IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 5, Number 5, October 2013

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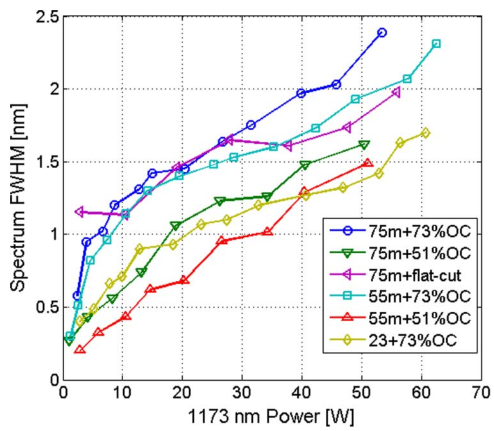

DOI: 10.1109/JPHOT.2013.2277071

119-W Monolithic Single-Mode 1173-nm Raman Fiber Laser

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DOI: 10.1109/JPHOT.2013.2277071

Manuscript received July 1, 2013; revised July 29, 2013; accepted July 31, 2013. Date of publication August 7, 2013; date of current version September 19, 2013. This work was supported in part by the National Nature Science Foundation of China under Grant 11274386 and in part by the Hunan Provincial Innovation Foundation for Postgraduate Students. Corresponding author: P. Zhou (e-mail: zhoupu203@163.com).

Abstract: We report a high-power high-efficiency single-mode all-fiber Raman fiber laser (RFL) operating at 1173 nm. With the core pumped by a 144-W 1120-nm Yb-doped fiber laser, an output power of 119 W at a wavelength of 1173 nm was obtained, corresponding to an optical efficiency of 82%. To the best of our knowledge, it is the highest power at the 1150–1200-nm laser band by using common silica fiber. The optical efficiency of the RFL with high output coupler (OC) reflectivity and short fiber length is discussed. We also carefully measured the output Raman spectrums under different cavity parameters and presented primary analysis. The results show that the bandwidth increases near linearly with laser output power, rather than a square-root law concluded for high *Q*-value and long-cavity RFLs in previous published literatures. Increasing the length of the gain fiber and the reflectivity of the OC would also broaden the output spectral bandwidth.

Index Terms: Raman fiber laser, high power, Raman spectrum.

1. Introduction

The study of fiber lasers in the wavelength range of 1150-1200 nm have recently drawn more and more attention due to its abundant applications in industrial, scientific and medical fields. For example, 1150 nm fiber lasers can be used to pump Ho^{3+}-doped fiber [1]. In addition, in metrology and medicine areas, yellow lasers are widely used and can be obtained by frequency doubling via using 1150-1200 nm lasers [2], [3]. Especially, high brightness 1178 nm laser can be used to generate 589 nm yellow light for laser guide star generation, which is a useful tool to high-resolution ground-based astronomical imaging [4].

Yb-doped silica fiber laser (YDFL) is a potential laser source to achieve 1150-1200 nm lasing due to its wide emission spectrum [5]. Pumped by 915 nm laser diode (LD), a 1154 nm YDFL with maximal output power of 18 W was realized [6]. However, further power scaling is prevented by the strong gain competition from wavelengths of 1030-1100 nm that have much larger emission cross sections, which would induce the amplified spontaneous emission (ASE) and parasitic lasing [6]–[8]. Several methods have been employed to increase the output power, such as tandem pumped by using fiber lasers with wavelength of 1070-1090 nm and heating the gain fiber at the same time [8], [9]. But by now, the highest power in 1150-1200 nm is still less than 20 W in the case of using common double-cladding Yb-doped fiber. Power scaling of 1150-1200 nm YDFL can be realized by using specially designed photonic bandgap (PBG) fibers [10], [11]. The highest power achieved by using this fiber is 167 W at 1178 nm [10]. In addition, Raman fiber laser (RFL) can also be used to

