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Simultaneous two-color CW Raman fiber laser with maximum output power of 1.05 W/1239 nm and 0.95 W/1484 nm using phosphosilicate fiber

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Abstract

High-power two-color CW Raman fiber laser is obtained with simultaneous outputs at 1239 nm and 1484 nm which uses CW 8.4 W Yb-doped double-clad fiber laser at 1064 nm as a pump, phosphosilicate fiber, and cascaded cavities consisting of two pairs of fiber Bragg grating mirrors. Maximum output powers are 1.05 W at 1239 nm and 0.95 W at 1484 nm with 700 m of phosphosilicate fiber. The output characteristics of this laser for different fiber lengths are reported.

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1. Introduction

The optical power in the conventional fiberoptic communication system is limited by the intrinsic properties of the single-mode diode-lasers. Their power range is from milliwatts for single-frequency signal diode lasers to tens of milliwatts for diode-laser pumps for erbium-doped fiber amplifiers. However, recent advances in construction of practical high-power pump lasers sources like narrow-stripe lasers diodes (LD) with maximum output powers of 150 mW to 200 mW at 1484 nm, and Yb-doped double-clad fiber lasers (DCFL) [1–3] with output power in tens of watts at wavelengths ranging from 1040 nm to 1120 nm, have boosted the available optical power in single-mode fibers and have renewed interest in Raman fiber lasers (RFL) and Raman fiber amplifiers (RFA). The RFL at 1240 nm [4–6] is the only low-loss pump source used in 1310 nm RFA, since there are very few commercial laser diode (LD) sources at this wavelength. The RFL at 1480 nm [5,7,8] is a good alternative for pumping Er-doped fiber amplifiers. However, in system deployments with optical fiber amplifiers, we seldom find pump sources which can simultaneously pump fiber amplifiers at 1310 nm and 1550 nm wavelengths. We

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demonstrate for the first time a high-power RFL source that can produce simultaneous outputs at 1239 nm and 1484 nm wavelengths. The output characteristics of the simultaneous two-color RFL at 1239 nm and 1484 nm for different PDF fiber lengths are reported.

The stimulated Raman scattering (SRS) in the RFL and the RFA involves a frequency-conversion process in which light traveling down a fiber interacts with the vibrating molecules in silica material. This interaction triggers a spectral shift that transfers the energy from a shorter-wavelength pump beam to a longer-wavelength signal. Although the Raman gain can be obtained for any silicate fiber, the value of Raman gain coefficient is higher for germanosilicate fiber than for silicate fiber. Hence, the germanosilicate fiber is used extensively in the RFL and the RFA. When the germanosilicate fiber with a peak Raman shift of 440–490 cm^{-1} is pumped at 1060 nm, the third and the sixth Stokes orders produce outputs at 1240 nm and 1480 nm, respectively. However, the low-loss phosphosilicate (P_2O_5–SiO_2) fiber which we will herein call P-doped fiber (PDF) has a peak Raman shift of 1330 cm^{-1} and when pumped with 1060 nm pump source, the first and the second Stokes orders occur at 1240 nm and 1480 nm, respectively [5,6,8,9].

High-power two-color single-mode RFL with maximum output powers of 1.05 W/1239 nm and 0.95 W/1484 nm is realized using 700 m PDF, two cascaded cavities formed by two pairs of fiber Bragg grating (FBG) mirrors at 1239 nm and 1484 nm, and CW 8.4 W Yb-doped DCFL. The output powers of residual pump, first Stokes (S_1) and second Stokes (S_2) modes, and the spectral profiles for both S_1 and S_2 modes are observed for the change in the input pump power (IPP). Three-step process in the variation of the residual pump power (RPP) for the change in the IPP is observed.

2. Experiment and discussion

The experimental setup is shown in Fig. 1. The pump source is a Yb-doped DCFL with single-mode fiber output and with a maximum output power of CW 8.4 W at 1064 nm, and was manufactured by IRE-Polus. The Yb-doped DCFL output is spliced with a low loss to the cascaded Raman cavities, which consist of two pairs of FBG mirrors written in the Flexcor-1060 fiber. The FBG1 and the FBG4 have reflectivities of 99.9% and 50%, respectively, at 1239 nm and form the S_1 cavity. While FBG2 and FBG3 with reflectivities of 99.9% and 50% at 1484 nm, form the S_2 cavity. PDF length of 300/700/1150 m is used for Raman gain medium and its core contains 12 mol% of phosphorous which results in a refractive index difference of 0.0107. For 1064, 1239, 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 MFD of the Flexcor-1060 fiber is 6.14, 7.13, and 9.10 μm at 1060, 1239, and 1480 nm wavelengths. The MFD mismatch between Flexcor-1060 and PDF results in splice-loss between them and the average splice loss in our setup is 0.22 dB. The average total insertion-loss due to the four FBG mirrors is 1.32 dB, which is relatively high. This is measured after configuring the RFL and before the generation of the S_1 or S_2 modes. The PDF and the FBGs were obtained from the Fiber Optics Research Center at the General Physics Institute, Russia. The output specta were measured using AQ-6315B optical spectrum analyzer manufactured by ANDO Co. The output power was measured using LaserMate optical power meter manufactured by Coherent Inc.

