# High-Power and High-Order Random Raman Fiber Lasers

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*(Invited Paper)*

***Abstract*—High-order random Raman fiber lasers are investigated for generating high-power widely wavelength-tunable light sources. By cascaded random Raman lasing and adjusting pump laser wavelength, continuous wavelength tuning from 1 to 1.9 $\mu$m is reported. For power scaling, a high-power Yb-doped fiber laser at 1064 nm with improved temporal stability is developed as the pump source. The ninth-order cascaded random Raman fiber laser with a spectral purity of 86.6% is achieved at 1806 nm. Up to 100.1-W inband power is obtained with an optical efficiency of 38.4% from 1064 nm and 27.2% from 915 nm. The results prove that cascaded random Raman fiber laser is a versatile technology to generate high-power fiber laser at wavelength outside the rare earth emission bands.**

***Index Terms*—Fiber laser, random laser, Raman laser, tunable laser.**

## I. Introduction

RECENTLY, random Raman fiber lasers (RRFLs) have drawn extensive attention due to their simple cavityless configuration, high efficiency and wavelength agility. As a result, they find diverse applications in the scientific research, optical communication and industrial community. Since the first demonstration of RRFL in [1], much efforts are put on the performance improvement. For the power scaling, the output power of the RRFL increased from hundreds of milliwatts [1], [2] to hundreds of watts [3]–[7], and even to kilowatt with a master oscillator power amplification (MOPA) configuration [8], [9]. For the optical efficiency, RRFLs demonstrated pump-to-Stokes wave conversion of up to 89% [5], [10]. For the polarization characteristic, linear polarization output due to the polarization dependent Raman gain was reported with RRFLs [10], [11]. Also, different kinds of fibers, such as conventional single mode fiber [1], Raman fiber [12], phosphorus-doped fiber [6], and even tapered fiber [13] were adopt to supply the Raman gain and distributed feedback Rayleigh scattering. Besides that the performance of the RRFLs is approaching that of conventional Raman fiber lasers, new operation schemes of pulsed [14], [15] and diode pumped RRFLs [16] are developing and pave the way for more applications.

For conventional fiber lasers, the wavelength tunability explores the emission spectra of rare earth doped glass fibers, whose gain bandwidths are narrow with a few hundred nanometers. Stimulated Raman scattering is well-known for its wavelength flexibility. Raman gain is available at arbitrary wavelength across the transparency window of an optical medium with appropriate pump laser. But the tuning range of conventional Raman fiber lasers was reported within 100 nm [17], [18], due to limited tunability of optical feedback mechanism. RRFL offers a new possibility, since the feedback is provided by Rayleigh scattering, which is also available at any wavelength. The wavelength tunability of RRFL was explored both within one Raman shift and by cascaded operation [2], [4], [12], [19]–[22]. The RRFLs with order from the 2nd to 10th were achieved with wavelength covering from 1070 to 1940 nm [12]. However, the output power is less than 10 W.

As mentioned above, lots of effort were paid on the power scaling of the RRFL. At 1080 nm, up to kilowatt near-diffraction-limited linearly polarized narrow-linewidth random fiber laser was reported with a MOPA configuration [9]. At 1178 nm, 100 W linearly polarized random Raman laser was achieved with an half open RRFL cavity [3]. At 1230 nm, 9.1 W high-order random Raman lasing in a polarization maintaining (PM) fiber with 77% efficiency and narrow bandwidth was reported [4]. However, for RRFLs with more than tens of watts output, the wavelength range was limited within 1–1.2 $\mu$m, which is still within the emission spectrum of Yb-doped fiber (YDF). Power scaling of high-order RRFL at wavelength from 1.2 to 1.9 $\mu$m will truly demonstrate the wavelength versatility, as compared with the rare-earth doped fiber lasers.

