Stimulated-Brillouin-scattering-suppressed high-power single-frequency polarization-maintaining Raman fiber amplifier with longitudinally varied strain for laser guide star

Lei Zhang,[1,2] Jinmeng Hu,[1,2] Jianhua Wang,[1] and Yan Feng[1,*]

[1]*Shanghai Key Laboratory of Solid State Laser and Application and Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Qinghe Road 390, Jiading, Shanghai 201800, China*

[2]*Graduate University of the Chinese Academy of Sciences, Beijing 100049, China*

**Corresponding author: feng@siom.ac.cn*

Received August 29, 2012; revised September 30, 2012; accepted October 4, 2012; posted October 4, 2012 (Doc. ID 175174); published November 15, 2012

An up to 44 W, 1 MHz linewidth, 1178 nm CW laser is obtained by Raman amplification of a distributed feedback diode laser in a variably strained polarization-maintaining fiber with a record-high optical efficiency of 52%, pumped by a linearly polarized 1120 nm fiber laser. A polarization extinction ratio of 30 dB is achieved due to the all-polarization-maintaining configuration and the polarization dependence of Raman gain. The strain distribution is designed according to the signal power evolution along the fiber. A 20 times reduction in the effective stimulated Brillouin scattering coefficient is achieved. A 24.3 W 589 nm laser is generated by an external resonant doubling cavity with an optical efficiency of 68.5%. The laser is locked to 589.1591 nm for a laser guide star.

OCIS codes: 140.3510, 140.3550, 190.2620.

A laser guide star adaptive optics system requires high-power narrow-linewidth lasers at 589 nm to excite a layer of sodium atoms in the mesosphere at 80–100 km altitude. Dye lasers are the first generation yellow lasers for astronomical community. The most developed solid-state laser alternative is frequency sum mixing of the Nd:YAG 1064 and 1319 nm laser lines. 50 W facility-level laser systems have been developed and deployed [1,2]. Two competitive fiber laser technologies have advanced in recent years. With Yb-doped photonic bandgap fiber, an up to 24.6 W single-frequency amplifier at 1178 nm was reported, although 1178 nm is at the far wing of the Yb gain spectrum [3]. A maximum 14.5 W, 589 nm laser has been generated by single pass through a PPMg:SLT crystal with a fiber amplifier of 0.05 nm linewidth at 1178 nm [4].

A raman fiber laser and amplifier make up the other fiber laser technology for the laser guide star and have been studied since 2003 [5–7]. Until now, a maximum 39 W, 1178 nm laser has been reported from a single narrowband Raman fiber amplifier (RFA) [8]. Using frequency doubling in an external resonant cavity, a 28 W, 589 nm laser was generated. With coherent beam combination of two [9] and later three [10] RFAs, a maximum 50.9 W, 589 nm laser has been reported. Non-polarization-maintaining fibers were used in those RFAs, and therefore, free-space waveplates were required after the output to adjust polarization in real time. In those high-power narrowband RFAs, stimulated Brillouin scattering (SBS) is the limiting nonlinear optical effect, which has to be suppressed. However, the SBS suppression method was not disclosed in these publications. Several institutions have followed up with theoretical analysis of single-frequency RFAs [11,12], and an 18 W single-frequency polarization-maintaining (PM) RFA at 1178 nm has been demonstrated with acoustically tailored fiber [13].

In this Letter, we report a two-stage RFA generating an up to 44 W single-frequency laser at 1178 nm with a record efficiency of 52%. SBS is suppressed by applying longitudinally varied strain along the gain fiber. The polarization extinction ratio (PER) is as high as 30 dB due to the PM configuration and polarization-dependent nature of Raman gain. The output is frequency doubled to 589 nm with an external resonant doubling cavity, achieving 24.3 W. The wavelength is locked to a sodium D2a line for laser guide star application.

