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Ultra-wide wavelength tuning of a cascaded Raman random fiber laser

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An ultra-broadband tunable cascaded Raman random fiber laser pumped by a tunable (1020–1080 nm) ytterbium-doped fiber laser is investigated. By continuously adjusting the pump laser wavelength, the Raman random laser tunes accordingly due to the Raman gain competition. By increasing the pump power, up to the 5th order Raman random laser is achieved. As a result, 300 nm of continuous wavelength tuning from 1070 to 1370 nm is achieved by adjusting the pump wavelength and power altogether. The highest output power is 1.8 W at 1360 nm with an optical efficiency of 15% from 1080 nm. To the best of our knowledge, this is the widest wavelength tuning range reported for a random fiber laser so far. © 2016 Optical Society of America

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Widely tunable fiber lasers are of significant interest to the scientific and industrial community due to their application diversity, such as pumping mid-IR lasers, optical fiber sensors, spectroscopy, and fiber component testing. Gain medium with broad gain spectrum such as ytterbium (Yb) [1], erbium [2], or thulium [3] were adopted to achieve widely tunable lasers, however their lasing wavelengths are still limited by their emission spectra. The Raman fiber laser is well known for its wavelength flexibility, because Raman gain is available at arbitrary wavelength across the transparency window of an optical medium [4]. In traditional Raman lasers formed by a pair of fiber Bragg gratings (FBGs) and a piece of Raman gain fiber [5,6], its wavelength is mainly decided by the FBGs, which could not fully explore the wavelength flexibility of the Raman laser. Although numerical [7] and experimental [8] works on the tunable conventional Raman laser are reported, the configuration is complex and the tuning range is still limited. Recently, fiber random lasers operating via extremely weak random distributed Rayleigh scattering and amplified through Raman gain in a long piece of fiber have been proposed and studied [9–11]. Rayleigh scattering is available at any wavelength, whose strength is characterized to be $\alpha_R = C_R/\lambda^4$. Therefore, the Raman random fiber laser is born to have the ability of ultra-wide spectral tunability.

Random fiber lasers with flexible wavelength have drawn attention. In 2011, Vatnik *et al.* reported a random fiber laser emitting at the 1st and 2nd Raman Stokes at 1 micron [12]. In 2012, Zhang *et al.* achieved a 2nd order 1555 nm cascaded Raman random laser with 50 km single mode fiber (SMF-28) as gain fiber [13]. In 2013, Wang *et al.* reported the 3rd cascaded Raman random laser and its threshold is only 2.5 W [14]. Because of the wide gain spectrum of Raman scattering, Babin *et al.* demonstrated a 1535–1560 nm tunable random laser by inserting a tunable filter into the cavity [15]. With tunable FBG, Sarmani achieved a 1550–1571 nm tunable random laser [16]. With an all-fiber Lyot filter for wavelength selection, Sugavanam demonstrated the 1st and 2nd order Raman multiwavelength random laser [17]. Most recently, Du *et al.* used Yb-doped fiber as laser gain, 1 km long fiber for distributed Rayleigh feedback, and tunable filter for wavelength selection, and achieved a 1040–1090 nm tunable random fiber laser [18]. However, the reported random fiber lasers either emit at discrete Raman Stokes wavelengths or exploit the gain spectrum of a single Raman shift or rare earth ion only, so a maximum of 50 nm continuous tuning range has been achieved.

In this Letter, the characteristic of wide gain spectrum and cascaded operation of stimulated Raman scattering are incorporated jointly in the random fiber laser for the first time, to the best of our knowledge. By increasing the pump power, up to the 5th order Raman shifting is achieved in an Yb fiber laser pumped random fiber laser. Moreover, by continuously tuning the pump laser wavelength from 1020 to 1080 nm, the Raman random fiber laser can cover the wavelength gaps between the Raman cascades. As a result, a Raman random fiber laser continuously tunable from 1070 to 1370 nm is demonstrated.

