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1239/1484 nm cascaded phosphosilicate Raman fiber laser with CW output power of 1.36 W at 1484 nm pumped by CW Yb-doped double-clad fiber laser at 1064 nm and spectral continuum generation

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Abstract

CW 1.36 W/1484 nm Raman fiber laser is obtained using 8.4 W/1064 nm Yb-doped double-clad fiber laser as a pump, 1 km phosphosilicate fiber, and cascaded cavities with two pairs of fiber Bragg grating mirrors for 1239 nm and 1484 nm. We observed that there is a three-step process for the power transfer from the pump to the second Stokes powers. In addition, a 100 nm spectral continuum was obtained by connecting the 1484 nm output to single-mode fiber. © 2000 Elsevier Science B.V. All rights reserved.

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High-speed optical fiber transmission systems using dense wavelength division multiplexing technology have been actively developed and deployed and more than 100 channels are adopted. Those systems require high-power optical amplifiers with higher output power and wider spectral bandwidth than the usual Er-doped fiber amplifier (EDFA) with 15–30 nm bandwidth. The spectral band under 0.3 dB/km loss in ordinary single-mode fiber is divided into five narrow bands such as S^{+}-band (1450–1490 nm), S-band (1490–1530 nm), M-band (1530–1570 nm), L-band (1570–1610 nm), and L^{+}-band (1610–1650 nm). Among studies using all spectral bands, Raman fiber amplifiers and lasers showed a fast enhancement with help of high-power double-clad single-mode fiber laser (DCFL) since they can create optical gain in any wavelength band for a proper pump wavelength and have the advantage of inherent low noise [1,2]. Maximum available power from a pump laser-diode is about 100–200 mW and polarization or wavelength multiplexed pumping can launch some more power. Therefore, high-power Raman fiber

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laser (RFL) of output power over 1 W is very useful in many areas including distributed or independent Raman fiber amplifiers and remote pumping of EDFA. To make the RFL over 1 W, single-mode fiber lasers of over several watts are essential and an output power of several tens of watts is now available from high-power Yb-doped DCFL at wavelength 1060–1120 nm [3,4]. To get a fiber laser at 1480 nm, the Ge-doped RFL with a peak Raman shift of 430 cm^{-1} needs to use six cascaded cavities from 1060 to 1117, 1175, 1240, 1315, 1395, and 1480 nm wavelengths using fiber Bragg grating (FBG) mirrors and endure high insertion and splicing losses [5]. But, the low loss phosphosilicate fiber (PDF) has peak Raman shift of 1330 cm^{-1} and low insertion and splicing losses since the RFL at 1480 nm is configured with two cascaded cavities from 1064 to 1239 and 1480 nm [6]. In this paper, high-power single-mode RFL at 1484 nm with 1.36 W was realized using the PDF and two cascaded cavities by two pairs of FBG mirrors at 1239 and 1484 nm and pumped by CW 8.4 W Yb-doped DCFL. The output powers of the residual pump, the first (S1) and second Stokes (S2) lights and the spectral profile for the S2 light were observed for the change of input pump power (IPP). From the measurement, we observed that the residual pump power (RPP) in the cascaded cavities showed three steps of increasing, decreasing, and again increasing. In addition, a 100 nm spectral continuum was obtained by connecting the 1484 nm output to single-mode fiber.

The experimental setup is shown in Fig. 1. The pump source is CW 8.4 W Yb-doped DCFL at 1064 nm using laser-diode pumping (from IRE-Polus) and its output is connected to Flexcor-1060 single-mode fiber. The output power is launched into the Raman cavities maintaining a very low loss since the FBG mirrors are written in the Flexcor-1060 fiber after hydrogen loading. The reflectivities of both mirrors at 1239 nm are more than 99% and those of the

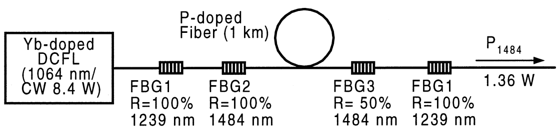

Fig. 1. Experimental setup of the 1484 nm Raman fiber laser pumped by a CW 8.4 W Yb-doped double-clad fiber laser.

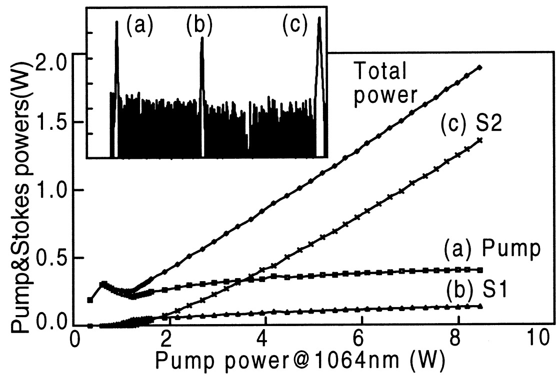

Fig. 2. Output powers of the residual pump, the first Stokes, and the second Stokes lights with change of input pump power and output spectrum at 1.36 W second Stokes power in inset.

mirrors at 1484 nm are more than 99% for the full mirror and 50% for the output coupler, respectively. The PDF has a 1 km length and its core includes 12 mol.% of phosphorous. For 1064, 1239, and 1484 nm wavelengths, the mode-field diameters of the PDF are 5.96, 7.05, and 8.25 μm, respectively, and its fiber loss is 1.84, 1.23, and 1.00 dB/km, respectively. The total cavity loss of 3.14 dB at 1064 nm was measured with the RPP before the S1 and the S2 lights are generated. Considering the 1.84 dB loss of the 1 km PDF, the net insertion loss is 1.30 dB, which is relatively high.