The experimental setup is illustrated in Fig. 1. A distributed feedback (DFB) diode laser (Toptica) at 1178 nm is used as seed. The fiber-coupled seed power is about 10 mW, which is amplified by two RFA stages. The RFAs have the same configuration, which are backward pumped by 1120 nm Yb-doped fiber lasers via fused fiber wavelength division multiplexers (WDMs), which can sustain high power. The 1120 nm linearly polarized pump sources are built in-house with maximum powers of about 20 and

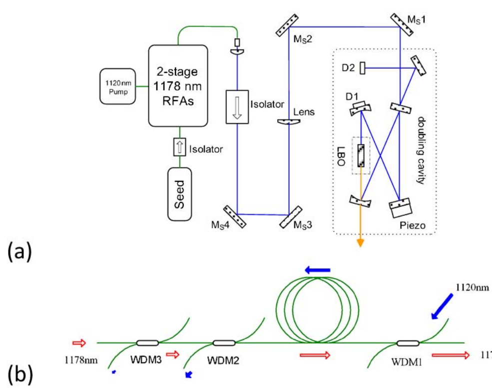

Fig. 1. (Color online) (a) Schematic diagram of the laser system, including the seed laser, RFAs, and doubling cavity and (b) diagram of a single-stage RFA. Ms1, Ms2, Ms3 and Ms4, mirrors with high reflection at 1178 nm. D1 and D2, photoreceivers; LBO, LiB_3O_5 crystal; Pizeo, piezoceramic.

0146-9592/12/224796-03$15.00/0

85 W, respectively, for the first and second amplifiers. The unused pump power is coupled out of the amplifiers with two WDMs. The first stage uses 200 m PM 980 fiber as the gain media, which delivers up to 1 W, limited by the damage threshold of the fiber pigtailed isolator between the two amplifier stages. The second amplifier uses 50 m PM 980 fiber with a 30-step strain distribution as the Raman gain fiber. The backward-propagating light from the amplifier is analyzed at the free ports of WDM2 and WDM3.

Suppressing SBS by applying strain distribution along the length of fiber is not new [14,15]. However, most studies focused on light transmission in passive fiber. We find that in the case of a fiber amplifier, the situation is very different, where the narrowband laser power increases nonlinearly along the fiber. It is necessary to take the power distribution into consideration when designing the strain distribution for optimum SBS suppression.

We have developed a numerical model to simulate a narrowband RFA [16]. The SBS spectrum and variation along the fiber are included in the model. We focus our simulation on stairstep strain distributions with varying step lengths. At each step, SBS light is generated at a different frequency because of the different applied strain. With a given step number, the best SBS suppression happens when each strain step sees the same SBS light generation at a different frequency shift. This can be achieved by adjusting the individual step lengths, since SBS gain is an integration along the fiber length. In the simulation, the Raman and SBS gain coefficients are 0.00185 and 0.5 $m^{-1} W^{-1}$, respectively, which were determined experimentally. The SBS gain spectrum is assumed to have a Lorentzian profile of 60 MHz FWHM width. It is assumed that the spectral peak position shifts linearly with respect to the strain, but the spectral width and height don't change. The exact coefficient of SBS shift with respect to strain is unknown for PM980 fiber. We set it as 0.65 GHz/%, which is calculated according to Eq. (2) in [17], taking the SBS peak at zero strain as 14.2 GHz at 1178 nm.

A number of designs with different fiber lengths and step numbers have been tested experimentally, which leads to the design reported in this Letter. Given a maximum pump power of 85 W, a seed power of 0.8 W, a gain fiber length of 50 m, a strain step number of 30, and a SBS spectral separation between neighbor steps of 60 MHz, an optimum strain distribution is calculated and shown in Fig. 2. Also shown in Fig. 2 are a calculated signal power distribution along the fiber length and an experimental realization of the strain distribution. The length of fiber at the highest level of strain is 0.4 m. The strain is applied to the fiber by spooling with a varying force. The force to strain conversion is calculated according to a tool provided by Corning [18]. The strain increases progressively along the fiber, but the final step is chosen to be free of strain for easy splicing. The maximum applied strain is as high as 2.4%. Therefore, the fiber reliability was a concern. We have prepared a number of fiber spools with similar strain. However, no fiber failure has been observed after more than half a year. This is understood by the fact that the highly strained fiber is short, so that the probability of finding a flaw is very small.

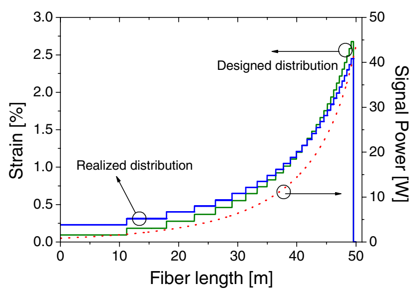

Fig. 2. (Color online) Calculated signal power evolution (dotted), the designed strain distribution (solid, green), and the applied strain distribution (solid, blue) along the fiber.

