Single-wavelength ring-cavity fiber laser employed pre-amplification technique to reduce threshold by circulating spontaneous brillouin scattering

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Article Info

ABSTRACT

In this paper, two types of ring-cavity fiber laser structures that operate as a single wavelength laser were investigated on the threshold performance. The two structures are namely Brillouin fiber laser and Brillouin erbium fiber laser. In the first structure, the Brillouin pump signal was amplified before being injected into the laser cavity which namely as Brillouin fiber laser. Meanwhile, for second structure respectively, the Brillouin pump signal was pre-amplified in the laser cavity which namely as Brillouin Erbium fiber laser. We found that the stimulated Brillouin scattering threshold power was lowered significantly by circulating the spontaneous Brillouin scattering in the gain medium utilizing the pre-amplification technique. The optimum stimulated Brillouin scattering threshold power was about 1.4 mW, and this was achieved at optimum output coupling ratio of 95%. By comparing to the first structure in which the Brillouin pump signal was amplified before entering the laser cavity, stimulated Brillouin scattering threshold power was only achieved at 2.62 mW at a similar wavelength. The pre-amplification technique proposed in this paper has been shown to improve the performance of single-wavelength ring-cavity fiber lasers via significant reduction of the stimulated Brillouin scattering threshold power which was around 1.22 mW.

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1.   INTRODUCTION

Stimulated Brillouin scattering (SBS) is the attractive nonlinear effects in optical fibers that noticeable over the generation of backward propagating optical waves [1]. The counter-propagating optical waves, typically designate as Stokes waves or Brillouin Stokes (BS) signal, emerges when the injected input signal power achieves a particular value named as Brillouin threshold. Consequently, above the threshold condition, SBS creates a downshifted frequency Stokes wave from an input pump signal through the nonlinear medium. As a result, the energy rapidly transfer from input pump signal to a Stokes wave. The input pump signal is downshifted in frequency is attributed to the Doppler shift related with grating moving at acoustic velocity [2]. For a standard silica single-mode fiber (SMF), the BS signal is found to be experience a frequency downshift of by about 10 GHz [3].

SBS in an optical fiber has been useful in a number of applications. It has been used in optical fiber characterization [4], interferometric and distributed sensors [5], optical frequency metrology [6], narrow-bandwidth application and perhaps most interest in SBS has arisen from the use of Brillouin gain generation in producing fiber laser with single [7] or multiple [8-9] wavelengths. In using SBS to create fiber laser, achieving a lower threshold value is one of the main important parameters of the fiber laser system [10]. Researchers have demonstrated significant interest in reducing Brillouin threshold in optical fibers. A method of Brillouin threshold reduction in photonic crystal fiber has been reported [11]. Other schemes that employed Stokes noise initiation that reduce the SBS establishing time, thereby reducing the Brillouin threshold has been reported [12]. However, most of the reported schemes for Brillouin threshold reduction utilized structures that add to the difficulty of the experimental setups. Brillouin threshold reduction through pump recycling technique has been reported in [13]. In this particular work, the experimental set up is not complex. However, the linear cavity did not allow for freedom of choice of the percentage amount of light to be released from the cavity.

In this paper, two structures of single-wavelength ring-cavity assisted by Erbium gain were proposed and investigated for the Brillouin threshold power reduction. In the first structure, the Brillouin pump (BP) signal was amplified before being injected into the laser cavity. In the second structure, the BP power was pre-amplified inside the laser cavity. Both of these structures demonstrate a simple method to produce the Brillouin threshold power by circulating the spontaneous Brillouin scattering from an 11 km long dispersion compensating fiber (DCF) in the ring cavity structure. For the second structure which BEFL, the Brillouin threshold power reduction around 0.1 mW, 0.2 mW, 0.7 mW, 0.9 mW, 0.98 mW and 1.15 mW and 1.22 mW were recorded at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 95%.