In this paper, our recent works on ultra-wide wavelength tuning of RRFL is reviewed briefly at first. Cascaded random Raman lasing and tuning of pump laser wavelength are coordinated in a half-open RRFL to realize a continuously wavelength tuning from 1 to 1.9 $\mu$m. After that, power scaling of high order RRFLs is investigated. The temporal characteristic of the

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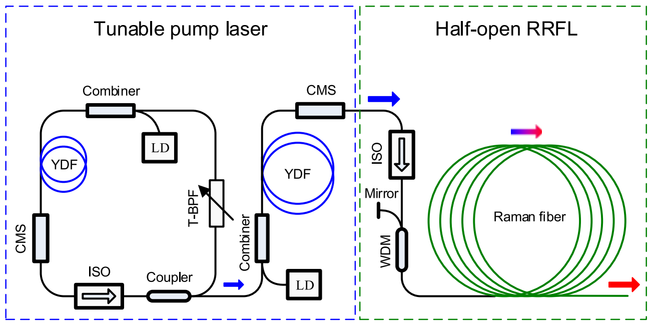


Fig. 1. Schematic diagram of the half-open RRFLs in the low power wavelength tuning experiments.

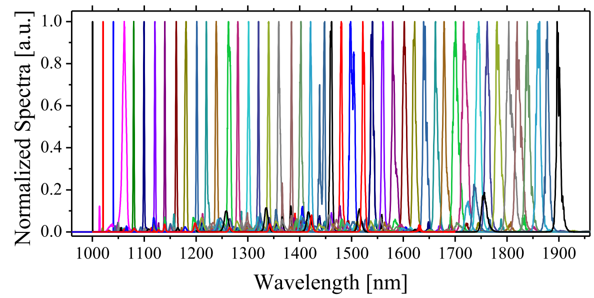


Fig. 2. Continuous wavelength tuning. Output spectra plotted for every 20 nm from 1 to 1.9 $\mu$m.

YDF pump laser is optimized by increasing the cavity length of the seed oscillator. The pump laser power is increased to ~250 W, and the laser setup is modified to withstanding the power. With a 240 m long RRFL, high spectral-purity (86.6%) laser at the 9th Raman Stokes of 1806 nm is achieved with an inband power of 100.1 W, which corresponds to an optical efficiency of 38.4% from 1064 nm and 27.2% from 915 nm. To the best of our knowledge, both the tunable range and the power at 1806 nm are the new record for random Raman fiber laser.

## II. Ultra-Wide Wavelength Tuning

The experimental setup includes two functionally different parts as shown in Fig. 1, a tunable Yb-doped fiber laser used as the pump laser [23] and a half-open RRFL. The pump laser has a standard MOPA configuration using all PM active and passive fibers with a core diameter (MFD) of 10 $\mu$m and numerical aperture of 0.075. They are pumped by laser diodes, which have a nominal 4.8 dB/m absorption at 976 nm in the gain fiber. The tunable seed laser has a ring cavity geometry. A tunable bandpass filter (T-BPF) based on the thin film cavity is used to select the operating laser wavelength, which is tunable from 1000 to 1099 nm with a tuning resolution of 0.02 nm and a bandwidth of 1 nm at 3 dB. The amplifier is built and optimized for the 1020–1080 nm wavelength range. The whole pump laser system is all-fibered and polarization-maintained.

The tunable pump laser is injected into the half-open Raman random laser through a broadband (1020–1080 nm) isolator to prevent the backward distributed Rayleigh feedback into the amplifier. A wavelength division multiplexer (WDM) is spliced between the isolator and a long piece of Raman fiber. Different types of fibers are tested in the experiments for comparison, including SMF-28, HI1060, and Raman fiber from OFS Optics. The zero dispersion wavelength of the first two fibers is around 1.3–1.4 $\mu$m. Cascaded Raman shifting beyond 1.4 $\mu$m is found to be impossible. Broadband supercontinuum-like light is generated instead due to the four wave mixing process near zero dispersion wavelength. The latter produces best results. In the experiments described in this section, 2 km of Raman fiber is used. The randomly distributed Rayleigh scattering in the core of Raman fiber provides necessary feedback for the laser action. The output end of this fiber is cleaved at an angle >8° to suppress the backward reflection. 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. More details of the laser setup can be found in Refs. [12]. The output spectra from 1000–1600 nm and 1200–2000 nm of the laser are measured with spectrum analyzer Yokogawa AQ6370D and AQ6375, respectively.

