ISSN 1054-660X, Laser Physics, 2011, Vol. 21, No. 11, pp. 1925–1931.

Comparison of Brillouin-Raman Comb Fiber Laser in Two Different Configurations[1]

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Received April 28, 2011; in final form, May 3, 2011; published online September 2, 2011

Abstract—The properties of a Brillouin-Raman comb fiber laser are compared for two different configurations: co-propagating and counter-propagating Raman pump. The optical spectrum is compared for changing the Raman pump power and the power or the wavelength of seed laser. A Brillouin-Raman comb with 400 linewidth lasers in a flat-amplitude bandwidth of 32 nm between 1538 and 1570 nm, with an average optical power 20 dB above the nearby frequencies was generated. The lasers in the comb had an OSNR of 20 dB and a wavelength spacing of 0.08 nm. The results for the counter-propagating configuration were observed to have better quality.

DOI: 10.1134/S1054660X11190248

1. INTRODUCTION

The use of multiwavelength lasers in optical communication systems is pushing the research in this field. These types of lasers can be produced by external channel filtering; the technique is based in slicing a broadband spectrum from a supercontinuum source and has been shown to produce more than 1000 channel optical frequency [1]. Another way to produce these multi-wavelength lasers consists in an internal channel generation based in an in-fiber comb filter such as a transmissive wideband Bragg grating Fabry–Perot resonator [2], reflective sampled Bragg grating [2], Sagnac interferometer [3], fiber loop mirror [4], dual–pass Mach–Zehnder (M–Z) interferometer [5] or nonlinear optical loop mirror (NOLM) [6]. Also, a hybrid-gain configuration can be used, using a broadband gain (such as Raman gain) and a narrowband Brillouin gain assisted by Rayleigh scattering, which uses a seed laser in the broadband gain peak to generate several lasers in a cascaded process [7–9].

Different parameters have been tested to improve the quality and number of generated channels. Early studies used erbium gain as the broadband gain [10] and recently, muitiwavelength lasers with a power of up to 11 dBm using bismuth based erbium doped fibre amplifier (Bi-EDFA) have been shown [11]. But this presents some problems: the gain is limited to a few nanometers which limits the number of generated channels. Raman gain provides a broader band gain and architectures with two, or more, Raman pumps with different wavelengths to increase the gain region have been demonstrated to generate up to 798 channels [12]. Schemes with bi-directional pumping have also been tested [13]. Recently, large effective area fibers (LEAF) have been used to enhance the optical signal-to-noise ratio (OSNR) of the spectrum [8, 14]. The use of cooperative Rayleigh scattering [9, 15] and double Rayleigh scattering [16] as distributed mirrors in the fiber has also been studied. Forward Raman pumping decreases the threshold to start the Brillouin process [17, 18] but counter-propagating Raman is more efficient and produces less noise in the amplified spectrum [19, 18]. The dependence of the stimulated Brillouin scattering threshold on the Raman pump power has also been studied [20]. The effects of four-wave mixing in fibers with different dispersion curves have been studied [21, 22] and used to generate combs with tunable wavelength spacing [13, 23]. Different schemes have been shown to generate broadly tunable region lasers [11, 14, 24] of up to 150 nm [13] and adjustable number of lasing lines [8].

In this paper the properties (optical signal-to-noise ratio (OSNR), number of channels and flatness) of a multiwavelength Brillouin/Raman comb fiber laser are compared when the Raman pump is co-propagating and when the Raman pump is counter-propagating.

2. EXPERIMENTAL RESULTS

Figure 1 presents the experimental setup for the co-propagating Brillouin Raman comb laser. A Raman pump laser at 1455 nm with a maximum power of 5 W, a co-propagating tunable seed laser with a maximum power of 11 dBm and two wavelength division multiplexers (WDMs) (1450/1550 nm) are used. A one kilometer dispersion compensating fiber (DCF) with a dispersion coefficient of –132 ps/nm/km is used to create a distributed mirror and Raman gain. An Optical Spectrum Analyzer (OSA) with a maximum reso-

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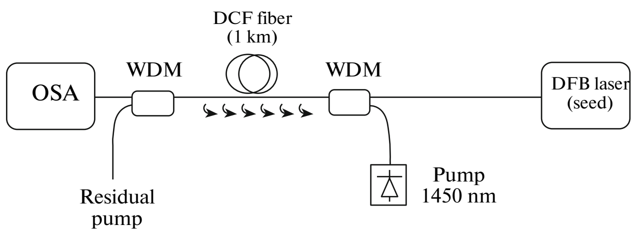

Fig. 1. Experimental setup used to generate a comb laser with Raman co-propagating configuration.