2. EXPERIMENTAL SETUP

The two structures of single-wavelength ring-cavity Brillouin fiber laser (BFL) assisted by erbium gain were depicted in Figure 1. BP signal amplification structure was presented in Figure 1(a) where the BP signal was amplified prior to been injected into the ring cavity. Meanwhile, the structure of the ring cavity Brillouin erbium-doped fiber laser (BEFL) with BP signal pre-amplification technique was depicted in Figure 1 (b). The erbium-doped fiber amplifier (EDFA) was placed inside the laser cavity thereby amplifying the BP signal before being propagated into the Brillouin gain medium. Dispersion compensation Fiber (DCF), with the specification of 8.18 dB total insertion loss, an effective area of 20 μm2 and the nonlinear coefficient of 7.3 (W.km)-1, was used as a low-threshold highly nonlinear Brillouin gain medium. In both structures, an external tunable laser source (TLS) with output maximum power of 3 mW was employed as the source of the BP signal. The EDFA gain block comprises of 8 meters erbium doped fiber (EDF), a wavelength division multiplex (WDM) coupler and pumped by 1480 nm laser pump.

The WDM coupler was used to multiplex the BP signal and the 1480 nm laser pump signals. The EDFA gain block was principally employed to amplify the low power BP signal. The 3-port optical circulator was utilized in both structures to provide a unidirectional path for both the BP signal and the generated backward propagating BS signals. Also, in both structures, the variable optical coupler was utilized so as to extract the laser's output and be monitored through the optical spectrum analyzer (OSA). The variable coupler provides a means of controlling the ratio of the amount of light directed to the OSA for monitoring and measurements. As can be seen from Figure 1, the EDFA was placed at two different locations which are outside ring cavity and in the ring cavity (BP pre-amplification technique) as depicted in Figure 1 (a) and Figure 1 (b) respectively. The BP signal enters the circulator through port-1. The BP signal afterward be directed into the DCF through port-2 of the circulator. SBS would be initiated once the input power surpasses the threshold power of the DCF. Consequently the input signal generate a Brillouin gain in the DCF. This condition generate the first order BS signal, which was propagate in the opposite direction to the propagation direction of the BP signal.

Thus, the BS signal enters the circulator through its port-2 and be guided to the OSA through port-3 of the circulator and the variable coupler. The OSA with resolution bandwidth of 0.015 nm was used for monitoring, observations and measurement.
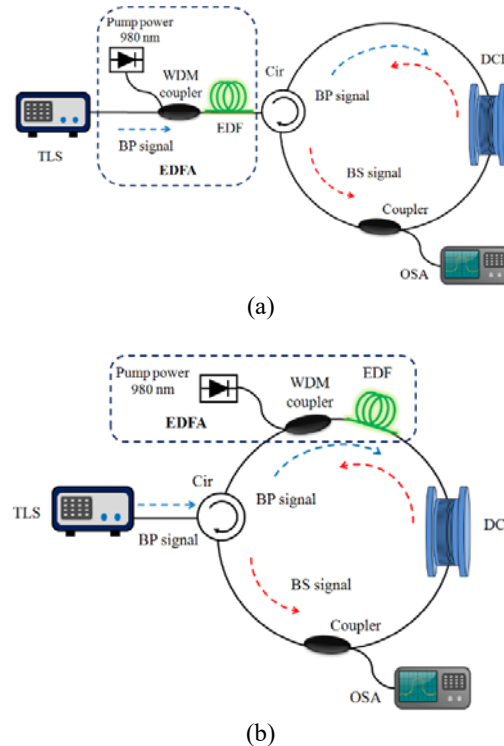
(a)

(b)

Figure 1. Structure of the single-wavelength fiber laser with two location of EDFA: (a) BFL in which EDFA was located outside ring-cavity and (b) BEFL in which EDFA was situated in the ring-cavity

3. RESULTS AND DISCUSSION

In order to compare the output signal characteristics of the two proposed structures, the spectrum in Figure. 2 was plotted. It shows the output spectra at 1550 nm wavelength of BP signal while 1.5 mW of BP power was injected. Meanwhile, the output spectrum was extracted at 50% of output coupling ratio. It was clearly observable that BFL and BEFL are capable of generating BS signals with 0.08 nm spacing. The BFL spectrum shown in Figure 2 has lower peak power (below threshold) in comparison with the peak power (above threshold) of BS signal for BEFL spectrum, which are formed by the stronger Brillouin scattering effect. At the same BP power, the BS signal that was generated from BEFL acquires extremely higher gain which about 47 dB.
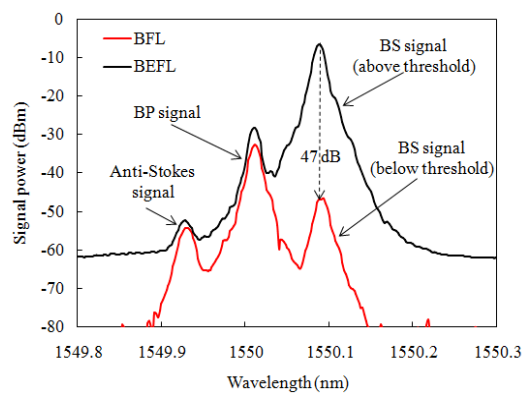

