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Letter

Simultaneous Double-Color Continuous Wave Raman Fiber Laser at 1239 nm and 1484 nm Using Phosphosilicate Fiber

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Simultaneous double-color high-power continuous wave (CW) Raman fiber laser at 1239 nm and 1484 nm is demonstrated which uses CW 8.4 W Yb-doped double-clad fiber laser at 1064 nm as a pump, 1 km phosphosilicate fiber, and cascaded cavities consisting of two pairs of fiber Bragg grating (FBG) mirrors. Maximum output powers are 0.65 W at 1239 nm and 0.97 W at 1484 nm with a 50%/50% output mirror reflectivity pair, and 0.37 W at 1239 nm and 1.06 W at 1484 nm with a 75.5%/50% pair. The output characteristics of this laser for different FBG mirror reflectivities are reported.

Key words: Raman fiber laser, phosphosilicate fiber, stimulated Raman scattering, Raman fiber amplifiers, optical fiber communications, optical amplifiers

1. Introduction

High-power singlemode fiber lasers like ytterbium-doped double-clad fiber laser (DCFL) with very high reliability and efficiency have regenerated interest in Raman fiber lasers (RFL) for use as pump sources at 1240 nm and at 1480 nm[1–4] for optical fiber amplifiers operating in the 1310 nm and 1550 nm wavelength regions. In system deployments with optical fiber amplifiers, we seldom find pump sources which can simultaneously pump fiber amplifiers in both these spectral regions. We demonstrate for the first time a high-power Raman fiber laser source that can simultaneously produce output at 1239 nm and at 1484 nm.

The value of Raman gain coefficient is about eight times higher for germanosilicate fiber than the one for the silica fiber[5], hence the germanosilicate fibers are used extensively in the RFL and amplifiers[6]. Using the germanosilicate fiber with a peak Raman shift of 440–490 cm^{-1}, the third and the sixth Stokes orders produce outputs at 1240 nm and 1480 nm, respectively, with a 1060 nm pump source. However, the phosphosilicate fiber or phosphorous doped fiber (PDF) has a peak Raman shift of 1330 cm^{-1} as shown in Fig. 1. The first and the second Stokes orders occur at 1240 nm and 1480 nm, respectively, when pumped with a 1060 nm pump source[1]. RFL using PDF greatly reduces the number of in-fiber components needed to enhance the Raman conversion at the required wavelength and thereby increases the efficiency of such systems compared to the germanosilicate ones.

Double-color high-power singlemode RFL at 1239 nm and 1484 nm with 0.65 W and 0.97 W, respectively, was realized using 1 km PDF, cascaded cavities formed by two pairs of fiber Bragg grating (FBG) mirrors at 1239 nm and 1484 nm, and continuous wave (CW) 8.4 W Yb-doped DCFL. With increase of the input pump power (IPP), the output powers of residual pump, and the first Stokes (S_1) and the second Stokes (S_2) modes and the spectral profiles for both the S_1 and the S_2 modes were observed. The slope efficiencies of the S_1 and the S_2 modes for two different output FBG mirrors are also reported. A three-step process in the variation of the residual pump power (RPP) for the change in the IPP was first observed in this RFL.

2. Experiment and Discussion

The experimental setup is shown in Fig. 2. The pump source is a Yb doped DCFL with singlemode fiber output and maximum output power of CW 8.4 W at 1064 nm which was manufactured by IRE-Polus. The Yb-doped DCFL output was spliced with a low loss to the cascaded Raman cavities, which consist of two pairs of FBG mirrors written in the Flexcor-1060 fiber. In the setup of Fig. 2(a), the FBG1 and the FBG4 for 1239 nm cavity have reflectivities of 100% and 50%, respectively, and the FBG2 and the FBG3 for the 1484 nm cavity have reflectivities of 100% and 50%, respectively. The PDF is 1 km long and its core contains 12 mol% of phosphorous which results in a refractive index difference of 0.0107. For 1064 nm, 1239 nm, and 1484 nm wavelengths, the mode-field diameter (MFD) of the PDF is 5.96, 7.05, and 8.25 μm, respectively, and fiber losses are 1.84, 1.23, and 1.00 dB/km. The MFDs of the Flexcor-1060 fiber are 7.1 μm and 12.7 μm at 1060 nm and 1480 nm wavelengths.

The total cavity loss of 3.50 dB at 1064 nm was determined by measuring the RPP before the S_1 and the S_2 modes were generated. Considering the 1.84 dB loss for the 1 km PDF, the cumulative loss due to insertion losses for the four FBG mirrors and splicing losses at five points is 1.65 dB, which is relatively high.

