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دینامیک لیزر فیبری چند طول موجی بریلوئین-رآمان در تقویت با فرآیندهای ترکیب چهار-موج در یک کاواک حلقوی

محمدرضا رضازاده شیرازی

کرمان، دانشگاه آزاد اسلامی واحد کرمان، بخش فیزیک

چکیده-دینامیک لیزر فیبری چند طول موجی بریلوئین-رآمان در تقویت ترکیب چهار موج از طریق نمو خطوط استوکس و آنتی استوکس با ترکیب گوناگون پمپهای بریلوئین و رآمان و طرحهای گوناگون پمپاژ رآمان در یک کاواک حلقوی بررسی شده است. بدلیل ترکیب چهار موج تبهگن، توان آستانه یک خط استوکس با مرتبه بالاتر از 3 کمتر از توان اشباع خط استوکس قبل از آن پدیدار می شود.جالب آنکه ترازهای توان آنتی استوکس مرتبه*(n)* واستوکس مرتبه*(n+4)* بطور غیر منتظره ای تقریبا" یکسان افزایش می یابند.

کلید واژه- پراکندگی بر انگیخته بریلوئین، لیزرهای فیبری، اپتیک غیر خطی.

Dynamics of multi-wavelength Brillouin-Raman fiber laser assisted by multiple four-wave mixing processes in a ring cavity

M.R Shirazi

Physics Department, Kerman Branch, Islamic Azad University, Kerman, Iran

Abstract- Dynamics of a multi-wavelength Brillouin-Raman fiber laser (MBRFL) assisted by four-wave mixing has been investigated through the development of Stokes and anti-Stokes lines under different combinations of Brillouin and Raman pump power levels and different Raman pumping schemes in a ring cavity. The threshold power of a Stokes line of order higher than 3 has appeared sooner than the saturation power of the last Stokes line due to degenerate FWM processes involved in the MBRFL generation. It is interesting to note that the n^{th} order anti-Stokes and $(n+4)^{th}$ order Stokes power levels increased unexpectedly almost the same before the Stokes wave reached at its threshold power.

Keywords: Stimulated Brillouin Scattering, Fiber lasers, Nonlinear Optics.

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Dynamics of Multi-wavelength Brillouin-Raman Fiber Laser Assisted by Multiple Four-Wave Mixing Processes in a Ring Cavity

M. R. Shirazi
Physics Department, Kerman Branch, Islamic Azad University, Kerman, Iran
behshirazi@yahoo.com

1 Introduction

Stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) are important nonlinear inelastic scattering processes that can occur in optical fibers [1]. Since the peak value of Raman gain is typically much less than that of the Brillouin gain, the threshold power level for SRS is typically much higher than the SBS threshold power level. SRS is therefore relatively harmless, by comparison with SBS, for applications such as multi-wavelength Brillouin fiber lasers (MBFLs) [2]. SRS can be applied to produce Raman amplification [3]. Raman amplifiers can be used to increase the number of Brillouin Stokes lines in multi-wavelength Brillouin Raman fiber laser (MBRFL) generation [4]. Although both SRS and SBS are the third-order nonlinear optical effects, SBS suppression and, at the same time, an increase in Raman amplification are also achieved by utilizing a longitudinally varying core fiber [5]. The issue of SBS effects on Raman amplification, MBRFL, and Raman gain has also been recently of interest [6,7,8]. In a recent paper, we have generated a MBRFL assisted by four-wave mixing (FWM) processes in a ring cavity [9].

In the present work, dynamics of the earlier generated MBRFL has been experimentally analyzed along with additional results, and described in order to achieve a thorough understanding of the interesting physical relations revealed among lines of the MBRFL and the measured parameters. The development of Stokes and anti-Stokes lines has been described in detail and the threshold and the saturation power levels of Stokes lines have been measured.