Figure 2. The BFL and BEFL spectrum at 1550 nm wavelength of BP signals while 1.5 mW of BP power was injected and output coupling ratio of 50%

Next, to study the Brillouin threshold power in the two proposed structures, the amplified BP power was varied from minimum value of 0 mW to the maximum value of 3 mW. Mwanwhile, the BP wavelength was fixed at 1550 nm when the first BS signal appears. The Brillouin threshold power was obtained when the BP power exceeded a critical value, and most of it was converted into BS power as depicted in Figure 3. The BS power against the BP power at output coupling ratio of 20%, 50%, 80% and 90% were plotted in Figure. 3 (a) to 3 (d). In all values of output coupling ratios, ring cavity BEFL with pre-implication technique was able to reduce threshold power. For both techniques, the BS signal occurred in opposite direction from injected BP signals and circulated in the ring cavity. A weak BS signal with low peak power already appears at lower BP power of 0.06 mW. In order to produce Brillouin threshold power in both structures, BP power was increased from 0.06 mW to the value where it was strong enough to generate a high intensity BS power. Once the threshold condition was satisfied, the first BS signal was backscattered with 0.08 nm spacing through SBS and Brillouin gain was created in the DCF. To understand the theory of the Brillouin gain, the interactions between BP signal intensity (Ip) and the BS signal intensity (Is) in the process of SBS in the gain medium was described by two coupled Equations in 1 and 2 [2], [14] as follows:

$$\frac{dP_p}{dz} = -\frac{\omega_p}{\omega_s} g_B I_p I_s - \alpha I_s \qquad (1)$$

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha I_s \qquad (2)$$

Where α was fiber loss for the gain medium and are nearly the same for the BP and Stokes waves for Equation 1. Meanwhile $\omega_p \approx \omega_s$ owing to the relatively small value of the Brillouin shift for Equation 2. Ip and Is are the intensity of BP and BS signal respectively, and gB was the Brillouin gain coefficient. By referring to the Figure. 3 (a) to 3 (d), ring-cavity BEFL structure produces lower Brillouin threshold power in comparison with the ring cavity BFL structure, which formed by the pre-amplification technique where the EDFA was placed inside the laser cavity. In this case, the SBS was originated by the spontaneous Brillouin scattering signal, by the amplified BP signal before entering the DCF and circulated spontaneous Brillouin scattering. Therefore, more SBS emissions can become initiated to reduce the Brillouin threshold power. The Brillouin threshold power of 1.0 mW, 1.0 mW, 1.1 mW and 1.3 mW were produced at 20%, 50%, 80% and 90% of output coupling ratio, respectively. Afterward, when the threshold condition was satisfied, the BS signal power increases with increasing BP power with linearity increment. Otherwise, ring cavity BFL structure where the EDFA was placed out of the laser cavity produced 1.2 mW, 2.0 mW, 2.1 mW and 2.45 mW of Brillouin threshold power which significantly higher than ring cavity BEFL structure. This condition was due to the additional energies provided by the circulated BP signal that has the ability to initiate more SBS emission and additional amplification for BS signal. For clarification, output optical spectra of the BS signal by varying BP power at output coupling ratio of 50% for BFL and BEFL structure were illustrated in Figure 4 (a) and Figure 4(b), respectively.These optical spectra show the characteristic of the BS signals, below and above the Brillouin threshold condition. In this case, Brillouin threshold can be explained as the input pump power at which the backscattered power initiates to increase rapidly or equivalently the BP powers begins to be depleted [15]. Furthermore, the Brillouin threshold power was written as [16],

