

Generation of 10.5 W, 1178 nm Laser Based on Phosphosilicate Raman Fiber Laser

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The phosphorous-doped Raman fiber laser fabricated based on a Fabry-Perot cavity is demonstrated. The fiber length (L) values of 300 m and 700 m, and the reflectivity (R) values of the output fiber Bragg grating (FBG) of 15%, 30% and 50% are adopted. Under the optimum configuration of $L=300$ m, and $R=15\%$, a 10.5 W, 1178 nm laser is obtained. Considering the pump power of 19.2 W, the optical-optical conversion efficiency is 54.7% and the corresponding slope efficiency is 80%. The 1178 nm light is frequency-doubled to generate 589 nm light as a source for the laser guide star (LGS) for the mesospheric sodium layer. [DOI: 10.1143/JJAP.42.L1439]

KEYWORDS: Raman fiber laser, phosphosilicate fiber, stimulated Raman scattering, frequency doubling, laser guide star

Recently, diode-pumped Nd-doped lasers were developed as compact all-solid-state sources in the blue, green, and red spectral regions by intracavity frequency doubling. However, the wavelength region from 550 to 650 nm was seldom covered because of the absence of fundamental lasers that operate efficiently there.¹⁾ Laser sources in yellow-orange spectra are of particular interest for many applications in metrology, remote sensing, medicine, biology, and display technology.²⁾ Especially, a cw 589 nm narrow bandwidth laser at the sodium D_2 line is needed for laboratory spectroscopy and atmospheric remote-sensing applications. Several groups engaged in this field use the 589 nm narrow bandwidth laser as a laser guide star (LGS) in the mesospheric sodium layer for telescopic imaging.^{3–5)} Generally, the 589 nm laser is generated based on a dye laser or a solid-state laser and frequency conversion technology.^{6,7)} However, this suffers from the disadvantages of much greater complexity and higher cost.^{8,9)} As the LGS, the spectrum width of the 589 nm laser is usually approximately 100–500 MHz and the power level is 10 W or more. These targets can be achieved reasonably by fiber laser technology. Thus, in our experiment, we generated a 1178 nm laser based on a Raman fiber laser, and the output laser will be frequency-doubled in a nonlinear crystal LiB_3O_5 (LBO) or periodically poled KTiOPO_4 (PPKTP) to produce light at 589 nm. This laser system is compact, stable and highly efficient. At present, we have already obtained a 10.5 W, 1178 nm laser from this system using a pump power of 19.2 W. The optical-optical conversion efficiency is 54.7%, and the corresponding slope efficiency is 80%. To our knowledge, this is the highest power of the 1178 nm laser output from the Raman fiber laser.

Figure 1 shows the experimental setup for the 1178 nm Raman fiber laser. In our experiment, a simple Fabry-Perot cavity is adopted, which is composed of a fiber Bragg grating (FBG)1, gain fiber and FBG2 as the output coupler. The pumping source is an ytterbium-doped double-clad fiber laser (DCFL) with a cw 20 W/1100 nm single-mode output and its output pigtail is a Flexcor-1060 single-mode fiber (SMF) with a core diameter of 6 μm . FBG mirrors are fabricated on a Flexcor-1060 fiber. The reflectivity of the FBG1 mirror at 1178 nm is more than 99%. The adopted reflectivity values of the FBG2 mirror are 15, 30 and 50%, and the bandwidth is 1 nm. The Raman gain medium is a

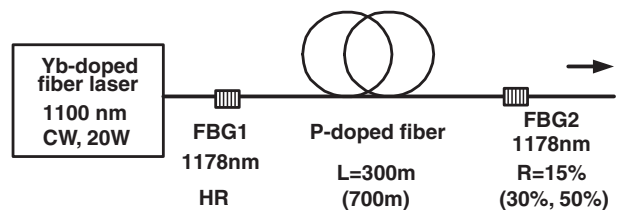


Fig. 1. Experiment setup of Raman fiber laser. The fiber length is 300 m (700 m), and the reflectivity of FBG2 is 15% (30%, 50%) at 1178 nm.

phosphorous-doped single-mode optical fiber (PDF), which has 12 mol% of P_2O_5 and the refractive index difference is 0.0107. A low splicing loss could be achieved since the fibers for the DCFL output and the FBG are identical, and the 6 μm mode-field diameter of the PDF is also similar to that of the Flexcor-1060 fiber. The output spectrum and the output power are measured using an AQ-6315A optical spectrum analyzer (ANDO Co.) and a LABMASTER optical power meter (Coherent Inc.), respectively. Then, the absolute output power of each spectral component is calibrated using the absolute output power.