With the 50 m variably strained fiber, an up to 44 W, 1178 nm light is obtained with a maximum 1120 nm pump of 85 W, where SBS reaches threshold and starts to increase quickly, as shown in Fig. 3. The optical–optical efficiency reaches 52%, which is the highest reported efficiency for narrowband RFAs. The second amplifier is tested with a 50 m PM980 fiber without strain distribution as well. It is found that SBS starts at an injected seed power as low as 0.7 W, even without pumping. These results are fitted with our simulation model. The effective SBS coefficient of the variably stained fiber is found to be about 0.025 $m^{-1} W^{-1}$, as compared to 0.5 $m^{-1} W^{-1}$ for the nonstrained PM980 fiber. Therefore, we achieve a 20 times reduction in effective SBS gain coefficient with 30 strain steps. The ideal 30 times reduction is not obtained because of the likely overlap between the SBS gain spectra of the neighbor steps.

An optical spectral analyzer (AQ6370) is used to check the spectral purity of the laser output. The signal-to-noise ratio (SNR) is found to be 60 dB, as shown in Fig. 4. The linewidth is measured by the self-heterodyne method with a 1000 m long fiber delay line. As shown in Fig. 4, the Gaussian fit of the resulting rf spectra gives a linewidth of 1 MHz, and no linewidth broadening is observed

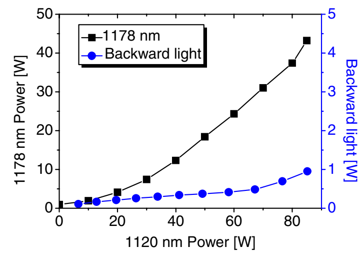

Fig. 3. (Color online) 1178 nm output power and backward light power as a function of the 1120 nm pump power.

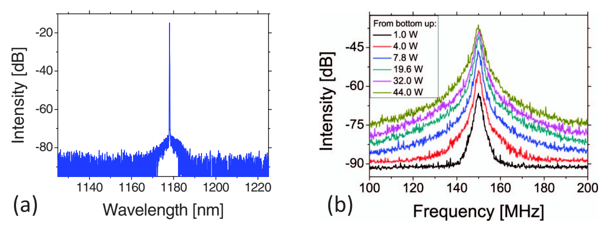

Fig. 4. (Color online) (a) Spectrum of the 1178 nm RFA output and (b) the rf spectra from the self-heterodyne linewidth measurement at different powers.

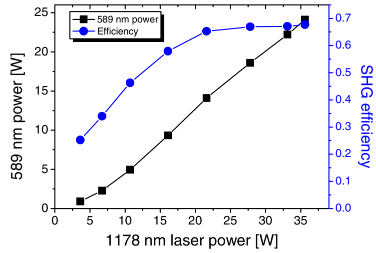

Fig. 5. (Color online) 589 nm laser power and second-harmonic generation (SHG) efficiency as a function of the incident 1178 nm laser power.

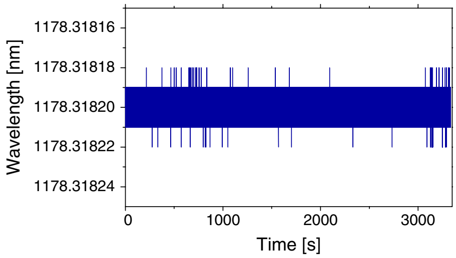

Fig. 6. (Color online) Wavelength stability test with a duration of 1 h.

with increasing output power. It is also interesting to note that as a result of the all-PM fiber configuration and the polarization-discriminating gain of Raman scattering, a PER of 30 dB is measured for the 1178 nm RFA output.