The wavelength tunable master oscillator of the pump laser emits from 1010–1090 nm. The laser power reaches over 2 W from 1020 to 1080 nm. The fiber amplifier can output over 45 W from 1020 to 1080 nm without parasitic oscillation, which is used to pump the RRFL. The 3 dB linewidth and signal to noise ratio keep less than 0.5 nm and over 50 dB for all the wavelengths, respectively.

The 1st order RRFL is investigated at first. When the pump laser wavelength tunes from 1020 to 1080 nm, the random laser wavelength changes accordingly from 1070 to 1136 nm. When the pump power increases, cascaded Raman random lasing are generated successively. Specific Stokes light can be selected just by tuning the pump power. When the pump wavelength varies, the wavelengths of the cascaded Raman Stokes light change accordingly. Therefore, by adjusting the pump laser wavelength and power altogether, extremely wide wavelength tuning of RRFL is achieved.

Fig. 2 shows the result of continuous wavelength tuning from 1 to 1.9 $\mu$m. For each output, the wavelength is determined by tuning the pump wavelength, and the spectral purity is optimized by adjusting the pump power. As is shown in Fig. 3, the output power increases with respect to the wavelength, because higher power is required to generate higher Stokes. And the spectral purity is higher than 80%. These behavior changes suddenly above 1.8 $\mu$m, which is the 10th Stokes. The output power drops, and the conversion efficiency is low. The spectral purity decreases, and only 50% power ratio is achieved at the wavelength of 1.9 $\mu$m. This is due to the increased fiber loss at longer wavelength. The Raman fiber is specified to work at wavelength from 1.1 to 1.7 $\mu$m.

Therefore, by pump wavelength tuning and cascaded Raman shifting, ultra-wide wavelength tuning from 1 to 1.9 $\mu$m is achieved from a single laser system. It is the widest wavelength tuning range ever reported for continuous wave fiber lasers to the best of our knowledge. A natural perspective is the power scaling of such cascaded RRFL. The wavelength range

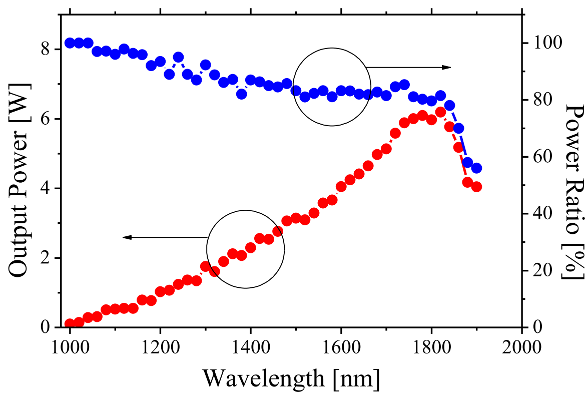


Fig. 3. Inband output power and power ratio as a function of wavelength. (Inband power means the output power at the desired signal wavelength, and the power ratio means the ratio of the inband power to the total output power.)

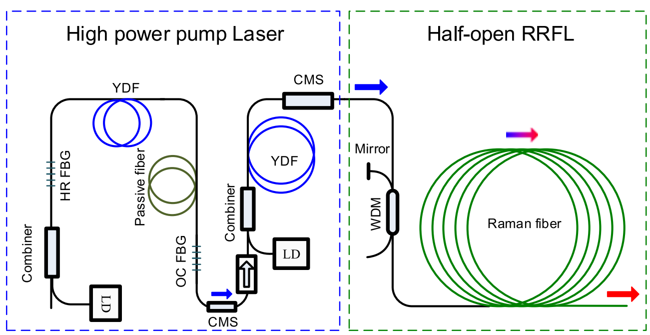


Fig. 4. Schematic diagram of the high power RRFL.

from 1.6 to 1.8 $\mu$m, for example, is particularly interesting, since high power operation with rare earth doped fiber is difficult.

