NRC Publications Archive
Archives des publications du CNRC

Evaluation of parameters in stimulated backward Brillouin scattering

de Oliveira, C. A. S.; Jen, Cheng-Kuei

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.
For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:
https://doi.org/10.1117/12.50204

Submolecular Glass Chemistry and Physics, Proceedings of SPIE, pp. 101-106, 1991-11-01

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=cf0c7703-0295-404a-a7c2-0e6e70b2fef5
https://publications-cnrc.canada.ca/fra/voir/objet/?id=cf0c7703-0295-404a-a7c2-0e6e70b2fef5

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada
Conseil national de recherches Canada

Evaluation of parameters in stimulated backward Brillouin scattering

C. de Oliveira, Cheng-Kuei Jen

C. A. S. de Oliveira, Cheng-Kuei Jen, "Evaluation of parameters in stimulated backward Brillouin scattering," Proc. SPIE 1590, Submolecular Glass Chemistry and Physics, (1 November 1991); doi: 10.1117/12.50204

Event: OE Fiber, 1991, Boston, MA, United States

Evaluation of parameters in stimulated backward Brillouin scattering

C.A.S. de Oliveira* **and C.K. Jen**

Industrial Materials Institute, National Research Council,
Boucherville, Quebec, Canada J4B 6Y4

ABSTRACT

A perturbation analysis of stimulated backward Brillouin scattering (SBBS) in single mode optical fibers is presented. The nonlinear interaction between the pump and Stokes waves, optical loss and Bragg diffraction have been all considered. The analytic expressions of the threshold, output Stokes intensity, efficiency for the SBBS fiber amplifiers and lasers are derived. We show that the stronger Bragg diffraction will increase the Brillouin diffraction efficiency and decrease the threshold of SBBS. Effects of acoustic guidance conditions of optical fibers on the above SBBS parameters will be discussed.

1. INTRODUCTION

The attractiveness of coherent optical fiber transmission systems are their long repeater spacing and large transmission capacity. To utilize the available bandwidth and to increase the system margins, a narrow optical spectra and high transmitter powers are required. However, these two requirements will ultimately be limited by optical nonlinear effects such as stimulated backward Brillouin scattering (SBBS) [1]. It has been demonstrated that over 60% of the input power of a 13.5 km single mode optical fiber (SMOF) can be reflected back to the input end due to SBBS [2]. Since SBBS imposes a serious limitation on the input power launching into the fiber, it is then necessary for a SMOF long transmission system to operate at input power levels below the threshold of SBBS, P_{Th}. Thus high P_{Th} is desired for such application. SBBS can be also used as a sensing tool for distributed strain [3] and temperature [4] sensors. It also plays an important role in fiber Brillouin lasers [5]. These sensor and laser applications prefer low P_{Th}.

SBBS involves three important mechanisms: (1) the nonlinear coupling between the pump and Stokes waves, (2) optical loss and pump depletion and (3) Bragg diffraction. Recently many theoretical studies have been devoted to SBBS in SMOFs [1,2,6-12], however, it appears that none of them has considered the above three factors simultaneously. Moreover, P_{Th} was studied only in [1,6]. In this article, we include the above three parameters and use a perturbation analysis to investigate the Brillouin diffraction efficiency and P_{Th} of SBBS theoretically.

2. COUPLED MODE EQUATIONS

The development of SBBS in optical fibers requires the consideration of mutual interaction between the pump and Stokes waves. Under steady-state conditions, applicable for a cw or quasi-cw pump, such an interaction is governed by the coupled wave equations

$$\frac{dE_s}{dz} = -\frac{1}{2} g |E_p|^2 E_s + \frac{\alpha}{2} E_s - i\kappa E_p \tag{1a}$$

$$\frac{dE_p}{dz} = -\frac{1}{2} g |E_s|^2 E_p - \frac{\alpha}{2} E_p + i\kappa E_s \tag{1b}$$

where E_s and E_p represent the Stokes wave and pump wave respectively. z is the distance along the longitudinal axis of the fiber. g is the Brillouin-gain coefficient. α is the optical loss in the fiber and this loss is normally very small (< 1 dB/km). κ is the coupling coefficient between the pump and the Stokes waves due the Bragg diffraction.

