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High-power linearly-polarized tunable Raman fiber laser*

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In this study, we demonstrate an all-fiber high-power linearly-polarized tunable Raman fiber laser system. An in-house high-power tunable fiber laser was employed as the pump source. A fiber loop mirror (FLM) serving as a high reflectivity mirror and a flat-cut endface serving as an output coupler were adopted to provide broadband feedback. A piece of 59-m commercial passive fiber was used as the Raman gain medium. The Raman laser had a 27.6 nm tuning range from 1112 nm to 1139.6 nm and a maximum output power of 125.3 W, which corresponds to a conversion efficiency of 79.4%. The polarization extinction ratio (PER) at all operational wavelengths was measured to be over 21 dB. To the best of our knowledge, this is the first report on a hundred-watt level linearly-polarized tunable Raman fiber laser.

Keywords: Raman laser, linearly polarized, tunable, fiber laser

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1. Introduction

Tunable fiber lasers have attracted a great deal of attention for applications in spectroscopy, metrology, laser cooling, medical treatments, and scientific research. The broad emission spectrum of rare-earth doped fiber allows the wide tunability of fiber lasers.[1–3] Power scaling of tunable fiber laser is challenging for special wavelengths, for example, the edge of the emission band of rare-earth doped fibers.[4–7] Compared with the common wavelengths around the peak of the emission band that have larger net gain, it is difficult to generate special wavelengths owing to the gain competition induced by amplified spontaneous emission (ASE) and parasitic lasing. In stark contrast, Raman fiber lasers, which employ stimulated Raman scattering within the fiber,[8–10] have shown great advantages of wavelength flexibility as Raman gain can be obtained at nearly arbitrary wavelengths with appropriate pump wavelengths combined with proper excitation of desired order Stokes waves.[11–14] In recent years, significant investigations on tunable continuous wave (CW) Raman fiber lasers have been undertaken.[12–14] In 2007, Babin *et al.* developed a widely tunable Raman fiber laser with an output power of 3.2 W.[12] In 2008, Belanger *et al.* demonstrated a Raman fiber laser with 60 nm tuning range that delivered up to 5 W of Stokes wave power.[13] Recently, Zhang *et al.* demonstrated a nearly-octave wavelength tuning of a CW fiber laser.[14] It is to be noted that, although several high-power Raman fiber lasers with fixed wavelengths have been reported with hundred-watt level output power,[15–19] the output power of tunable Raman fiber lasers is still rather low, i.e., no more than the 10 W level. Besides high output power, linearly polarized operation is also an important demand in many applications owing to high efficiency,[20,21] such as harmonic generation,[22,23] parametric conversion,[24,25] coherent detection, coherent beam combination,[26,27] spectral beam combination,[28,29] and supercontinuum generation.[30,31] Nevertheless, to the best of our knowledge, there have been no reports on high power linearly-polarized tunable Raman fiber lasers yet.

In the present paper, we report a high-power linearly-polarized Raman fiber laser pumped by a tunable pump source. A home-made high-power tunable fiber laser was adopted as the pump source. The cavity was composed of a fiber loop mirror (FLM) providing high reflectivity and a flat-cut endface serving as an output coupler. The Raman fiber laser had a 27.6 nm tuning range with a maximum output power of 125.3 W. The polarization extinction ratio (PER) of the Raman fiber laser was more than 21 dB for all lasing wavelengths. To the best of our knowledge, this is the first report on a hundred-watt level linearly-polarized tunable Raman fiber laser, and this is also the highest-power linearly-polarized tunable Raman fiber oscillator to date.

2. Experimental setup

The schematic diagram of the linearly-polarized Raman fiber laser pumped by a tunable fiber laser is depicted in Fig. 1(a). The pump source is a tunable ytterbium-doped fiber amplifier (YDFA) based on a master oscillator power amplifier (MOPA) structure, the detailed configuration of which is shown in Fig. 1(b). The pump source is seeded by a 1.6 W linearly-polarized tunable ytterbium-doped fiber laser (YDFL). The capability of wavelength tuning of the seed laser

