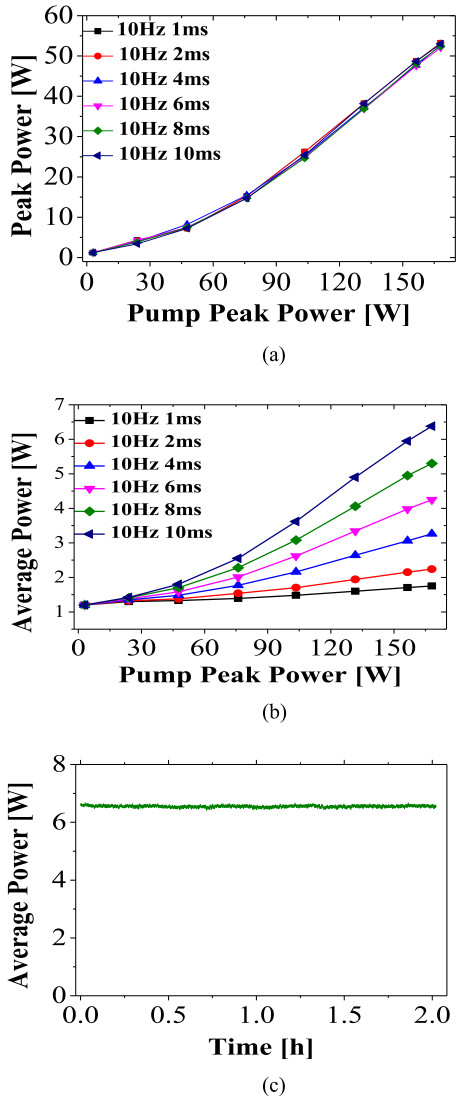

Fig. 3. 1336 nm output peak power (a) and average power (b) as a function of the pump peak power with different pulse parameters. (c) 2 hours power stability test.

Raman light as a function of the output power. When the output power increases, the 1256 nm laser ratio firstly increases rapidly. However, when the pump power increases to above 350 W, high order Raman laser begins to increase, which prevents the Raman shift from 1077 to 1256 nm. As a result, the 1256 nm power ratio keeps almost constant. The output spectrum of the dual-wavelength laser at full output power is depicted in Fig. 2(c), and the power ratios of 1077, 1256 nm and high order Raman were measured to be 16, 78 and 6%, respectively. Therefore, maximum 235 W is achieved at 1256 nm. The optical efficiency from 976 to 1256 nm reaches 47%. At full output, the linewidth of the 1256 nm laser is 2.2 nm. And the higher order spontaneous Raman emission is centered at 1335.8 nm with a linewidth of 6 nm.

Then the 1256 nm laser are injected into the 1336 nm Raman amplifier after 3 WDMs including one 1080/1256 nm WDM (eliminating the residual 1077 nm laser) and two 1256/1336 nm WDMs (isolating the 1336 nm amplifier with the 1256 nm pump laser). The remaining laser has a maximum

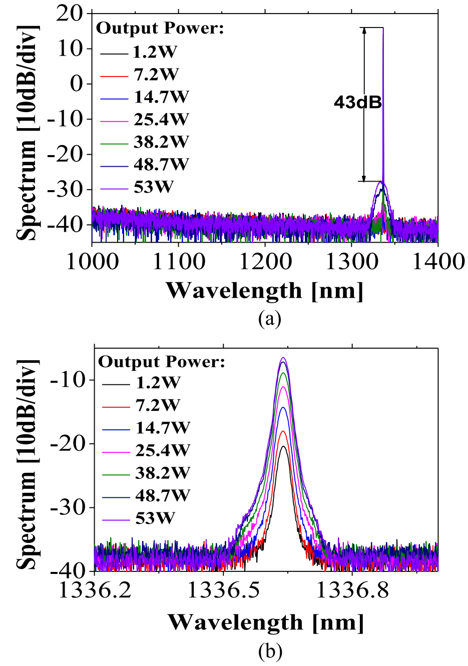

Fig. 4. 1336 nm laser spectrum with (a) 400 nm and (b) 0.8 nm range.

power of 200 W, which however is spectrally clean. The power ratio of the 1256 nm light reaches 99.5%, as measured from the spectrum depicted in Fig. 2(d).

Then the 1336 nm RFA is investigated in QCW format. Because the response time of SRS is in ∼100 fs scale in silica fiber, the output pulse waveform of the RFA will follow that of the pump laser in the pulse duration regime interested here [15]. A stepwise strain distribution is designed considering a 1256 nm pump power of 200 W. In the experiment, with a 38 m variably strained fiber, the 1.5 W 1336 nm laser from the 1st amplifier is further amplified to a maximum 53 W peak power at a pump power of 168 W, as shown in Fig. 3(a). The optical–optical efficiency reaches 31.5%. The average power as a function of the pump power with different pulse parameters are depicted in Fig. 3(b). To assess the long term stability of the laser, 2 hours power stability measurement gives a peak to peak fluctuation of 3.8% and a mean square deviation of 0.5%, as showed in Fig. 3(c).