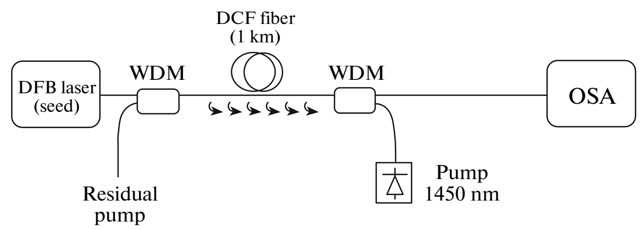

Fig. 2. Experimental setup used to generate a comb laser with Raman counter-propagating configuration.

lution of 0.01 nm was used to observe the optical spectrum. For the counter-propagating configuration (Fig. 2) a similar architecture was used, but the seed laser position was switched with the OSA.

The seed laser is used to start the Brillouin cascaded process. Each new wavelength laser is generated by Brillouin Stokes scattering from the previous laser wavelength, and amplified by Raman gain. Each wavelength laser has maximum amplitude determined by the stimulated Brillouin threshold, and therefore lasers in the same wavelength region have the same amplitude. When the laser's wavelength is out of the Raman gain peak, the gain is not enough to amplify the laser seeds, and no more lasers wavelengths are formed. Since the Brillouin Stokes scattering generates counter-propagating waves, then in order to be observed in the OSA (for both configurations), and counting the seed laser as the 0th order Stokes laser, the odd order Stokes lasers (formed by Brillouin Stokes scattering) need an odd number of Rayleigh scattering reflections and the even order Stokes lasers need an even number of Rayleigh scattering reflections. Therefore, there is a difference in the form of the odd and even order Stokes lasers [7].

The Brillouin Raman comb fiber laser spectrum is observed for co-propagating (Fig. 3) and counter-propagating (Fig. 4) configurations for different Raman pump powers (at 1455 nm) with 10 dBm seed

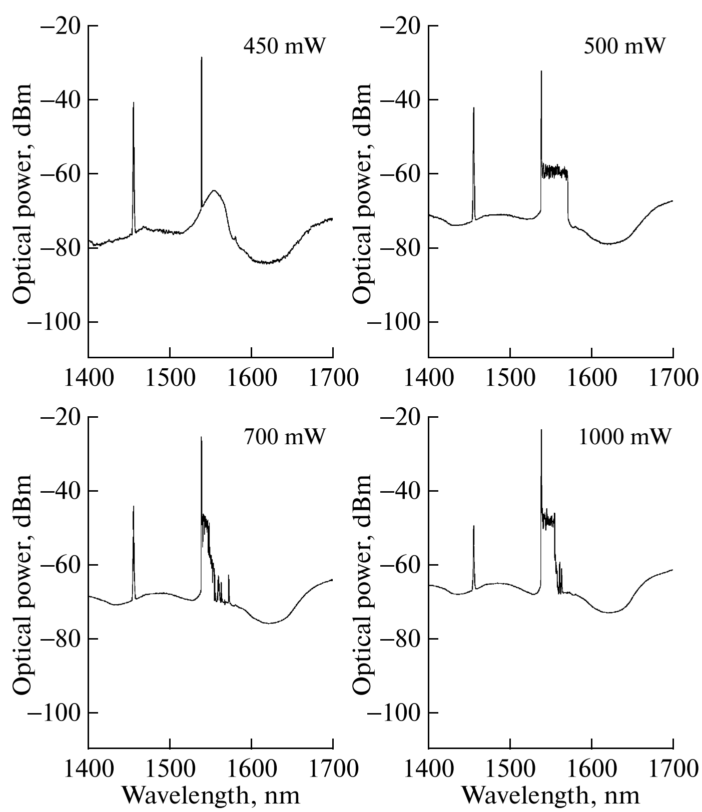

Fig. 3. Optical spectrum for different Raman pump powers, with co-propagating configuration and 10 dBm seed at 1538 nm (span 300 nm).