Figure 1 illustrates the schematic diagram of the tunable Yb-doped fiber laser, which is used as pump source, and the cascaded Raman random fiber laser. The tunable pump laser has a standard master oscillator power amplifier configuration. Yb-doped polarization maintaining double-clad fibers with core diameter of 10 μm and a numerical aperture of 0.075 are used

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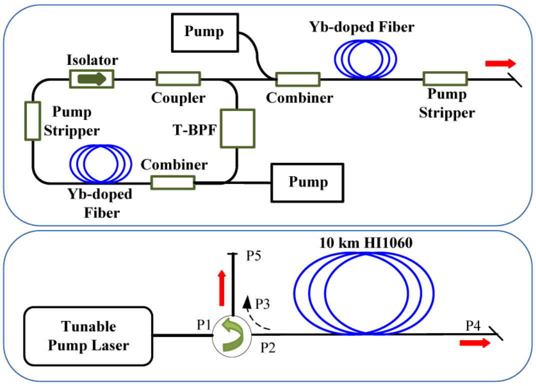

Fig. 1. Schematic diagram of the tunable Yb-doped fiber laser (top), which is the pump source for the ultra-broadband tunable cascaded Raman random fiber laser (bottom). T-BPF, tunable bandpass filter.

as gain media for the seed laser and amplifier. They are pumped by 976 nm laser diodes that have a nominal 4.8 dB/m absorption in the gain fiber. The seed laser has a ring cavity geometry. A tunable bandpass filter 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. Then the tunable pump laser is injected into the Raman random laser through a broadband (1020–1100 nm) circulator. A piece of 10 km-long HI1060 fiber (from YOFC) is used as the gain fiber, which supplies the distributed Rayleigh scattering and the Raman gain simultaneously. The output end of this fiber (P4) is cleaved at an angle >8° to suppress the backward reflection. P3 of the circulator is 0° cleaved to increase the feedback. The isolation of the circulator from P3 to P2 is 20 dB, so the effective reflection for the Raman fiber laser from the circulator side is about 4×10^{-4} at the specified circulator wavelength range.

The wavelength tunable master oscillator emits from 1000–1099 nm. The laser power reaches over 2 W from 1020–1080 nm and the amplified spontaneous emission (ASE) is 50 dB lower than the laser line in the output spectrum. The fiber amplifier can operate without parasitic oscillation from 1010 to 1080 nm. As is depicted in Fig. 2, the output power is over 45 W from 1020 to 1080 nm, which is used to pump the random fiber laser, and the maximum output power reaches 58 W at 1030 nm. The 3 dB linewidth of all the wavelengths keep less than 0.5 nm.

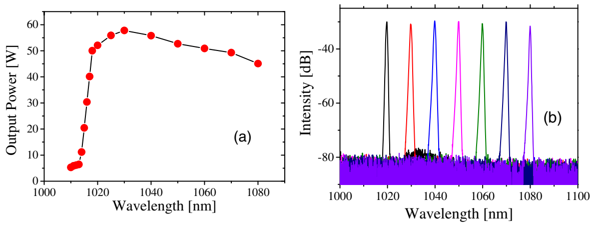

Fig. 2. (a) Output power of the pump fiber laser as a function of the laser wavelength. (b) Spectra of the tunable laser from 1020 to 1080 nm.

The tunability of the 1st order Raman random laser is investigated at first. When the pump laser tunes from 1020 to 1090 nm, the random laser wavelength changes accordingly from 1070 to 1146 nm, as depicted in Fig. 3(a). The ratio between the Raman signal and the residual pump is over 20 dB. Figure 3(b) shows the signal spectra with the increase of pump power, which shows a clear threshold characteristic of random lasing. At low pump, broadband Raman ASE is observed. When the pump power increases, the spectra narrows suddenly because of the random lasing. When the pump power increases further, at this wavelength region the output spectrum tends to have dual peaks corresponding to the dual peaks in the Raman gain spectrum as shown in Fig. 3(a).