The inset of Fig. 2 shows the output spectrum of the RFL at 1.36 W which includes the residual pump, the S1, and the S2 lights and was measured using AQ-6315A optical spectrum analyzer by ANDO. There was no silicate Stokes lights at 1120 nm and 1310 nm similar as in Ref. [6]. The large levels of RPP and the S1 power are believed to be due to relatively lossy cascaded cavities. Fig. 2 shows the RPP, the S1 and the S2 powers with change of IPP. The threshold powers for the S1 and the S2 lights were 0.70 and 1.26 W, respectively. With change of the IPP, the RPP increased from 0.19 to 0.31 W in the first step, decreased to 0.21 W in the second one, and increased slowly up to 0.40 W in the third one. The three-step change of the RPP was observed in this experiment using the cascaded RFL cavities for the S1 and the S2 lights. The RPP in the first step is proportional to the IPP that is below the thresholds for the S1 and the S2 lights and

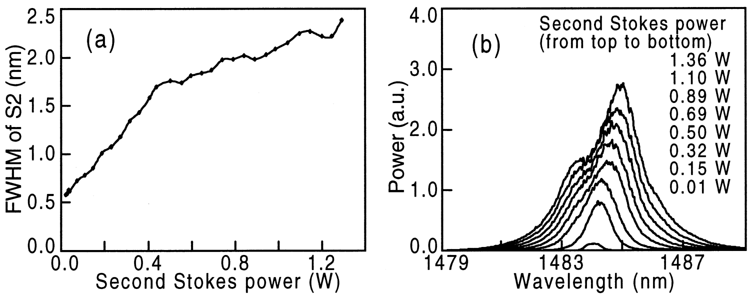

Fig. 3. (a) Spectral full-width at half maximum and (b) output spectrum of the second Stokes light at 1484 nm from the cascaded Raman fiber laser.

sees only the fiber, the FBG insertion, and the splicing losses in the whole cavity. The RPP in the second step is inversely proportional to the IPP that overcomes the threshold for the S1 light and is transferred to the S1 power more quickly than the increase of the IPP. Here, the Raman gain is proportional to the product of the IPP and the S1 power. In the third step, the RPP proportional to the IPP is believed because both of the S1 and S2 lights exist and the power transfer from the input pump to the S1 light is slower than the increase rate of the IPP due to the reduced Raman gain. The decrease of the Raman gain for the S1 light is ascribed to the power transfer from the S1 to the S2 lights. The S1 power increases slowly to 0.13 W with the IPP and is overtaken by the S2 power at the IPP of 1.89 W. The S2 power increases up to 1.36 W with the IPP and it is believed to be the highest reported value in 1064/1239/1484 nm cascaded RFL and its slope efficiency is 18.1% from the IPP. The net slope efficiency from absorbed pump to the S2 powers is 37.2% considering total cavity loss of 3.14 dB and a higher output power is expected when the total cavity loss is reduced. The spectral full-width at half maximum (FWHM) is shown in Fig. 3(a) with change of the IPP. The FWHM is around 0.60 nm at the S2 power under 50 mW and increases to 2.30 nm where the rate decreases after 1.59 nm FWHM at 400 mW. Fig. 3(b) shows the spectrum of the S2 light that is Gaussian in shape for S2 power under 400 mW and shows a shoulder around 1483.5 nm over 400 mW. To understand the phenomena better, the S1 lights with single- and double-peak in wavelength were applied but the same shoulder, in both cases, appeared with increasing the S2 power. Therefore, it is ascribed to self-phase modulation or other nonlinear phenomena due to the high S2 power. The peak wavelength of the S2 light was 1484.00 nm initially and shifted up to 1484.80 nm at the maximum output power of 1.36 W.

In addition, we observed a 100 nm broad spectral continuum by connecting the 1484 nm output to Flexcor-1060 single-mode fiber of 500 m length as shown in Fig. 4. The previous experiments to generate a spectral continuum used a dispersion shifted fiber and ultra-short pulse [7,8], but our spectral continuum generation is unique in the sense that ordinary single-mode fiber was adopted. The physical mechanism for the spectral continuum may be due to stimulated Brillouin back-scattering, four-wave mixing, stimulated Raman scattering, and other nonlinear processes.

In conclusion, we developed a CW 1.36 W/1484 nm phosphosilicate Raman fiber laser using two

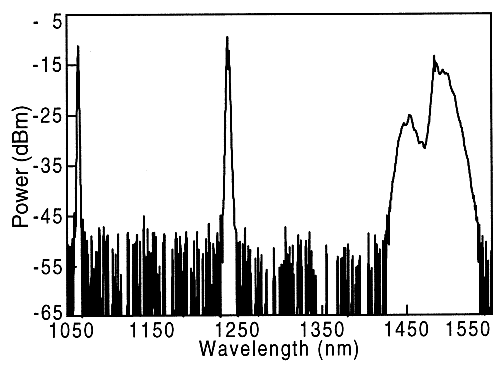

Fig. 4. Spectral continuum centred at 1484 nm generated by connecting the 1484 nm output to 500 m single-mode fiber.

cascaded cavities for 1239 and 1484 nm wavelengths which is pumped by CW 8.4 W Yb-doped DCFL. It was observed that there is a three-step process in the power transfer from the input pump through the S1 to the S2 light in the cascaded cavities. The slope efficiency from the pump to the S2 light was 18.1% and the net slope efficiency considering the total cavity loss was 37.2%. The developed RFL is all-fiber type, generates 1484 nm light by two-step Raman conversion, and does not require a suppression filter since there is no nonresonant light. Therefore, we believe that the RFL with more than 1 W and about 2.00 nm FWHM will give advantages for high-power fiber amplifiers including remotely pumped EDFA. In addition, a 100 nm broad spectral continuum was obtained by connecting the 1484 nm output to 500 m single-mode fiber.

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