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High order cascaded Raman random fiber laser with high spectral purity

JINYAN DONG,[1,2] LEI ZHANG,[1,4] HUAWEI JIANG,[1,2] XUEZONG YANG,[1,2] WEIWEI PAN,[1,2] SHUZHEN CUI,[1] XIJIA GU,[3] AND YAN FENG[1,*]

[1]*Shanghai Institute of Optics and fine Mechanics, Chinese Academy of Sciences, and Shanghai Key Laboratory of Solid State Laser and Application, Shanghai 201800, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*Department of Electrical and Computer Engineering, Ryerson University, Toronto M5B 2K3, Ontario, Canada*
[4]*zhangl@siom.ac.cn*
[*]*feng@siom.ac.cn*

Abstract: An up to 8th order cascaded Raman random fiber laser with high spectral purity is achieved with the pumping of a narrow linewidth amplified spontaneous emission source. The spectral purity is over 90% for all the 8 Stokes orders. The highest output power is 6.9 W at 1691.6 nm with an optical conversion efficiency of 21% from 1062.0 nm. As a comparison, with conventional FBG-based fiber oscillator as pump source, only 47% spectral purity is achieved at 8th order. The temporal stability of the pump laser is proved to play a key role, because the time fluctuation of pump laser is transferred directly to Raman outputs and results in power distribution among different Stokes orders.

OCIS codes: (140.3510) Lasers, fiber; (140.3550) Lasers, Raman; (290.5870) Scattering, Rayleigh.

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1. Introduction

Random Raman fiber lasers (RRFLs) have received significant attention since its first demonstration in 2010 [1]. As compared to the point-like feedback in traditional fiber lasers, the necessary feedback of RRFLs is based on the distributed Rayleigh scattering inside the optical fiber. Thus RRFLs have unique characteristics, for instance, low coherence, modeless emission and simple configuration. As a result, RRFLs have found applications in many fields, such as fiber optical sensing, pumping mid infrared laser and spectroscopic monitoring [2–4]. In previous studies, RRFLs with narrow linewidth, polarized output, cascaded generation, power scaling and pulsed operation have been realized [5–11].

Because of the Raman gain and Rayleigh scattering based feedback, RRFLs are wavelength versatile and can lase at arbitrary wavelength across the transparency window of an optical fiber. Cascaded RRFLs can extend the laser wavelength range. Babin *et al*. achieved 4 W output at 1308 nm and 5.2 W output at 1398 nm with 1.65-km phosphosilicate fiber [12]. Wu *et al*. reported a cascaded RRFL with output power amounts to 2.7 and 4 W for the first (1115 nm) and second (1175 nm) order Stokes waves, respectively [13]. Zhang *et al*. demonstrated a 900 nm nearly-octave wavelength tunable random laser with up to the 10th order cascaded Raman scattering [14]. Recently, Lobach *et al*. demonstrated a cascaded linearly polarized RRFL based on phosphosilicate fiber, getting 8 W output at 1262 nm and 9 W output at 1515 nm [15]. Cascaded RRFL is an effective approach to generate stable laser beyond rare earth emission bands.

However, in cascaded RRFL, the residual low order Raman lasers would decrease the spectral purity of the output. Here the spectral purity is referred as power concentration at the target Raman order, defined as the ratio of the output at the target Raman order to the total output. The spectral purity is a pivotal specification for the cascaded RRFL. However, no relevant analyses on improving the spectral purity of the RRFL have been reported in the previous research. For improving the spectral purity of each order RRFLs, the time domain stability of the pump laser is very important. Due to the fact that stimulated Raman scattering (SRS) is nonlinear effect with the response time in the level of femtosecond, the temporal characteristics of the pump laser would be transferred to the RRFLs. Amplified spontaneous emission source (ASE, also referred to as superfluorescent laser) with rare-earth doped fiber as the gain medium without the conventional resonant cavity has high temporal stability. Recently, over 100 W 2nd order RRFL at 1178 nm pumped by a broadband ASE were reported. Because of the good stability of broadband ASE source, the RRFLs have high temporal stability [16, 17]. But no discussion on the effect of ASE pumping on the spectral purity of the RRFLs was made. There was still some undepleted ASE pump laser even at the maximum pump power, which we think is due to broad linewidth of the ASE pump source, 3 dB linewidth of 9.1 nm. The Raman gain is less for broadband pump source, which decreases the conversion from the pump to the Raman laser.