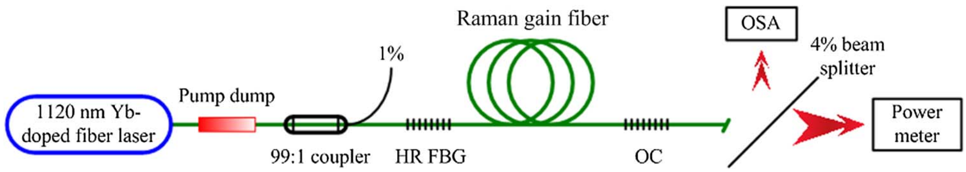


Fig. 1. Configuration of the core pumped 1173 nm RFL pumped by 1120 nm YDFL.

boost the laser power. Combined with the high-power, high-brightness characters of YDFL in wavelength range of 1060-1120 nm, RFL is a promising source to generate high power output at 1150-1200 nm wavelength. Y. Feng and his co-workers reported a 150 W highly-efficient RFL worked at 1120 nm, core-pumped by a 1070 nm YDFL [12]. It indicates that RFL can realize high power and high efficiency output in the above-mentioned wavelength.

In this paper, we report a high power, single-mode RFL operating at 1173 nm, which extends the laser to a longer wavelength. The maximal output power is 119 W, and the optical efficiency is as high as 82% with respect to launched pump power. We analyze the characters of high output coupler (OC) reflectivity cavity. The output RFL spectral bandwidths depending on the 1173 nm power, fiber length, and OC reflectivity are also carefully measured and discussed. To the best of our knowledge, it is the highest power emission at 1150-1200 nm laser band by using common double-cladding fiber.

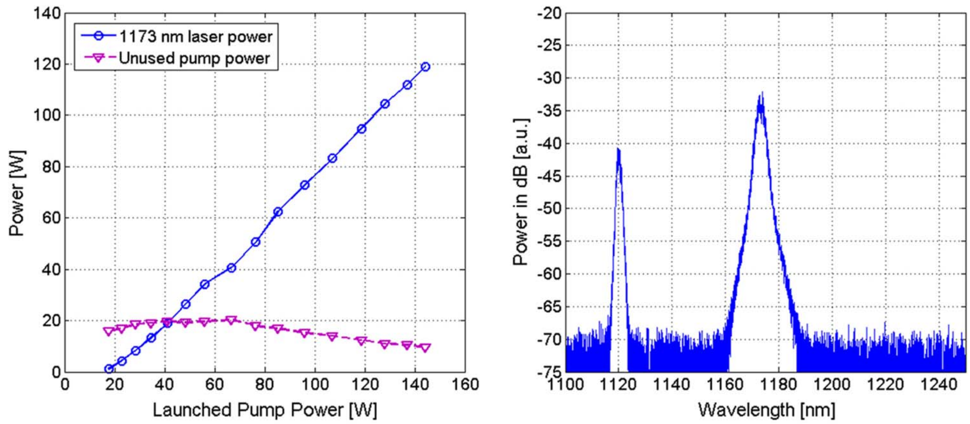
2. Experimental Setup

The structure of the core pumped 1173 nm RFL is depicted in Fig. 1. The cavity consists of a piece of Raman gain fiber and a pair of fiber Bragg gratings (FBGs). The Raman gain fiber is a 75-meters-long commercial passive fiber with core diameters of 10 μm and NA of 0.075, respectively. The nominal core attenuation at 1200 nm is less than 0.02 dB/m. The high reflectivity (HR) FBG and OC compose a linear cavity with reflectivities of 99.8% and 51%, respectively. The 3 dB bandwidth of the HR FBG is 1.49 nm, while the OC is 0.52 nm. The home-made high power 1120 nm YDFL is delivered by the fiber with core diameter of 10 μm and is spliced to a 99/1 coupler, which is used to monitor the stability of pump source. Around the splice point, a high refractive index gel is employed to strip the cladding mode in order to protect the FBG. At the output end, a wide bandwidth 4% beam splitter separates a little part of the output laser into the optical spectrum analyzer (OSA, Yokogawa Corporation AQ6370C). The main part of the output laser is collected by the power meter (Coherent Corporation PM1K).

In our experiment, we chose a relatively high OC reflectivity compared with other work [12], [13] in order to reduce the length of Raman gain fiber. As we know, longer laser cavity corresponding to more longitude modes that would enhance the nonlinear wave-mixing effects which are attributed to the spectral broadening [14], [15]. The intensity of most nonlinear effects is proportional to the fiber length. So using short gain fiber may obtain relatively narrow output spectrum. This character will further be discussed below. Moreover, short fiber length would also reduce the background loss of Raman gain fiber in the cavity.