## III. Power Scaling of High Order RRFLs

In Section II, the RRFL shows great wavelength tuning capability. However, because of the limited pump power and the long Raman gain fiber resulted large loss of the laser, the output power of the RRFL is limited to several watts. In this section, a higher power pump laser with fixed wavelength is used to pump the RRFL. For the power scaling of high order RRFL, the pump laser power is increased to ~250 W and the temporal stability of pump laser is improved.

Fig. 4 illustrates the setup for the high power cascaded RRFL. The main difference is in the pump laser. The seed laser of the pump laser emits 10 W randomly polarized light at 1064 nm. It consists of a pair of FBGs ($R > 99\%$ high reflector and $R = 10\%$ output coupler), 5 m of YDF with the same specifications as in previous experiments and followed by a cladding mode stripper (CMS). Note that a piece of ~200 m long passive fiber is spliced between the YDF and the OC grating to increase the cavity length and the number of longitudinal modes in the laser cavity. Assuming the longitudinal modes are with random phases, the larger the number of modes, the smaller the intensity fluctuation induced by mode beating. On the other hand, the addition of a long section of passive fiber was shown to stabilize the fiber laser by making the gain recovery faster than the self-pulsation

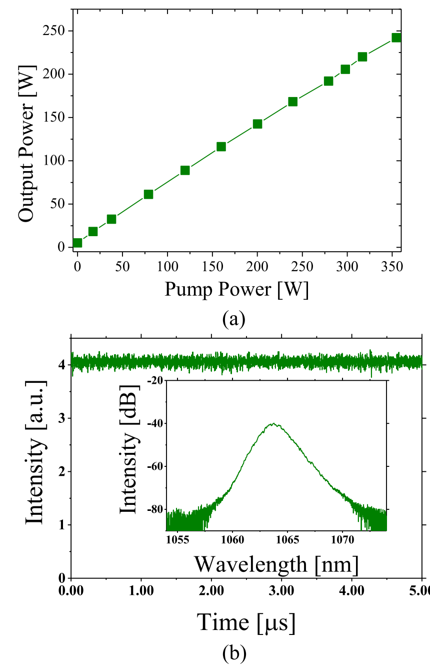


Fig. 5. Output performance of the 1064 nm pump laser. (a) Output power as a function of the 915 nm diode laser power. (b) The temporal characteristics of the 1064 nm pump laser. Inset is the output spectrum at full power.

dynamics [24]. The 1064 nm seed light is coupled into the YDF power amplifier with a (6+1)×1 pump and signal combiner. The multimode input ends of the combiner are connected to six 70 W 915 nm laser diodes. The available pump power, measured from the output end of the combiner, is 350 W. 12 m YDF with the same fiber parameters as that in the oscillator is used as the gain fiber. A second CMS is spliced after the amplifier to remove the residual pump laser in the cladding.

As is depicted in Fig. 5, the 1064 nm pump laser can output up to ~250 W. The corresponding optical efficiency is 70%. The temporal behavior of the 1064 nm laser is more stable than that of shorter oscillator without the addition of 200 m passive fiber and no self-pulse phenomenon is observed. The central wavelength and bandwidth of the pump laser are 1063.74 and 1.6 nm, respectively.

Since single mode fiber pigtailed optical isolator withstanding hundreds of watts laser is not available, the high power pump laser is delivered into the RRFL directly without an isolator. Concern is on the feedback from the RRFL towards the pump laser. Due to the high seeding power of the Yb fiber amplifier, the Rayleigh scattering feedback from the Raman fiber at 1064 nm has negligible effect on the pump laser performance. The 1st order Raman laser is spectrally isolated with the pump laser by the WDM. Higher order Raman light which is outside the Yb emission spectrum should have no influence on the system. We find the 2nd order Raman laser would couple with the YDF pump laser, which is discussed later in this section.