2 Experimental setup

The experimental set-up for the generation of the MBRFL is shown in Fig. 1. Our available dispersion compensating fiber (DCF) with a mode effective area, A_{eff} of 15 μm^2, was used to provide simultaneously high Brillouin and Raman gains compared with other fibers. The attenuation coefficient, α, of the DCF of length L=7.7 km was about 0.13 km^{-1} (0.58 dB/km) at 1530 nm, together with a dispersion value of -584 ps/nm. By using the effective interaction length, $L_{eff} = [1-\exp(-\alpha L)]/\alpha = 4.86\,\text{km}$, and the Brillouin gain coefficient, $g_B = 5\times10^{-11}$ m/W, the Brillouin threshold power was found to occur at the critical pump power $P_{cr} \approx 21\cdot A_{eff}/(g_B \cdot L_{eff}) \approx 1.3\,\text{mW}$, therefore, SBS was detected to be the dominant nonlinear process in the DCF [1]. An external-cavity tunable-laser source amplified by an erbium doped fiber amplifier was used as a Brillouin pump (BP) - with a maximum pump power level of 15.8 dBm at a wavelength 1530 nm and a linewidth of about 20 MHz. These two parameters, BP power and BP linewidth, are two effective factors in cascaded SBS processes in MBFL systems [2]. The DCF could also be pumped by two laser diodes (LDs) through two wavelength division multiplexing (WDM) couplers from both ends, so as to provide Raman gain. In this case, the LDs were designated as Raman pumps (RPs) at a wavelength of 1430 nm, with a combined maximum total power of 24.1 dBm (257 mW). When the BP was injected into the DCF through both Port 1 and Port 2 of the optical circulator (OC) and then the (WDM1) coupler, the first Brillouin Stokes wave was created - via spontaneous Brillouin scattering propagating backwardly through Port 2 into Port 3 of the OC. This first Stokes line, which was due to the spontaneous Brillouin scattering, then returned to the other end of the DCF through the optical coupler (C) and (WDM2) in a counter-clockwise direction (backward). When the BP level reached the 1st Stokes SBS threshold power, the generated first Stokes oscillated in the ring cavity through the DCF, which acted as the Brillouin gain medium. The first Stokes signal was able to generate the second Brillouin Stokes line which propagated in a clockwise direction (forward) and the same process could be repeated. The Nth Stokes line is generated

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at the frequency $\omega_{NS} = \omega_{BP} - N\Omega_B$ where Ω_B is the Brillouin shift in the DCF.

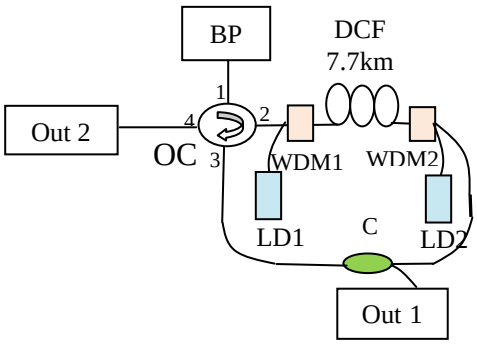


Figure 1: The proposed experimental setup for the MBRFL generation.

3. Results and discussion

When the Raman pump power is set in the 'Off' state, generation of a multi-wavelength output (i.e. MBFL operation) is obtained simply by injecting the BP into the ring cavity. By increasing the BP power level, all of the even-and odd-order Stokes lines can be generated as shown in Figs. 2 (a) and 2(b), respectively [9]. It can also be deduced that there is a Brillouin shift of about 0.0775 nm, due to SBS in the used DCF. At the maximum BP power level of 15.8 dBm, the 1st and 3rd Stokes lines are generated in the backward direction - whereas only the 2nd Stokes line is obtained in the forward direction when the Raman pumps (RPs) are in the 'Off' state. The anti-Stokes lines are also generated - due to a degenerate four-wave mixing processes between the BP line and the Stokes lines. By using Raman amplification, the other even and odd order Stokes and anti-Stokes lines are created as shown in Figs. 2(a) and 2(b), respectively. As a result, MBRFL sources with the double Brillouin-shift line-spacing of 0.155 nm are generated in the backward and forward direction. Since the BP travels in the forward direction, Rayleigh scattering of the BP can be observed in Fig. 2(b). Moreover, Rayleigh scattering of odd-order Stokes waves appears in the forward direction between even-order Stokes waves, whereas there is negligible Rayleigh scattering for even-order Stokes waves in the backward direction. This is due to the fact that the circulation of the odd-order Stokes waves in the backward direction in the ring cavity creates the Rayleigh scattering that appears in the forward direction; however, there is no cavity for circulation of the even Stokes lines in the forward direction. It should also be noted that MBRFL action in the forward direction can originate only from randomly distributed feedback Brillouin Raman fiber laser action [10]. In addition, the loss against the output spectrum at the Out-2 port is about 20 dB higher than that at the Out-1 port due to the use of an output coupler ratio of 1/99. In order to investigate quantitatively the dynamics of the MBRFL operation, it is important to find out the power level of each Stokes line as a function of the BP power, both with and without RP power injection. When the total RP power is fixed at approximately 22.1 dBm (163 mW) in bi-directional Raman amplification scheme, power levels of the Stokes lines against different BP power levels are depicted in Fig. 3. We use the definition of the SBS threshold power as the BP power level at which SBS power level is at the level of Rayleigh back-scattering power [2].