Figure 3 shows the powers for the S_1 and the S_2 modes with change in the IPP for the setup shown in Fig. 2(a).

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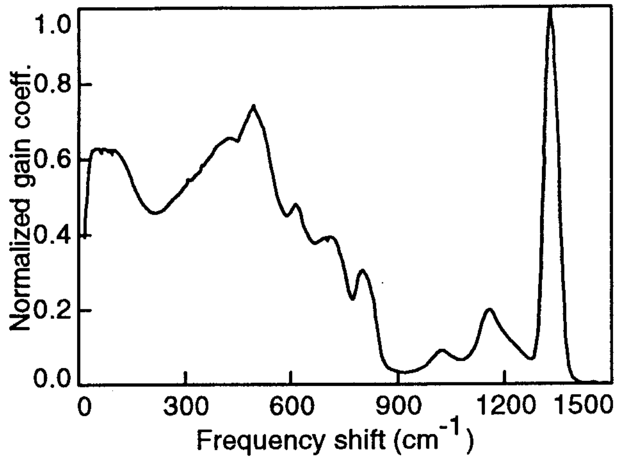

Fig. 1. Raman spectrum of the phosphosilicate fiber.

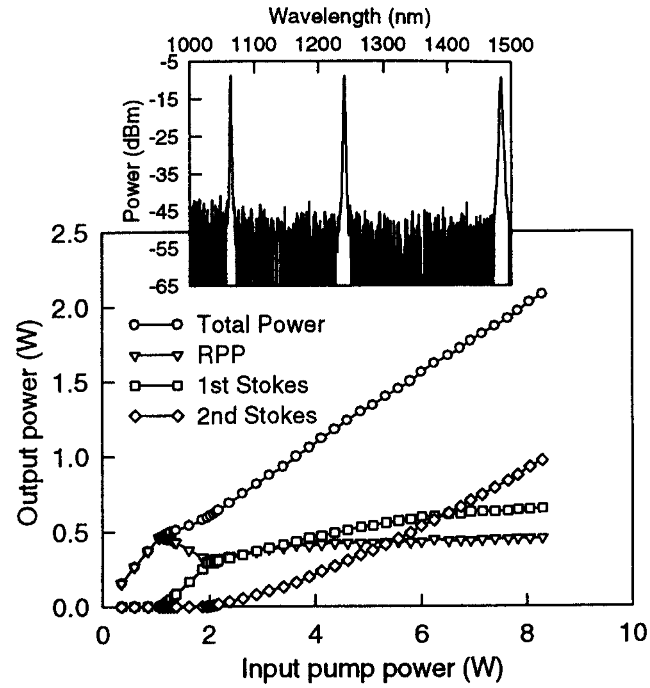

Fig. 3. Variation of output power of the residual pump, and the S_1 and the S_2 modes, with change in the input pump power. Inset: spectrum of the total output.

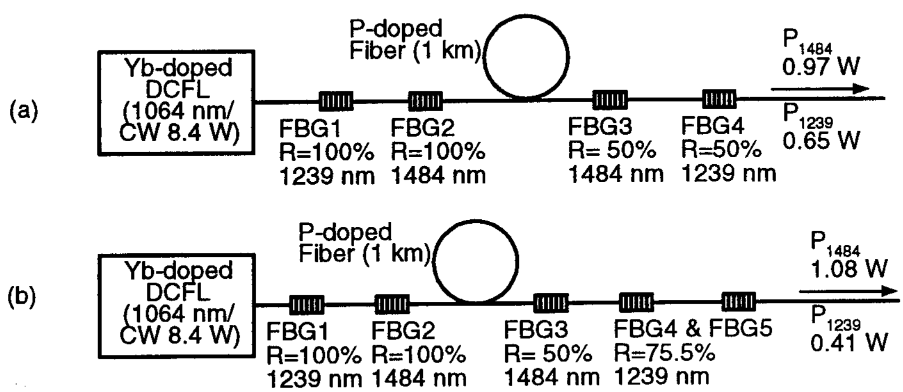

Fig. 2. Experimental setups of Raman fiber lasers: (a) Output coupling with 50% at 1239 nm and 50% at 1484 nm. (b) Output coupling with 75.5% at 1239 nm and 50% at 1484 nm.