In this paper, high order cascaded RRFL with a narrow linewidth ASE as pump source is investigated for improving spectral purity. An up to 8th order RRFL with a maximal output power of 6.9 W is achieved with a spectral purity of >90% for all the 8 Stokes orders. As a comparison, with a FBG-based fiber oscillator as pump source, the spectral purity and conversion efficiency is much less. Only 47% spectral purity is achieved for the 8th order

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RRFL with an output power of 3.7 W. The results prove that ASE pumping is an effective way to improve the output performance of high order cascaded Raman fiber lasers.

2. Experimental setup

As shown in Fig. 1, the experimental setup consists of two functionally different parts, an ASE source that is used as the pump laser, and a cascaded RRFL. The pump laser has a standard master oscillator power amplification (MOPA) configuration using all polarization-maintaining (PM) active and passive fibers with a mode-field diameter (MFD) of ~10 µm and numerical aperture of 0.075. They are pumped by 976 nm laser diodes, which have a nominal 4.8 dB/m cladding absorption in the gain fiber. For the ASE seed source, an all open cavity is built with isolators spliced at both ends to avoid lasing. A filter with 10 nm bandwidth centered at 1062.0 nm and a wavelength tunable filter with 1 nm bandwidth are spliced successively after the ASE seed source to narrow the linewidth to less than 1 nm with high sideband suppression. Then PM Yb-doped amplifiers with the same configuration are adopted to amplify the ASE seed source. The output from the ASE source is optically isolated and injected into a 2000 m long piece of Raman fiber (OFS Raman optical fiber) after a wavelength division multiplexer (WDM). A broadband fiber pigtailed metallic mirror is attached to the rear free end of the WDM, which forms a "half-open" random laser cavity together with the long piece of Raman fiber. The half-open configuration can greatly reduce the random laser threshold [18]. The far end of Raman fiber is angle cleaved to minimize the back reflection. The configuration of the RRFL has been detailed in [14].The randomly distributed Rayleigh scattering in the core of Raman fiber provides necessary feedback for the random laser action. For comparison experiments, a conventional FBG-based fiber oscillator at 1064 nm is built as well to pump the RRFL.

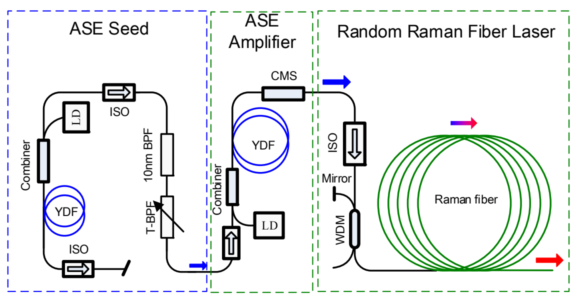

Fig. 1. Schematic diagram of the narrow linewidth Yb-doped ASE source and the cascaded Raman random fiber laser.