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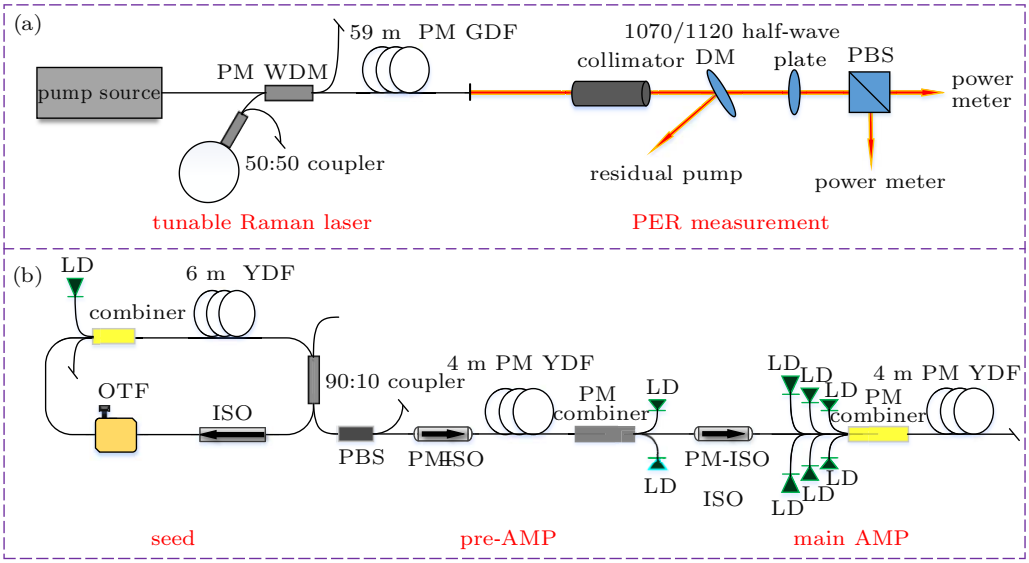


Fig. 1. (color online) (a) Schematic diagram of the linearly polarized tunable Raman fiber laser. (b) Detailed configuration of the tunable pump source. WDM: wavelength division multiplexer. GDF: germanium-doped fiber. DM: dichroic mirror. PBS: polarization beam splitter. PM: power meter. LD: laser diode. YDF: ytterbium-doped fiber. OTF: optical tunable filter. ISO: isolator. PM: polarization maintaining. AMP: amplifier.

is realized by an optical tunable filter (OTF), and the linear-polarized operation is achieved by a polarization beam splitter (PBS). After the pre-amplifier and the polarization maintaining isolator (PM-ISO), the seed laser is boosted to $\sim$ 20 W. After final boosting by the main amplifier, the maximum pump power of 172.8 W could be obtained at 1075 nm.

As shown in Fig. 1(a), the output of the pump is injected into the 1070-nm port of a 1070/1120 nm wavelength division multiplexer (WDM). It is to be noted that the central working wavelengths of the WDM are 1070 nm and 1120 nm. At pump wavelengths of 1060 nm, 1070 nm, and 1080 nm, the insertion losses of the WDM were measured to be 0.35 dB, 0.54 dB, and 1.25 dB, respectively, under the hundred-watt level pump power. These insertion losses are acceptable in the tunable laser system. The cavity of the tunable Raman laser consisted of an FLM formed by splicing together the two output ports of a 50/50 wideband coupler centered at 1120 nm as a high reflectivity mirror, a piece of 59-m commercial polarization maintaining passive double clad fiber (germanium-doped fiber, GDF) as a gain medium, and a flat-cut endface as an output coupler providing 4% reflectivity. The FLM was spliced to the 1120-nm port of the WDM. The core and cladding diameters of the passive fiber were 10 and 125 μm, respectively. The GDF was a single-mode fiber at the working wavelength in our experiment. The Raman gain profile of the GDF was similar to the classic Raman gain spectrum.[32] The design of this cavity met the requirement of wideband tunable operation at low cost. In the entire laser system, all the free fiber ends except for the output end were angle-cleaved to 8° to suppress the unexpected backward reflection. The passive fiber components used in the amplifiers and the Raman oscillator were manufactured using polarization maintaining fibers with core/inner cladding diameters of 10 μm/125 μm, respectively. The normalized frequency V was equal to 2.1, which is less than 2.4. Therefore, single-mode fiber lasing was obtained in this experiment. An optical spectrum analyzer (OSA) was employed to measure the spectral information.

