High power linearly polarized Raman fiber laser at 1 120 nm

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An all-fiber linearly polarized Raman fiber laser at 1 120 nm is demonstrated. With a 1 070-nm linearly polarized Yb-doped fiber laser as pump source, an output of up to 7.7 W at 1 120 nm is obtained with an optical efficiency of 55%. The polarization extinction ratio of the linearly polarized Raman fiber is higher than 18 dB. A numerical simulation model is developed to determine the Raman coefficient of the gain fiber and to evaluate the laser performance. The spectral isolation between the Raman fiber laser and the pump fiber laser is determined to be necessary for further improvements of performance.

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In recent years, fiber lasers have achieved enormous developments due to the high demands for their applications in the industrial, defense, and scientific fields. While high output power is always pursued, the extension of the operation wavelength range is another focus in fiber laser research. Fiber laser operating at 1 120 nm is an example. It has applications in pumping up the conversion of the Tm-doped fiber lasers[1] and Raman fiber amplifiers at 1 178 nm[2,3] which can be frequency-doubled to 589 nm for laser guide star and frequency-doubled to 560 nm for flow cytometry[4]. For the last two applications, a linearly polarized laser is required.

A fiber laser operating at 1 120 nm can be generated by Yb-doped silica fiber because of its wide gain spectrum[5−8] which stretches up to 1 200 nm. Liem *et al.* reported a fiber laser system operating at 1 120 nm[9]. The system was seeded with a Raman fiber laser of 1.5 W. A power of up to 25 W with a slope efficiency as high as 46% was achieved using Yb-doped fiber amplifier. Meanwhile, Raman fiber lasers have shown better performance in producing high power 1 120-nm fiber laser. Employing a clad pumping scheme, a 100-W continuous wave (CW) Raman fiber laser has been demonstrated by Codemard *et al.*[10]. Feng *et al.* have built a single mode Raman fiber laser at 1 120 nm with output power of more than 150 W[11]. In spite of these advancements, linearly polarized Raman fiber laser has not been well studied. Only a few research has been reported, which reported a 4.7-W linearly polarized 1 120 nm Raman fiber laser with optical efficiency of 50%[12]. Bi-doped fiber has also been shown as a promising method that can produce 1 120-nm laser because of its broadband emission[13]. Unfortunately, the high loss and low emission sections of the Bi-doped fiber at 1 120 nm are serious challenges in relation to power improvement. In this letter, a linearly polarized, all-fiber Raman laser emitting at 1 120 nm, which is pumped by a linearly polarized 1 070-nm Yb-doped fiber laser is reported. A power of up to 7.7-W laser is obtained with an optical efficiency of 55% and polarization extinction ratio (PER) of higher than 18 dB.

The experimental setup is shown in Fig. 1. The pump laser is a linearly polarized Yb-doped fiber master-oscillator power amplifier operating at 1 070 nm, and pumped by two 10-W laser diodes (LDs) at 976 nm. The seed laser is a high performance linearly polarized fiber oscillator with PER of 30 dB at 1 070 nm. The Yb-doped fiber amplifier has produced a 14-W laser output with PER that is higher than 20 dB.

The Raman fiber laser mainly consists of Raman fiber and a pair of fiber Bragg gratings (FBGs). FBG1, which is spliced with the Yb-doped amplifier, has a peak reflectivity of 99% at 1 120 nm. The full-width at half-maximum (FWHM) bandwidth is 1.1 nm. FBG2 with a peak reflectivity of 11% at 1 120 nm is used as the output coupler and its FWHM is 0.3 nm. The gain medium is a 200-m polarization-maintaining (PM) single-mode fiber (PM980, Nufern, USA), whose core and cladding diameters are 6 and 125 μm, respectively. Stokes wave at 1 120 nm is generated by stimulated Raman scattering of the 1 070-nm laser in the single mode PM fiber. The produced Raman laser and the residual pump laser are emitted from the FBG2. The output end of the FBG2 is cleaved at an angle of 8° to avoid back reflection.

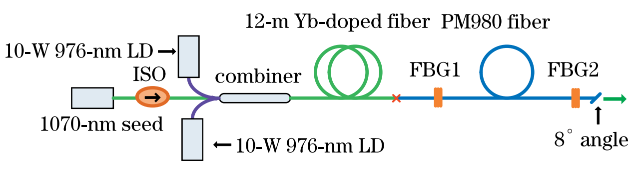

Fig. 1. (Color online) Schematic of the experimental setup. Blue line represents the PM signal-mode fiber, and green line represents the Yb-doped double-clad fiber.