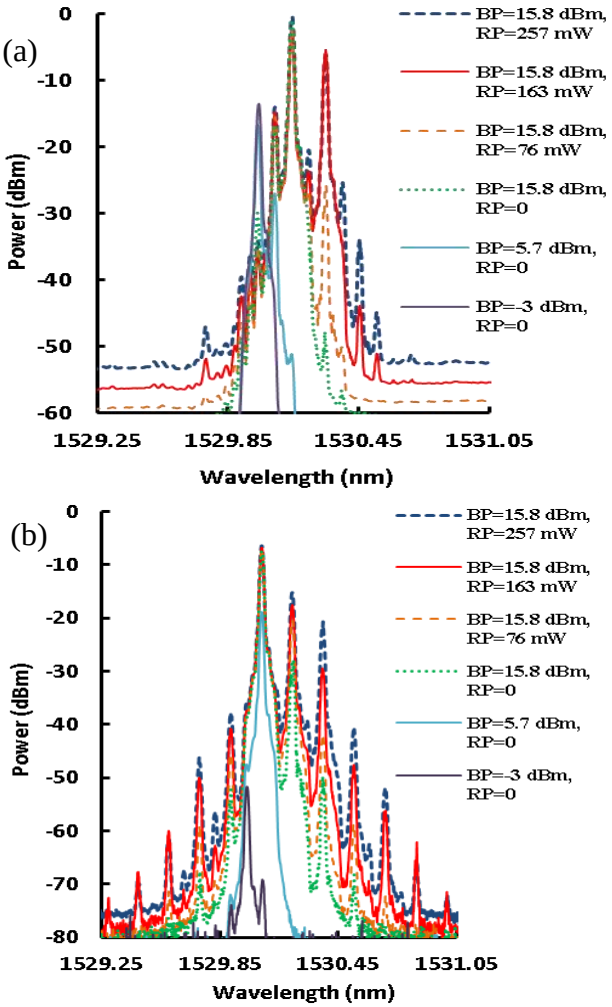


Figure 2: MBFL and MBRFL generation with double Brillouin shift line spacing of 0.157 nm in a) forward (Out-1) and b) backward direction (Out-2). Rayleigh scattering of odd-order Stokes lines appear between even-order Stokes lines at forward direction.

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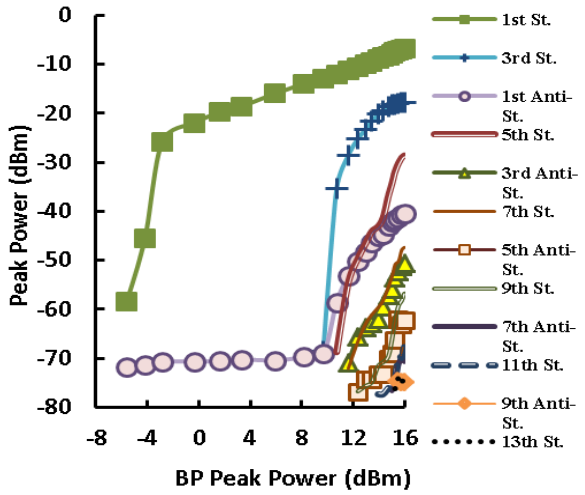


Figure 3: Interesting dynamics of the odd Stokes and anti-Stokes lines in MBRFL generation detected at backward direction (Out-2) when DCF is pumped bi-directionally at the total RP power 22.1 dBm (163 mW).

The threshold power of a Stokes line with an order higher than 3 is less than the saturation power of its last Stokes line. For example, the threshold power of the 4^{th} and 5^{th} Stokes lines, 13.89 and 14.32 dBm, are lower than the BP power of 14.72 and 15.04 dBm at which the 3^{rd} and 4^{th} Stokes lines start to saturate, respectively. Another important observation of this work is that, the n^{th} order anti-Stokes and the $(n+4)^{th}$ order Stokes lines, unexpectedly have nearly the same power level before the Stokes line reaches its threshold power [11]. According to the best of author's knowledge, this is a new issue which is left here for a theoretical research in the future.

4. Conclusion

In this work, multi-wavelength Brillouin Raman fiber laser assisted by four-wave mixing processes is demonstrated and investigated. It is interesting to note that the nth anti-Stokes wave and (n+4)th order Stokes waves behave surprisingly almost the same and their powers increases similarly before the threshold power of the Stokes wave is achieved. In addition, the threshold power of a Stokes line of order higher than three is less than the saturation power of its last Stokes line due to degenerate FWM processes.

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