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Multi-wavelength Brillouin–Raman fiber laser generation assisted by multiple four-wave mixing processes in a ring cavity

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Abstract

A multi-wavelength Brillouin–Raman fiber laser (MBRFL) is generated by using a 7.7 km long dispersion compensating fiber which acts as both the Brillouin and Raman gain media. The MBRFL is pumped at 16 dBm with two Raman pumps at 125 mW. Eleven Stokes and anti-Stokes lines are generated with a line spacing of about 0.155 nm (~19.86 GHz) without any forward line reflection. By combining the backward and forward outputs, more lines can be generated, with narrower line spacings of about 0.077 nm (~9.93 GHz). The number of lines can be increased by having higher Brillouin and Raman pump powers. Since Raman amplification can be arranged at any wavelength region, the MBRFL can be obtained at any wavelength as long as all of the equipment and components are prepared in the proposed operational wavelength region.

1. Introduction

Multi-wavelength fiber lasers with constant line spacing have attracted great interest due to their various applications in optical sensors, microwave signal processing systems, optical spectroscopy instruments, high capacity communication networks and metrology systems [1–7]. Multi-wavelength fiber lasers can be obtained by various methods, such as frequency shifted feedback [8], four-wave mixing [9] and non-linear polarization rotation [10]. However, these approaches are complex and more often than not result in unstable lasing wavelengths with large channel spacings, making them unsuitable for the generation of closely spaced multi-wavelength outputs. Alternatively, stimulated Brillouin scattering (SBS) can provide a reliable and low-cost method for the generation of a multi-wavelength fiber laser with a narrow output comb. A multi-wavelength Brillouin fiber laser (MBFL) can easily be designed using a Brillouin Stokes signal as a seed signal [11, 12]. Hybrid designs, which combine SBS with other non-linear optical phenomena such as stimulated Raman scattering (SRS) or with doped fibers such as erbium-doped fibers (EDFs) can also be employed to generate multi-wavelength outputs with higher gains and more lasing wavelengths [13–15]. A disadvantage of the MBFL is that the channel spacing, which is typically 0.08 nm (~10 GHz), is extremely hard to de-multiplex, thus rendering the MBFL unsuitable for practical applications. In order to address this problem, research has now explored the development of MBFLs with channel spacings that approximate double Brillouin shifts using two ring cavities [16–19].

Nevertheless, the generated multi-wavelength fiber lasers suffer from a number of problems. One of them is the existence of a strong Brillouin pump (BP) line between even orders of Brillouin Stokes signals producing BFL lines. As a physical fact, a BFL is a highly coherent light source, which has a linewidth much narrower than the linewidth of the BP [20]. Another issue is the reflection of the even-order Brillouin Stokes signals, which appear in between each two consecutive odd-order lines of the output spectrum; this is due to the reflection in the optical couplers. On top of these, the noise level is also high as reported.

As an improvement with respect to these issues, an MBRFL with an odd Brillouin Stokes line spacing of 0.155 nm without any effective noise, which is due to the reflections of the BP and the even Stokes lines, is proposed in this paper using a simple ring cavity.

2. Experimental set up

The proposed configuration of the MBRFL generation is shown in figure 1. The elements of the cavity consist of one optical coupler (C), an optical circulator (OC), two wavelength division multiplexing (WDM) couplers and a 7.7 km dispersion compensating fiber (DCF) which acts as both Brillouin and Raman gain media. The DCF has a dispersion of −584 ps nm^{-1} and an attenuation loss of 1.5 dB km^{-1} at 1530 nm. This fiber can also be pumped bi-directionally through the WDM couplers by using the two laser diodes (LDs) which act as Raman pumps with a total pump power of about 250 mW at a wavelength of 1430 nm. The Brillouin pump (BP) is an external-cavity tunable laser source (TLS) with the output wavelength set at 1530 nm, with a linewidth of approximately 20 MHz. This is then amplified by an erbium-doped fiber amplifier (EDFA) so as to provide a seed signal with a peak power of 16 dBm. The BP is injected in the clockwise direction into the DCF from port 1 to port 2 of the optical circulator (OC) which is connected to a WDM coupler so as to generate the first Brillouin Stokes signal. When the BP power exceeds the first stimulated Brillouin Stokes (SBS) threshold power, the first Stokes signal propagates in a counter-clockwise direction, travels back to port 2 and then is emitted at port 3. The signal will then travel around the loop and back to the DCF via the second WDM. This first Stokes signal can also act as a BP and generate the second Brillouin Stokes signal which will then propagate in the clockwise direction.

