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Numerical analysis on impact of temporal characteristics on stimulated Brillouin scattering threshold for nanosecond laser in an optical fiber

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ABSTRACT

The effects of temporal characteristics on stimulated Brillouin scattering (SBS) threshold for nanosecond laser in an optical fiber is studied in detail. It is found that SBS threshold is highly related to temporal characteristics such as pulse width, pulse period and pulse shape. The fiber length and self-phase modulation (SPM) will also intensively influence SBS thresholds in some situations. This analysis method can provide design guidelines for optical fiber systems of nanosecond fiber lasers.

1. Introduction

Stimulated Brillouin scattering (SBS) has attracted general attention for its importance in fiber-based systems such as fiber optic communications and fiber lasers [1–5]. SBS is characterized by efficient energy conversion from the pump laser to the back-scattered wave, which is potentially destructive. An important feature of SBS is that it occurs only when the pump intensity exceeds a certain threshold level. SBS threshold may be the power limitation of the fiber-based system [6–9], as SBS has almost the lowest threshold among the nonlinear effects in fiber lasers with narrow-linewidth. Usually, SBS threshold is defined as the pump power at which the Stokes wave increases rapidly and comparable with some fraction μ (such as 1%) of the maximum pump power [3]. SBS threshold was intensively studied in continuous wave (CW) laser [3,4]; however, the process of SBS for nanosecond laser is more complicated because the pulse width could be compared with the phonon lifetime T_B, which is always less than 10 ns [4]. In fact, SBS in nanosecond laser has also been extensively studied in recent years [10–19]; nevertheless, the relationship between SBS threshold and the temporal characteristics has not been studied in detail, which is very important for system designers.

In this paper, we illustrate the impact of temporal characteristics on stimulated Brillouin scattering threshold for nanosecond laser in optical fibers in detail. Dependences of SBS threshold on pulse width, pulse period and pulse shape are discussed, and the impact of self-phase modulation (SPM) has also been take into consideration.

2. Theoretical model

The dynamic aspects of SBS should be considered in nanosecond fiber laser because the medium response in the SBS case is governed by the phonon lifetime $T_B < 10$ ns. The dynamic process of SBS phenomenon in optical fibers can be depicted by the interaction among pump wave, Stokes wave and acoustic wave, which can be expressed as three coupled amplitude equations [4]:

$$\frac{\partial A_p}{\partial z}+\frac{1}{v_g}\frac{\partial A_p}{\partial t}=-\frac{\alpha}{2}A_p+i\gamma(|A_p|^2+2|A_s|^2)A_p+i\kappa_1 A_s Q \quad (1)$$

$$-\frac{\partial A_s}{\partial z}+\frac{1}{v_g}\frac{\partial A_s}{\partial t}=-\frac{\alpha}{2}A_s+i\gamma(|A_s|^2+2|A_p|^2)A_s+i\kappa_1 A_p Q^* \quad (2)$$

$$v_A\frac{\partial Q}{\partial z}+\frac{\partial Q}{\partial t}=-\frac{1}{2}\Gamma_B Q+\frac{i\kappa_2}{A_{eff}}A_p A_s^*+f \quad (3)$$

where A_p, A_s and Q are normalized amplitudes of pump wave, Stokes wave and acoustic wave respectively, $v_g=c/n_g$ is group velocity, c is the velocity of light in vacuum, n_g is group index, $\Gamma_B=T_B^{-1}$ is the acoustic damping rate, A_{eff} the effective mode area, v_A is the acoustic velocity. $\gamma=n_2\omega_p/cA_{eff}$ is a nonlinear parameter, where n_2 is the nonlinear-index coefficient and ω_p is the pump wave frequency. The two coupling coefficients are defined as [4]

$$\kappa_1=\gamma_e\omega_p/2n_p c\rho_0 \quad (4)$$

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$$\kappa_2 = \gamma_e \omega_p / c^2 v_A \tag{5}$$

where γ_e is the electrostrictive constant, ρ_0 is material density, and n_p is the refractive index of the pump wave. In Eq. (3), f represents a Langevin noise source that describes the thermal excitation of acoustic waves. f is supposed to be a Gaussian random term with zero mean and can be expressed as [20]

$$\langle f(z,t) f^*(z',t'0) \rangle = N_Q \delta(z-z')\delta(t-t') \tag{6}$$

where $N_Q = 2kT_0\rho_0\Gamma_B / v_A{}^2 A_{eff}$ is the fluctuation strength parameter, k is the Boltzmann constant and T_0 is temperature. The initial boundary conditions associated with the above coupled amplitude equations are written as follows:

$$\begin{aligned} &A_p(z,0)=0, \quad A_p(L,t)=0, \quad A_p(0,t)=\sqrt{P_{pump}(t)} \\ &A_s(z,0)=0, \quad A_s(L,t)=0, \quad A_s(0,t)=0 \\ &Q(z,0)=0, \quad Q(L,t)=0, \quad Q(0,t)=0 \end{aligned} \tag{7}$$