Let

$$E_s = \sqrt{I_s}\, e^{i\psi_s} \tag{2a}$$

and

$$E_p = \sqrt{I_p}\, e^{i\psi_p} \tag{2b}$$

where I_s and I_p, and ψ_s and ψ_p are the amplitude and phase of Stokes and pump waves respectively. Substituting (2a) and 2(b) into (1a) and (1b) we obtain

$$\frac{dI_s}{dz} = -gI_pI_s + \alpha I_s + 2\kappa \sin\Delta\psi\sqrt{I_pI_s} \tag{3a}$$

$$\frac{dI_p}{dz} = -gI_pI_s - \alpha I_p + 2\kappa \sin\Delta\psi\sqrt{I_pI_s} \tag{3b}$$

$$\frac{d\psi_s}{dz} = -\kappa \cos\Delta\psi\sqrt{\frac{I_p}{I_s}} \tag{3c}$$

$$\frac{d\psi_p}{dz} = -\kappa \cos\Delta\psi\sqrt{\frac{I_s}{I_p}} \tag{3d}$$

where

$$\Delta\psi = \psi_p - \psi_s \tag{4}$$

Since the Stokes waves is generated by a backward Bragg scattering from a moving index grating or acoustic guided waves that represents the phonon field, we can say that the phase of E_s to be locked to that of E_p. It means $d(\Delta\psi)/dz = 0$. We have found that $\Delta\psi = -\pi/2$. Then we have

$$\frac{dI_s(z)}{dz} = -gI_p(z)I_s(z) + \alpha I_s(z) - 2\kappa\sqrt{I_s(z)I_P(z)} \tag{5a}$$

$$\frac{dI_p(z)}{dz} = -gI_p(z)I_s(z) - \alpha I_p(z) - 2\kappa\sqrt{I_s(z)I_P(z)} \tag{5b}$$

In Fig.1 we show the schematic diagram for the propagation of the pump and Stokes wave in a long single mode optical fiber transmission system. L is the length of the fiber.

In previous analyses, [6], [1] & [7] and [8] had assumed $\alpha = 0$ & $\kappa = 0$, $\alpha \neq 0$ & $\kappa = 0$ and $\alpha = 0$ & $\kappa \neq 0$, respectively; [9], [10] and [11] only investigated the Bragg diffraction mechanism and neglected the nonlinear coupling between the pump and Stokes waves and optical loss. In this article we used Eqns.(5a) and (5b) to evaluate the Brillouin diffraction efficiency and P_{Th} of SBBS in SMOFs.

Since it is very complex to solve Eqns.(5a) and (5b) directly, here a perturbation method is used. First, a small κ is assumed. We neglect the third term at the R.H.S. of Eqn.(5b), solve the Eqn.(5b) and obtain [12]

$$I_p(z) = \frac{(1-b_0)A(z)}{A(z)-b_0} I_p(0)\exp(-\alpha z) \tag{6}$$

where

$$A(z) = \exp\{(1-b_0)(g_0/\alpha)[1-\exp(-\alpha z)]\} \tag{7}$$

$$b_0 = I_s(0)/I_p(0) \tag{8}$$

Also $g_0 = gI_p(0)$. The parameter b_0 is the conversion efficiency from the pump power to the Stokes power. The parameter g_0 is the small signal gain associated with the SBBS process. It is noted that Eqns.(6-8) have included the effects of the pump depletion.

Substituting Eqns.(6-8) in Eqn.(5a) we obtain $I_s(z)$ including the first order perturbation effect due to κ,

$$I_s(z) = \frac{A(L)-b_0}{A(z)-b_0} \chi(z)^2 I_s(L)\exp[-\alpha(L-z)] \tag{9}$$

where

$$\chi(z) = 1 + \frac{2\kappa[A(L)^{1/2} - A(z)^{1/2}]}{g_0 b_i^{1/2}(1-b_0)^{1/2}[A(L)-b_0]^{1/2}} \tag{10}$$

and

$$b_i = \frac{I_s(L)}{I_p(0)} \tag{11}$$

The parameter b_i can be considered as the initial SBBS signal at $z = L$ which will be amplified through the fiber length L. At $z = 0$, b_0 in Eqn.(8) indicates what fraction of the input pump power is converted to the Stokes power. The relation between b_i and b_0 can be expressed as:

$$b_i = \left\{ b_0^{1/2} - \frac{2\kappa[A(L)^{1/2} - 1]}{g_0(1-b_0)} \right\}^2 \frac{(1-b_0)\exp(\alpha L)}{A(L)-b_0} \tag{12}$$