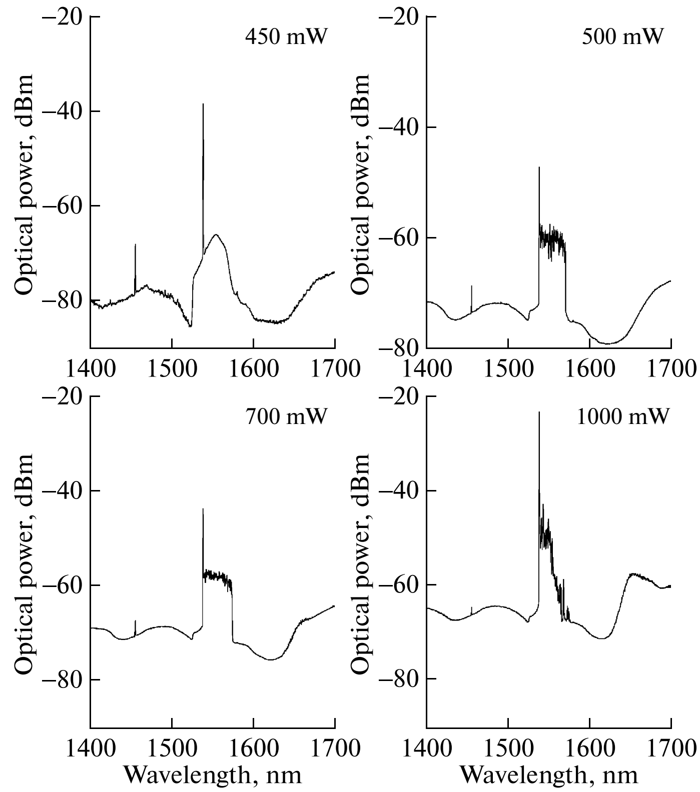

Fig. 4. Optical spectrum for different Raman pump powers, with counter-propagating configuration and 10 dBm seed at 1538 nm (span 300 nm).

laser at 1538 nm with a span of 300 nm. The Raman gain was observed to increase rapidly (0.3 dB/nm) at 1538 nm and to have a maximum peak at 1555 nm. For higher Raman pump powers, the average optical power was observed to be lower for higher wavelengths in the comb. For the counter-propagating configuration (Fig. 4) a break in the optical power is observed at 1525 nm due to the WDM action. This effect is not observed for the co-propagating configuration since the WDMs have different optical spectrum filters. Note that the resolution is not enough to see Rayleigh lasing peaks, but only the average energy of the spectrum.

Using the same parameters of Figs. 3 and 4, the Brillouin Raman comb fiber laser spectrum was observed at magnified span (50 nm) for co-propagating (Fig. 5) and counter-propagating (Fig. 6) for different Raman pump powers. The Raman pump power necessary to achieve the Brillouin cascaded threshold power was measured to be 460 mW. For a Raman pump power of 470 mW, a flat-amplitude spectrum 20 dB above the optical power of nearby frequencies starting at 1538 nm (laser seed) were generated in both configurations. The spectrum stopped at 1569 nm for co-propagating and 1570 nm for counter-propagating. For higher pump powers, random Rayleigh lasing occurs at any wavelength in the comb. Therefore the Raman gain is higher in the earlier wavelengths of the comb, but lower power is left to amplify the later wavelengths of the comb (1000 mW). Also, for higher pump powers the average energy in the comb decreases with increasing wavelength and there is no sudden amplitude break at the end of the comb.

Using the same parameters of Figs. 5 and 6, the Brillouin Raman comb fiber laser spectrum was observed at magnified span (1 nm) for co-propagating (Fig. 7) and counter-propagating (Fig. 8) for different Raman pump powers. For increasing Raman pump powers, both the maximum (i.e., the average of the Rayleigh lasing peaks of each laser) and the minimum power of the optical spectrum were higher in both configurations, but the minimum was more sensible to the pump power changes. Therefore, the highest optical signal-to-noise ratio (OSNR) and stability and the lowest noise were achieved with lower Raman pump powers, immediately over the threshold at 470 mW. Also, a Rayleigh lasing threshold (constant for all the pump powers) is observed at about −57 dBm. Due to the random properties of the Rayleigh lasing the maximum gain in each peak is unstable, which generates non-flat amplitude.

