Influence of medium parameters on power limiting characteristic in stimulated Brillouin scattering process

Huaping Gong (龚华平)[1,2], Zhiwei Lü (吕志伟)[1], Dianyang Lin (林殿阳)[1], and Songjiang Liu (刘松江)[1,3]

[1]*Institute of Opto-Electronics, Harbin Institute of Technology, Harbin 150001*

[2]*Institute of Opto-Electronics, China Jiliang University, Hangzhou 310018*

[3]*Department of Physics, Daqing Petroleum Institute, Daqing 163318*

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By adopting noise initiation model of stimulated Brillouin scattering (SBS), the influence of phonon lifetime and gain coefficient of medium on power limiting characteristic is numerically investigated. Through using actual parameters of three media, CCl_4, acetone, and CS_2, the waveforms of transmitted pulses are simulated. The result shows that different media have little effect on the front peak of waveform, while have an obvious effect on the height of power limiting platform. When the medium which has short phonon lifetime and small gain coefficient is used, the height of power limiting platform is comparatively high. In experiment, by focusing 1064-nm, 8-ns, 18-mJ pulses into these three media, the waveforms of transmitted pulses are obtained. The experimental results are in good agreement with conclusions of theoretical simulations.

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With the development of laser technology and the extension of applications, laser protection is getting more and more attention. Optical limiting device has been investigated extensively in recent years, for it has the characteristic of protecting optical sense organ from the damage of high power laser radiation. The optical limiting mechanisms based on various nonlinear effects, such as two-photon absorption[1], inverse saturated absorption[2,3], nonlinear refraction, reflection, diffraction[4], etc. have been studied. As a kind of nonlinear optical process, stimulated Brillouin scattering (SBS) also has the optical limiting characteristic. Recently, Lü *et al.* investigated the transmission characteristic of laser pulses in CCl_4 medium, and obtained the rules of transmitted pulse energy and power[5,6]. The results indicated the characteristic of energy and power optical limiting in SBS process. In the applications of optical limiting device based on SBS, for specific laser pulses, the medium parameter is important so that it affects the output power. By using different Brillouin media, the characteristic of power limiting could be changed. In this paper, we investigate the influence of medium parameters on power limiting characteristic in SBS process, and obtain the rules of power limiting characteristic of different media, which are significant for the applications of optical limiting device based on SBS process.

For SBS optical limiting, the pump light and the Stokes light pass the SBS medium cell with opposite directions. The pump light is along positive z axis, while the Stokes light is along negative z axis. Because the backward Stokes light is produced, the power and energy of transmitted light is limited, as shown in Fig. 1.

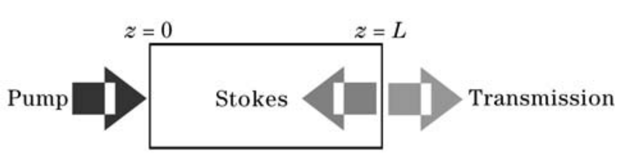

Fig. 1. Sketch of optical limiting based on SBS.

Under the condition of slowly varying envelope approximation, the coupling wave equations of one-dimensional transient SBS are written as[7]

$$\left[\frac{n}{c}\left(\frac{\partial}{\partial t}\right)+\frac{\partial}{\partial z}\right]E_{\mathrm{P}}=-\alpha E_{\mathrm{P}}+iK\rho E_{\mathrm{S}}, \quad (1)$$

$$\left[\frac{n}{c}\left(\frac{\partial}{\partial t}\right)+\frac{\partial}{\partial z}\right]E_{\mathrm{S}}=\alpha E_{\mathrm{S}}-iK\rho^{*} E_{\mathrm{P}}, \quad (2)$$

$$\frac{\partial\rho}{\partial t}+\frac{\Gamma_{\mathrm{B}}}{2}\rho=i\Lambda E_{\mathrm{P}}E_{\mathrm{S}}^{*}, \quad (3)$$