3. NUMERICAL RESULTS

In order to show the relation among the conversion efficiency b_0, the Bragg diffraction effect κL and the normalized distance z/L, the normalized Stokes intensity $I_s(z/L)/I_p(0)$ is evaluated and shown in Fig.2 as a function of z/L for different values of κL and a fixed value of $b_i = 0.01$. $I_s(z/L)/I_p(0)$ can be obtained with the use of Eqns.(8-11) together with some changes in variables. The parameter $b_i = 0.01$ was chosen arbitrarily but Agrawal also used this value in [12]. It is noted that in our analysis acoustic attenuation is assumed to be negligible and also very low α exists in the fiber, therefore the imaginary of κ is considered to be negligible as well. Hence we use real values of κ in our numerical calculations. Figure 2 indicates that a larger κL converts more pumped energy into the Stokes energy, thus a higher conversion efficiency. With a constant Brillouin gain $g_0 L = 5$ in the fiber, the relation between b_0 and b_i (Eqn.(12)) is given in Fig.3 for different values of κL. A larger b_i and κL implies a higher b_0.

4. BRILLOUIN THRESHOLD

As mentioned earlier, the threshold P_{Th} is a very important parameter of SBBS. So far, P_{Th} has been reported [6,1,12] without the consideration of pump depletion and Bragg diffraction. In the following section, we would like to express P_{Th} with the inclusion of the above two parameters.

Let us define the saturate gain of the Brillouin amplification process [12], G_s, be

$$G_s = \frac{I_s(0)}{I_s(L)\exp(-\alpha L)} \tag{13}$$

and we can have

$$G_s = \frac{A(L) - b_0}{1 - b_0}\chi(0)^2 \tag{14}$$

The Brillouin threshold P_{Th} is defined as the input pump power at which the Stokes power becomes equal at a fiber length l, or $P_{th} = P_s(l) = P_p(l) = P_0\exp(-\alpha l)$, where $P_0 = I_p(0)A_{eff}$. Following the approaches taken by Smith (Eqns.(9) and (17) in [1]), at the threshold we obtain

$$\frac{\sqrt{\pi}}{2}\left(\frac{f_s}{f_a}\right)KT\left(\frac{A_{eff}}{g_B P_{th} L_{eff}}\right)^{1/2}\Delta f G_s \,|_{P_0 = P_{th}} = P_{th}\left(\frac{P_{th} g_B L_{eff}}{A_{eff}}\right) \tag{15}$$

In Eqn.(15) the Brillouin gain is assumed to have a Lorentzian spectral profile and g_B is the peak gain. Δf is the spectral width of the Brillouin-gain spectrum [12]. K is Boltzmann's constant. T is the temperature and f_a is frequency of the acoustic phonon [1,6]. Substituting Eqn.(14) to (15) we can have

$$\frac{\sqrt{\pi}}{2}\left(\frac{f_s}{f_a}\right)KT\left(\frac{g_B L_{eff}}{A_{eff}}\right)\Delta f = \left(\frac{P_{th} g_B L_{eff}}{A_{eff}}\right)^{5/2}\Bigg[\frac{1 - b_0}{A(L) - b_0}$$

$$\left\{1 + \frac{2\kappa[A(L)^{1/2} - 1]}{g_0 b_i^{1/2}(1 - b_0)^{1/2}[A(L) - b_0]^{1/2}}\right\}^{-2}\Bigg]_{P_0 = P_{th}} \tag{16}$$

Equation (16) is an improved expression for P_{Th} because both pump depletion and Bragg diffraction effects are included. We have evaluated Eqn.(16) and found that increasing κL decreases the threshold P_{Th}.

5. CONCLUSIONS

A perturbation analysis including the nonlinear interaction between the pump and Stokes waves, pump depletion, optical loss and Bragg diffraction of stimulated backward Brillouin scattering (SBBS) in single mode optical fibers has been presented. With the consideration of the pump depletion and Bragg diffraction, an improved expression for the threshold of SBBS has been derived. We have also found that a larger κL induces a higher Brillouin conversion efficiency b_0 and decreases the threshold of SBBS P_{Th}, and this phenomenon has been experimentally observed in Ref.[13].