After that, cascaded Raman random lasing is investigated. Figure 4(a) shows the typical output spectra at different pump power with the pump wavelength fixed at 1045 nm. With the increase of pump laser power, the 1st to 5th order Raman emissions are observed successively. Figure 4(b) shows the power ratio of each Raman Stokes light within the random laser output as a function of the pump power. It is seen that most of the power can reside in the 1st to 4th order Raman wavelength with proper pump power. However, when the laser wavelength approaches 1400 nm for the 5th order Raman emission, the power ratio reaches only 60% and then rolls off. The 6th order Raman laser starts to generate almost at the same pump power with the 5th order Raman laser. The observation is related to the dispersion property of the Raman gain fiber, whose zero dispersion wavelength is close to 1400 nm. Near the zero dispersion wavelength, the four-wave mixing (FWM) process is efficient. The FWM between the Raman Stokes lights results in the low threshold generation of the higher order Raman emission. In addition, the 6th order Raman light is spectrally broadened due to non-linear processes, which prohibits the further wavelength expanding of the random Raman

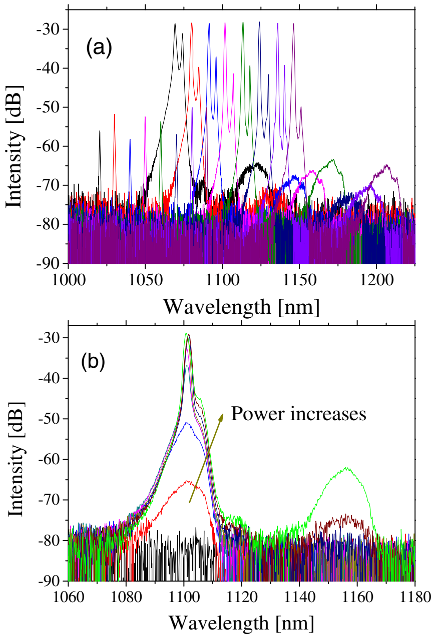

Fig. 3. (a) Spectra of the 1st order tunable Raman random laser. (b) Spectra of the random laser with increasing pump power.

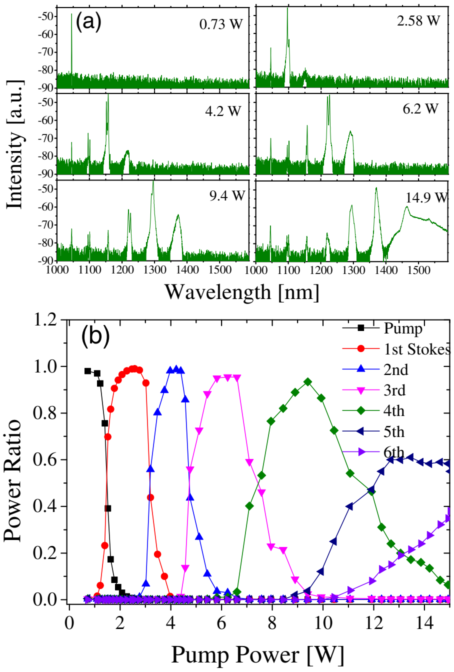

Fig. 4. (a) The output spectra of the Raman random fiber laser at different pump power. (b) Power ratio of the pump, 1st to 5th order Raman light within the output of the random fiber laser as a function of the pump power.