$$P_{th} \cong 21bA_{eff} \, / \, g_B L_{eff} \qquad (3)$$

Where, L_{eff} is the effective length of interaction and A_{eff} is the effective core of the fiber. Meanwhile, g_B is the peak value of the Brillouin gain. For this Equation in 3 the numerical factor of 21 is only estimated as it according on the explicit value of Brillouin gain linewidth. Furthermore, the polarization factor b lies among 1 and 2 depending on relative polarization of pump signal and Stokes waves [17].
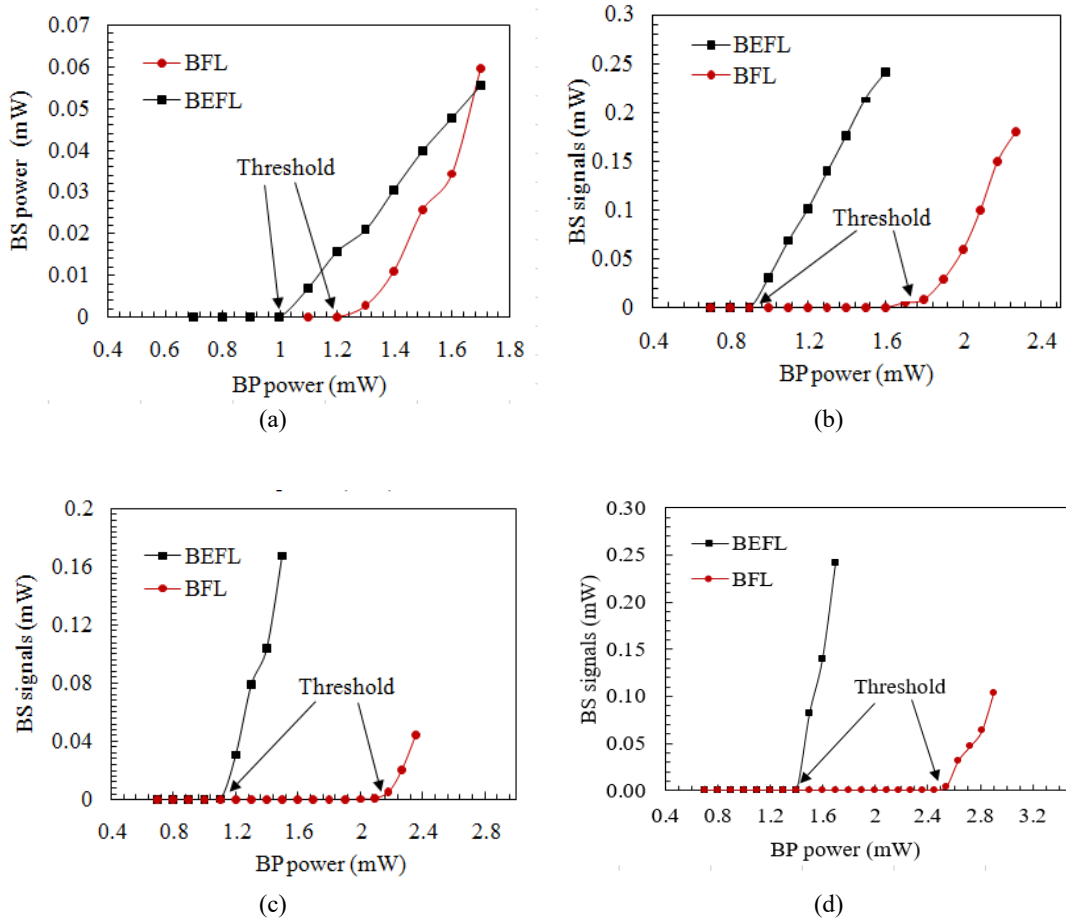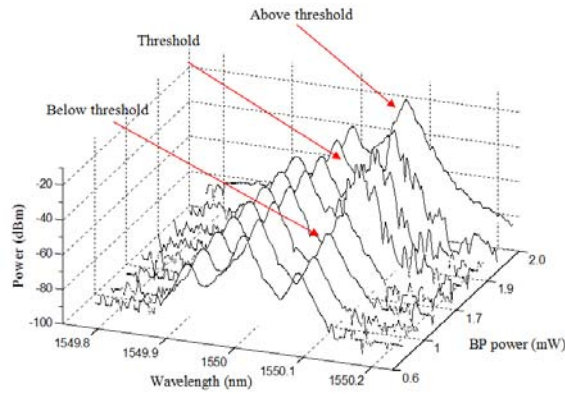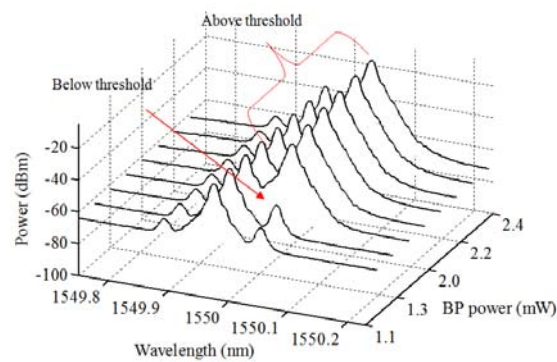
Figure 3. The Brillouin threshold for BFL and BEFL at different output coupling ratio. (a). 20 % of output coupling ratio, (b). 50% of output coupling ratio, (c) 80 % of output coupling ratio and 90% of output coupling ratio