where $E_{\mathrm{P}}(z,t)$ and $E_{\mathrm{S}}(z,t)$ are amplitudes of pump light and Stokes light respectively; α is absorption coefficient of medium; Γ_{B} is Brillouin linewidth, $\Gamma_{\mathrm{B}}=1/(2\tau_{\mathrm{p}})$, τ_{p} is phonon lifetime of medium; n is refractive index; c is velocity of light in vacuum; $\rho(z,t)$ is medium density; K and Λ are Brillouin photon-phonon coupling coefficients, $K=\frac{\gamma^{\mathrm{e}}\omega_{\mathrm{P}}}{4cn\rho_0}$, $\Lambda=\frac{\gamma^{\mathrm{e}}T^2}{16\pi\omega}$, γ^{e} is electrostriction coupling coefficient, ρ_0 is average density of medium, ω_{P} is angular frequency of pump light, T is wave vector of photon, n is the average refractive index of medium, and ω is angular frequency of phonon. Generally, we think that the Stokes light builds up from the noise at the end of cell, so the noise intensity is used as border condition of Stokes light, which is chosen with the initial value of 10^{-16}[8]. The temporal shape of pump pulse is assumed as Gaussian profile, which is chosen as $E_{\mathrm{P}}(z=0,t)=\sqrt{P_{\max}/S_0}\exp\{-4\ln 2[(t-t_0)/t_{\mathrm{P}}]^2\}$, here S_0 is the cross-section area of pump beam at the incidence window, t_0 is the initial time corresponding to the pump peak power, t_{P} is pulse duration of pump light. So $E_{\mathrm{P}}(z=0,t)$, $E_{\mathrm{S}}(z=L,t)$ constitute the border conditions of above equations. The equations can be solved numerically by finite difference method[6].

Because Eqs. (1)—(3) do not consider the influence of focusing beam, so we substitute $E_{\mathrm{P,S}}$ in these equations by $E_{\mathrm{P,S}}/\sqrt{S_j}$, where S_j is the cross-section

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area of Gaussian beam at arbitrary position, $S_j = \pi\omega_0^2(1 + (j \times \Delta z)^2/Z_R^2)$, $j = 0, 1, \cdots, J$, $\Delta z = L/J$, Z_R is the Rayleigh length of beam, $Z_R = \pi\omega_0^2/\lambda$, the length of medium cell $L = 60$ cm, the beam waist at focus $\omega_0 \approx f\theta$, θ is divergence angle of pump beam, $\theta = 0.8$ mrad, the focal length $f = 20$ cm. The parameters of pump light are taken as follows: wavelength 1064 nm, pulse duration $t_P = 8$ ns, peak power $P_{max} = 2$ MW.

The parameters taken into account are phonon lifetime and gain coefficient of Brillouin medium. Firstly, fixing the phonon lifetime $\tau_p = 1.0$ ns, varying gain coefficient from 3 to 15 cm/GW gradually, and substituting these values into Eqs. (1)—(3), we can obtain the transmitted pulse waveforms of various gain coefficients, as shown in Fig. 2(a). Fixing the gain coefficientes $g = 5$ cm/GW, varying phonon lifetime from 0.5 to 2.5 ns gradually, and substituting these values into Eqs. (1)—(3), we can obtain the transmitted pulses of various phonon lifetimes, as shown in Fig. 2(b). From Fig. 2 we can see that, the transmitted pulses of various medium parameters show the characteristic of optical limiting, that is to say, the tail of pulse forms a "platform"[5]. The reason is that, when the pump power is above the SBS threshold, the interaction between pump and Stokes pulses is relatively strong, which leads to the energy transfer from pump light to Stokes light. The Stokes light increases rapidly, and the pump light is exhausted, thus the tail of transmitted pulse starts to drop steeply. Then, because the power of following part of the pulse cannot reach the SBS threshold, the power of pulse tail maintains near the platform.