When the length of the PDF is 300 m, the reflectivity of the FBG2 is 15%, the net pump power is 19.2 W, and a 10.5 W, 1178 nm Raman laser output is obtained, the bandwidth is 1.3 nm. The optical-optical conversion efficiency is 54.7%, and the corresponding slope efficiency is 80%. To our knowledge, this is the highest power of the 1178 nm laser output from the Raman fiber laser.

Figure 2 shows the Raman spectrum of the PDF. There are

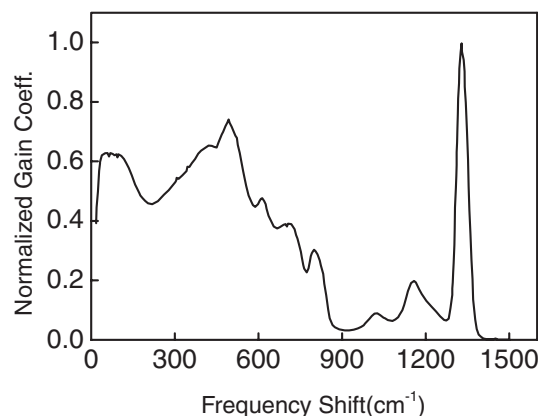


Fig. 2. Raman spectrum of the phosphosilicate fiber. The gain at the 601 cm^{-1} point is estimated to be approximately 2.7 dB/km/W.

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two peaks in the spectrum: one lies at the 1330 cm^{-1} point, which is due to oxygen double-bonded to P atoms, and the other lies at the 490 cm^{-1} point, which is due to oxygen double-bonded to Si atoms.¹⁰⁾ In our experiment, in order to generate a 1178 nm laser according to the formula

$$\Delta\left(\frac{1}{\lambda}\right) = \left(\frac{1}{\lambda}\right)_p - \left(\frac{1}{\lambda}\right)_s = \frac{1}{1100\text{ nm}} - \frac{1}{1178\text{ nm}} = 601\text{ cm}^{-1},$$

we used a 601 cm^{-1} Raman shift to convert the pump wavelength of 1100 nm to the first Stokes mode of 1178 nm wavelength. The gain at the 601 cm^{-1} point is estimated to be approximately 2.7dB/km/W and the loss of the PDF for 1178 nm is estimated to be approximately 1.3dB/km. Thus, this fiber is a good candidate for generating a highly efficient 1178 nm laser.

Figures 3 and 4 show the output spectrum and power evolution of two typical configurations: one is fiber length, $L=300\text{ m}$, and FBG2 reflectivity, $R=15\%$, and the other is $L=700\text{ m}$, and $R=50\%$. It is clearly observed that when L and R were increased, under a high pump power, a higher order Stokes mode appeared in Raman fiber laser. Typically as shown in Fig. 3(b), in addition to the residual pump and 1178 nm laser, there appeared 1250 nm and 1288 nm emissions. The 1250 nm light is considered to be the second Stokes mode of the 1100 nm pump laser, generated from 1178 nm through the Raman shift of 490 cm^{-1} , and the 1288 nm light is considered to be another first Stokes mode of the 1100 nm pump laser, generated through the Raman shift of 1330 cm^{-1} . A high-order Stokes mode appears due

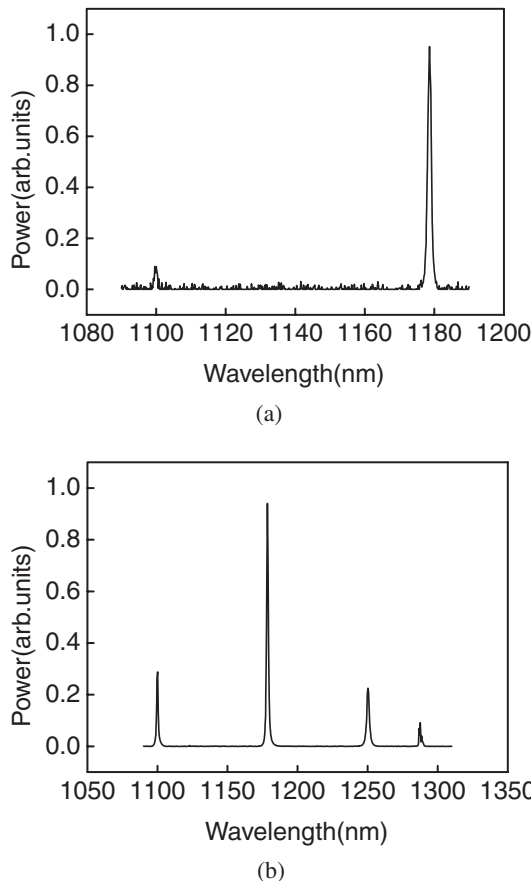


Fig. 3. Output spectrum from the Raman fiber laser. (a) $L=300\text{ m}$ and $R=15\%$, and (b) $L=700\text{ m}$ and $R=50\%$.