where $P_{pump}(t)$ is the instantaneous power of the input pump wave. It should be noted that Eqs. (1)–(3) include the nonlinear phenomena of self-phase modulation (SPM) and cross-phase modulation (XPM). SBS threshold is defined as the pump power at which the Stokes wave increases rapidly and comparable with μ of the pump power [3]. In many optical fiber systems, SBS is undesirable; for example, in a fiber amplifier with output power of 1 kW, 0.3% backward power equals 3 W, which is potentially destructive. If it is not specified otherwise, we suppose μ to be 0.3% in this paper. The Stokes pulse at threshold (0.3% times the pump power) thus contributes only by a very small fraction of XPM in the overall Kerr term of Eq. (1). It should also be noted that the phonon–photon coupling coefficients in Eqs. (1) and (2) are generally 100 times (or more) higher than the SPM/XPM coefficients, so the Stokes pulse is firstly excited by the last term of Eq. (2). As mentioned above, we assume that the pulsed laser is transform limited, so XPM can be neglected. In this way, spectral broadening of the pump laser is mainly induced by SPM. In order to illustrate the impact of temporal characteristics of the pulses, we can eliminate the influence of SPM by assuming n_2 to be zero.

Table 1
Parameters used in the numerical analysis.

Parameters	Values	Parameters	Values
γ_e	0.902	n_g	1.46
λ_p	1064 nm	T_B	5 ns
n_2	2.6×10^{-20}	A_{eff}	4.42×10^{-11} m^2
ρ_0	2210 kg/m^3	k	1.38×10^{-23}
v_A	5900 m/s	T	293 K
α	0 dB		

3. Numerical results and discussion

We numerically solve Eqs. (1)–(7) by using the finite-difference method [21–23]. The dynamic aspects of SBS are important for nanosecond lasers, so we should focus on temporal characteristics such as pulse width, pulse period and pulse shape. It should be noted that SBS threshold is dependent on μ, which is supposed to be 0.3% if it is not specified otherwise. The other key parameters used in numerical analysis are given in Table 1.

3.1. Pulse width

SBS threshold is highly dependent on pulse width (t_p), which is the full width of the pulse. It is well known that the quasi-CW regime is valid only for pump pulses with t_p of 100 ns or more, and SBS nearly ceases to occur for short pump pulses (width < 1 ns). Fig. 1(a) shows the calculated SBS peak power thresholds ($P_{th\text{-}peak}$) for Gaussian-shape pump pulses of different full widths at half-maximum (t_{FWHM}) in a 6-m-long fiber. Here we assume that the repetition rates of the pulses are low enough (1 MHz or less), so the Stokes wave created by each pump pulse decays before the next pump pulse arrives. Firstly, we neglect the influence of the SPM induced spectral broadening and assume n_2 to be zero. One can see that pulses with shorter t_p have a higher threshold. SBS thresholds are higher for pulses with shorter t_{FWHM} because phonon waves become more difficult to excite. When SPM is taken into consideration, the calculated SBS thresholds are higher, especially for pulses with t_{FWHM} of less than 10 ns. Fig. 1(b) shows the spectral width at half-maximum (ν_{FWHM}) of the output pump laser at the SBS thresholds. One can find that the spectral width increases because of SPM. For pulses with shorter t_{FWHM}, SBS thresholds are higher, which lead to larger spectral width because of SPM. It is well known that the bandwidth of Brillouin gain spectrum is approximately less than 100 MHz, so pump laser with broader spectral width has a higher SBS threshold.

It should be noted that the influence of the fiber length was neglected in the above discussion. As shown in Fig. 2, in pulsed lasers, the backward Stokes wave (A shown in Fig. 2) created by the forepart of the pump pulse at the exit end of the fiber will be

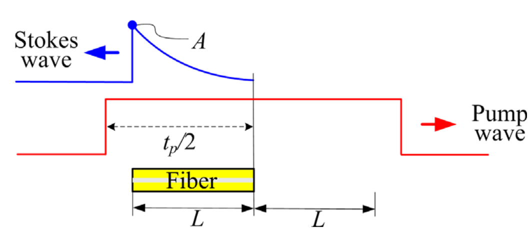

Fig. 2. Schematic of interaction between Stokes wave and one pump pulse in optical fiber.

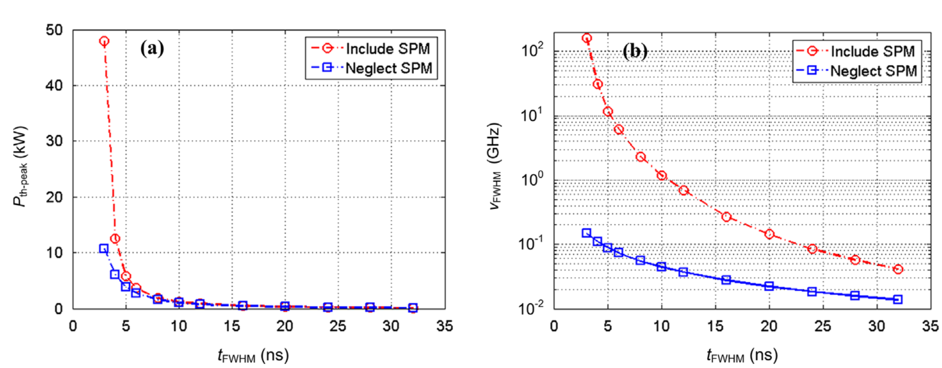

Fig. 1. (a) SBS threshold and (b) spectral linewidth as a function of pulse width for Gaussian-shape pump pulses in a 6-m-long fiber.