The linearly-polarized Raman fiber laser was obtained using the linearly-polarized pump source and polarized maintaining components. The PER of the output power was measured. A collimator was used to maintain the output laser from diverging. A 1070/1120 nm dichroic mirror (DM) was placed after it to extract the first order Stokes wave. When the pump wavelength was tuned to around 1070 nm, the DM could separate the pump laser from the first order Stokes wave. A half-wave plate was used to adjust the polarization direction of the first order Stokes wave, so that the polarization beam splitter (PBS) centered at 1120 nm could distinguish the fast and slow axes of the linearly polarized Stokes wave. The output power was recorded by the power meter.

3. Results and discussion

First, we tested the properties of the in-house tunable pump source. The output spectra and the output power as a function of wavelength are shown in Figs. 2(a) and 2(b), respectively. Owing to the higher net gain at longer wavelengths (1070–1080 nm) for high-power YDFLs[3,33] the output power at 1070–1080 nm laser light is higher than that at shorter wavelengths (1055–1065 nm).

Then by increasing the output power of the pump source, the properties of the tunable Raman fiber laser were recorded.

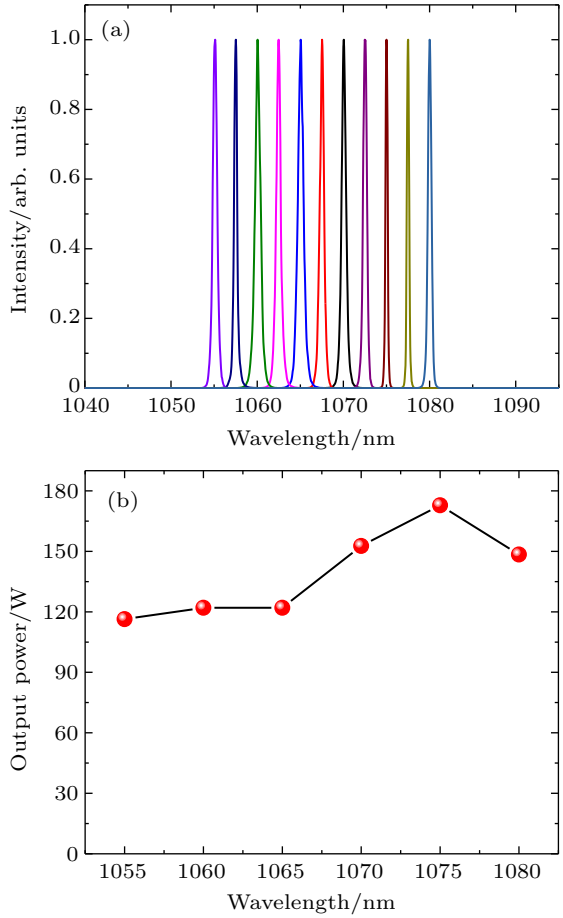


Fig. 2. (color online) (a) Spectra and (b) output power of the tunable pump source.

Figure 3(a) shows the threshold power for Raman lasing at 1112 nm, 1118.3 nm, 1122.7 nm, 1128.5 nm, 1133 nm, and 1139.6 nm corresponding to pump wavelengths of 1055 nm, 1060 nm, 1065 nm, 1070 nm, 1075 nm, and 1080 nm, respectively. The threshold power at 1070 nm was 38.6 W, which was lower than that of other wavelengths, while the maximum was 49.7 W at 1080 nm. The difference in threshold power at different wavelengths may be attributed to the insertion losses of the optical devices. The central wavelength of the coupler was 1120 nm; thus, the fiber loop mirror had the highest reflectivity at 1120 nm. The threshold power at pump wavelengths longer than 1070 nm was higher than those of wavelengths shorter than 1070 nm. The reason for this can be attributed to the higher insertion losses of the WDM at longer wavelengths, as mentioned above. As the pump power increases, Raman lasing can be tuned from 1112 to 1139.6 nm when the pump wavelength is tuned from 1055 to 1080 nm. As shown in Fig. 3(b), at the maximum output power, the second-order Stokes wave appears but the intensity is no more than 3% of the first order Stokes wave. High-order Stokes waves can be further suppressed by optimizing the length of the passive fiber. Figure 3(c) depicts the output power of the first order Stokes wave and the corresponding conversion efficiency versus the

