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Ultra-Broadband CW Supercontinuum Generation Centered at 1483.4 nm from Brillouin/Raman Fiber Laser

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About 100 nm CW supercontinuum centered at 1483.4 nm was generated from Brillouin/Raman fiber laser (BRFL). The BRFL consists of a Raman cavity with 700 m of phosphosilicate fiber (PDF) and pairs of fiber Bragg grating (FBG) mirrors and a Brillouin cavity with the PDF, 500 m of flexcor-1060 fiber, and output FBG mirrors. With 8.4 W/1064 nm Yb-doped double-clad fiber laser as pump and 50% feedback FBG mirror at end of BRFL, output power of over 1 W with 100 nm bandwidth centered at 1483.4 nm and weak 0.11 nm spectral modulation were observed.

KEYWORDS: Raman fiber laser, supercontinuum, phosphosilicate fiber, stimulated Raman scattering, Brillouin fiber laser

1. Introduction

Supercontinuum (SC) is a very attractive phenomenon and has invoked many potential applications because of its excellent properties. Optical fibers are used to efficiently generate SC with a broad bandwidth and are used in various areas like spectroscopy, optical communications, optical sensing, and others.

SC generated by parametric interactions has been reported in many kinds of configurations. In a recent experiment using 120 fs pulses and a high-nonlinear dispersion shifted fiber (DSF), SC of over 420 nm was reported.1) In another experiment, SC with 280 nm bandwidth was generated with 650 fs pulses and dispersion-flattened and decreasing fiber.2) SC generated using DSF have been used as wavelength division multiplexing sources by spectral splicing3, 4) and for characterizing fiber Bragg gratings (FBG).5)

SC can also be generated by stimulated Raman scattering6–8) and by superfluorescence9–11) and are used for loss and dispersion measurement in optical fiber,12) optical fiber component characterizations, optical coherence tomography,13) fiber-optic gyroscopes,14, 15) sensors,16, 17) and other applications.

Most of the SC sources require a very short high-peak power pulses and a DSF. Although good results with wide bandwidth were achieved from the previous experiments,1–4, 8) very few groups have reported on high-power CW SC sources.

In this paper, we demonstrate a 100 nm bandwidth CW SC source with maximum output power of 1.26 W centered around 1483.4 nm, using CW Brillouin/Raman fiber laser (BRFL). The output characteristic of this laser was studied for different feedback FBG mirror reflectivities.

2. Experimental Setup

The BRFL setup is shown in Fig. 1. It consists of two cavities: Raman and Brillouin cavities. Raman cavity is made of two cascaded cavities of FBG mirrors at 1239 nm and 1483.4 nm, and 700 m of phosphosilicate fiber (PDF).18) When pumped by CW 8.4 W/1064 nm Yb-doped double-clad fiber laser (DCFL), the Raman cavity oscillates to generate 1483.4 nm light cascaded through 1239 nm by stimulated Raman scattering. The reflectivities of FBG full mirrors at 1239 nm and 1483.4 nm are more than 99% whereas reflectivity of the FBG output coupler at 1483.4 nm is 15%. The PDF has a Raman shift of 1330 cm^{-1} and the first and the second Raman shift occur at 1239 nm and at 1483.4 nm respectively when pumped at 1064 nm. The Brillouin cavity consists of 700 m of PDF (which is also included in the Raman cavity) and 500 m of Flexcor-1060 fiber. The core diameter of the PDF and the Flexcor-1060 fiber are 6.1 μm and 6.2 μm, respectively. As the FBG mirrors are written on the Flexcor-1060 fiber, the splicing loss between PDF and flexcor-1060 fiber could be minimized. To enhance the Brillouin SC output, feedback FBG at 1483.4 nm is introduced to reflect the light at 1483.4 nm back into the Brillouin cavity.