With the increase of gain coefficient, the front peak of transmitted pulse decreases gradually, and the height of power limiting platform decreases gradually. This is because the increasing gain coefficient leads to the diminishment of the SBS threshold, and the SBS produces at lower location of pump pulse. At the same time, the increasing gain coefficient leads to the enhancement of SBS effect, so the height of power limiting platform decreases. With the increase of phonon lifetime, the front peak of transmitted pulse increases gradually, while the height of power limiting platform decreases gradually. The reason is that the phonon lifetime has correlativity with the Brillouin linewidth of medium. Considering Brillouin linewidth of medium, the gain coefficient g_B is expressed as[9]

$$g_B = g\frac{1}{1 + (\Gamma_L/\Gamma_B)}, \tag{4}$$

where Γ_L is the linewidth of pump light, Γ_B is the Brillouin linewidth of medium. As $\Gamma_B \propto 1/\tau_p$, when the linewidth of pump light is fixed, the increase of phonon lifetime leads to the diminishment of Brillouin linewidth. Then it leads to the decrease of gain coefficient from Eq. (4). Further, the SBS threshold increases because of the decrease of gain coefficient. So the front peak of transmitted pulse increases gradually. At the same time, because of the increase of phonon lifetime, the decay of phonon field slows down, and thus the SBS effect enhances. So it causes the height of power limiting platform to decline.

In fact, the phonon lifetime and gain coefficient of medium do not vary independently. These two parameters usually increase or decrease together. In order to study the influence of different media on the characteristic of power limiting, the true parameters of three kinds of media, i.e. CCl_4, acetone, and CS_2 (see Table 1) are used for numerical simulation. The results are shown as Fig. 3. It is shown that, although the phonon lifetimes and gain coefficients of different media are quite different, they have little effect on the front peak of transmitted pulse, while have an obvious effect on the height of power limiting platform. The reason is that, the increase of phonon lifetime makes the front peak become higher, and makes the height of power limiting platform become lower; while the increase of gain coefficient makes the front peak become lower, and makes the height

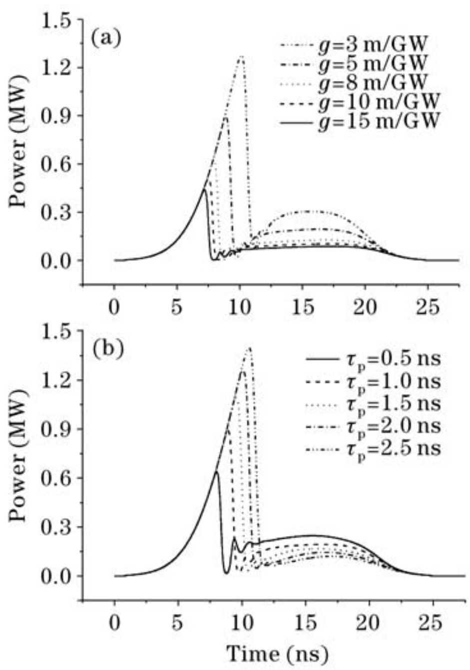

Fig. 2. Temporal shapes of transmitted pulses with various (a) gain coefficients and (b) phonon lifetimes in theoretical simulation.

Table 1. Parameters of Three Brillouin Media

Medium	Gain Coefficient (cm/GW)	Phonon Lifetime (ns)
CCl_4	6	0.6
Acetone	15.8	2.67
CS_2	68	6.4

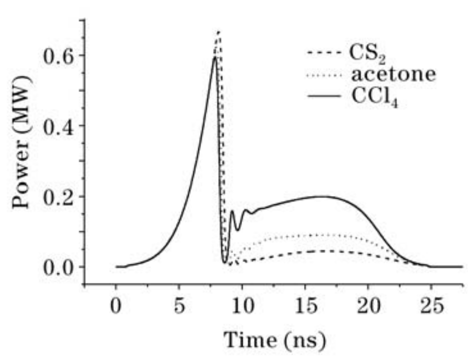

Fig. 3. Temporal shapes of transmitted pulses with various media.

of power limiting platform become lower. The two parameters work together, which leads to the results shown in Fig. 3.