The collimated and optically isolated 1178 nm laser is then coupled into a home-made bowtie-configured doubling cavity with a pair of steering mirrors and a mode-matching lens, as shown in Fig. 1. A 3 mm × 3 mm × 30 mm noncritically phase-matched LBO crystal with a phase matching temperature of 40°C is placed between two curved mirrors (curvature radius 100 mm). The beam radius inside the LBO is calculated to be 43 μm. The cavity is locked to the laser using the well-established Pound–Drever–Hall method. Figure 5 shows the generated 589 nm laser power and conversion efficiency as a function of the input 1178 nm power with an incoupling mirror of 92% reflectivity. An up to 24.3 W 589 nm laser with a conversion efficiency of 68.5% with respect to the incident fundamental light is obtained. Better conversion efficiency is expected with an optimized incoupling mirror and an improved 589/1178 nm dichroic mirror, which currently has a transmission of only 94% at 589 nm. The fundamental laser is locked to the D2a line of sodium by a wavelength meter (HighFinesse WS-6-200) and a PID proportional–integral–derivative control loop to control the wavelength of the DFB seed. Figure 6 shows a 1 h wavelength measurement of the RFA output, whose wavelength is locked to 1178.3182 nm. Correspondingly, the wavelength of the second harmonic is 589.1591 nm, resonant to the sodium D2a line. The linewidth of the yellow light is estimated to about 2 MHz, since the RFA output has a linewidth of 1 MHz.

In conclusion, we reported a 44 W single-frequency RFA at 1178 nm with a record efficiency of 52%. A 20 times reduction in the effective SBS gain coefficient is achieved by applying longitudinal varied strain along the Raman gain fiber. The stairstep strain distribution is optimized by taking into consideration the signal power evolution along the fiber. The laser is frequency doubled and locked to the sodium D2a line for laser guide star application.

The work is supported by Hundred Talent Program of Chinese Academy of Sciences.

References and note

1. C. A. Denman, P. D. Hillman, G. T. Moore, J. M. Telle, J. E. Preston, J. D. Drummond, and R. Q. Fugate, Proc. SPIE **5707**, 46 (2005).
2. I. Lee, M. Jalali, N. Vanasse, Z. Prezkuta, K. Groff, J. Roush, N. Rogers, E. Andrews, G. Moule, B. Tiemann, A. K. Hankla, S. M. Adkins, and C. d'Orgeville, Proc. SPIE **7015**, 70150N (2008).
3. M. Chen, A. Shirakawa, X. Fan, K. Ueda, C. B. Olausson, J. K. Lyngsø, and J. Broeng, Opt. Express **20**, 21044 (2012).
4. A. Shirakawa, M. Chen, K. Ueda, C. B. Olausson, J. K. Lyngsø, and J. Broeng, in *Advanced Solid-State Photonics*, OSA Technical Digest Series (CD) (Optial Society of America, 2010), paper APDP6.
5. Y. Feng, S. Huang, A. Shirakawa, and K. I. Ueda, Jpn. J. Appl. Phys. **43**, L722 (2004).
6. D. Georgiev, V. P. Gapontsev, A. G. Dronov, M. Y. Vyatkin, A. B. Rulkov, S. V. Popov, and J. R. Taylor, Opt. Express **13**, 6772 (2005).
7. Y. Feng, L. Taylor, and D. B. Calia, Opt. Express **16**, 10927 (2008).
8. Y. Feng, L. R. Taylor, D. Bonaccini Calia, R. Holzlöhner, and W. Hackenberg, in *Frontiers in Optics*, OSA Technical Digest (CD), (Optical Society of America, 2009), paper PDPA4.
9. Y. Feng, L. R. Taylor, and D. B. Calia, Opt. Express **17**, 19021 (2009).
10. L. R. Taylor, Y. Feng, and D. B. Calia, Opt. Express **18**, 8540 (2010).
11. C. Vergien, I. Dajani, and C. Zeringue, Opt. Express **18**, 26214 (2010).
12. J. Leng, S. Chen, W. Wu, J. Hou, and X. Xu, Opt. Commun. **284**, 2997 (2011).
13. C. Vergien, I. Dajani, and C. Robin, Opt. Lett. **37**, 1766 (2012).
14. N. Yoshizawa and T. Imai, J. Lightwave Technol. **11**, 1518 (1993).
15. J. M. Chavez Boggio, J. D. Marconi, and H. L. Fragnito, J. Lightwave Technol. **23**, 3808 (2005).
16. L. Zhang and Y. Feng Share preparing a manuscript to be titled "SBS suppression in narrow band Raman fiber amplifier with longitudinally varied strain."
17. T. Horiguchi, K. Shimizu, T. Kurashima, M. Tateda, and Y. Koyamada, J. Lightwave Technol. **13**, 1296 (1995).
18. Corning Inc., http://www.corning.com/opticalfiber/library/fiber_mechanical_reliability/calculators.aspx.