3. Results and Discussion

Figure 2 shows the output spectrum from simple 1483.4 nm Raman fiber laser (RFL) without Brillouin cavity and the BRFL. The spectrum shows the input pump at 1064 nm, the first Stokes order at 1239 nm, and the second Stokes order at 1483.4 nm. The second Stokes output with maximum output power of 2.11 W and full width at half maximum of 2.0 nm is obtained at 1483.4 nm. We used 15% output coupler for 1483.4 nm wavelength and 700 m phosphosilicate fiber for the Raman gain medium. For the first Stokes wavelength of 1239 nm, we used two high-reflecting FBG mirrors with more than 99% reflectivity. In the total spectrum as shown in Fig. 2, there is no silicate Stokes line at 1120 nm as reported by Karpov *et al.*18)

When the 500 m singlemode fiber (SMF) is spliced to output end of the RFL, the broadband SC spectrum is generated and extends from 1433 nm to 1533 nm. A strong central peak at 1483.4 nm wavelength is observed and over 1.0 mW/0.1 nm power is distributed between 1434.9 nm and 1526.9 nm. There is also an additional broad peak from 1446 nm to 1455 nm, which is blue-shifted from the main RFL output at 1483.4 nm. The SC extends on either side of the RFL output with a total SC output power of 1.15 W. The spectral intensity of the SC is greater than 1.0 mW/0.1 nm over 100 nm range and has an average spectral intensity of over 10 mW/nm.

In order to reflect the central peak power back into the cavity for power redistribution, FBG mirror with 50% reflectivity at 1483.4 nm is introduced. The spectrum at the

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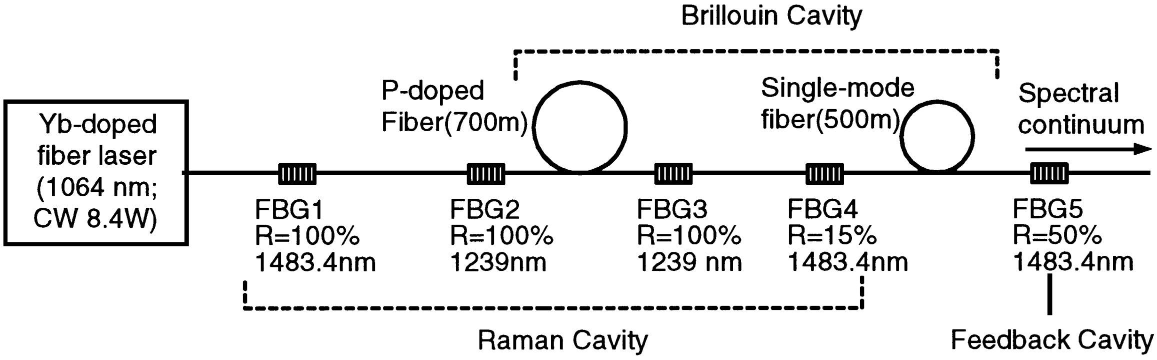

Fig. 1. Experimental setup for 100 nm supercontinuum source using ordinary singlemode fiber and CW Brillouin/Raman fiber laser.

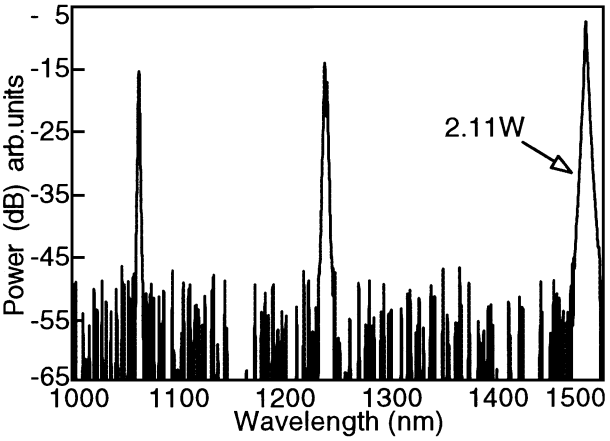

Fig. 2. Output spectrum for the 1483.4 nm Raman fiber laser (without Brillouin cavity).