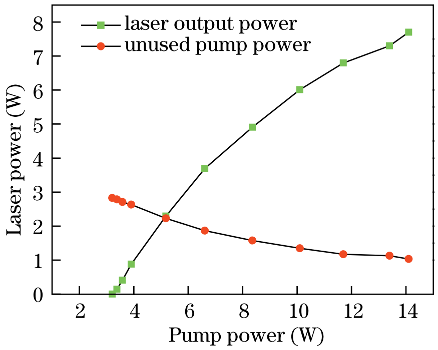

Fig. 2. Raman output and residual pump power as a function of launched pump power.

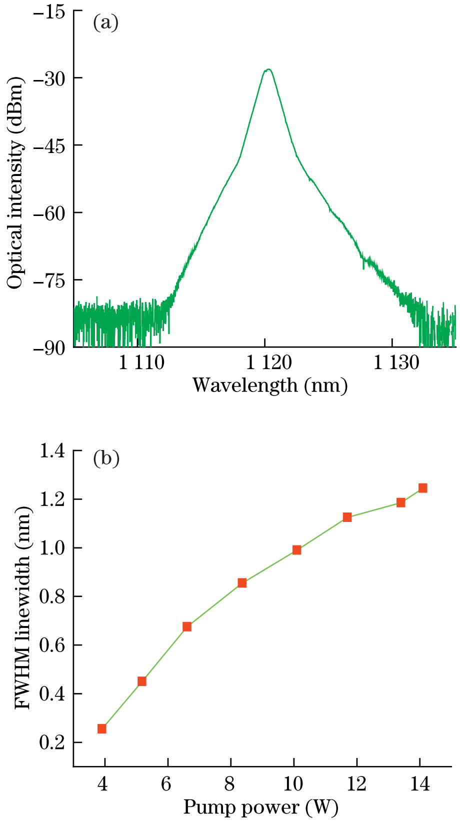

Fig. 3. (a) Laser output spectrum and (b) FWHM linewidth as a function of the pump power.

The Raman output and residual pump power as a function of launched pump power are shown in Fig. 2. A maximum output power of 7.7 W is obtained with a 14-W pump, whereas the residual pump power is 1.0 W. In this letter, we have attempted to clean the remaining 1 070-nm pump by adding a 10.5-m Yb-doped double-clad fiber (5/130 μm, Nufern, USA) after the output, which has nominal cladding pumped absorption of 1.7 dB at 976 nm. The fiber has higher absorption for 1 070 nm than 1 120 nm. As a result, the residual 1 070-nm pump laser is reduced to 0.2 W, and the 1 120-nm output drops slightly to 7.1 W.

The laser output spectrum, measured by an Ando optical spectral analyzer, is shown in Fig. 3. The FWHM increases with the pump power, which is typical for Raman fiber laser because of the four-wave mixing among numerous longitudinal modes. The maximum linewidth is 1.24 nm which is four times that of FBG2. Therefore, the real reflectivity of the output from the FBG2 is considerably less than the specified peak reflectivity of 11%.

The PER of the laser is measured with a high quality Glan polarizer. PER values of 18.7 dB and higher than 20 dB are measured at a pump powers of 14 W and below 12 W, respectively. Because stimulated Raman scattering is polarization dependent, PM Raman fiber laser exhibits a polarization cleaning effect. The PER of the Raman output can be higher than that of the pump laser[12]. In our experiments, the PER of the pump laser is higher than 20 dB whereas the PER of the Raman laser is 18.7 dB at full power, which is lower than that of the pump laser. The polarization degradation of output power is attributed to the polarization cross talk at the fiber splicing points, which have to be improved to obtain a Raman fiber laser with high PER. Nevertheless, a PER of higher than 18 dB already meets the requirements of pumping a PM Raman fiber amplifier at 1 178 nm for the laser guide star applications.

Figure 4 shows the output spectrum of the Raman fiber laser at pump power of 14 W. The spontaneous second Stokes Raman emission is negligible because it is lower than the 1 120-nm laser by more than 40 dB.

To evaluate the Raman laser and determine the Raman gain coefficient, a simulation code that models the Raman oscillator is developed. The code can be expressed as[11]

$$\frac{\mathrm{d}P_{\mathrm{p}}}{\mathrm{d}z} = -\frac{\upsilon_{\mathrm{p}}}{\upsilon_{\mathrm{s}}} \cdot g_{\mathrm{R}} \cdot P_{\mathrm{p}} \cdot (P_{\mathrm{f}} + P_{\mathrm{b}}) - \alpha_{\mathrm{p}} \cdot P_{\mathrm{p}}, \tag{1}$$

$$\frac{\mathrm{d}P_{\mathrm{f}}}{\mathrm{d}z} = g_{\mathrm{R}} \cdot P_{\mathrm{p}} \cdot P_{\mathrm{f}} - \alpha_{\mathrm{s}} \cdot P_{\mathrm{f}}, \tag{2}$$