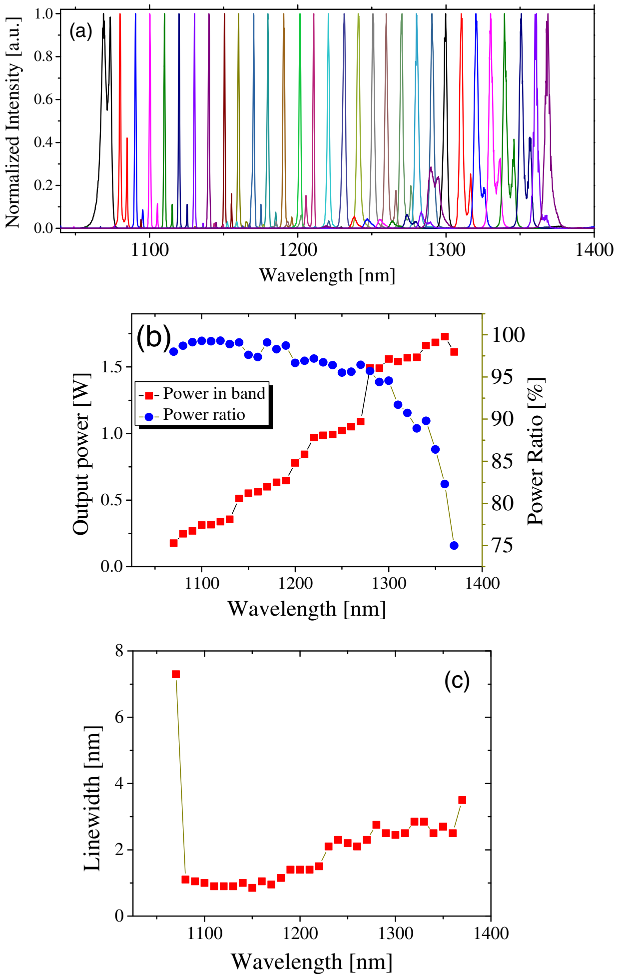

Fig. 5. (a) 300 nm tuning of the Raman random fiber laser from 1070 to 1370 nm. (b) In-band laser power and its ratio in the total output at different wavelengths. (c) Linewidth as a function of the laser wavelength.

fiber laser. For further red-extended wavelength, gain fiber with longer zero dispersion wavelength should be chosen.

By adjusting the pump laser wavelength and power together, wavelength tuning over 300 nm is achieved with the Raman random fiber laser. Figure 5 shows the output spectra of the laser optimized for wavelengths from 1070 to 1370 nm with 10 nm intervals. The tuning accuracy is less than 0.5 nm. The laser power as a function of the wavelength is depicted in Fig. 5(b). The laser power increases with the wavelength because higher pump power is required for generating a longer wavelength. The highest output power at 1360 nm reaches 1.8 W, corresponding to an optical efficiency of 15% from 1080 nm. To increase the optical efficiency, fiber with higher Raman gain coefficient can be used to shorten the fiber length and meanwhile the total cavity loss. Also, half-open random laser configuration and broadband components with small insertion loss could help to increase the optical efficiency as well [19]. After 1360 nm, the laser power rolls off, which is due to the FWM-induced low threshold generation of higher order Raman light preventing the further power conversion from low order to high order Stokes laser. Because of the insufficient conversion, the power ratio decreases when the lasing wavelength is longer. To future improve the power ratio at each individual lasing wavelength, fiber with longer zero-dispersion should be adopted as the Raman gain fiber. The general trend for laser linewidth is increase with respect to wavelength as depicted in Fig. 5(c). However, at 1070 nm, the laser has two peaks corresponding to the dual-peak in the Raman gain spectrum of germanium-doped silica fiber. Except for the 1070 nm laser, the maximum laser linewidth is 3.5 nm at 1370 nm. At long wavelength near the zero dispersion wavelength (1400 nm) of the Raman gain fiber, although the laser power is as low as 1.8 W, FWM effect broadens the laser linewidth significantly.

The time and frequency domain characteristics of the laser are analyzed with an oscilloscope of 1 GHz bandwidth and a radio frequency spectrum analyzer with bandwidth of 20 GHz, while keeping the pump wavelength at 1045 nm. Figures 6(a) and 6(b) show the normalized time and frequency domain characteristics of the pump, 1st to 5th order Raman lasers. The pump laser is stable. When the order of Raman process increases, there is some modulation in the output, which probably relates to the stimulated Brillouin scattering effect [10,20]. For the frequency domain, no features at around 10 kHz ($c/2nL$~10 kHz, corresponding to the round-trip frequency for a fiber laser cavity with a length of ~10 km) could be observed, which indicates that there is no conventional mode structure, but only uniformly distributed frequency from 10 Hz to 100 kHz caused by the random distributed feedback lasing.