3. Results and discussion

Figure 2(a) shows the spectra of the ASE seed after filtering and the amplified ASE source. The ASE seed directly after the isolator has a broadband spectrum with a 3 dB linewidth of about 15 nm. After the bandpass filter and the tunable filter, the linewidth is reduced to 0.85 nm. The ASE seed is then boosted in Yb-doped fiber amplifiers. Maximum power of 34 W is obtained with a linewidth of 0.9 nm and a sideband suppression of 37 dB. The conventional FBG-based fiber oscillator at 1064 nm has a similar linewidth of 0.7 nm and is used at similar power level. The temporal domain characteristics of the ASE source and the conventional oscillator are analyzed with an oscilloscope of 1 GHz bandwidth while keeping the same output power. Figure 2(b) shows the normalized time domain measurements in the time scale of 200 µs. The ASE pumping is stable, with a peak to peak fluctuation of 9% and a standard deviation of 1.05%. In contrast, the peak to peak fluctuation of the 1064 nm oscillator is 119% and a standard deviation of 13.85%. As seen in Fig. 2(b), the intensity of the fiber oscillator is highly fluctuating due to the longitudinal mode beating and optical nonlinearity.

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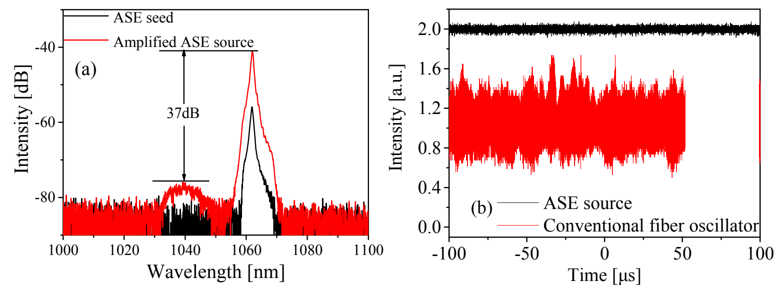

Fig. 2. (a) Output spectra of the ASE seed and the amplified ASE source. (b) Temporal behavior of the ASE source and the conventional fiber laser at the same power, which are normalized to 2 and 1 respectively for comparison.

When the Raman gain reaches the round trip losses in the half-open cavity with increasing pump power, the RRFL starts to lase. As depicted in Fig. 3(a), with the increase of ASE pump power, the 1st (1114.5 nm) to 8th (1691.6 nm) order Raman emissions are generated successively. Due to the highly stable ASE pump source, the power conversion from the lower order Raman pump laser to the higher order random laser is complete. As a result, all the 8 orders RRFLs have high spectral purity after pump power optimization. The spectrally pure output is indicated in Fig. 3(a) as the lower order Raman light is negligible. Figure 3(b) shows the 8 orders random laser spectra with the 1064 nm oscillator as pump source after power optimization. Significant lower order Raman emissions are observable in the spectra. The spectral purity is much less, compared with the ASE source pumped RRFL. The spectral purity also decreases with the increase of the Stokes orders.

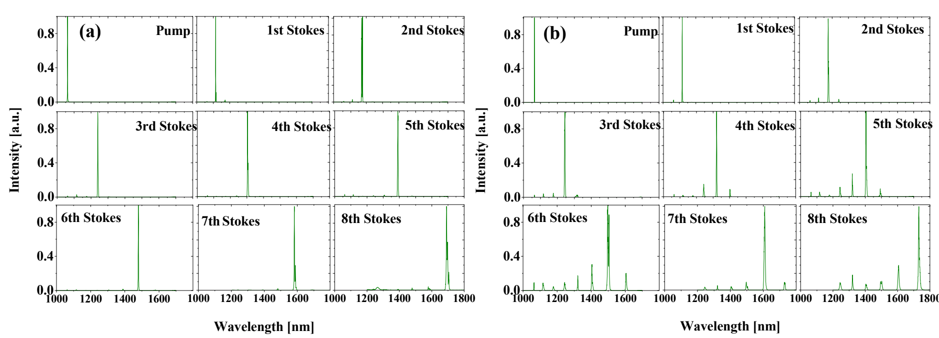

Fig. 3. Output spectra of the 8 orders RRFL pumped by (a) the narrow linewidth ASE source and (b) the 1064 nm oscillator.