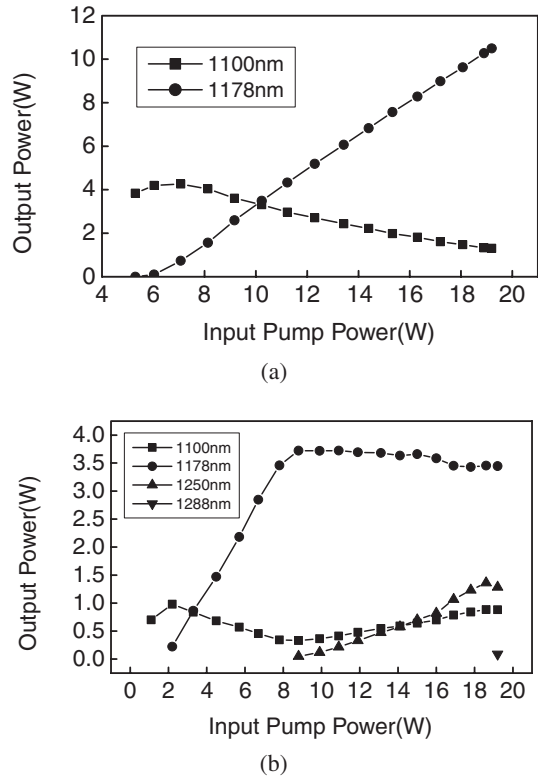


Fig. 4. Evolution of the residual pump and the Stokes lights powers with the pump power increased. (a) $L=300\text{ m}$ and $R=15\%$, and (b) $L=700\text{ m}$ and $R=50\%$.

to stimulated Raman scattering (SRS), and is a typical cascaded nonlinear phenomenon occurring in optical media.¹¹⁾ In the Raman fiber laser, the injected pump power is converted through the Raman scattering process into the first Stokes mode power, starting from the amplification of spontaneous emission noise. Increasing the pump power above the threshold, the first Stokes mode is rapidly saturated and converted to Stokes radiation of successive orders. This cascade ends when the last Stokes beam is below the threshold for the generation of Stokes beams of the next order. In Fig. 4, we can also observe the process in detail. In Fig. 4(a), the power of the 1178 nm laser increases monotonically as the pump power increases, but in Fig. 4(b), it saturates when the output power reaches 3.72 W. Then the 1250 nm and 1288 nm Raman laser emissions appear one after the other. Because of the competition among the Raman modes of different orders, the power of the 1178 nm Raman laser decreases.

Figure 5 shows the spectra of the 1178 nm laser at different output powers. It is evident that the peak level does not change markedly with the increase in output power, but the laser bandwidth is broadened with the increase in output power. It is also evident that the broadest bandwidth is 1.3 nm under the highest output power of 10.5 W, which is desired for applications and frequency doubling using a nonlinear crystal such as LBO or PPKTP.

We constructed a phosphosilicate Raman fiber laser, and investigated its output characteristics. The reflectivity values of the output coupler of 15%, 30% and 50%, and the fiber length values of 300 m and 700 m were adopted. Under the optimum configuration of 15% reflectivity and 300 m PDF,

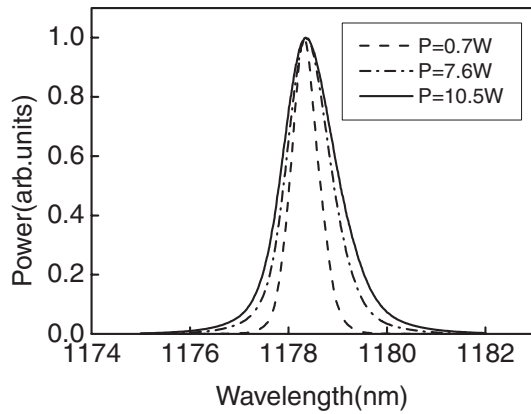


Fig. 5. Spectra of 1178 nm laser at different output powers (P).

we obtained a 10.5 W, 1178 nm laser using a pump power of 19.2 W. The optical-optical conversion efficiency was 54.7%, and the corresponding slope efficiency was 80%. To our knowledge, this is the highest output power of the 1178 nm laser from PDF Raman lasers.

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