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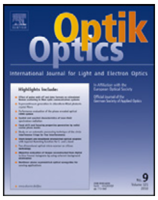

Investigation on the suppression of stimulated Brillouin scattering in single-frequency Raman fiber amplifiers

Jinyong Leng*, Shengping Chen, Wuming Wu, JingHou, Shaofeng Guo, Xiaojun Xu

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha, Hunan 410073, China

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ABSTRACT

High power operation of single-frequency Raman fiber amplifiers (SF-RFAs) is usually limited by the onset of stimulated Brillouin scattering (SBS). In this paper, we present our theoretical investigation on the suppression of SBS in SF-RFAs, based on the intensity equations combining SBS and stimulated Raman scattering (SRS). The effects of increasing the mode area of fiber and utilizing temperature and strain gradients along the fiber on the suppression of SBS are discussed. The simulation results suggest that it is not an advisable method to suppress SBS in SF-RFAs by increasing the mode area. Besides, although tensile strain and temperature gradients can suppress SBS in RFA singly, the conditions are too rigorous to realize. Based on the numerical simulation results, a feasible scheme for the suppression of SBS in RFA is proposed using the temperature gradients together with tensile strain gradients along the fiber length, resulting in an increase of ∼3 times of amplifiers output power.

1. Introduction

Raman fiber lasers and amplifiers have found various applications for broad gain spectrum and wavelength versatility of stimulated Raman scattering (SRS), but they are seldom utilized to generate high power single-frequency lasers. Because hundred meters of fibers should be used to provide enough Raman gain in Raman fiber lasers and amplifiers which makes stimulated Brillouin scattering (SBS) easily to be initiated. So the achievable powers of single frequency Raman fiber lasers and amplifiers are usually limited.

A number of methods have been applied in single-frequency Yb-doped fiber amplifiers to suppress SBS and increase the output power of amplifiers. Special fibers have been designed to differentiate acoustic and optical waves and reduce their overlap, thereby to terminate the stimulated process of Brillouin scattering [1–3]. More than 500 W amplified single-frequency laser has been got using large mode area fibers to reduce the power density [4]. The temperature and strain gradients along the fibers can broaden the effective SBS linewidth and thereby reduce the effective gain which has been demonstrated to be a good approach to mitigate SBS [5,6].

Previous research on the suppression of SBS in single-frequency Raman fiber amplifiers (SF-RFAs) always focuses on the experimental investigations [7–9]. On the other hand, theoretical part has, to the best of our knowledge, not yet been elaborately investigated. In this paper, a model considering the process of SRS together with SBS has been set up to describe the limitation of SBS on single-frequency RFA. Then the influences of mode area and temperature and strain gradients on the suppression of SBS in SF-RFAs are discussed. In the end of this paper, a feasible suppression scheme is proposed, resulting in an increase of ∼3 times of amplifier output power.

2. The intensity equations in RFA limited by SBS

A typical RFA is illustrated in Fig. 1. The gain is not provided by stimulated rare earth ions, but by SRS instead. Usually, a relative long gain fiber is needed in order to provide enough Raman gain in a RFA. The long gain fiber also initiates SBS, which seriously limits the single frequency output power of the RFA, while the RFA is utilized to amplify single frequency signals. See the RFA in Fig. 1 as an example: 1178 nm single frequency seed is amplified forward along the single mode fiber pumped at 1120 nm by SRS effect. The 1178 nm signal increases along the gain fiber and initiates backward SBS at a certain power level. Because of the narrow signal linewidth and the long gain fiber, SBS is easy to be initiated in this amplifier. An SBS frequency shift is usually at the order of 10 GHz (less than 0.1 nm). So, the backward SBS exhibits a wavelength around 1178 nm, near to the signal wavelength, which locates at the peak wavelength of the Raman gain profile with 1120 nm pump. Because the Raman gain is bidirectional effective along the fiber, the backward SBS will also be amplified by SRS effect. The backward amplified SBS signal will then compete with the seeded signal, causing an unwanted amplifier power limitation.

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* Corresponding author. Tel.: +86 073184573763/8607; fax: +86 073184574214.
E-mail address: jinyongleng@gmail.com (J. Leng).