Figures 4(a) and 4(b) plot the development and evolution trend of different Raman Stokes. The pump power is limited by the allowed input of the optical isolator. With the increase of pump power, the 1st order Stokes power starts to grow and the pump power is depleted and converted into the Raman light. For higher order Raman laser the process repeats till the 8th order RRFL. Obvious threshold behavior of the power ratio and laser power is observed. Stokes light increases quickly after the pump power across the threshold. At the threshold of high order Stokes light, the previous order reaches the highest output power and power ratio. Figure 4(b) shows the power evolution for different Stokes light, which indicates that the maximum output power increases with the Raman orders. This is because higher order Raman laser is generated at higher pump power. Interesting to note that, spectrally pure laser at different Raman orders can be obtained simply by adjusting the pump power.

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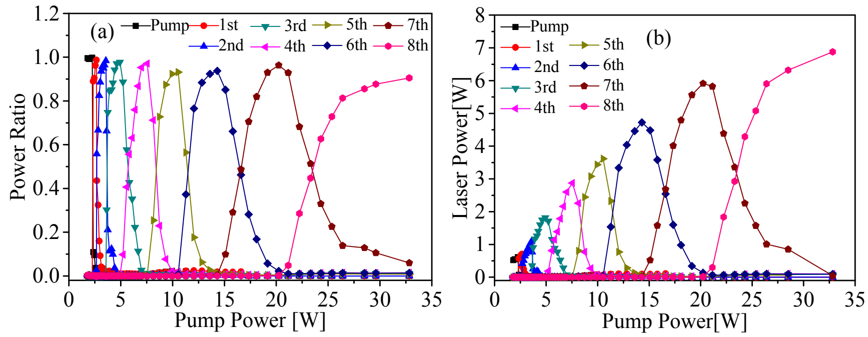

Fig. 4. (a) The power ratio of different Raman Stokes light with respect to the pump power. (b) Output power of different Raman Stokes light with respect to the pump power.

The output power and power ratio of each order Stokes at optimum pump power are summarized in Fig. 5 for the cases of ASE pump source and fiber oscillator pump. It is observed that, when pumped with the ASE source, the power ratio is over 97.7% from 1st to 3rd order Stokes and over 93.1% for 4th to 7th orders Stokes. For the 8th order Stokes, the power ratio decreases to be 90.8%, because of the limited pump power and increasing fiber loss. Therefore, more than 90% power ratio is achieved for up to 8th order Stokes light, which is a significant improvement for high order (>3) cascaded RRFLs. However, there is still some undepleted pump laser in every Raman conversion. The residual low order Raman lasers can be accumulated with Stokes order, which decrease the spectral purity of higher order Stokes laser. Hence, the spectral purity decreases with the increase of the Stokes order. The highest output power reaches 6.9 W at 1691.6 nm, corresponding to an optical efficiency of 21.0% from 1062 nm. When pumped by the 1064 nm fiber oscillator, the power ratio drops dramatically from 98.5 to 47.0% with the Stokes order from 1st to 8th. As a result, the highest output power at 1731.6 nm is only 3.7 W, and the optical efficiency is only 11.2% from 1064 nm. The incomplete power conversion from the lower order to the higher order Stokes reduces the spectral purity and meanwhile lowers the optical efficiency. The power of the fiber oscillator fluctuates greatly. Since the order of the cascaded Raman emission depends on the pump power, the RRFL emits at different Raman orders at different time. Thus, the output laser is distributed among different Stokes orders. The difference in the exact wavelength of the 8th order Raman output for the two pumping cases is a result of the complicate gain competition due to the double peak Raman gain spectra, which has been investigated in [19].

