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Analysis of stimulated Brillouin scattering in multi-mode fiber by numerical solution *

ZHOU Tao (周涛), CHEN Jun (陈军)†

(*The State Key Lab of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China*)

†E-mail: Chenjun1@zju.edu.cn

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Abstract: Stimulated Brillouin scattering in optical fibers is described by a theoretical model and numerical analysis. The results showed that, for an optical fiber pumped by a laser beam with ns-order-pulse width and kW-order peak-power, SBS reflectivity tends to saturate when the fiber length exceeds a limit, named "effective fiber length". Using small core-diameter and long enough fiber, the SBS reflectivity level could be raised but is limited by optical damage of the entrance surface of the fiber. Therefore, just a small dynamic range can be obtained.

Key words: Optical fiber, Phase conjugation, Stimulated Brillouin scattering
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INTRODUCTION

Phase conjugation via stimulated Brillouin scattering (SBS) is widely used in MOPA system of pulsed solid-state lasers (Eichler *et al.*, 1997a; 1998; 2000; Offerhaus *et al.*, 1996) and other types of lasers (Eichler *et al.*, 1996; Kurnit *et al.*, 1989; Filippo *et al.*, 1992) to compensate phase distortions in resonator. This stimulated process leads to the wave-front reversal of the reflected beam and the compensation of phase aberrations experienced by the input beam (Baranova *et al.*, 1980; Dane *et al.*, 1995). Generally, typical SBS materials with standard geometries exhibit thresholds of 500 kW for solids, 100 kW for gases and 10 kW for liquids (Eichler *et al.*, 1997b), while much lower thresholds can be obtained by using wave-guide structures such as optical fiber (Eichler *et al.*, 1997b; Jones *et al.*, 1996; Heuer *et al.*, 1998). As a type of phase-conjugator by SBS, multimode quartz fiber can provide good performance of low power threshold and high fidelity in a broad wavelength range from the near infrared wavelength above the visible spectrum down to the near ultraviolet wavelength (Eichler *et al.*, 1997c; 1997d), and is a good alternative to fluid and gaseous SBS-media that are toxic or operated under high pressure. Therefore, we will discuss optical fiber's SBS characteristics of a model based on the solutions of the coupled wave equations (Haus *et al.*, 1965; Menzel *et al.*, 1992; Kummrow *et al.*, 1991; Suni *et al.*, 1986), and analyze the whole SBS procedure by numerical method.

The procedure of stimulated Brillouin backscattering (SBS) can be described by coupled equations of waves and the Naive-Stokes equation for the variation of sound grating (Haus *et al.*, 1965). Generally, those equations are so complicated that some approximations are necessarily applied to achieve three simpler descriptions in scattering medium (Menzel *et al.*, 1992), considering the variation of beam area during light propagation and replacing the light intensity by power, so that the optical fiber's SBS process can be described by the following equations:

$$\frac{\partial P_L(z,t)}{\partial z} = -S(z,t)[P_L(z,t)P_S(z,t)]^{\frac{1}{2}}$$
$$\frac{\partial P_S(z,t)}{\partial z} = -S(z,t)[P_L(z,t)P_S(z,t)]^{\frac{1}{2}} \quad (1)$$

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$$\frac{\partial S(z,t)}{\partial t} = \frac{1}{2\tau_B}\left\{g\frac{[P_L(z,t)P_S(z,t)]^{\frac{1}{2}}}{A(z)} - S(z,t) - S_0\right\}$$

P_L and P_S here are powers of pump wave and Stokes wave respectively while S is a value proportional to the amplitude of sound grating. The phonon lifetime τ_B and gain coefficient g are dependent on the fiber medium used. $A(z)$ is the area of the beam cross section in the SBS medium. In the case of optical fiber, it is always equal to the fiber core area πr^2.

It should be pointed out that in the model above, the spontaneous Stokes wave is treated as a result of the initial sound constant S_0. Therefore, it is more reasonable to treat S_0 as spontaneous Stokes noise incited by phonon fluctuation. Thus, a stochastic process can be applied to analyze it as follows (Kummrow *et al.*, 1991): Near the threshold of SBS, the transient reflectance is so weak that the depletion of the pump wave can be neglected. We denote the power of the spontaneous Stokes wave as P_{S0}. Therefore, for the spontaneous Stokes wave the Eq. (1) become:

$$\frac{\partial P_1}{\partial z} = 0 \quad \frac{\partial P_{S0}}{\partial z} = -(P_L P_{S0})^{1/2} S$$

$$2\frac{\partial S}{\partial t} = \frac{1}{\tau_B}\left\{g\frac{(P_L P_{S0})^{1/2}}{\pi r^2} - S\right\} + N(t,z) \quad (2)$$

Here a random factor $N(t,z)$ is introduced to describe the spontaneous noise of the sound grating. Because of the random characteristics of the noise, $N(t,z)$ is not correlated in different positions and at different time. So this autocorrelation function could be expressed by Dirac Delta function:

$$\overline{N(t,z)N(t',z')} = (8\Gamma_B r_0/L)\delta(z-z')\cdot\delta(t-t') \quad (3)$$