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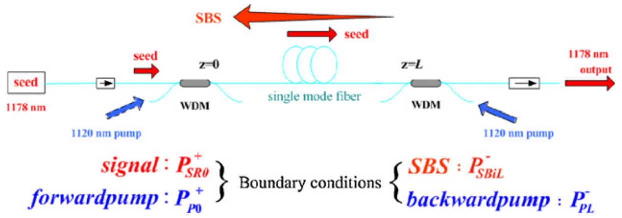

Fig. 1. Schematic diagram of a Raman fiber amplifier.

The intensity equations of SRS and SBS can be described as [10]:

$$\begin{cases} \dfrac{dI_{SR}}{dz} = g_R I_P I_{SR} - \alpha_{SR} I_{SR} \\ \dfrac{dI_P}{dz} = -\dfrac{\upsilon_P}{\upsilon_{SR}} g_R I_P I_{SR} - \alpha_P I_P \end{cases} \tag{1}$$

$$\begin{cases} \dfrac{dI_{SB}}{dz} = -g_B I_P I_{SB} + \alpha_{SB} I_{SB} \\ \dfrac{dI_P}{dz} = -g_B I_P I_{SB} - \alpha_P I_P \end{cases} \tag{2}$$

where I_{SR} and I_{SB} are the intensity of Raman wave and Brillouin wave. I_P is the pump intensity. g_R and g_B are the gain coefficients of Raman scattering and Brillouin scattering. υ_P and υ_{SR} are the frequencies of pump and Raman wave. α_P, α_{SR} and α_{SB} are the intrinsic background losses in the fiber for pump, Raman and Brillouin wave. z is the location along the fiber.

Considering the described physical processes in Fig. 1, the intensity equations describing the SF-RFA with SBS can be written as:

$$\frac{dI_P^+}{dz} = -\frac{\upsilon_P}{\upsilon_{SR}} g_R I_P^+ I_{SR}^+ - \frac{\upsilon_P}{\upsilon_{SB}} g_R I_P^+ I_{SB}^- - \alpha_P I_P^+ \tag{3a}$$

$$\frac{dI_P^-}{dz} = \frac{\upsilon_P}{\upsilon_{SR}} g_R I_P^- I_{SR}^+ + \frac{\upsilon_P}{\upsilon_{SB}} g_R I_P^- I_{SB}^- + \alpha_P I_P^- \tag{3b}$$

$$\frac{dI_{SR}^+}{dz} = g_R I_P I_{SR}^+ - g_B I_{SR}^+ I_{SB}^- - \alpha_{SR} I_{SR}^+ \tag{3c}$$

$$\frac{dI_{SB}^-}{dz} = -g_R I_P I_{SB}^- - g_B I_{SR}^+ I_{SB}^- + \alpha_{SB} I_{SB}^- \tag{3d}$$

where "+" stands for forward propagated waves and "−" stands for backward propagated waves in Eq. (3). υ_{SB} is the frequency of the Brillouin wave. The subscript "P", "SR" and "SB" represent the 1120 nm pump light, the 1178 nm Raman signal light and the Brillouin scattering light near 1178 nm, respectively. Eq. (3c) describes the power variation of the 1178 nm Raman signal light. It is not only a signal light of the Raman scattering process, but also a pump light of the Brillouin scattering process. The three items at the right side of the equation correspond to the Raman gain, the Brillouin consumption and the intrinsic loss, respectively.

Substitute power for intensity and considering the Brillouin gain spectrum, Eq. (3) should be changed as follow:

$$\frac{dP_P^+}{dz} = -\frac{\upsilon_P}{\upsilon_{SR}} \frac{g_R P_P^+ P_{SR}^+}{A_{eff}} - \frac{\upsilon_P}{\upsilon_{SB}} \frac{g_R P_P^+ \sum_i P_{SB_i}^-}{A_{eff}} - \alpha_P P_P^+ \tag{4a}$$

$$\frac{dP_P^-}{dz} = \frac{\upsilon_P}{\upsilon_{SR}} \frac{g_R P_P^- P_{SR}^+}{A_{eff}} + \frac{\upsilon_P}{\upsilon_{SB}} \frac{g_R P_P^- \sum_i P_{SB_i}^-}{A_{eff}} + \alpha_P P_P^- \tag{4b}$$

$$\frac{dP_{SR}^+}{dz} = \frac{g_R P_P P_{SR}^+}{A_{eff}} - \frac{P_{SR}^+ \sum_i g_{Bi} P_{SB_i}^-}{A_{eff}} - \alpha_{SR} P_{SR}^+ \tag{4c}$$

$$\frac{dP_{SB_i}^-}{dz} = -\frac{g_R P_P P_{SB_i}^-}{A_{eff}} - \frac{g_{Bi} P_{SR}^+ P_{SB_i}^-}{A_{eff}} + \alpha_{SB} P_{SB_i}^- \tag{4d}$$

Table 1
Parameters used in the model.