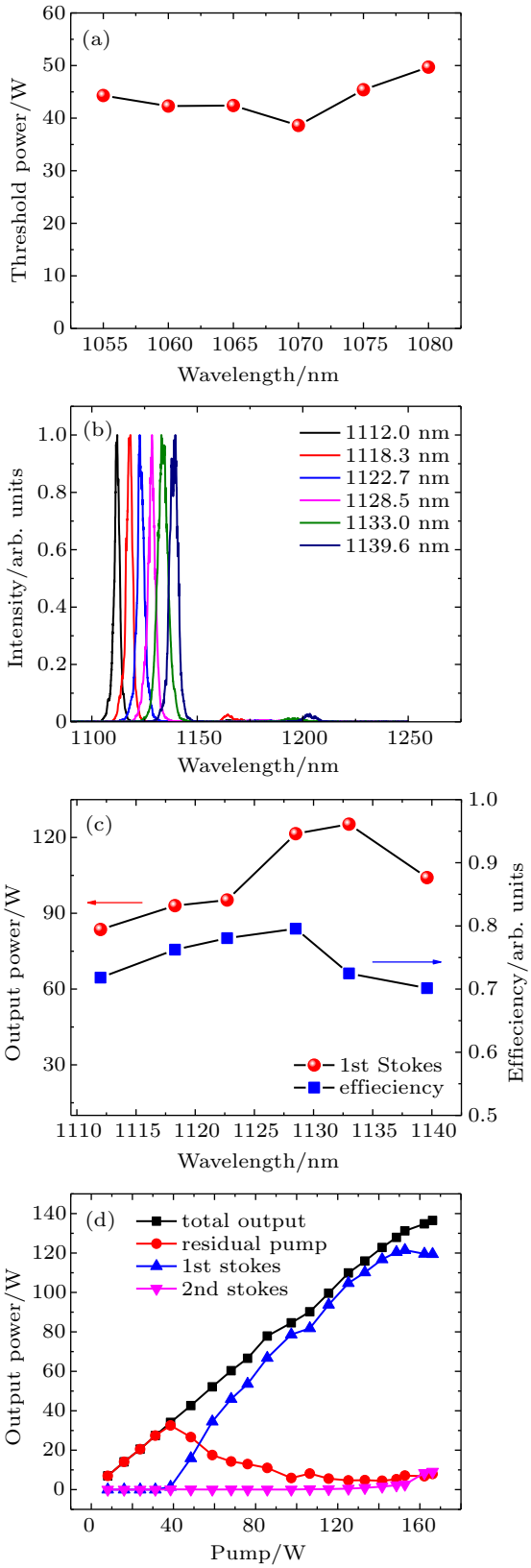


Fig. 3. (color online) (a) Threshold power of the first order Stokes wave, (b) spectrum of the output Stokes wave, (c) output power of the first order Stokes wave and corresponding efficiency, and (d) the output power versus pump power at 1070 nm.

wavelength of the first-order Stokes wave. The maximum power of the first-order Stokes wave is 125.3 W with the pump power of 157.8 W at 1075 nm corresponding to an optical

conversion efficiency of 79.4%, while the minimum power is 83.6 W under the pump power of 116.4 W at 1055 nm corresponding to the conversion efficiency of 71.8%. As each device used in the cavity has its own central working wavelength, the differences among the output powers mainly stem from the insertion losses of the devices. The inferior conversion efficiency at wavelengths deviating from 1070 nm is due to the conversion to the second-order Stokes wave, which is probably related to the polarization property,[34] insertion loss of the WDM and coupler, and so on. The conversion efficiency at the pump wavelength of 1070 nm is the highest, and the conversion to the second-order Stokes wave at 1070 nm is the lowest. Taking 1070 nm as an example, the output power versus pump power is shown in Fig. 3(d). When the pump power reaches the Raman threshold of around 40 W, the first order Stokes wave at 1128.8 nm increases rapidly with the pump power corresponding to a conversion efficiency of 79.6%. The output power of the first order Stokes wave is scaled to 121.5 W while the total power is 131.2 W. When the pump power is higher than 140 W, the power of the Stokes wave at 1128.8 nm saturates owing to the conversion to a second-order Stokes wave.