The threshold powers for the S_1 and the S_2 modes are 1.11 W and 2.08 W, respectively. The RPP varied as a function of the IPP in three distinct steps, increasing from 0.16 W to 0.46 W in the first step, decreasing to 0.31 W in the second, and finally increasing gradually to 0.45 W. This three-step change of the RPP was observed for the first time in this experiment. When we raised the IPP to 0.11 W in the first step, the RPP was increased because the IPP was below the S_1 and the S_2 thresholds and the input light underwent only splice and fiber losses. When the IPP was increased from 0.11 W to 1.96 W in the second step, the RPP was decreased because the IPP was above the S_1 threshold and used in generation of the S_1 mode. In the third step, when the IPP was above the S_2 threshold, the RPP was increased very gradually because the IPP was transferred to both the S_1 and the S_2 modes. The rate of generation of the S_2 mode was larger than that of the S_1 mode because most of the IPP had been used in conversion to the S_2 mode through the S_1 mode.

The inset of Fig. 3 shows the total output spectrum of the RFL at the S_1 and the S_2 modes and the residual pump. The large value of the RPP might be due to the lossy cascaded cavities.

For the IPP of 8.4 W, the S_1 output power is 0.65 W. The slope efficiencies of S_1 can be determined in two dis-

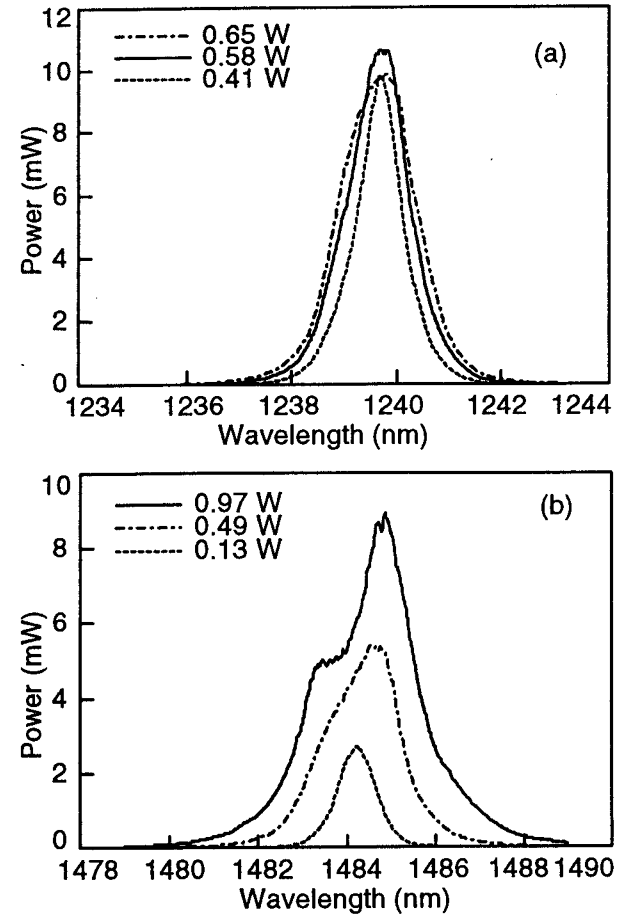

Fig. 4. Spectrum of the laser output. (a) The S_1 output spectrum for different S_1 outputs. (b) The S_2 output spectrum for different S_2 outputs.

tinct regions: one before the generation of S_2 and the other after. Slope efficiencies of S_1 are 28.7% and 6.1% before and after the generation of S_2 mode, respectively. The net slope efficiencies of S_1 after considering the cavity loss are 64.2% and 13.7% before and after the generation of S_2 mode, respectively. The S_2 output power is 0.97 W with 15.4% and 34.4% slope efficiency and net slope efficiency, respectively. A higher output power is expected when the total cavity loss is further reduced.

Figure 4(a) and (b) shows the S_1 and the S_2 spectrum at different output powers. It is evident from (a) that the peak level of the S_1 mode spectrum does not change appreciably during the growth of the S_1 mode but the mode spectrum is broadened with the increase in the IPP. From (b) it can be observed that the peak of the S_2 mode is shifted from 1484.02 nm to 1484.86 nm with increase in the IPP, and additionally the S_2 spectrum shows a shoulder at 1483.48 nm when the S_2 output power is greater than 490 mW. This may be due to self-phase modulation or other nonlinear phenomena arising from a high-level of the S_2 power. As shown in Fig. 5, the full-width at half maximum (FWHM) of the S_1 and the S_2 spectra increased as a function of the IPP and the