Where r_0 is the noise coefficient related to the noise intensity and L is the interaction length of the SBS process. Riemann integration (Suni *et al.*, 1986) was used to obtain the following solutions of Eq.(2) and Eq.(3):

$$P_{S0}(z,t) = 2r_0 P_L(t)\Gamma_B L^{-1}\int_0^t \exp(-2\tau\Gamma_B)\cdot d\tau\int_0^z I_0^2[\psi(t,\zeta)]d\zeta \quad (4)$$

$$\psi(t,\zeta) = (2\zeta\Gamma_B g\int_{t-\tau}^{t}\frac{P_L(t')}{\pi r^2}dt')^{\frac{1}{2}} \quad (5)$$

Where I_0 is modified Bessel function. In case of a very low pump power, the approximation $I_0[\psi(\tau,\zeta)] \approx 1$ can be used to obtain:

$$P_{S0}(z,t) \approx r_0 P_L(z,t)\cdot z/L \quad (6)$$

It means that the power of the Stokes wave increases linearly with the pump wave power before SBS occurs. The power of the Stokes wave in Eq. (1) is divided into two parts: the power of the stimulated Stokes wave created by wave coupling and the power of the spontaneous Stokes wave describled by Eq.(6). Thus the P_S(z, t) in Eq.(1) can be rewritten as the sum of P_{S0}(z, t) and P_{SS}(z, t) to replace S_0. The revised Eq.(1) can describe the whole SBS process in an optical fiber. The numerical solutions of Eq.(1) explained the distributions of pump power, Stokes power and amplitude of the sound grating anywhere in the fiber at any timepoint during the pump pulse persistence.

The distributions of pump power, Stokes power and sound amplitude are illustrated in Fig.1, wherein a 3 m long, 0.2 mm core diameter fiber is used pumped by a 1.064 μm laser pulse with 80 kW peak power and 60 ns pulse width and on assumption of Gauss distribution form pump pulse.

In Fig.1a, the $P_L - t$ curves show the pump pulse form at a certain location z. The curves where $z = 0$ and $z = L$ represent the input wave shape and transmitted wave shape, respectively. It shows clearly that the pump wave transmitted the fiber with nearly no loss before SBS occurs, and that its power decreases greatly immediately after that. Accordingly, the intensity of Stokes wave, as shown in Fig.1b, is near zero before SBS occurs and increases quickly just after the energy threshold is reached. To detail energy-exchange between coupled waves, the calculated curves of pump wave and Stokes wave on the entrance surface and the transmitted wave on the end surface are shown in Fig.2. From Fig.2 we can see that the power of the transmitted wave is almost equal to that of the pump wave before SBS occurs; and that nearly no back Stokes wave occurs here. As soon as the pump wave power is large enough to excite SBS process, a huge and

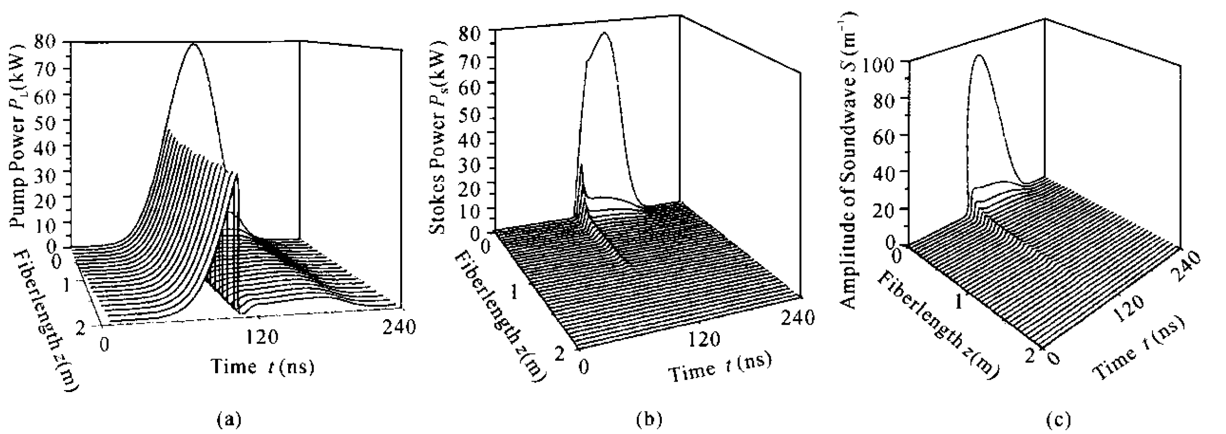

Fig.1 Distributions of pump wave, Stokes wave and sound grating in fiber during pump pulse, (a) pump wave, (b) Stokes wave, and (c) Sound grating