The spectral purity of the 1336 nm laser emission at different output power is checked with an optical spectral analyzer (AQ6370). Although a spectral pedestal is observed, the signal to noise ratio is over 43 dB at the maximum power, as shown in Fig. 4(a). Fig. 4(b) shows the fine spectra under different output powers with a 0.02 nm resolution. According to previous studies on backward pumped single frequency Raman fiber amplifiers [6], [7], the linewidth is not expected to change significantly during the amplification. The unresolved real linewidth should be around 100 kHz, determined by the external cavity diode seed laser. Fig. 5(a) and (b) shows the backward laser spectrum in wide and narrow wavelength range, respectively. Most of the power is the backward amplified spontaneous Raman emission around 1335 nm. In the fine spectra of the backward laser, the SBS feature is indeed observed, but the power fraction is small

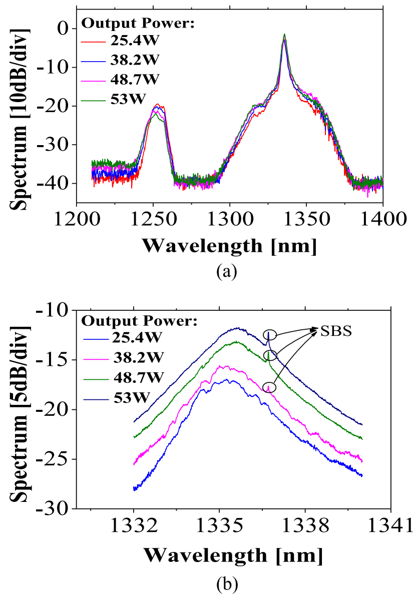

Fig. 5. Backward laser spectrum with (a) 200 nm and (b) 8 nm range.

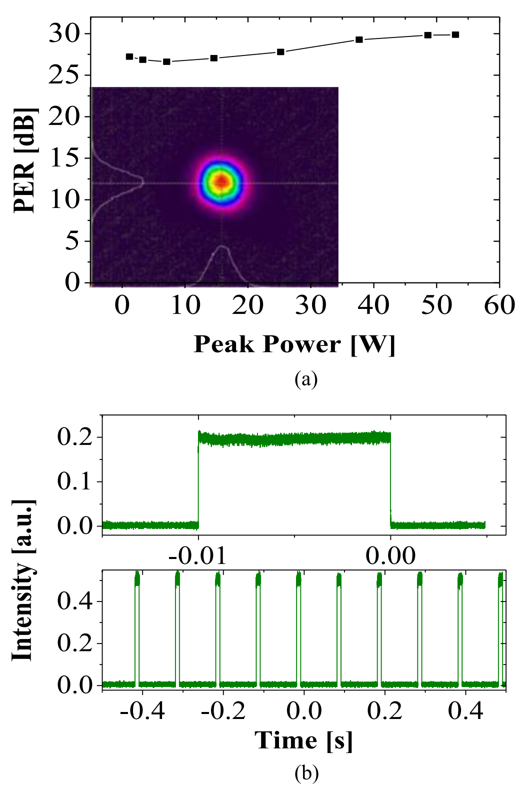

Fig. 6. (a) PER of the 1336 nm laser as a function of the output peak power, inset, collimated beam profile. (b) single pulse and pulse trains of the laser at 10 ms pulse duration and 10 Hz repetition.

because of its narrow spectrum. So the SBS is well suppressed and does not reach its threshold.

The polarization extinction ratio (PER) of the output as a function of the output power is depicted in Fig. 6(a), which is measured with a Glan-Laser polarizer with a PER of 50 dB. The PER varies from 26 to 30 dB when the output peak powers changes, which is high due to the all PM fiber configuration and

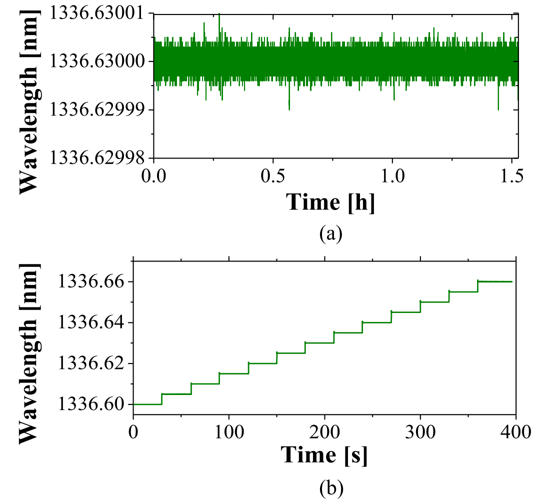

Fig. 7. (a) Wavelength stability test with a duration of 1.5 hour. (b) continuous wavelength tuning from 1336.60 to 1336.66 nm.

the polarization dependent gain of stimulated Raman scattering. The delivery fiber of the laser system is a PM1310 fiber from Corning, so a near diffraction-limited beam quality can be expected, and the collimated beam profile is showed in the inset of Fig. 6(a) at full output. The pulse duration and repetition rate are adjusted in the experiments from 1 ms to 10 ms and 1 Hz to 10 Hz, respectively. Fig. 6(b) shows typical single pulse and pulse train of the 1336 nm amplifier, where the pulse duration is 10 ms at a repetition rate of 10 Hz. As seen in the figure, the pulses have clean leading and falling edge without relaxation oscillation spikes, which is highly preferable in the application.