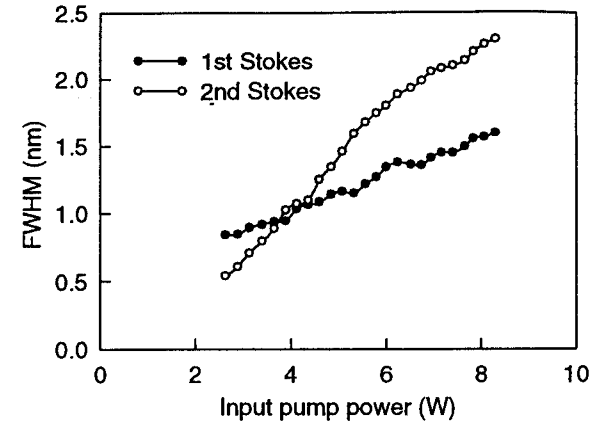

Fig. 5. Full-width at half maximum of the S_1 and the S_2 modes with change in the input pump power.

Table 1. Comparative table for setup (a) and (b) as shown in Fig. 2.

Parameter	Setup (a)	Setup (b)
Output FBG mirror reflectivity (%) at S_1	50	75.5
Maximum power (W) of S_1	0.65	0.37
Maximum power (W) of S_2	0.97	1.06
S_1 Threshold (W)	1.11	0.86
S_2 Threshold (W)	2.08	1.73
Slope Efficiency (%) of S_1		
Region I*	28.7	19.2
Region II**	6.1	3.2
Net Slope Efficiency (%) of S_1		
Region I*	64.2	45.9
Region II**	13.7	7.6
Slope Efficiency (%) of S_2	15.4	15.7
Net Slope Efficiency (%) of S_2	34.4	37.5

*Before the generation of S_2
**After the generation of S_2

FWHM of the S_2 mode increased much faster than that of the S_1 mode.

In order to study the laser output for a different output FBG mirror, we changed the FBG4 to a combination of two FBGs to get a total reflectivity of 75.5% at 1239 nm. The experimental setup is shown in Fig. 2(b). As the distance between FBG4 and FBG5 is over 2 m and as each FBG has a reflectivity greater than 50%, the combination of the two FBGs did not have the severe Fabry-Perot Etalon effect, nor did we observe any severe power fluctuation with time. The total reflectivity of the FBG4-FBG5 combination is obtained by $R_1+R_2\,(1-R_1)^2\,[1+R_1R_2+(R_1R_2)^2+\ldots]$, where R_1 and R_2 are the reflectivities of the FBG4 and FBG5, respectively. The total loss in this experimental setup was 3.78 dB at 1064 nm, before the generation of the Stokes modes. The threshold power for the S_1 and the S_2 modes was 0.86 W and 1.73 W, respectively, and the output power was 0.37 W and 1.06 W.

The slope efficiencies of S_1 mode are 19.2% and 3.2%

before and after the generation of S_2 mode, and the net slope efficiencies are 45.9% and 7.6%. The S_2 output power is 0.97 W with 15.7% and 37.5% slope efficiency and net slope efficiency, respectively.

The increase in the S_2 power and decrease in the S_1 power for change in FBG4 reflectivity is because a relatively large level of the S_1 power is reflected back into the cavity and converted to the S_2 power. The S_2 mode spectrum shows the shift in the S_2 peak from 1484.07 nm to 1484.89 nm, and also shows a shoulder at 1483.58 nm for maximum S_2 output level. The S_1 mode spectrum has a shift in the S_1 peak from 1239.74 nm to 1239.51 nm when the IPP is increased. Table 1 summarizes the comparative results for the experimental setup as shown in Fig. 2(a) and 2(b).

3. Conclusions

We have developed a double-color CW RFL with simultaneous outputs of 0.65 W at 1239 nm and 0.97 W at 1484 nm using the PDF and two cascaded cavities for 1239 and 1484 nm wavelengths which is pumped by CW 8.4 W Yb-doped DCFL. As far as we know, this output level is the highest one reported for the simultaneous operation at 1239 nm and 1484 nm. It was observed for the first time that the RPP undergoes a three-step process with increase in the IPP during the generation of the S_1 and the S_2 modes.

For an output FBG mirror reflectivity of 50% for the two modes, the slope efficiency for the S_2 mode was 15.4% and the net slope efficiency was 34.4%. When two output FBG mirrors with 75.5% total reflectivity at 1239 nm were used, the slope efficiency for the S_2 output increased slightly from 15.4% to 15.7%, whereas the slope efficiency and net slope efficiency of S_1 before and after the generation of S_2, decreased.

This high-power double-color Raman fiber laser will be useful to pump a 1310 nm Raman fiber amplifier and a 1550 nm Er-doped fiber amplifier simultaneously. It can also be used to characterize optoelectronic integrated circuits and for optical fiber sensors.

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