* on leave of absence from Escola Politécnica da Universidade de São Paulo, São Paulo, Brazil

6. ACKNOWLEDGEMENT

C.A.S de Oliveira would like to thank FAPESP (Fundação de Amparo a Pesquisa do Estado de São Paulo) for a fellowship.

7. REFERENCES

[1] R.G. Smith, "Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering", Appl. Opt. Vol.11, pp.2489-2494, 1972.
[2] D. Cotter, "Stimulated Brillouin scattering in monomode optical fibers", J. Opt. Comm., Vol.1, pp.10-19, 1980.
[3] T. Horiguchi, T. Kurashima and M. Tateda, "A technique to measure distributed strain in optical fibers", IEEE Photonics Tech. Lett., Vol.2, pp.352-354, 1990.
[4] T. Kurashima, T. Horiguchi and M. Tateda, "Distributed temperature sensing using stimulated Brillouin scattering in optical silica fibers", Opt. Lett., Vol.15, pp.1038-1040, 1990.
[5] L.F. Stokes, M. Chodorow and H.J. Shaw, "All-fiber stimulated Brillouin ring laser with submilliwatt pump threshold", Optics Lett., Vol.7, pp.509-511, 1982.
[6] C.L. Tang, "Saturation and spectral characteristics of the Stokes emission in the stimulated Brillouin process", J. Appl. Phys., Vol.37, pp.2945-2955, 1966.
[7] R.H. Enns and I.P. Batra, "Saturation and depletion in stimulated light scattering", Phys. Lett., Vol.28A, pp.591-592, 1969.
[8] X.G. Gu and P. Yeh, "Contradirectional nonlinear-optical Bragg scattering in Kerr media", Opt. Lett., Vol.16, pp.129-131, 1991.
[9] P.J. Thomas, N.L. Rowell, H.M. van Driel and G.I. Stegeman, "Normal acoustic modes and Brillouin scattering in single mode optical fibers", Phys. Rev. B, Vol.19, pp.4986-4998, 1979
[10] N. Shibata, K. Okamoto and Y. Azuma, "Longitudinal acoustic modes and Brillouin-gain spectra for GeO_2 doped core single mode fibers", J. Opt. Soc. Am. B, Vol.6, No.6, pp.1167-1174, 1989.
[11] C.K. Jen and N. Goto, "Backward collinear guided-wave-acousto-optic interactions in single mode fibers", IEEE J. Lightwave Tech., Vol.7, pp.2018-2023, 1989.
[12] G.P. Agrawal, "Nonlinear Fiber Optics", Academic Press, N.Y., Chap.9, pp.263-288, 1989.
[13] C.K. Jen, J.C.H. Yu, C. Neron, A. Shang, C. Saravanos, K. Abe and L. Bonnell, "Effects of acoustic properties on stimulated Brillouin scattering of single mode optical fibers", Proc. 1st IEEE Int'l Workshop on Photonic Networks, Components and Applications, in Series in Optics and Photonics, Vol.2, World Scientific, NJ (J. Chrostowski and J. Terry eds.) pp.308-314, 1990.

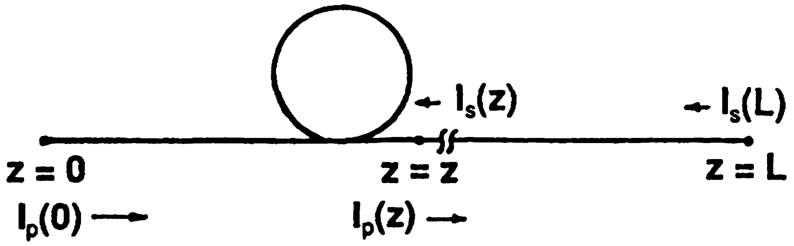

Fig.1 Schematic diagram showing propagation of the pump and the Stokes wave in a long single mode optical fiber transmission system.