For lower Raman pump powers, the Rayleigh lasing only occurs in the peaks of each laser, but for Raman pumps higher than 550 mW for co-propagat-

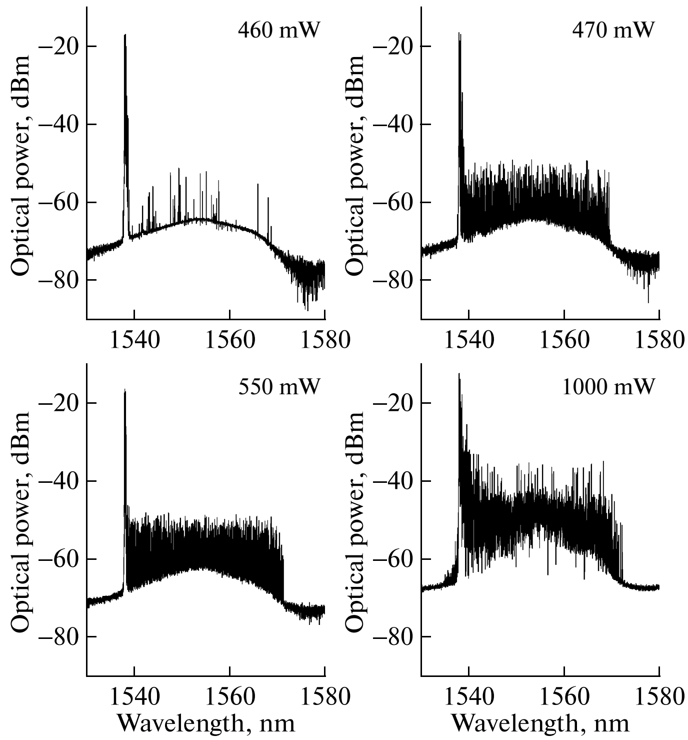

Fig. 5. Optical spectrum for different Raman pump powers, with co-propagating configuration and 10 dBm seed at 1538 nm (span 50 nm).

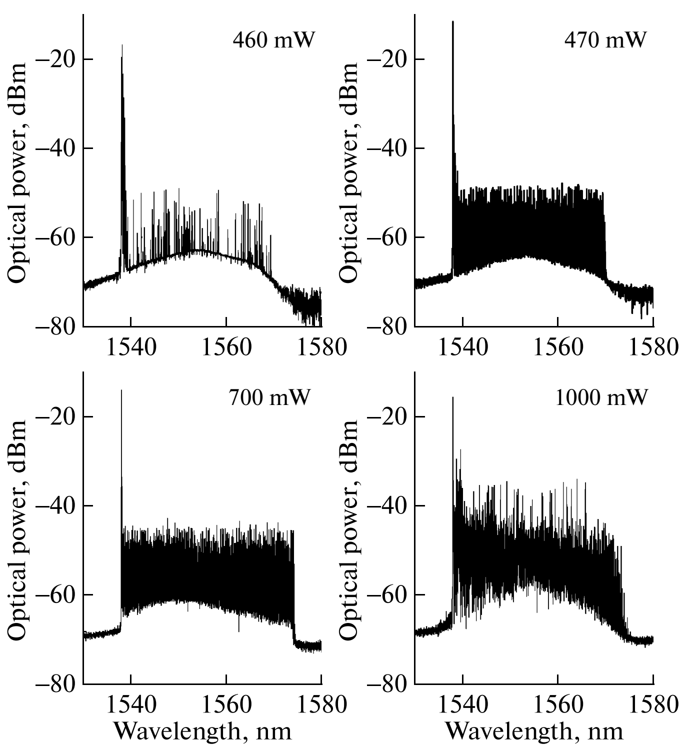

Fig. 6. Optical spectrum for different Raman pump powers, with counter-propagating configuration and 10 dBm seed at 1538 nm (span 50 nm).

ing and 700 mW for counter-propagating, the minimum spectral power in the comb is above the Rayleigh lasing threshold, and therefore Rayleigh lasing can occur at any wavelength, generating a very unstable, non-flat and noisy spectrum (1000 mW). Overall, the counter-propagating configuration had a better OSNR (at 470 mW: 16.5 dB for co-propagating and 20 dB for counter-propagating), less noise (Figs. 7 and 8), higher stability and spectrum flatness (Figs. 5 and 6) for different Raman pump powers.