The output characteristics of the RFL for fiber lengths of 300/700/1150 m are reported. Fig. 2 shows the powers of the total power, RPP, S_1 and S_2 modes with change in IPP for the setup shown in

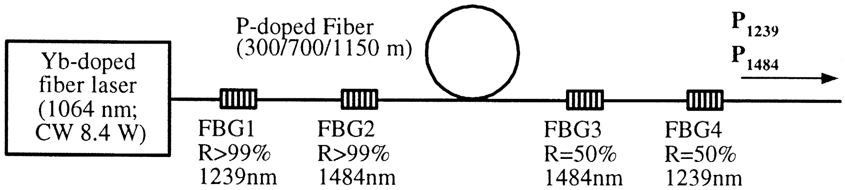

Fig. 1. Experimental setups of the Raman fiber lasers.

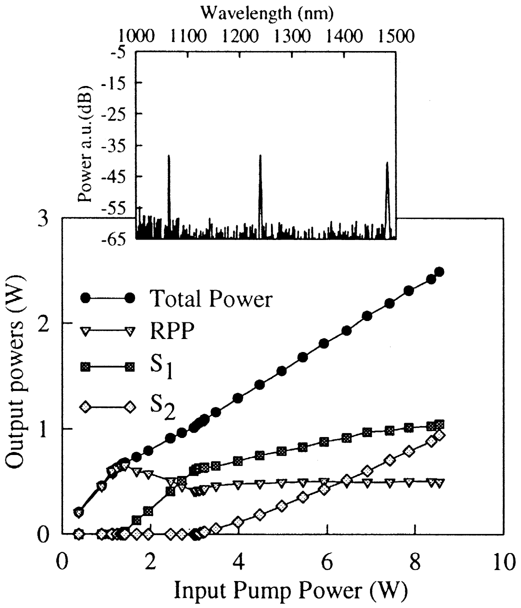

Fig. 2. Variation of output powers of the total power, residual pump power, S_1, and S_2 modes, with change in the input pump power. Inset: spectrum of the total output.

Fig. 1 with 700 m of PDF. The threshold powers for the S_1 and S_2 modes are 1.32 W and 3.09 W, respectively. The RPP varies as a function of IPP in three distinct steps [6,8], increasing from 0.20 W to 0.65 W in the first step, decreasing to 0.41 W in the second one, and finally increasing to 0.50 W. When we raise the IPP to 1.32 W in the first step, the RPP increases because the IPP is below the S_1 and the S_2 thresholds and the input light undergoes only splice and fiber losses. When the IPP is increased from 1.32 W to 3.03 W in the second step, the RPP decreases because the IPP is above the S_1 threshold and is used in generation of the S_1 mode. In the third step, when the IPP is above the S_2 threshold, the RPP increases very gradually because the IPP is transferred to both the S_1 and the S_2 modes. The rate of generation of the S_2 mode is larger than that of the S_1 mode because most of the IPP has been used in conversion to the S_2 mode through the S_1 mode.

The slope efficiencies of S_1 mode can be determined in two distinct regions: one before the generation of S_2 and the other after. Slope efficiencies of S_1 are 36.44% and 26.46% before and after the generation of the S_2 mode, respectively. The net slope efficiency is for the convertible IPP which excludes the non-conversion loss such as splice loss, total cavity loss for the FBG mirror, and the RPP from the IPP and can be converted to the S_2 mode through the S_1 mode. The net slope efficiency is a measure of the system performance and gives us an estimate of how much slope efficiency can be improved if we reduce the non-conversion loss. The net slope efficiencies of S_1 are 70.12% and 50.89% before and after the generation of S_2 mode, respectively. The S_2 slope efficiency and net slope efficiency of 16.80% and 30.80%, respectively, is obtained. A higher output power is expected when the total cavity loss is reduced further.