The relation between the Brillouin threshold power for both structures and the Brillouin threshold power reduction was demonstrated and plotted in Figure 5. In this study, output coupling ratio increased from a minimum value of 10% to the maximum value of 95%. In both structures, it shows that, as output coupling ratio was increased, the Brillouin threshold power also increased significantly. This condition can be due to the higher light intensities that oscillated in the ring-cavity and resulted in a reduction of the Brillouin threshold power. The minimum power of Brillouin threshold at 0.8 mW and 0.9 mW was achieved at output coupling ratio of 10% for BEFL and BFL structures, respectively. Meanwhile, the maximum power of Brillouin threshold at 1.4 mW and 2.62 mW was produced at output coupling ratio of 95% for BEFL and BFL structures, respectively. As depicted in Figure 5, the graph of threshold power reduction against the output coupling ratio was plotted. Meanwhile, the increment of the output coupling ratio from 10% to 95% led to increases the differential of Brillouin threshold power reduction between BEFL and BFL. As evidently seen in Figure 5, the higher Brillouin threshold power reduction for BEFL was recorded at 95% of output coupling ratio of output coupling ratio which around 1.22 mW. This indicates that the Brillouin threshold power for BEFL has reduced by 46.95%, compared to the BFL. From previous paper, the optimum coupling efficiency was recorded at 95% [7]. The Brillouin threshold power reduction around 0.1 mW, 0.2 mW, 0.7 mW, 0.9 mW, 0.98 mW and 1.15 mW and 1.22 mW were recorded at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 95% of output coupling ratio.

(a)

(b)

Figure 4. Output optical spectra with varying BP power at output coupling ratio of 50% for (a). BFL and (b) BEFL
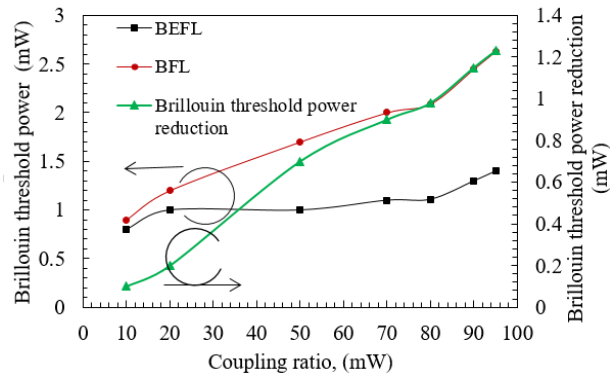

Figure 5. Brillouin threshold power for BFL, Brillouin threshold power for BEFL and Brillouin threshold power reduction between BEFL and BFL

4.   CONCLUSION

A pre-amplification technique proposed in this paper has been shown to improve the performance of single-wavelength ring-cavity fiber lasers via significant reduction of the Brillouin threshold power. The scheme used was applied to two types of ring-cavity fiber laser; BFL and BEFL. The BFL has the Brillouin pump signal amplified before being injected into the laser cavity, while in the BEFL, the Brillouin pump signal was amplified in the laser cavity. The highest Brillouin threshold power reduction for BEFL was

recorded at 95% of output coupling ratio which around 1.22 mW. This indicates that the Brillouin threshold power for BEFL has reduced by 46.95% compared to the BFL. In contrast, Brillouin threshold power only achieved at 2.62 mW at the similar wavelength, when BP signal was amplified before entering the laser cavity. The results presented in this paper, have clearly shown that the proposed laser structure produces a low threshold power of 1.4 mW via a simple and innovative scheme, by amplifying Brillouin pump signal in the laser cavity