The spectral properties have also been investigated. The linewidth of the pump and first-order Stokes wave at different pump wavelengths when the output power of the first order Stokes was around 80 W were recorded and are shown in Fig. 4(a), where obvious spectrum broadening is observed. Taking the pump wavelength of 1080 nm as an example, the spectral curves of the pump laser and the first-order Stokes wave under different pump powers are shown in Figs. 4(b) and 4(c). In this case, the wavelength of the first-order Stokes wave here is 1139.6 nm. The main mechanism of spectrum broadening could be ascribed to quasi-degenerate four-wave mixing (FWM) between different longitudinal modes.[35] It is to be noted that the entire spectrum of the first order Stokes wave shows a redshift trend as the pump power increases. This phenomenon can be explained by the interplay between the two peaks in the double-peak structure of the Raman gain spectral profile, i.e., those at 13.2 THz and 14.7 THz.[32] There is another wavelength subcomponent at the wavelength of 1134.28 nm emerging around the threshold of the first-order Stokes wave, which is also observed at other pump wavelengths. Based on the power balance model in Ref. [36], the power transfer between the adjacent subcomponents at the first order Stokes wave is attributed to the presence of Raman amplification at small detuning frequencies. The number of peaks at the same Stokes component depends on the competition between the generation of the subcomponents and the cascaded subsequent Stokes waves. In our experiment, the first subcomponent of the first-order Stokes wave corresponding to the frequency shift of 13.3 THz is in the ascendant in the beginning, while energy gradually transfers to the second one corresponding to the frequency shift of 14.5 THz as the pump power increases, which is consistent with Ref. [36]. This power transfer leads to the spectral variation of the first-order Stokes wave.

The PER of the output laser is calculated according to the formula

$$\mathrm{PER} = 10\log\frac{a}{b},$$

where a and b are the power values on the fast and slow axes of the polarization ellipse, which are measured by the two power meters denoted in Fig. 1. As shown in Fig. 5, the PER of the residual pump as a function of pump power at different wavelengths is measured when the pump power is lower than the

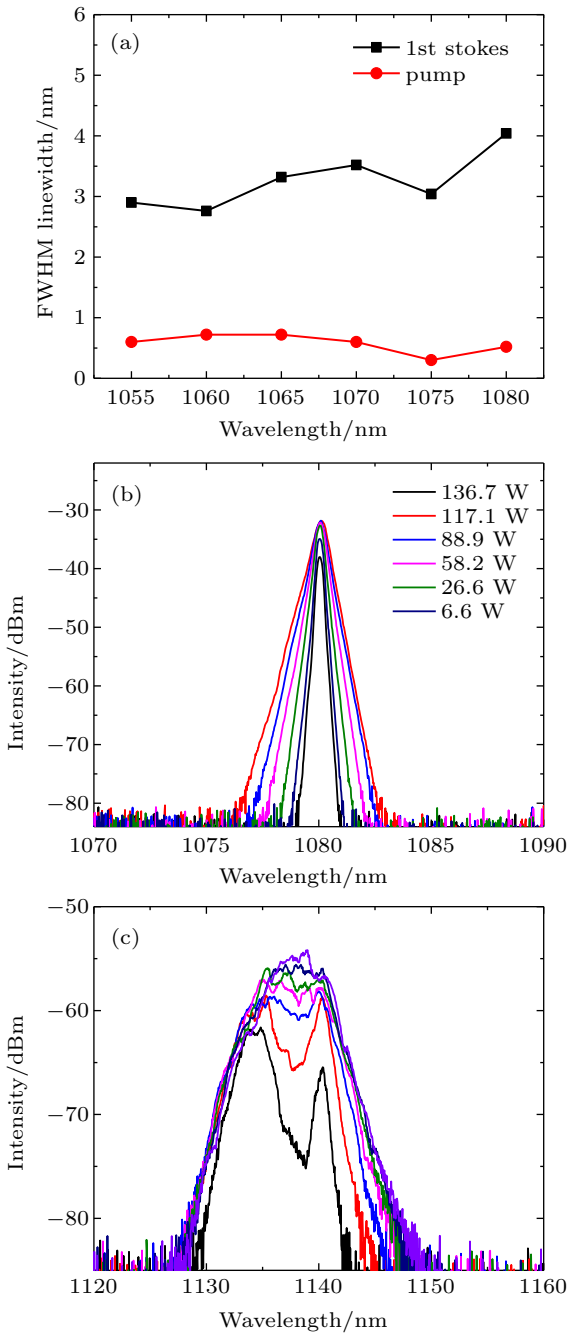


Fig. 4. (color online) (a) Linewidth of the pump and first order Stokes wave versus pump wavelength, (b) spectra of the pump laser under different pump powers, and (c) first-order Stokes wave under different pump powers at the pump wavelength of 1080 nm.