The inset of Fig. 2 shows the total output spectrum of the RFL which shows the S_1 and S_2 modes, and residual pump. The maximum output powers of 1.05 W and 0.95 W at 1239 nm and 1484 nm wavelengths, respectively, were obtained. There were no silicate Stokes mode at 1120 nm as reported by Karpov et al. [9]. As far as we know, this is the first report of high-power simultaneous output at 1239 nm and 1484 nm in fiber lasers.

Fig. 3 shows the maximum powers of the S_1 and the S_2 modes for different PDF lengths. It can be seen that for 300 m of PDF, the S_1/S_2 powers are 1.67 W/0.29 W respectively. This shows that this fiber length is not sufficient for efficient conversion from S_1 to S_2 mode. Whereas for 700 m of PDF, the

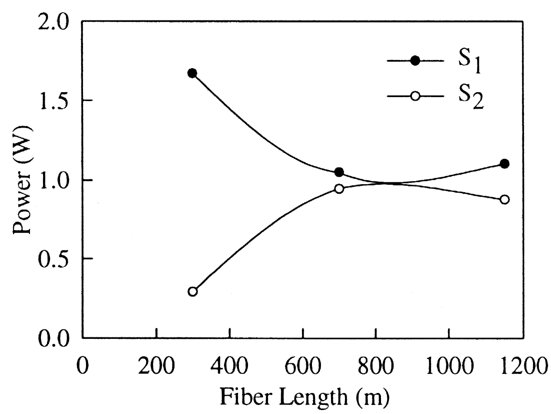

Fig. 3. Maximum powers of S_1 and S_2 modes for different PDF lengths.

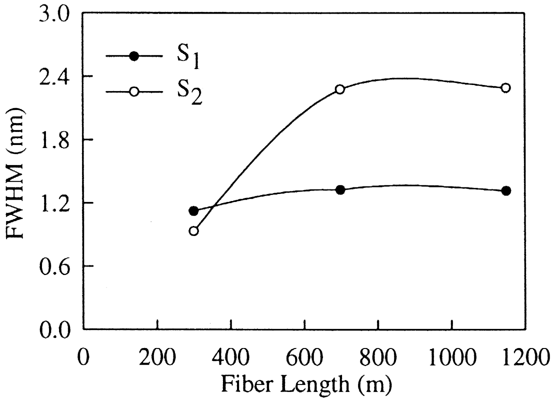

Fig. 4. Full width at half maximum of S_1 and S_2 modes for different PDF lengths.

S_1/S_2 powers are 1.05 W/0.95 W, respectively. For this fiber lengths, the S_1 power and S_2 powers are nearly identical. Whereas for 1150 m of PDF, the output powers at S_1/S_2 are 1.10 W/0.88 W, respectively. When compared to the 700 m of PDF case, in 1150 m one, the S_1 power increased whereas the S_2 power decreased.

Fig. 4 shows the full width at half maximum (FWHM) of the S_1 and S_2 modes for different PDF lengths at the maximum IPP. We see that the FWHM of S_1 mode does not change appreciably with increase in PDF lengths, whereas the S_2 mode FWHM changes very rapidly from 300 m to 700 m, however on further increase of PDF length to 1150 m, it does not change appreciably.

Fig. 5a and 5b show the S_1 and the S_2 mode spectrum at maximum IPP for different fiber lengths. The *y*-axis is calibrated to show the real values of power at S_1 and S_2 wavelengths. The S_1 mode spectrum shape does not change with increase in fiber length and as seen from Fig. 4, the FWHM does not change appreciably. Whereas the S_2 mode spectrum changes very drastically from 300 m to 700 m of PDF. But on further increase of PDF length to 1150 m, the mode spectrum of S_2 does not change very much. The peak spectrum of S_2 mode spectrum shifts from 1484.98 nm for 300 m of PDF to 1483.3 nm for 700 m and 1150 m ones. Additionally the S_2 mode spectrum is asymmetric and this is due to the spectral profile of the output FBG.