The cascaded RRFL has the same configuration as that in previous section. The only difference is that the Raman fiber used in the experiment is only 240 m long. When increasing the pump power, the Raman Stokes laser is generated cascadedly.

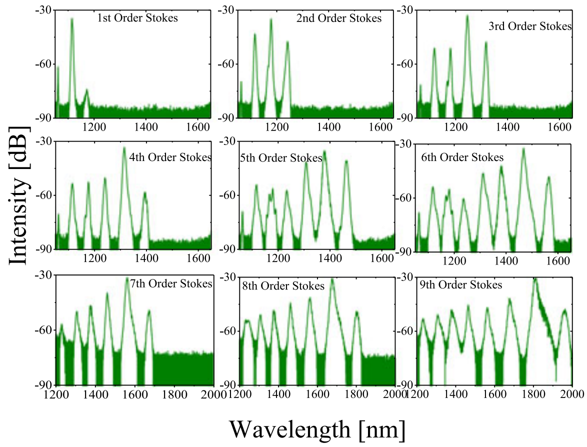


Fig. 6. Spectra of the cascaded generation of the 1st to 9th order RRFL.

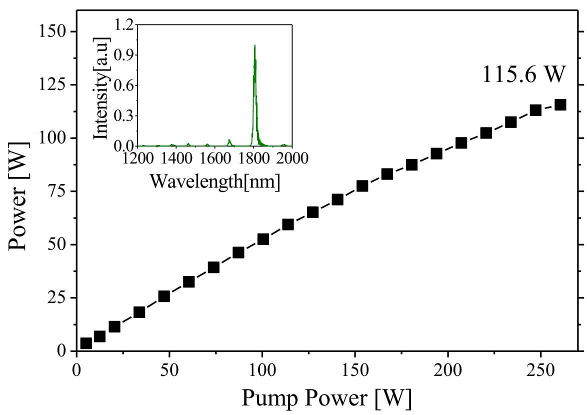


Fig. 7. Output power of the RRFL as a function of the 1064 nm pump laser power. Inset is the output spectrum of the 9th order RRFL at 1806 nm at full power.

Up to 9th order Raman laser at 1806 nm can be obtained. The 10th order Stokes light at 1955 nm starts to show in the spectrum. But the power is low. Output spectra of the laser optimized for the 1st to 9th Stokes light are shown in Fig. 6. The total output power from the RRFL as a function of the 1064 nm pump power is plotted in Fig. 7. A spectrum at highest output is depicted in the inset of Fig. 7 in linear scale, which shows that a majority of the output is at 1806 nm. The 3 dB linewidth are 13 nm. The ripples in the left wing of 1806 nm emission spectrum is caused by the water absorption line [25].

The output power and optical efficiency for different Raman Stokes light with respect to the pump power are summarized in Fig. 8(a) and (b). Clear threshold behavior is observed in the power and efficiency curves of different Raman orders. Above the threshold, the 1st order Raman laser starts to grow and the pump laser depletes until almost all the pump laser is converted into the Raman laser. Then, the 2nd order Raman laser repeats the same process, and so on for the higher order Raman lasers. The high order Raman lasers are generated successively. The maximum output power for each order increases with the order number, because high order Raman laser is generated at higher pump laser. The highest output powers at 1676 nm (8th Stokes) and 1806 nm (9th Stokes) are 69.9 and 100.1 W, respectively,