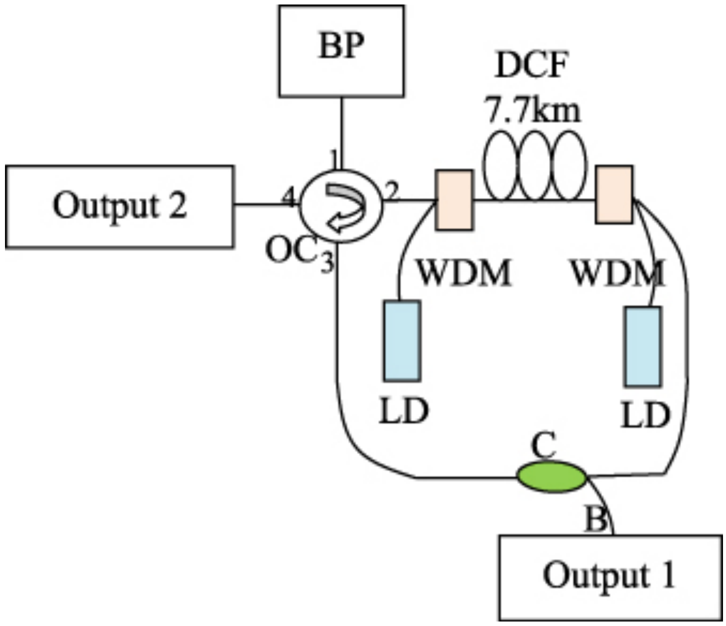

Figure 1. The proposed experimental setup for the MBRFL.

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Generally, when the *N*th Brillouin Stokes signal reaches its threshold power, while at the same time acting as a Brillouin pump, it will then create the ($N + 1$)th Brillouin Stokes signal, which will propagate in the opposite direction. This process is known as cascaded SBS. Finally, all the odd-order Stokes waves oscillate in the counter-clockwise direction in the cavity whereas the BP and all the created even-order Stokes waves, which exit from ports 3 to 4 of the OC, will appear at output 2. Although there is no cavity for the oscillation of the even-order Brillouin Stokes signal, the Raman amplification provides enough threshold power for an even Stokes wave to create the next-order odd Stokes wave [21]. The coupler at port B extracts the output spectrum of the odd-order Brillouin Stokes signal that is generated from the proposed MBRFL at output 1, which is detected with an optical spectrum analyzer (OSA) having a resolution of 0.02 nm.

3. Results and discussion

Figure 2 shows the generated MBRFL as observed in the backward and forward directions, taken at outputs 1 and 2 respectively. The traces are taken with the BP at 16 dBm and pumped with two Raman pumps at 250 mW with the output wavelength at 1430 nm. As long as the threshold condition is satisfied, the cascaded SBS will be generated; this will largely depend on the Raman pump power. From the figure, the even- and odd-order Stokes lines have a line spacing of about 0.155 nm between them. The first Brillouin Stokes line is down-shifted in frequency by the Brillouin shift ω_B($\omega_{1S} = \omega_P - \omega_B$). Then, due to the degenerate four-wave mixing (FWM), the first anti-Stokes wave is created at the frequency $\omega_{1AS} = 2\omega_P - \omega_{1S} = \omega_P + \omega_B$. Once the BP power exceeds the SBS threshold power condition, the first Brillouin Stokes wave working as a BP creates the second Stokes wave at the frequency $\omega_{2S} = \omega_{1S} - \omega_B = \omega_P - 2\omega_B$. The second anti-Stokes wave is also created at the frequency $\omega_{2AS} = 2\omega_P - \omega_{2S} = \omega_P + 2\omega_B$ due to the degenerate FWM between the BP wave and the second Stokes wave. The cascaded SBS process continues as long as the SBS threshold condition is satisfied, so that the *N*th Stokes and anti-Stokes waves are generated at the frequencies given by $\omega_{NS} = \omega_P - N\omega_B$ and

$\omega_{NAS} = \omega_P + N\omega_B$ respectively. In addition, the non-degenerate FWM process between the lines causes some small variations in the peak power.