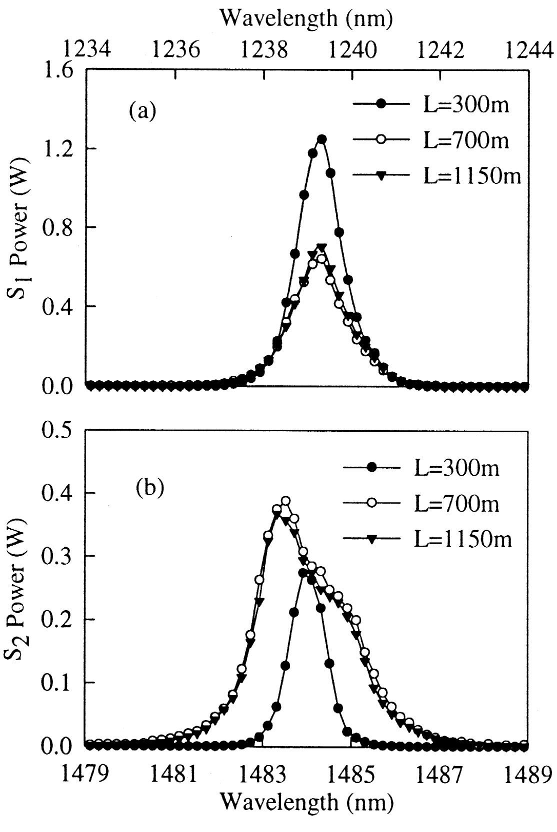

Fig. 5. Output spectrum of RFL at maximum IPP for different PDF lengths. (a) S_1 mode spectrum (b) S_2 mode spectrum.

Table 1
Comparative table for the 300/700/1150 m of PDF for the setup shown in Fig. 1

Parameters	PDF length		
	300 m	700 m	1150 m
Maximum power (W) of S_1	1.67	1.05	1.10
Maximum power (W) of S_2	0.29	0.95	0.88
S_1 threshold (W)	2.31	1.32	1.26
S_2 threshold (W)	5.66	3.09	2.97
Slope Efficiency (%) of S_1			
Region I [a]	12.17	36.44	36.02
Region II [b]	40.62	26.46	8.93
Net slope efficiency (%) of S_1			
Region I [a]	62.05	70.12	71.62
Region II [b]	18.59	50.89	17.76
Slope efficiency (%) of S_2	10.34	16.80	15.3
Net slope efficiency (%) of S_2	15.34	30.80	30.48

[a] Before the generation of S_2 mode.
[b] After the generation of S_2 mode.

Table 1 summarizes different parameters that were determined for the double-color RFL for 300/700/1150 m of PDF lengths. With increase in PDF length the S_1 and S_2 thresholds decrease whereas the slope efficiency and net slope efficiency of S_1 and S_2 modes are maximum for 700 m of PDF.

3. Conclusion

We have developed a high-power two-color CW RFL with simultaneous outputs of 1.05 W at 1239 nm and 0.95 W at 1484 nm using 700 m of 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. The RPP undergoes a three-step process with increase in the IPP during the generation of the S_1 and the S_2 modes.

The output characteristics of the two-color RFL were studied for different PDF lengths. With increase in fiber lengths, the S_1 and S_2 threshold decreased. Maximum S_1 and S_2 slope efficiency and net slope efficiency occurs for 700 m of PDF. Using a proper combination of output FBG and longer fiber lengths one can achieve identical results.

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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References

[1] R. Hofer, M. Hofer, G. Reider, Opt. Commun. 169 (1999) 135.
[2] C.C. Renaud, R.J. Selvas, J. Nilsson, P.W. Turner, A.B. Grudinin, IEEE Photonics Technol. Lett. 11 (1999) 976.
[3] V. Dominic, S.M. Cormack, R. Waarts, S. Sanders, S. Bicknese, R. Dohle, E. Wolak, Electron. Lett. 35 (1999) 1158.
[4] S.V. Chernikov, N.S. Platonov, D.V. Gapontsev, D.I. Chang, M.J. Guy, J.R. Taylor, Electron. Lett. 34 (1998) 680.
[5] E.M. Dianov, M.V. Grekov, I.A. Bufetov, S.A. Vasiliev, O.I. Medvedkov, V.G. Plotnichenko, V.V. Koltashev, A.V. Belov, M.M. Bubnov, S.L. Semyonov, A.M. Porkhorov, Electron. Lett. 33 (1997) 1542.
[6] M. Prabhu, N.S. Kim, K. Ueda, Opt. Rev., in press.
[7] D.I. Chang, H.K. Lee, K.H. Kim, Electron. Lett. 35 (1999) 1951.
[8] N.S. Kim, M. Prabhu, C. Li, J. Song, K. Ueda, Opt. Commun. 176 (2000) 219.
[9] V.I. Karpov, E.M. Dianov, V.M. Paramonov, O.I. Medvedkov, M.M. Bubnov, S.L. Semyonov, S.A. Vasiliev, V.N. Protopopov, O.N. Egorova, V.F. Hopin, A.N. Guryanov, M.P. Bachynski, W.R.L. Clements, Opt. Lett. 24 (1999) 887.