The difference between the form of wider and narrower Brillouin Stokes peaks can also be observed for both configurations, but was more noticeable in the counter-propagating configuration (since there was less noise). The spacing between peaks was observed to be 0.08 nm and is constant for all the measurements in the work.

The Raman pump power necessary to achieve the Brillouin cascaded threshold power were measured for different seed laser powers, at 1538 nm (Fig. 9) and different seed laser wavelengths, with 10 dBm (Fig. 10). Since for the co-propagating configuration the Raman gain close to the seed laser is higher, for lower seed laser powers (0 dBm) the necessary Raman pump power to achieve the Brillouin cascaded threshold power is lower for the co-propagating (490 mW) than for counter-propagating (580 mW). For seed laser powers higher than 8 dBm, the necessary Raman

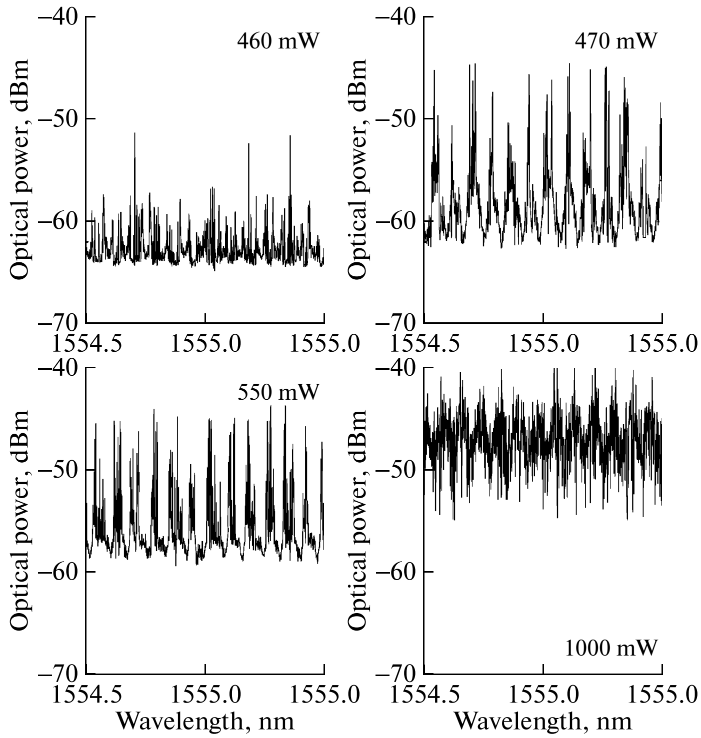

Fig. 7. Optical spectrum for different Raman pump powers, with co-propagating configuration and 10 dBm seed at 1538 nm (span 1 nm).

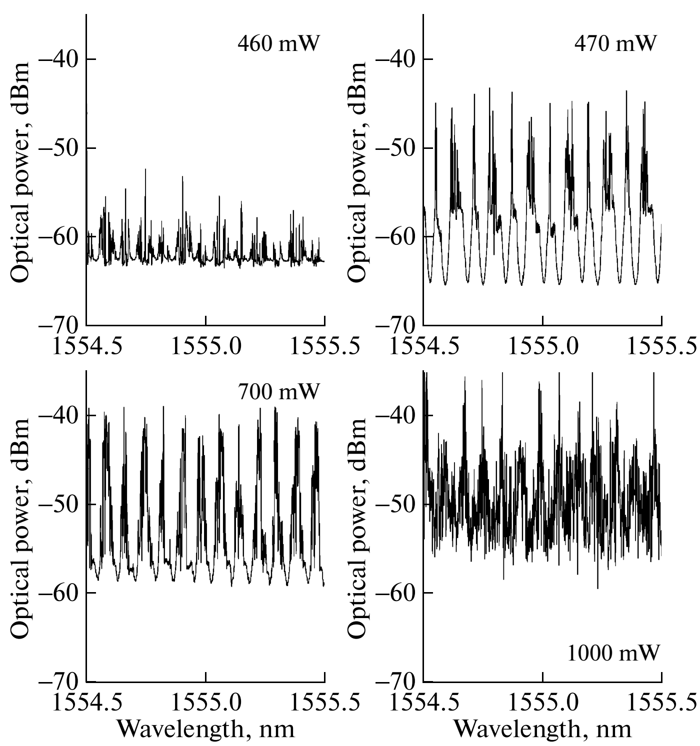

Fig. 8. Optical spectrum for different Raman pump powers, with counter-propagating configuration and 10 dBm seed at 1538 nm (span 1 nm).