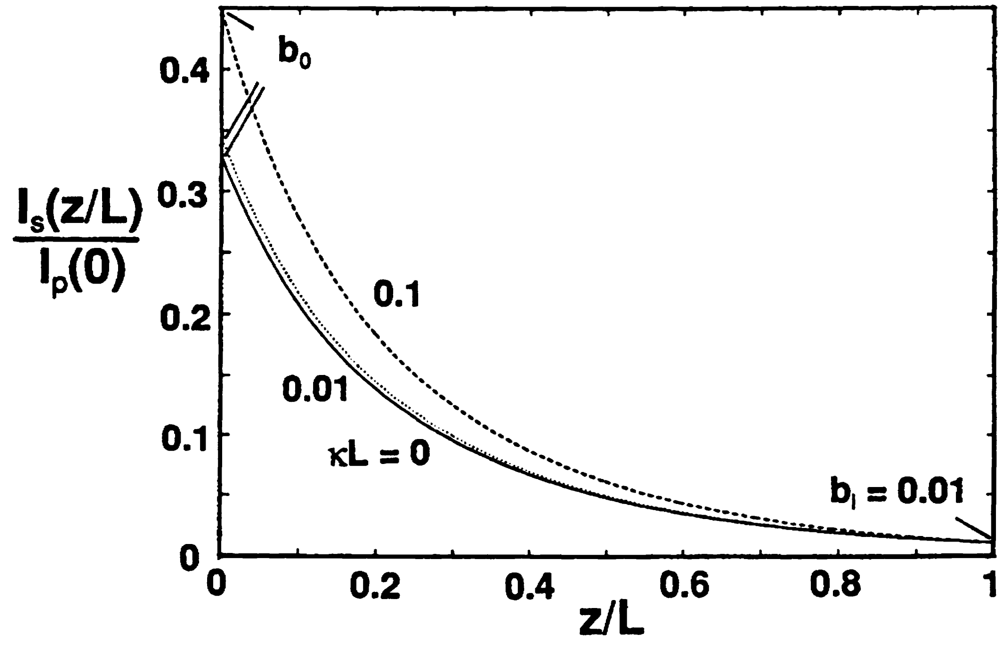

Fig.2 The normalized Stokes intensity $I_s(z/L)/I_p(0)$ versus z/L for different values of κ and a fixed value of $b_i = 0.01$.

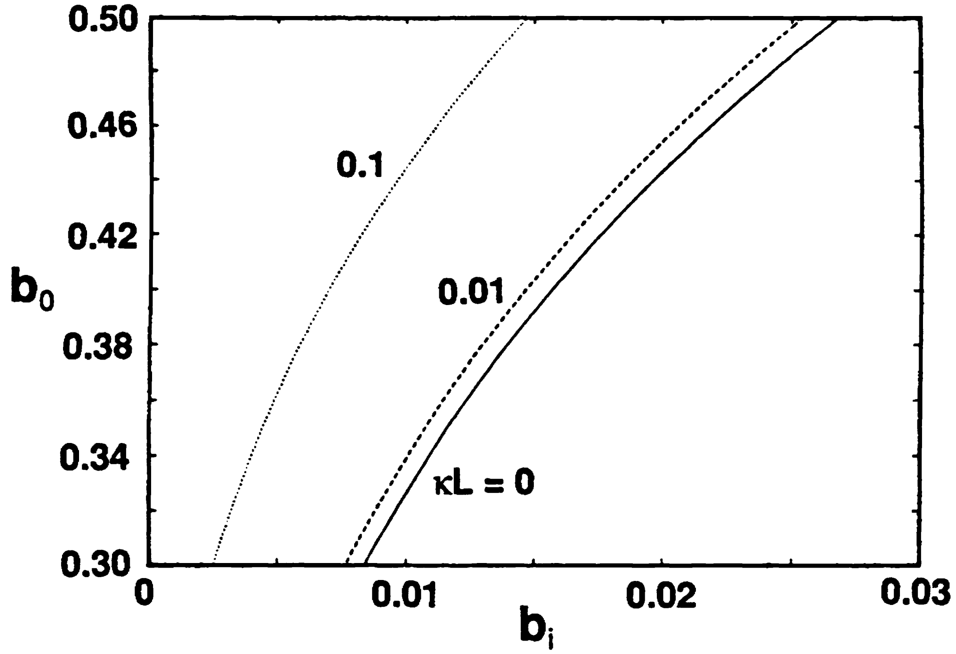

Fig.3 The conversion efficiency b_0 versus b_i (Eqn.(12)) for different values of κL and a fixed value of $g_0L=5$.