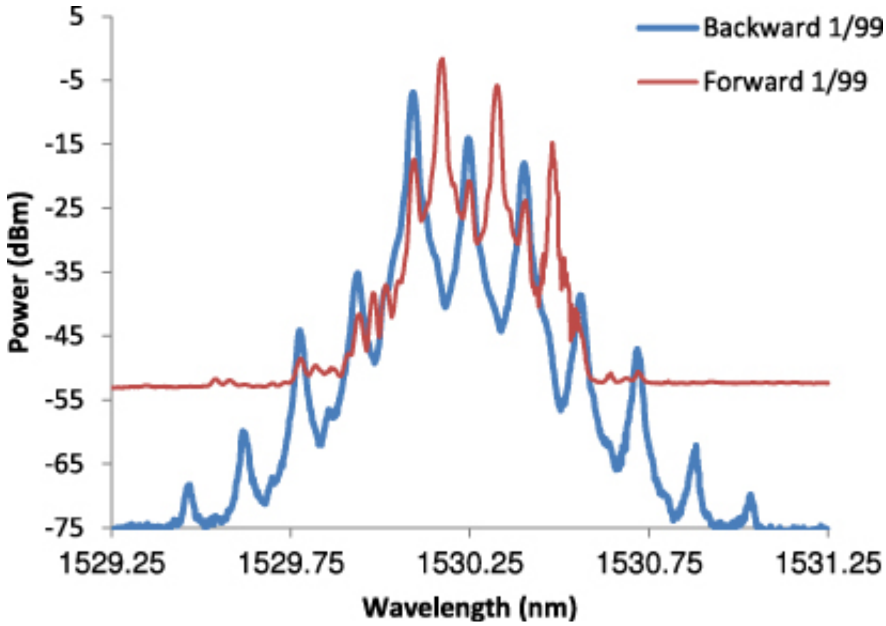

Figure 2. The generated Brillouin Stokes waves in the forward and backward directions obtained by using a coupler ratio of 1/99.

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Since the coupler ratio before output 1 is 1/99, the loss against the output spectrum is about 20 dB with respect to output 2, which is indicated in figure 2, where the odd Brillouin Stokes trace from output 1 has a much lower base line as compared to output 2, which is due to the 1% output port of the coupler. In analyzing the MBRFL generation, the threshold power of each line needs to be determined. The SBS threshold power, P_{SBS}, is defined as the input BP power at which the reflected BP peak power equals that of the output peak power of the Stokes lines; this has been clearly explained in [22]. Since each line works as a BP, which is then used to generate the next Brillouin Stokes line, as in the case of cascaded SBS generation, each line has its own threshold power. For example, the second Brillouin Stokes line threshold power can be obtained from the intersection of the second Brillouin Stokes line and the reflection of the first Stokes line peak powers in the forward direction, as depicted in figure 3. The threshold powers are measured to be about 3.65 dBm and 13.68 dBm of the BP power for the first and the second Brillouin Stokes lines, respectively, when the Raman pump power is off. The creation of SBS for the second Stokes line at the expense of the BP power is evident. Therefore, there is a power exchange between the lines due to the cross-talk process.

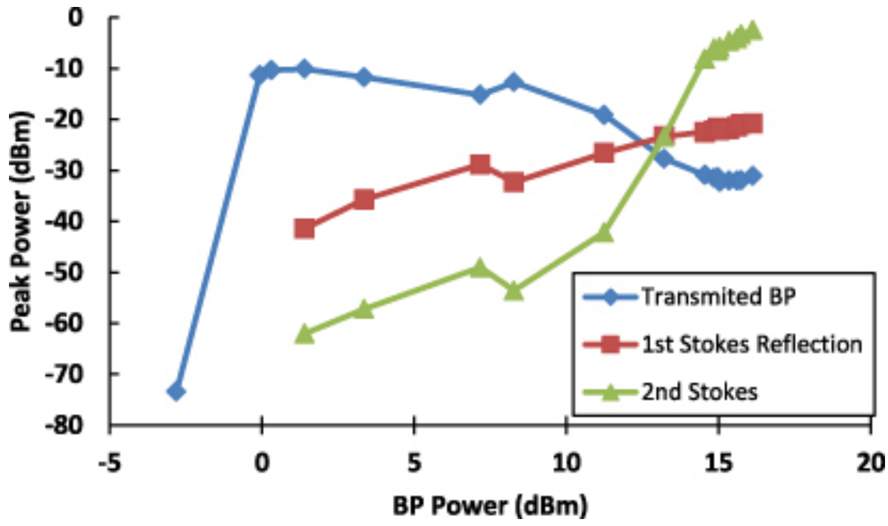

Figure 3. The threshold power of the second Stokes line can be obtained from the intersection of the second Stokes (triangle) and the first Stokes reflection (square) lines.

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Finally, all the other Stokes lines can be created by using Raman amplification and the DCF which acts as a Raman gain medium. Figures 4(a) and (b) show all the Stokes lines generated by increasing the Raman pump (RP) power measured in the forward and backward directions, respectively for the even- and odd-order Stokes lines. The BP is also fixed at its maximum power at 16 dBm and the RP power is increased gradually. The decibel units of the Raman pumps are chosen for comparison purposes.