$$\frac{\mathrm{d}P_{\mathrm{b}}}{\mathrm{d}z} = -g_{\mathrm{R}} \cdot P_{\mathrm{p}} \cdot P_{\mathrm{b}} + \alpha_{\mathrm{s}} \cdot P_{\mathrm{b}}, \tag{3}$$

where P_{p}, P_{f}, P_{b} are the pump power, forward signal power, and backward signal power, respectively; g_{R} is the Raman gain coefficient; υ_{p} and υ_{s} are the frequencies of pump and Raman signals, respectively; α_{p} and α_{s} denote the loss coefficient of pump and signal lasers. The pump loss coefficient is deduced to be 6.9×10^{-4} m^{-1} as measured below the laser threshold. This accounts for the fiber and splicing losses. The signal loss coefficient is estimated to be 5.7×10^{-4} m^{-1} according to the Rayleigh scattering approximation. The Raman gain coefficient is the most important parameter in the model, and it is

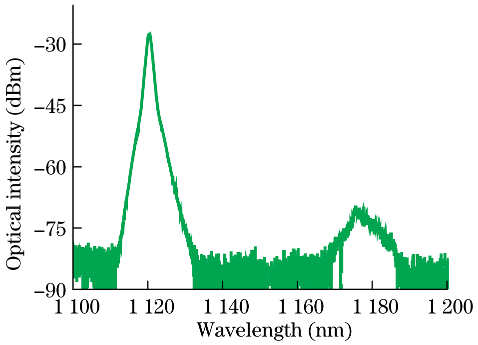

Fig. 4. Raman laser output spectrum at 14-W pump power.

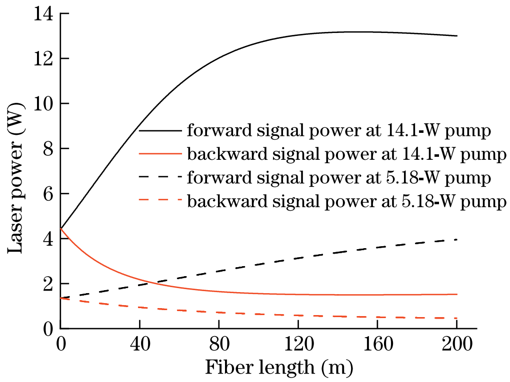

Fig. 5. Power evolution in the Raman fiber with different pump powers.

obtained by fitting the numerical model with the measured Raman lasing threshold, where the reflectivities of the two FBG mirrors are known as specified. The Raman gain coefficient of the fiber is determined to be 0.00187 $\mathrm{m}^{-1}\cdot\mathrm{W}^{-1}$.

As mentioned, the effective reflectivities of the two FBG mirrors are lower than the specified peak reflectivity except at the threshold due to linewidth broadening. The exact numerical model needs to determine the varying reflectivity of FBG2 at different power levels, which in reality, is not possible to achieve.

Figure 5 shows the power evolution in the Raman fiber with the given FBGs reflectivity at two different pump powers. At pump power of 5.18 W, the output power, which is the forward power minus the backward power at the output end, fits well with the measurement. At pump power of 14 W, an apparent discrepancy between the experimental observations and simulation results is observed. The output power of 11 W should be generated according to the calculation. However, only 7.7 W is obtained in the experiments, which cannot be reproduced even when the degradation of the effective reflectivity of FBG2 is taken into account by setting the FBG2 reflectivity as low as 2.5%.

The large discrepancy is actually the result of the coupling between the 1 120-nm Raman laser and the 1 070-nm Yb-doped amplifier. Even a slight back leakage through the FBG1 depletes partly the up-level population in the Yb-doped amplifier. This is verified by the detection of up to 3-W 1 120-nm laser from the other end of the 1 070-nm Yb-doped amplifier. The real 1 070-nm pump injected into the Raman laser is considerably lower. A spectral isolation between the 1 070-nm pump laser and 1 120-nm oscillator is necessary to improve the performance, which can either be a 1 070/1 120-nm wavelength division multiplexing (WDM)[11] or a long period grating which has high loss at 1 120 nm[14].

In conclusion, an all-fiber linearly polarized Raman fiber laser at 1 120 nm pumped by a 1 070-nm linearly polarized Yb-doped fiber laser is demonstrated. An output of up to 7.7 W at 1 120 nm is obtained using a 200-m PM fiber with an overall optical efficiency of 55% and PER of higher than 18 dB. Splicing has to be improved to reduce the polarization cross talk to obtain better PER. A numerical simulation model is developed to obtain the Raman coefficient and evaluate the laser performance. The spectral isolation between the Raman and pump fiber laser is established to be necessary.

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