REFERENCES

[1] L. Ji, H. Lee, and K. J. Vahala, Low-noise Brillouin laser on a chip at 1064 nm, Optic. Lett. 39 (2014) 287-290.
[2] G. P. Agrawal, Nonlinear Fiber Optics. Forth ed. 2004, New York: Academic Press. 466.
[3] D. Cotter, Stimulated Brillouin scattering in monomode optical fiber, J. Opt. Commun. 4 (1983) 10-19.
[4] J. C. Beugnot, T. Sylvestre, D. Alasia, H. Maillotte, V. Laude, A. Monteville, L. Provino, N. Traynor, S. Foaleng Mafang, and L. Thévenaz, Complete experimental characterization of stimulated Brillouin scattering in photonic crystal fiber, Opt. Express. 15 (2007) 15517-15522.
[5] X. Hu, W. Chen, L. Fan, Z.Meng, M. Chen, An optical modulation method to suppress stimulated Brillouin scattering and the phase noise in a remote interferometric fiber sensing system, Opt. Fiber Tech. 20 (2014) 547–551.
[6] T. R. Schibli, K. Minoshima, F. L. Hong, H. Inaba, A. Onae, H. Matsumoto, I. Hart, and M. E. Fermann, Frequency metrology with a turnkey all-fiber system, Opt.. Lett. 29 (2004) 2467-2469.
[7] N.A.M.A. Hambali, M. A. Mahdi, M. H. Al-Mansoori, M. I. Saripan, A. F. Abas and M. Ajiya, Single-wavelength ring cavity Brillouin/Raman fiber laser. Laser Phys. Lett. 7 (2010) 454-457.
[8] M. Ajiya, M.A. Mahdi, M.H. Al-Mansoori, N.A.M.A. Hambali, S.Y. Gang, Multiwavelength Brillouin-erbium fiber laser utilizing virtual reflectivity in dispersion compensating fiber, in: IEEE, 2008 International Conference on Electronic Design, 2008, pp. 1-4.
[9] N.A.M. Ahmad Hambali, M. Ali Toor, Z. Yusoff and M. Ajiya, L-band multi-wavelength Brillouin Raman fiber laser utilizing the reverse-S- shaped section, Nonlinear Opt. Phys., 23, 2014 pp. l450026-1-1450026-10.
[10] M. H. Al-Mansoori, B. Bouzid, S. Saharudin, B. M. Ali, M. K. Abdullah and M. A. Mahdi, Low-threshold characteristics of a linear-cavity multiwavelength brillouin/erbium fiber laser, Microw. Opt. Tech. Lett. 41 (2004) 114 - 117.
[11] Y. G. Shee, M. A. Mahdi , M. H. Al-Mansoori, A. Ismail, N.A.M.A. Hambali, A. K. Zamzuri,,R. Mohamad, S. Yaakob, Threshold reduction of stimulated Brillouin scattering in photonic crystal fiber, Laser Phy. 19 (2009) 2194-2196.
[12] H. S. Kim, S. H. Kim, D. K. Ko, G. Lim, B. H. Cha and J. Lee, Threshold reduction of stimulated Brillouin scattering by the enhanced Stokes noise initiation, Appl. Phys. Lett. 74 (1999) 1358.
[13] M. Ajiya, M. A. Mahdi, M. H. Al-Mansoori, Y. G. Shee, S. Hitam and M. Mokhtar., Reduction of stimulated Brillouin scattering threshold through pump recycling technique. Laser Phys. Lett. 6 (2009) 535-538.
[14] L. Chen and X. Bao, Analytical and numerical solutions for steady state stimulated Brillouin scattering in a single-mode fiber, Opt. Comm. 152 (1998) 65-70.
[15] D. Cotter, Observation of stimulated Brillouin scattering in low-loss silica fibre at 1.3 μm Electron. Lett. 18 (1982) 495–496.
[16] R. W. Boyd, Nonlinear Optics (Academic press, New Y
[17] E. P. Ippen and R. H. Stolen, Stimulated Brillouin scattering in optical fibers, Appl. Phy. Lett. 21 (1972), 539.

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