We performed experiments with the setup shown in Fig. 4. The Nd:YAG *Q*-switched laser system contains a 100% reflective mirror M_1, a *Q*-switch dye plate, a polarizer P_1, a Nd:YAG rod, an aperture, and a partial reflective mirror M_2. Another polarizer P_2 is parallel to P_1, which forms a light isolator together with a 1/4 wave plate to prevent backward SBS light from entering YAG oscillator. The oscillator outputs p-polarized fundamental-mode light with 16-mJ energy, 1064-nm wavelength, 8-ns pulse duration, $\sim$ 0.8-mrad divergence angle, and 1-Hz repetition rate. L_1 is a lens with the focal length of 20 cm, which focuses the pump light into the 60-cm-long medium cell. R is also a partial reflective mirror. The light reflected by R is measured by an energy meter ED200, and the transmitted light is detected by a PIN photodiode (response time $\sim$ 1.0 ns). The pulse waveform is recorded by a digital oscillograph TDS3032B.

The Brillouin media are orderly changed as CCl_4, acetone, and CS_2. The transmitted waveforms of different

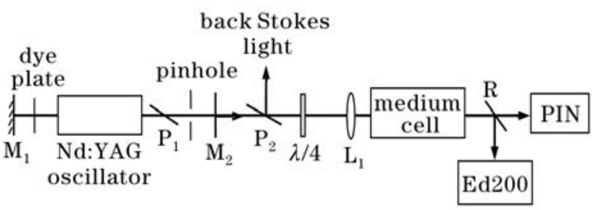

Fig. 4. Experimental setup.

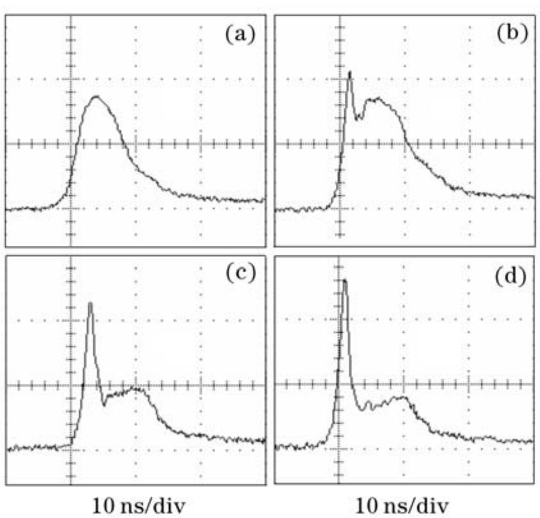

Fig. 5. Temporal shapes of (a) pump pulse and (b)—(d) transmitted pulses with various media in experiments: (b) CCl_4, (c) acetone, (d) CS_2.

media are measured in experiments, as shown in Fig. 5. From Fig. 5 it is shown that, the waveforms of experiments are very similar with those of theoretical simulation, and the pulse tails have obvious power limiting "platform". Moreover, there is little difference in the front peak of transmitted pulses for different media, the difference is mainly in the height of power limiting platform. It is the highest for CCl_4, secondary for acetone, and lowest for CS_2, which is consistent with the theoretical results. The difference between experimental and simulated results is that the front peak of pulse is closer to the height of power limiting platform in experimental waveform. The reason is that, the SBS energy reflectivity in theoretical simulation is comparatively high, while it is lower in experiments, because some factors such as loss, absorption and influences of other nonlinear effects lead to the decrease of SBS energy reflectivity, thus the "platform" height of transmitted pulse is higher.

The influence of medium parameters on the power limiting characteristic in SBS process is numerically investigated and proved in experiments. The experimental results are in agreement with the conclusions of theoretical simulations. It is indicated that, different media have little effect on the front peak of power limiting waveform, while have an obvious effect on the height of power limiting platform. When using the medium which has shorter phonon lifetime and smaller gain coefficient, the height of power limiting platform is comparatively high. These results will provide a significant guidance for design and application of SBS optical limiting device.

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