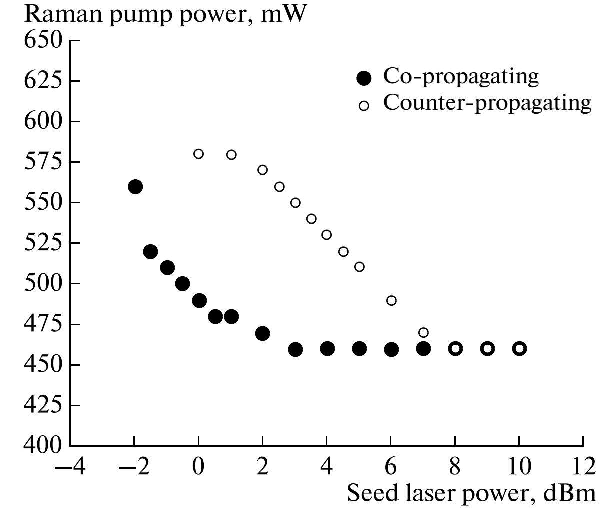

Fig. 9. Raman pump power necessary to achieve Brillouin cascaded threshold power for different seed laser powers at 1538 nm.

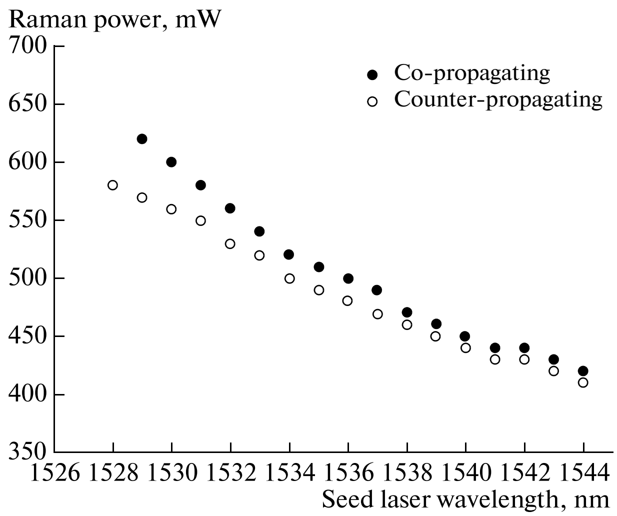

Fig. 10. Raman pump power necessary to achieve Brillouin cascaded threshold power for different seed laser wavelengths with 10 dBm.

pump power is constant (at 460 mW) and equal for both configurations.

Since the Raman gain is rapidly increasing in the region of 1538 nm, for higher seed laser wavelengths the necessary Raman pump power to achieve the Brillouin cascaded threshold power decreases (with approximately the same sensibility for both configurations). For lower seed laser wavelengths (1529 nm), the necessary Raman pump power is higher (40 mW) for the co-propagating configuration, but for wavelengths above 1538 nm the necessary Raman pump power is equal for both configurations.