threshold power of the first-order Stokes wave, which could manifest the linearly polarized property of the tunable pump source. Then, as the pump power increases, the PER evolution of the first-order Stokes is recorded as well. We can see that the PER of the residual pump is approximately 20 dB, while the PER of the first-order Stokes wave is around 25 dB. Overall, the PER at a certain wavelength under different pump powers is almost constant at most of the pump wavelengths. In general, the polarization property of the first order Stokes wave is better than that of the pump light, which proves the purification effect of Raman gain. The difference of PER at different wavelengths might be attributed to the wavelength-dependent polarization-maintaining properties of the WDM and the coupler.

The output stability of this tunable Raman fiber laser was also investigated through the output power. Using a power meter, the maximum total output power, which includes the power of residual pump light, first-order Stokes wave, and second-order Stokes wave, was measured to be around 133.2 W at 1075 nm. As shown in Fig. 6, the power evolution at the maximum total power was recorded every 5 s over 5 min by a power meter. The standard deviation (STD) of the normalized output power was merely 0.13%, which shows a quite stable output.

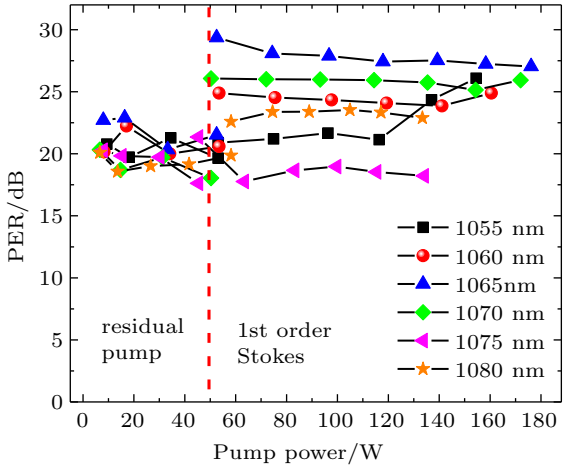


Fig. 5. (color online) Polarization extinction ratio (PER) evolution of the residual pump and the first Stokes wave.

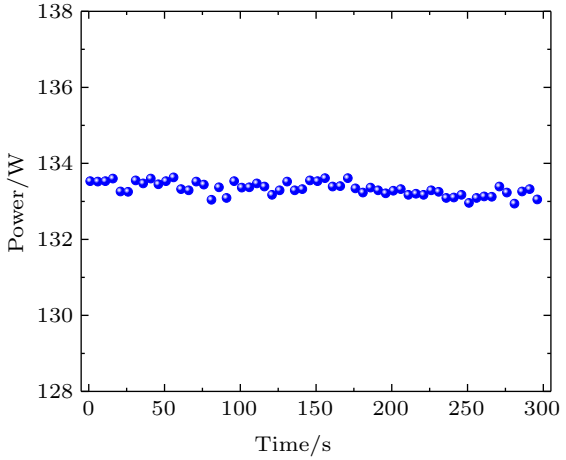


Fig. 6. (color online) Power evolution of output laser.

4. Conclusion

In summary, we experimentally demonstrated a hundred-watt level linearly-polarized Raman fiber laser pumped by a tunable YDFA. By continuously tuning the pump wavelength from 1055 to 1080 nm, the Raman fiber laser spanned a wavelength range of 27.6 nm from 1112.04 nm to 1139.6 nm. The PER of the tunable Raman laser ranged from 21 to 27 dB. We have recorded and discussed the properties of power and spectrum versus different wavelengths and various pump powers. The maximum output power was 125.3 W with the pump power of 157.8 W at 1075 nm, which corresponds to a conversion efficiency of 79.4%. As far as we know, it is the highest power that has been obtained in linearly-polarized tunable Raman fiber lasers. Further power scaling can be expected by optimization of the parameters of the laser, such as the reflectivity of output coupler and/or the length of the passive fiber. Such a high-power tunable linearly-polarized Raman fiber laser could provide a simple, low cost, and convenient light source for practical use.

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