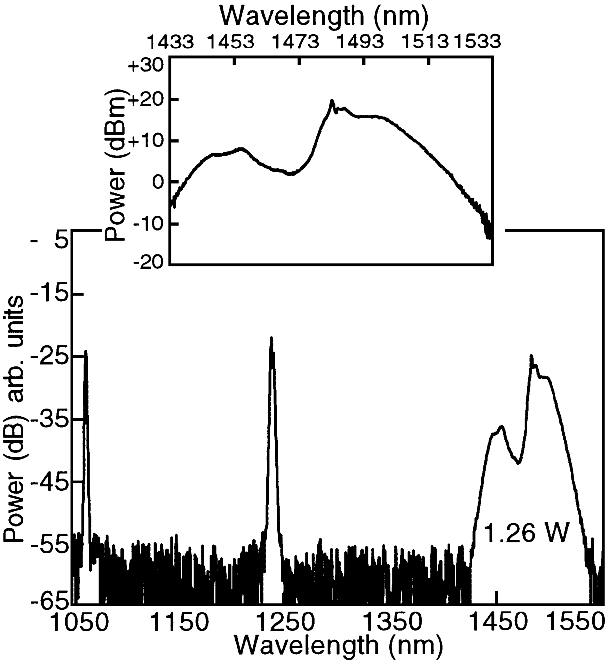

Fig. 3. Output spectrum for the Brillouin/Raman fiber laser with 50% feedback FBG mirror at 1483.4 nm. Inset: Zoom-in view of the supercontinuum. The vertical scale in the inset has been scaled to show the actual output power of the supercontinuum.

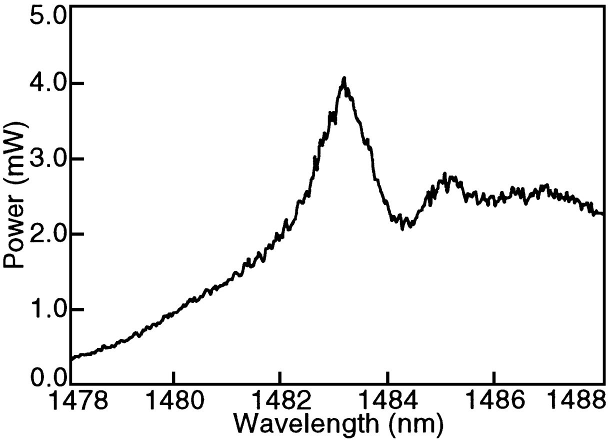

Fig. 4. Output spectrum in linear scale (with arbitrary units) showing a weak spectral modulation after including 50% feedback FBG mirror at 1483.4 nm.

output of BRFL is shown in Fig. 3. The inset in the figure shows a zoom-in view of the SC spectrum from 1433 nm to 1533 nm. Though we can still see the maximum peak power at 1483.4 nm, a lot of power has been redistributed to generate an ultra-broadband SC. The SC output power increased up to 1.26 W from the previous result of 1.15 W. Additionally, we observed a weak spectral modulation with a spectral interval of about 0.11 nm as seen in Fig. 4, which is due to strong coupling of stimulated Brillouin shift in the SMF.

On changing the reflectivity of the feedback FBG mirror reflectivity to 84% at 1483.4 nm, the total SC output power decreased to 1.13 W and the spectral modulation was not observed. The decrease in the output power is because, greater fraction of the RFL output power at 1483.4 nm is reflected back into the Brillouin cavity for power redistribution. Finally, temporal profile was observed for the SC output from the BRFL and we confirmed that there is only stable CW operation upto sub-ns regime.

This energy distribution in the SC can be explained as follows: The radiation produced at wavelength longer than 1483.4 nm is due to degenerate Stimulated Brillouin scattering from the Brillouin cavity. The blue shift from the input 1483.4 nm radiation could be due to four-wave mixing. The asymmetry in the SC spectrum is due to interplay of different nonlinear effects.

4. Conclusion

In our experiment, we observed over 100 nm CW SC using BRFL which is pumped by CW Yb-doped DCFL. There was a very clear difference in the output spectrum for the simple RFL and the BRFL since there was no SC output without the

Brillouin cavity. The spectral intensity of this SC was greater than 1 mW/0.1 nm over the 100 nm range and has an average value of over 10 mW/nm. The total output power in the 100 nm SC spectrum is over 1 W. In addition, we could observe spectral modulation after including the feedback FBG mirror at 1483.4 nm to the BRFL. This CW SC source can be used for a variety of applications like optical imaging, sensing, or communications, etc.

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