$\lambda_P = 1120\,\text{nm}$	$\lambda_{SR} = 1178\,\text{nm}$
$g_R = 7 \times 10^{-14}\,\text{m/W}$	$g_0 = 2.4 \times 10^{-11}\,\text{m/W}$
$\alpha_P = 0.003\,\text{m}^{-1}$	$\alpha_{SR} = \alpha_{SB} = 0.005\,\text{m}^{-1}$
$\Omega_{SBS} = 58\,\text{MHz}$	$A_{eff} = 2.83 \times 10^{-11}\,\text{m}^2$
$n = 1.45$	$\nu_a = 5.96\,\text{km/s}$

where A_{eff} is the mode area of the fiber core. The differences of frequencies, Raman gain coefficients and background losses of these discrete Brillouin waves are neglected in Eq. (4).

SBS gain can be described by the following Lorentzian shaped profile with peak gain g_0 and bandwidth Ω_{SBS} [10].

$$g_B(\upsilon_i) = g_0 \frac{\Omega_{SBS}^2}{4(\upsilon_i - \upsilon_0)^2 + \Omega_{SBS}^2} \tag{5}$$

where υ_0 is the Brillouin frequency shift from the seed signal λ_{SR} which is defined by $\upsilon_0 = 2n\nu_a/\lambda_{SR}$, where n is the optical refractive index and ν_a is the acoustic velocity.

The boundary conditions of Eq. (4) are shown in Fig. 1. In practice, no injected Brillouin stokes input at $z = L$. They are initiated from noise, which could be thermally activated phonons, ASE, signal noise or back scattered light [11]. The differential equations are two point boundary value problems solved by the modified relaxation method in this paper [1].

The fibers used in the model are single mode polarization maintaining silica fibers. The bandwidth of the 1178 nm seed signal is far below the Brillouin scattering bandwidth Ω_{SBS}. Parameters used in the model are given in Table 1.

3. The suppression of SBS in RFA

Based on the above theoretical model, Fig. 2 shows the relationships between output power and pump power with different fiber lengths. The seed signal power is 10 mW. Backward pump scheme has been adopted. It should be noted that there is a critical value for the pump power of the RFA. Once the pump power exceeds the critical value, the Brillouin scattering light will deplete the signal light rapidly. This corresponds to the situation that the second item on the right side of Eq. (3c) is higher than the first item. As a result, no amplified 1178 nm signal will be exported. The simulated results of forward pumped amplifiers have been demonstrated to almost have the same variation trend, comparing with that of backward pumped amplifiers.

It can be seen from Fig. 2 that a shorter fiber length corresponds to a higher pump power threshold and a higher maximal output

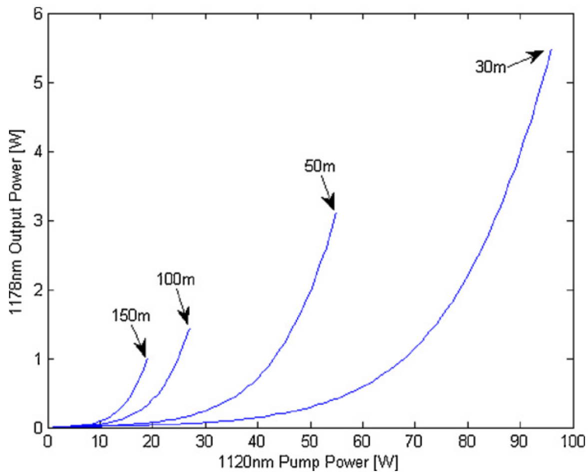

Fig. 2. Output power as a function of pump power with different pump schemes.