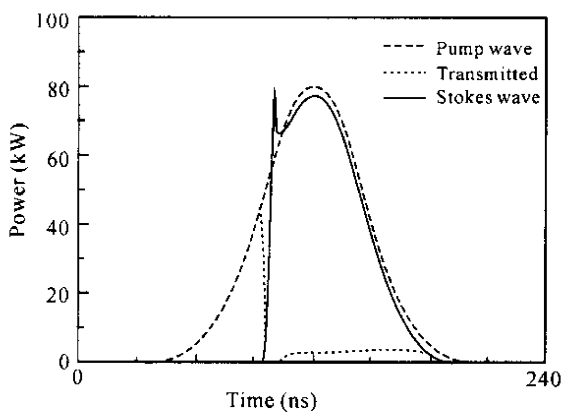

Fig.2 Power of pump wave, Stokes wave and transmitted wave vs. time

strong back-scattering Stokes wave will be created while the power of the transmitted wave decreases rapidly. The Stokes curve has a notably high spur just after SBS occurs and the power of the Stokes wave is larger than that of the pump wave, which means that the temporal reflectivity can exceed 1 here. In Fig.1c, before $t = 80$ ns, the sound waves in the whole fiber are very weak and distribute mostly in the frontal part of the 2 m long fiber. The sound grating increases with pump power and finally concentrates gradually to a small region about 2 mm – 3 mm near the entrance of the fiber. It means that a sufficiently long fiber is necessary for creating the sound grating cumulated from the beginning to raise SBS reflectivity up to near 100% and for the lower SBS threshold down to several kilowatts. Furthermore, it is easy to understand that the reflectivity increases with the decrease of fiber core-diameter.

Attention is often focused on the changing tendency of SBS reflectivity for a certain fiber while other parameters are changed (Eichler *et al.*, 1997c; 1997d). However, in practical cases where an optical fiber acts as phase conjugated mirror in MOPA system (Offerhaus *et al.*, 1996), the pump pulse width is nearly fixed or just varied in a small range. It is more practical to research how to select the parameters for a fiber phase conjugator with optimum performance than to find the optimum pulse width for the fiber. In this study, we fixed the pumping laser beam with the 30 ns pulse width and 25 kW peak power to find the optimum optical fiber dimensions for obtaining higher SBS reflectivity. The SBS reflectivities versus fiber length in different core diameter are shown in Fig.3.

Fig.3 shows that the SBS reflectivity increases with fiber length but shows saturate tendency for fiber length exceeding a certain length for a given fiber core diameter. We define the maximum reflectivity as "saturated SBS reflectivity", and define the fiber length when the reflectivity is up to 95% of saturated SBS reflectivity as "effective fiber length". The dependence of saturated SBS reflectivity on the fiber core diameter can be obtained from Fig.3 and is shown in Fig.4 showing clearly that small core diameter and long enough fiber length are necessary to obtain higher reflectivity for a given pump pulse. Unfortunately, small diameter will increase the possibility of optical damage in entrance surface of the fiber (Eichler *et al.*, 1997a).

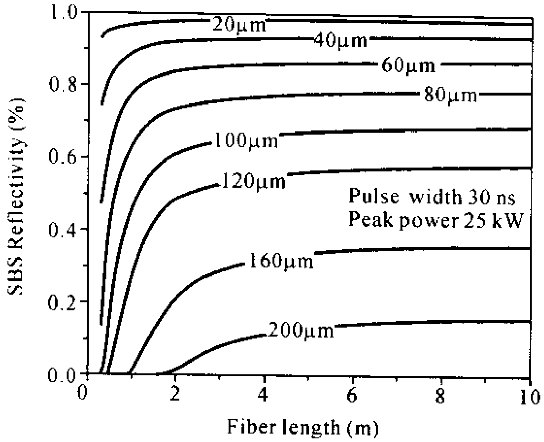

Fig.3 SBS reflectivity vs. fiber length in case of different core diameter

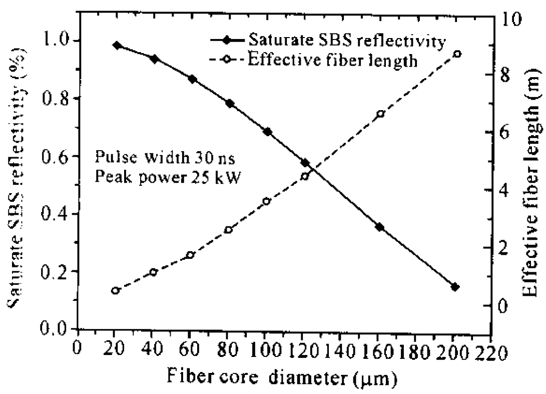

Fig.4 Saturated SBS reflectivity and corresponding effective fiber length vs. fiber core diameter

In conclusion, we have demonstrated a theoretical model by numerical method to obtain the distribution of pump power, Stokes power and amplitude of sound grating in optic fiber during pump pulse excitation. For a certain pump pulse, higher SBS reflectivity could be obtained in fiber with smaller core and longer length, but reflectivity tends to saturate along the fiber length. To obtain as high as possible reflectivity, small core diameter is necessary but this is limited by optical damage of the entrance surface of fiber, which leads to a small dynamic range.

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