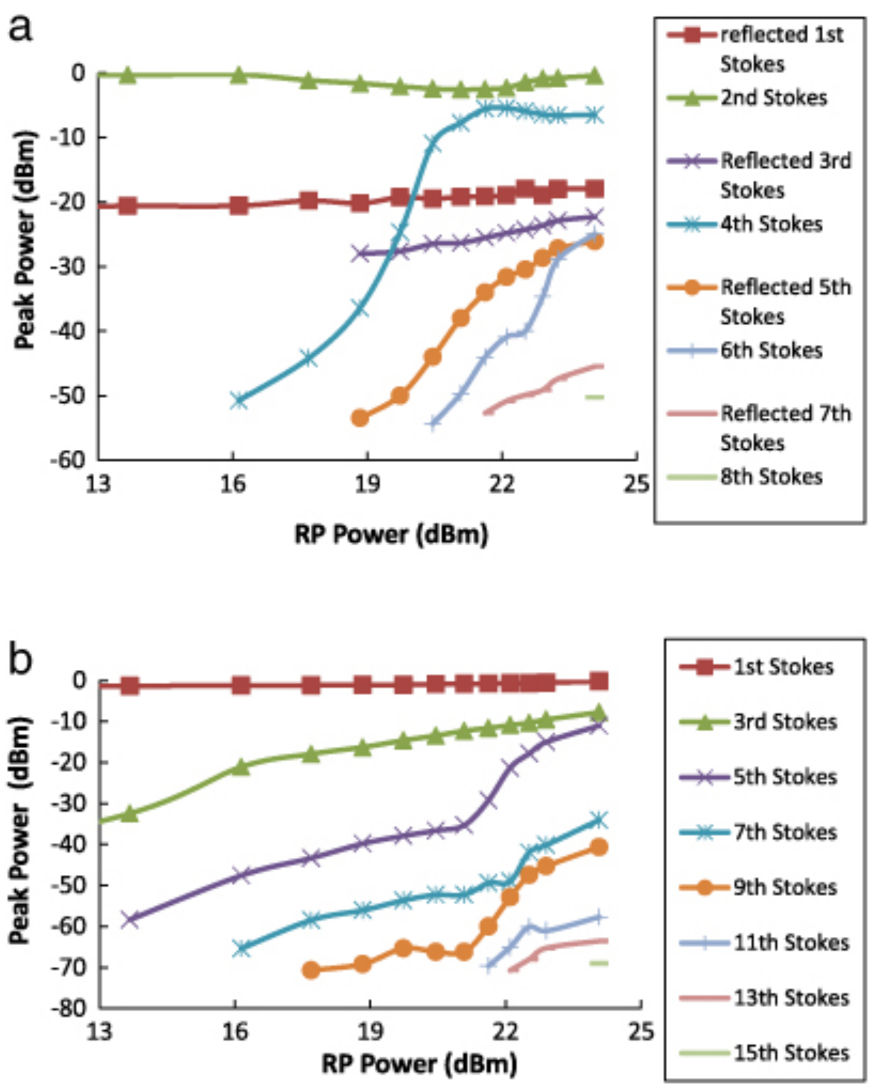

Figure 4. The development of lines in (a) the forward and (b) the backward directions by increasing the RP power so as to create the even- and odd-order Stokes lines respectively.

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From figure 4(a), the threshold power of the fourth Stokes line can be calculated to be around 19.72 dBm, which is the intersection of the fourth Stokes and reflected third Stokes peak power lines. However, since there is no reflection of the even Stokes lines in the backward direction, it can be inferred from figure 4(b) that the third and fifth Stokes threshold powers must be about 13.67 dBm and 21.62 dBm respectively where the lines rise rapidly before saturation. In addition, the line spacing in the DCF is about 0.155 nm, which is the typical line spacing for SBS based multi-wavelength sources using silica fibers. There could be some slight variations though, depending on the composition of the silica glass as well as different manufacturing materials and specifications. From figures 4(a) and (b), it is also confirmed that by increasing the pump power, other Stokes lines can also be generated as long as the threshold power is exceeded. Since there is no reflection of the BP and the even Stokes lines in the backward direction, the optical signal-to-noise ratio (OSNR) is also improved in the backward direction as compared to the values that have been reported in previous works [16–19].

4. Conclusion

An MBRFL with a double line spacing of 0.155 nm generated in a single ring cavity is proposed and demonstrated. The proposed MBRFL can act as a highly coherent light source, with the reported line width measured as about a few Hertz, and a very efficient source for Stokes line generation. The output has a high OSNR value for the odd-order Stokes lines generated, as the proposed design is able to eliminate the reflection of the BP as well as the even Stokes lines.

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