For the results reported above, the fiber end (P5) of the port 3 of the circulator is normal cleaved to provide a small forward feedback. Although the feedback is expected to be small due to

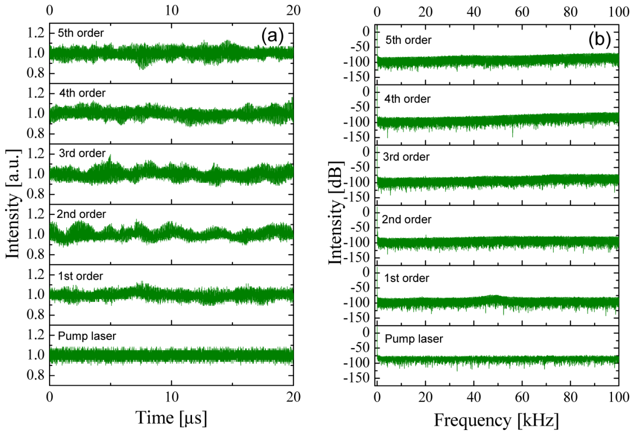

Fig. 6. (a) Time and (b) frequency domain measurements of the pump, 1st to 5th order Raman random laser.

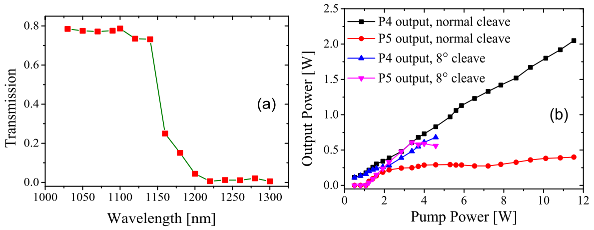

Fig. 7. (a) Transmission of the circulator from port 2 to port 3. (b) Output power at P4 and P5 under different cleaved conditions at P5.

the isolation and spectral bandwidth of the circulator, we find it can influence the random fiber laser significantly. The transmission spectrum of the circulator from port 2 to 3 is measured from 1020 to 1300 nm. As shown in Fig. 7(a), the transmittance is over 73% from 1020 to 1140 nm. After 1200 nm, it decreases to be less than 5%. The role of the feedback from the circulator is examined by comparing the laser performance with P5 normal or 8° angle cleaved. Figure 7(b) compares the output power from P4 of the laser and P5 of the circulator as a function of the pump laser when the end face of P5 is cleaved to be normal and 8°, respectively. When the P5 is cleaved to be normal, P4 outputs most of the laser power (2 W from P4 versus 0.4 W from P5 at full power). When P5 is cleaved to be 8°, with the increase of the pump power, the output power from P5 becomes larger than P4 due to the preferred backward emission of random laser. However, when the pump power exceeds 4 W, power from P4 keeps increasing while power from P5 begins to decrease because of the low transmittance of the circulator after 1150 nm. Therefore, the small feedback from the circulator could influence the lasing characteristics, especially the power distribution along the fiber. Similar observation has been reported [21].

In summary, we have demonstrated an ultra-broadband wavelength tunable cascaded Raman random fiber. By continuously tuning the pump laser wavelength and increasing the pump power, 300 nm wavelength tuning from 1070 to 1370 nm is achieved. The highest output power is 1.8 W at 1360 nm, corresponding to an optical efficiency of 15%. To the best of our knowledge, this is the widest tunable random Raman fiber laser so far. Future work will concentrate on the further wavelength expansion of the random Raman fiber laser and explore the application of such ultra-broadband tunable random fiber lasers.

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