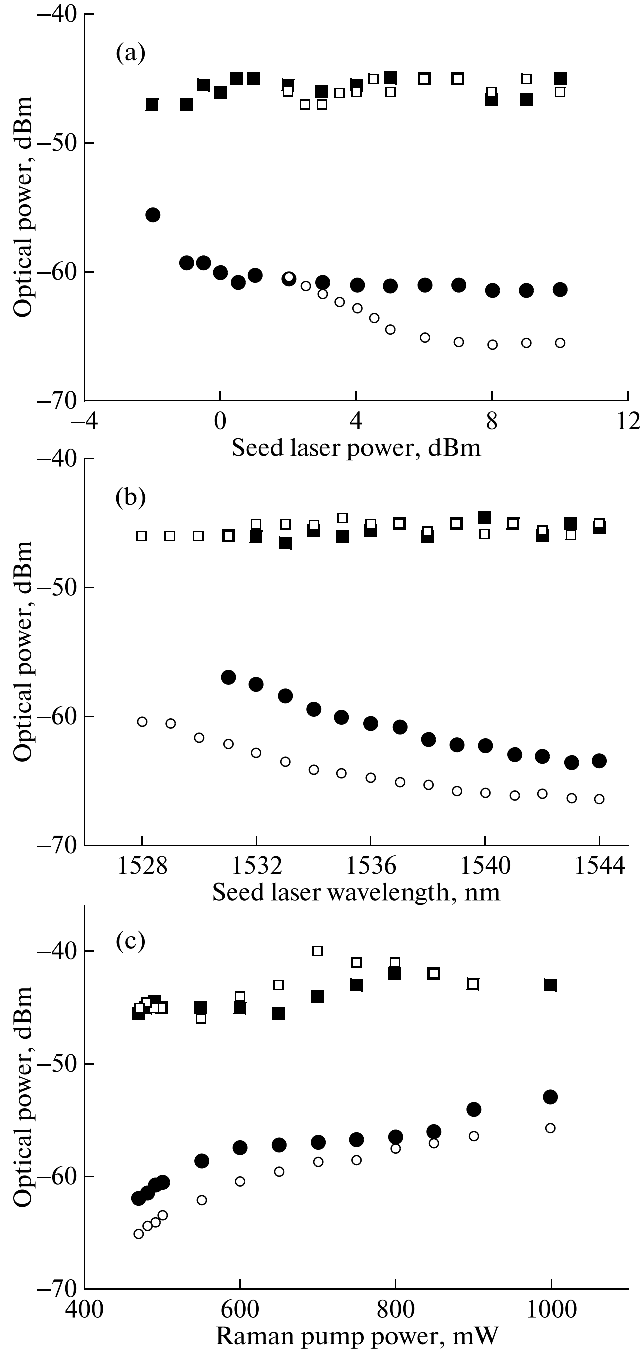

Fig. 11. Maximum (squares) and minimum (circles) optical powers of the spectrum for co-propagating (filled symbols) and counter-propagating (empty symbols) configurations for different parameters.

The maximum and minimum optical spectrum power were measured for different seed laser powers, at 1538 nm (Fig. 11a) and different seed laser wavelengths, with 10 dBm (Fig. 11b), using for each point a Raman pump power 20 mW over power necessary to achieve the Brillouin cascaded threshold power. The maximum and minimum optical spectrum power was also measured for different Raman pump powers with a seed laser at 1538 nm with 10 dBm (Fig. 11c).

For increasing seed laser powers (Fig. 11a), the maximum optical power remains approximately constant (at –45 dBm) for both configurations. The minimum optical power is equal (with –60.5 dBm) for both configurations at 2 dBm but is lower (by approximately 4 dB) for the counter-propagating (with –65.5 dBm) than for the co-propagating (with –61.4 dBm) configuration after 8 dBm. For increasing seed laser wavelengths (Fig. 11b), the maximum optical power remains approximately constant (at –45 dBm) for both configurations but the minimum optical power decreases, being always lower (by approximately 5 dB at 1531 nm and 3 dB at 1544 nm) for the counter-propagating configuration. The best OSNR is achieved with the seed laser at 1544 nm with 21 dB for counter-propagating and 18 dB for co-propagating. However, increasing the seed laser wavelength decreases the wavelength of the comb, resulting in a narrower comb spectrum with fewer lasers. For increasing Raman pump powers (Fig. 11c), the OSNR is observed to decrease for both configurations, being always higher for the counter-propagating.

3. CONCLUSIONS

The counter-propagating configuration was observed to produce a Brillouin-Raman comb fiber laser with a spectrum which had higher stability and flatness, had better (between 3 and 5 dB) OSNR and less noise than the co-propagating configuration with the same parameters. Also, the decrease of the quality of the spectrum due to Rayleigh lasing effects occurred at higher (700 mW) Raman pump powers. The highest optical signal-to-noise ratio (OSNR) and stability and the lowest noise were achieved with lower Raman pump powers, immediately over the threshold, for both configurations.

The necessary Raman pump power to achieve the Brillouin cascaded threshold power was equal for both configurations for seed laser powers over 8 dBm and seed laser wavelengths over 1538 nm. For the counter-propagating configuration, with a seed laser at 1538 nm with 10 dBm and a Raman pump power of 470 mW, a Brillouin-Raman comb between 1538 nm and 1570 nm, with an average optical power 20 dB above the nearby frequencies was generated. The lasers in the comb had an OSNR of 20 dB and a spacing of 0.08 nm. The difference between the form of wider and narrower Brillouin Stokes peaks was also be observed. This type of laser can be used in optical communications as a muitiwavelength source and also in metrology as a frequency ruler.

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