3. Results and Discussion

In the process of pumping the 1173 nm RFL, we did not observe obvious power fluctuation of 1120 nm fiber laser, which means the backward signal light would not affect the pump source that can be attributed to the low absorption and emission cross section of Yb-doped fiber at 1173 nm. Fig. 2(a) plots the 1173 nm output power with respect to the launched pump power. The threshold of RFL is around 18 W. With the increase in the pump power, 1173 nm output power increases linearly, and the maximal output power is 119 W with the pump power of 144 W, which corresponds to an optical efficiency of 82.6%. At full power, there is still 9 W pump light left, which corresponds to an optical efficiency of 88% to the used pump light. The efficiency is higher than common YDFL [16]. Fig. 2(b) is the output spectrum at the maximal power. The 1173 nm output



(a) (b)

Fig. 2. (a) 1173 nm laser output power and unused pump power as a function of launched pump power; (b) output spectrum at maximal power.

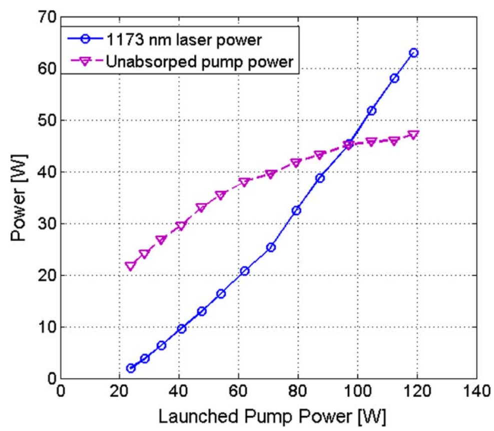


Fig. 3. The output power depends on the launched pump power when using a 73%–99.8% linear cavity with Raman gain fiber length of 23 meters.

power is calculated by integrating the corresponding region of the spectrum. In order to ensure the exactness, several spectrums are averaged. The percentage of 1173 nm output power in Fig. 2(b), for example, is 92%. The core diameter and NA are 10 μm and 0.075, respectively. The normalized frequency (V value) is about 2, less than 2.405, so we believe it is single mode operation. To the best of our knowledge, it is the highest power report at 1150-1200 nm laser band by using common silica fiber, and the whole system is simple, compact, and efficient.

Theoretically, for RFLs, a higher OC reflectivity would increase the signal laser intensity in the cavity, and the optimum fiber length may reduce to a certain pump power. For comparison, we reduced the Raman gain fiber to 23 meters and changed the reflectivity of the OC to 73%. The output power depends on the launched pump power, as shown in Fig. 3. The threshold approaches to the longer gain fiber case due to the high OC reflectivity, and it can be understood by threshold formula of RFL [17]:

$$P_{th} = \frac{\alpha A}{g}\left[\frac{\alpha L - (1/2)\ \ln(R_1 R_2)}{1 - \exp(-\alpha L)}\right] \tag{1}$$

where α is loss coefficient, it is about 0.002 m^{-1} for 1120 nm; A is the effective core area; g is the Raman gain coefficient; L is the Raman gain fiber length; R_1 and R_2 are the effective reflectivities of

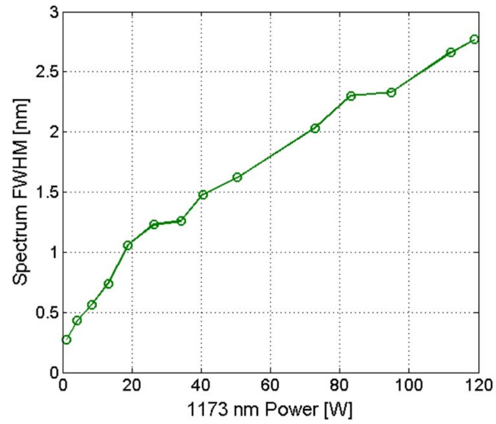


Fig. 4. The spectrum FWHM as a function of 1173 nm output power for the 119 W RFL.