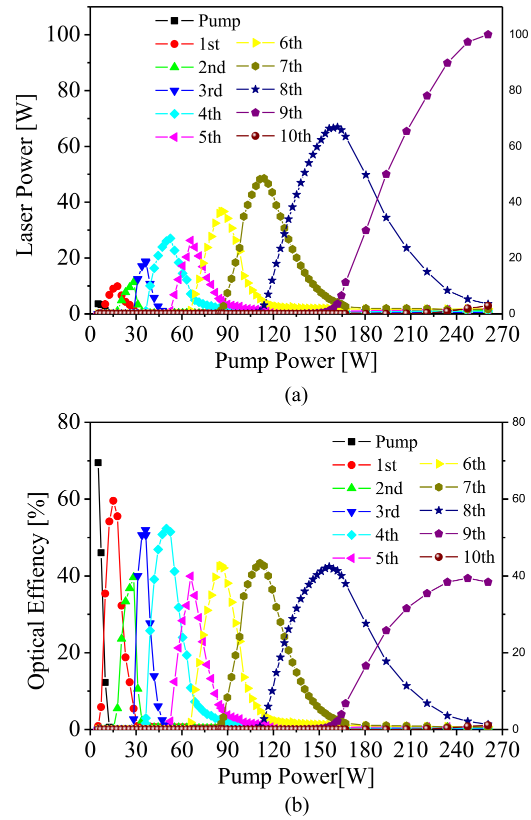


Fig. 8. (a) The output powers and (b) optical efficiencies for different order Raman Stokes lights with respect to pump power.

corresponding to an optical efficiency of 42.4% and 38.4% from 1064 nm. Both the output power and efficiency are the new record for the RRFL at wavelength longer than 1.3 $\mu$m.

Table I summarizes the inband power ratio and power at each order of Raman Stokes. Due to the excellent temporal stability of the pump laser, the inband power ratio is as high as 84.3% for the 8th order and 86.6% for the 9th order Raman laser. This is a rather unique property of RRFL among different cascaded Raman Stokes generation processes. With nested Raman oscillators and cascaded Raman fiber amplifiers, similar spectral purity is hard to achieve [26], [27]. In cascaded Raman amplification process pumped by a pulsed laser, usually supercontinuum-like multiple Raman Stokes output is generated [28]. An unexpected observation is that the inband power ratio for the 2nd and 5th order Raman laser are only 82.8 and 74.5%, respectively, much lower than adjacent orders. For the 2nd order Raman laser, the low power ratio relates to another observation of temporal fluctuation in power, which will be detailed in next paragraph. The power variation results in an averaged low inband power ratio. For the 5th order Raman laser, the low inband power ratio is maybe caused by the fiber loss peak around 1378 nm. At about 7th Raman Stokes, the fiber has lowest loss. Interestingly, although the fiber loss gets higher at 8 and 9th Raman orders, the inband power ratio increases. This in fact is a result of fast increasing loss over wavelength. Higher order Raman laser is suppressed due to the high attenuation. The Raman fiber is a natural "filter fiber" suppressing high order Raman conversion

TABLE I
OUTPUT CHARACTERISTICS OF DIFFERENT ORDERS OF RRFL

| Stokes order | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th |
|---|---|---|---|---|---|---|---|---|---|
| Wavelength (nm) | 1118 | 1179 | 1245 | 1317 | 1378 | 1467 | 1563 | 1676 | 1806 |
| Linewidth (nm) | 3.47 | 3.22 | 4.71 | 5.39 | 5.76 | 6.96 | 7.68 | 7.67 | 13.6 |
| Inband power Ratio (%) | 99.9 | 82.8 | 94.3 | 95.5 | 74.5 | 80.6 | 83.2 | 84.3 | 86.6 |
| Inband Power (W) | 9.9 | 11.3 | 18.8 | 27.0 | 26.0 | 36.7 | 48. 6 | 66.9 | 100.1 |
| Optical efficiency from 1064 nm (%) | 59.6 | 39.6 | 52.0 | 52.3 | 39.9 | 42.7 | 43.4 | 42.4 | 38.4 |