A wavelength meter (WS 7 from HighFinesse) is used to measure the wavelength, and a PID feedback loop controls the wavelength of the external cavity seed laser. Fig. 7(a) shows an example of the locking performance where the fundamental laser was locked to the wavelength of 1336.630 nm for 2 hours. The corresponding wavelength of the 8^{th} harmonic is 167.079 nm, which is required for laser cooling of $^{27}Al^{+}$ ions. Also shown in Fig. 7(b) is a demonstration that wavelength can be tuned from 1336.600 to 1336.660 nm.

IV. Conclusion

In summary, we have successfully developed a high power single frequency 1336 nm Raman fiber amplifier system. With an integrated Ytterbium-Raman fiber amplifier architecture, linearly-polarized 1256 nm laser with 235 W peak power is achieved by only one Raman shift. With two backward pumped single frequency Raman amplifiers, 1336 nm square-shaped pulsed laser with tunable repetition rate (1 to 10 Hz) and duration (1 to 10 ms) is produced. The peak power is as high as 53 W. The laser can be locked precisely to 1336.63 nm, which will be frequency doubled three times to 167.079 nm for laser cooling of $^{27}Al^{+}$ ions in optical frequency standard application. In view of the current state of high power Raman fiber laser, power scaling of single frequency Raman fiber lasers at even longer wavelength can be achieved with a similar architecture.

REFERENCES

[1] 1. E. M. Dianov, "Advances in Raman fibers," *J. Lightw. Technol.*, vol. 20, pp. 1457–1462, 2002.

[2] V. R. Supradeepa and J. W. Nicholson, "Power scaling of high-efficiency 1.5μm cascaded Raman fiber lasers," *Opt. Lett.* vol. 38, pp. 2538–2541, 2013.

[3] L. Zhang *et al.*, "Kilowatt Ytterbium-Raman fiber laser," *Opt. Express*, vol. 22, pp. 18483–18489, 2014.

[4] L. Zhang, H. Jiang, S. Cui, and Y. Feng, "Integrated ytterbium-Raman fiber amplifier," *Opt. Lett.*, vol. 39, pp. 1933–1936, 2014.

[5] Z. Hanwei, T. Rumao, Z. Pu, W. Xiaolin, and X. Xiaojun, "1.5-kW Yb-Raman combined nonlinear fiber amplifier at 1120 nm," *IEEE Photon. Technol. Lett.*, vol. 27, no. 6, pp. 628–630, Mar. 2015.

[6] L. Zhang, H. Jiang, S. Cui, J. Hu, and Y. Feng, "Versatile Raman fiber laser for sodium laser guide star," *Laser Photon. Rev.*, vol. 8, pp. 889–895, 2014.

[7] J. A. Nagel *et al.*, "High-power narrow-linewidth continuous-wave Raman amplifier at 1.27 μm," *IEEE Photon. Technol. Lett.*, vol. 23, no. 9, pp. 585–587, May 2011.

[8] R. Bauer *et al.*, "Miniaturized photoacoustic trace gas sensing using a Raman fiber amplifier," *J. Lightw. Technol.*, vol. 33, pp. 3773–3780, 2015.

[9] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, "Spectroscopy using quantum logic," *Science*, vol. 309, pp. 749–752, 2005.

[10] P. Koch, J. Bartschke, and J. A. L'huillier, "High-power actively Q-switched single-mode 1342 nm Nd:YVO4 ring laser, injection-locked by a CW single-frequency microchip laser," *Opt. Express*, vol. 23, pp. 31357–31366, 2015.

[11] S.-B. Dai *et al.*, "167.75-nm vacuum-ultraviolet PS laser by eighth-harmonic generation of a 1342-nm Nd:YVO4 amplifier in KBBF," *Opt. Lett.*, vol. 40, pp. 3268–3271, 2015.

[12] H. Li *et al.*, "Sub-pm linewidth nanosecond Nd: GYSGG laser at 1336.6 nm," *Opt. Lett.*, vol. 40, pp. 776–779, 2015.

[13] L. Zhang, J. Hu, J. Wang, and Y. Feng, "Stimulated-Brillouin-scattering-suppressed high-power single-frequency polarization-maintaining Raman fiber amplifier with longitudinally varied strain for laser guide star," *Opt. Lett.*, vol. 37, pp. 4796–4798, 2012.

[14] L. Zhang, S. Cui, C. Liu, J. Zhou, and Y. Feng, "170 W, single-frequency, single-mode, linearly-polarized, Yb-doped all-fiber amplifier," *Opt. Express*, vol. 21, pp. 5456–5462, 2013.

[15] G. P. Agrawal, *Nonlinear Fiber Optics*. New York, NY, USA: Academic, 2006.

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