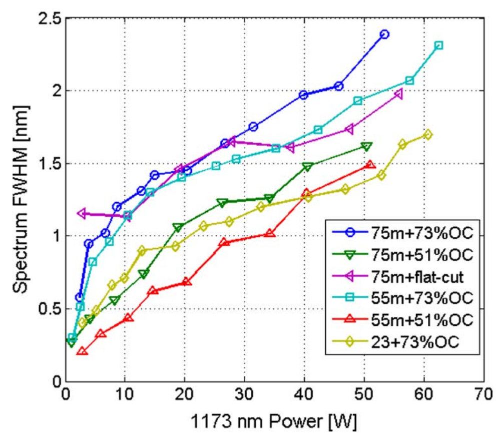


Fig. 5. The spectrum FWHM changes with output signal power at different cavity parameter cases.

the HR FBG and OC, respectively. By using the parameters in our experiments, we can derive that the threshold ratio of the 73% OC reflectivity case to the 51% one is 1.3. However, the efficiency is too low and most pump laser does not transfer to signal light. The reason is that the bandwidths of HR FBG and OC are about 1.5 and 0.5 nm, respectively; with the increasing of the output power, the spectrum is broadened by nonlinear effects in cavity, which results in the decrease of effective reflectivities of the two FBGs [12]. It is believed that the efficiency will increase by using wide bandwidth FBGs.

It is reported that Raman spectrums strongly depend on the cavity parameters and the output power. S. A. Babin et al. studied the spectrum of ultralong high-Q cavity RFL, and simple analytical expressions were presented to describe the output power and spectral shape. They discovered the square-root law for the output spectrum broadening [14]. However, our experiment result (Fig. 4) shows that, for short length cavities, the full width at half maximum (FWHM) increases more rapidly than the square-root law, or like a linear dependence on the output power. It also appeared in other work [12], [18], which should be further studied in future endeavors.

We experimentally study the output spectrum FWHM by changing the cavity parameters of Raman gain fiber lengths and OC reflectivities. The results are summarized in Fig. 5 (in the legend, the first number is the gain fiber length and the second number is the OC reflectivity). In all of these cases, the FWHM has a tendency to increase with the increase of 1173 nm output power but is not a square-root law. Comparing the cases, we can conclude that 1) higher OC reflectivity would increase the bandwidth of output spectrum at the same power; 2) longer Raman gain fiber length has more potential to broaden the output spectrum. This can be simply understood by that the efficiency of nonlinear effects is usually proportional to the fiber length and power in cavity, namely

$$\eta_{nl} \propto PL = \frac{P_{out}}{1 - R_2} L \propto \frac{L}{1 - R_2} \tag{2}$$

where η_{nl} is the efficiency of nonlinear effects, P is the power in cavity, L is fiber length, P_{out} is the output power, and R_2 is the reflectivity of the OC. So increasing L as well as R_2 would both enhance the nonlinear effects that are attributed to the spectral broadening. However, at a certain output power, there is an optimum cavity parameter to minimize the spectral FWHM, and it is important to some application with narrow spectrum demand. The quantitative relationship of the FWHM with the RFL cavity parameters will be further studied in our future work. It is interesting that the case of the output end flat cut seems to breach previous discussion. The FWHMs are higher than the case of 51% OC and the same length, as we know the reflectivity of flat cut end is about 4% to all wavelengths of our spectrum. We attribute the spectral broadening of the case of flat cut end to the wide Raman gain spectrum rather than nonlinear effects in our experiment. Furthermore, the flat cut end is a broad bandwidth OC without the function of spectral filtering that would limit the spectral bandwidth.

4. Conclusion

We demonstrated a high power, high efficiency, all-fiber, single-mode RFL working at 1173 nm. The maximal output power was 119 W, and the optical efficiency was more than 82% with respect to launched pump power. We discussed the influences of cavity parameters on the RFL efficiency and the output spectrum. An RFL spectral broadening dependence on output signal power, fiber length, and OC reflectivity is discovered. The FWHM increases with output signal power but is not a square-root law in our experiments. Increasing the gain fiber length and OC reflectivity would also broaden the output spectral bandwidth. It means that there is an optimum cavity to minimize the output bandwidth.

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