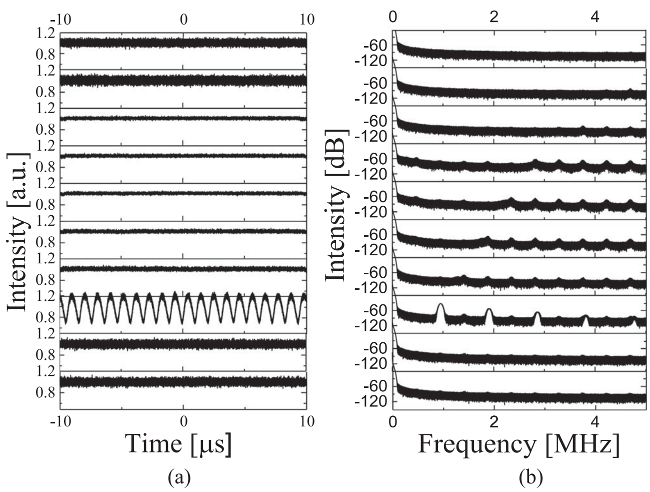


Fig. 9. (a) Time and (b) frequency domain measurements of the pump, 1st 2nd . . . and 9th (from the bottom to the top) order RRFL.

at wavelength longer than 1.8 $\mu$m. The laser linewidth increases from 3.47 to 13.6 nm with the increase of the Raman order. Higher order Raman laser has higher output, therefore, facing stronger nonlinear effects such as four wave mixing and cross-phase modulation, which broaden the laser linewidth.

The time and frequency domain characteristics of the lasers are analyzed. Fig. 9(a) and (b) shows the normalized time and frequency domain characteristics of the pump, 1st, 2nd . . . .9th order random lasers. The pump laser has excellent temporally stability, because of the elongated cavity. Only tiny beat note remains in the RF spectrum. The first order Raman laser looks noisier than other orders, which is artificial. When measuring the first order output, the signal was too weak that the detector noise dominates. For the second order Raman laser, an obvious periodical temporal fluctuation in the output is observed. We think it is a result of unwanted coupling between the RRFL and the YDF pump laser. The fused WDM used in the setup is specified to work at 1064/1120 nm. A fused WDM usually has a periodic transmission spectrum. It means that, for the 2nd order Raman laser at 1179 nm, a large fraction of the backwardly feedback light transmits the WDM and injects into the YDF amplifier. 1179 nm is still within the emission spectrum of YDF, so it unstablizes the YDF pump laser. The influence of the coupling between the 2nd order Raman laser and YDF pump laser persists in the higher order Raman lasers, as evidently shown in the RF spectra of them. The frequency features can be traced back to the beat notes of the pump laser. The even harmonics are enhanced in the 2nd order Raman laser for some reason, which may be explained by the details of the coupling between the random laser and the pump laser. When the order of Raman process increases, no obvious increase of intensity noise is observed. For the 8th and 9th order Raman stokes, the intensity noise looks stronger. This is artificial, because at these wavelength longer than 1.7 $\mu$m we has to use a photodiode with larger background noise to do the measurements.

## IV. CONCLUSION

In summary, the wavelength versatility and power scaling of high order RRFL are demonstrated. By continuously tuning the pump laser wavelength and increasing the pump power, RRFL tunable from 1 to 1.9 $\mu$m is achieved. Pumped by a temporally stable 1064 nm laser, up to 9th order cascaded Raman random fiber laser at 1806 nm is investigated. The highest output power reaches over 66.9 and 100.1 W at 1676 and 1806 nm, corresponding to an optical efficiency of 42.4 and 38.4% from 1064 nm pump laser, respectively. To the best of our knowledge, both the wavelength tuning range and the power at 1676 and 1806 nm are the new record for the random Raman fiber laser. The RRFL output is limited by the available pump power. To obtain higher output, pump laser with higher power should be developed. It will increase the Raman gain so as to decrease the length of Raman fiber and the overall loss. Future work will concentrate on the further power scaling of the RRFLs and explore the application of such ultra-broadband tunable random fiber lasers.

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