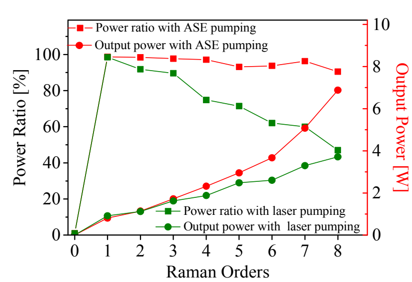

Fig. 5. Power ratio and output power of each Stokes order when the pump laser is the narrow linewidth ASE and 1064 nm oscillator, respectively.

Besides the spectral purity, the temporal characteristics of the pump laser also influences the temporal stability of the RRFL output. Figure 6(a) shows the normalized oscilloscope traces of the 8th order RRFL pumped by the ASE source and fiber oscillator, respectively. In the case of ASE pumping, there are some small modulation in the output with a peak to peak fluctuation

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of 9% and a standard deviation of 1.18%. In contrast, when pumped by the fiber oscillator the peak to peak fluctuation of the RRFL reaches 113% and a standard deviation of 16.27%. These observations confirm that the power fluctuation of the pump laser is transferred directly to Raman outputs. The linewidth of Raman outputs is investigated as well. Figure 6(b) shows the 3 dB linewidth of every Raman order at their maximum power. The RRFL linewidth pumped by the ASE source increases from 0.61 to 4.76 nm with the increase of the Raman order. In contrast, the RRFL linewidth pumped by the conventional fiber oscillator increases from 1.7 to 6.8 nm. The fiber oscillator has higher intensity fluctuation. Therefore, it induces stronger nonlinear effects such as cross phase modulation and self-phase modulation and leads to the severer linewidth broadening of the Raman lasers.

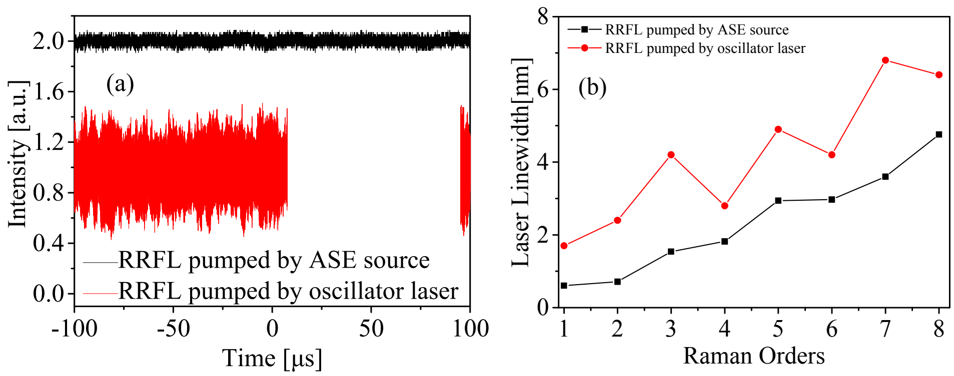

Fig. 6. (a) the normalized oscilloscope traces of the RRFL output pumped by narrow linewidth ASE and fiber oscillator, which are normalized to 2 and 1 respectively for comparison. (b) The linewidth of the cascaded RRFL pumped by narrow linewidth ASE source and fiber oscillator.

4. Summary

In summary, we have demonstrated a stable cascaded Raman random fiber laser up to 8th Stokes with high spectral purity pumped by a narrow linewidth (0.9 nm) ASE source. Owing to the highly stable ASE pump source, a spectral purity of over 90% is achieved for all the 8 orders of random Raman laser. The highest output power is 6.9 W at 1691.6 nm, corresponding to an optical efficiency of 21.0% from 1062.0 nm. In contrast, the power ratio of the cascaded Raman random fiber laser pumped by a FBG based fiber oscillator is only 47% at 8th Stokes order. It is the first report of high order (>3) cascaded Raman random laser pumped by a narrow linewidth ASE source. Through contrast experiment, it proves that the time domain characteristics of the pump laser plays a crucial role in the spectral purity of cascaded Raman random laser. The finding helps the understanding and further improvement of random Raman fiber lasers.

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