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Optical limiting effect based on stimulated Brillouin scattering in CCl_4*

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The optical limiting effect based on stimulated Brillouin scattering (SBS) in a nonlinear medium was investigated. We numerically treated the nonlinear propagation process with a theoretical model, which includes the spontaneous nature of the initiation of SBS, and obtained optical limiting effect in the process. Energy limiting, pulse reshaping and stabilization have been demonstrated on SBS mechanism with the nonlinear medium CCl_4. The input optical signals were Nd:YAG nanosecond laser pulses with width varying from 16ns to 7ns then to 2ns, the relationship between the transmitted signal and launched pump signal was shown. In the experimental regime, the most stable pulse and a superior energy stabilization of the transmitted pulse were obtained when the laser pulse-width became as short as 2ns. For the energy variation of laser pulses in a wide range of 14–88mJ, the output energy was limited in a quite narrow range 4.5–5.5mJ.

Keywords: stimulated Brillouin scattering, optical limiting
PACC: 4265C, 4225B

1. Introduction

Optical limiting has important potential application as effective devices for protecting sensitive optical components from high-power laser radiation damage. Recently, various mechanisms such as reverse saturated absorption (RSA),[1−4] two-photon absorption (TPA),[5,6] phase transition, nonlinear refraction[7,8] and optical scattering[9] have been studied for optical limiting. Here, optical limiting characteristics of a kind of induced scattering: stimulated Brillouin scattering (SBS) in a nonlinear medium are exhibited. For many years, most studies on SBS of nonlinear medium dealt with the performance of the backward scattering wave- Stokes field, in which phase conjugation (PC) of high-power laser beam by SBS was especially attractive.[10] Transmitted performance of SBS was seldom studied, and not to say optical limiting by SBS. In this paper, attempts are made to investigate optical limiting based on the nonlinear transmitted performance of nanosecond laser beams when they are scattered within a nonlinear optical medium. Investigations showed that SBS not only has the characteristics of optical limiting but also gives good output shape and stable output energy by choosing proper physical parameters of medium and pump parameters. In this paper, we report theoretical and experimental results of optical limiting with 1064nm nanosecond pulses based on SBS in CCl_4.

Firstly, we present a numerical simulation of optical limiting in the transient SBS process.[11] Output energy and output waveform are calculated as functions of pump energy with optimum parameters such as focus, cell length of SBS medium and separation between cell and lens. Theoretical calculation shows that when input signals are weak, they linearly transport in the medium, transmission can be almost as high as 100%, SBS does not occur, the nonlinear medium can be optically transparent. When the energy of input signals are high, SBS takes place in the nonlinear medium and input energy is back-scattered fractionally to set up Stokes field. With increase of the input energy, the energy of Stokes field increases nonlinearly. Neglecting the absorption of medium, the transmitted pulse transports with the remaining fraction of input energy, so the transmitted energy is confined to a certain value, thus optical limiting is achieved. We explored the character of optical limiting perfor-

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mance in a liquid single-cell of CCl_4 with a simple focusing geometry. This optical system is pumped by Q-switch single-longitudinal-mode Nd:YAG nanosecond laser. We chose CCl_4 as an SBS medium because it has a fast temporal response.

From theoretical and experimental results, we propose that the nonlinear SBS system can constitute an optical limiting device. Because our optical limiting threshold is high, the optical limiting based on SBS can be looked forward to being used as a protecting device in a high-power laser system. As we know, a laser system consists of a low-energy master and several optical amplifiers. If there is a small unexpected perturbation in the middle stage, the perturbation can be amplified and influence the quality of output laser beam. If we use optical limiting as a technical approach for stabilization of energy in the laser system then we can avoid optical damage caused by amplified perturbation. It is a simple optical set-up and self-pumping, so that we do not require an externally applied optic-electric field.

2. Theory

2.1. Model equations

The kinetic model is based on the Maxwell wave equations and medium's energy transport equation, under the condition of slow varying envelope approximation. The three-dimensional transient SBS equations can be changed into three one-dimensional equations. In a SBS medium, the nonlinear SBS process resonantly couples through electrostrictive effect, which produces an acoustic field in the medium. Thus a back-scattering Stokes field $A_s(z,t)$ is built up from the excited acoustic field $f(z,t)$, which is a theoretical model that includes the spontaneous nature of the initiation of SBS. In this process, neglecting the acoustic propagation and the optical Kerr effect, we can obtain the slowly varying envelope approximation for the complex amplitudes[11−13]

$$\left[\frac{n}{c}\left(\frac{\partial}{\partial t}\right)+\frac{\partial}{\partial z}\right]A_1=-\alpha A_1+\mathrm{i}k\rho A_s, \tag{1}$$

$$\left[\frac{n}{c}\left(\frac{\partial}{\partial t}\right)+\frac{\partial}{\partial z}\right]A_s=\alpha A_s-\mathrm{i}k\rho^* A_1, \tag{2}$$

$$\frac{\partial\rho}{\partial t}+\frac{\Gamma}{2}\rho=\mathrm{i}\Lambda A_1 A_s^*+f, \tag{3}$$

where α is the absorption coefficient, n is the effective refraction index, c is the speed of light, $\rho(z,t)$ is the density of medium, Γ is the acoustic damping rate, k and Λ are SBS coupled coefficient: $k=\dfrac{\gamma^{\mathrm{e}}\omega_{\mathrm{L}}}{4cn\rho_0}$ and $\Lambda=\dfrac{\gamma^{\mathrm{e}}K^2}{16\pi\omega}$, γ^{e} is electrostrictive coefficient. Because $f(z,t)$ is a Gaussian random process with zero mean and is δ correlated in space and time, there are relationships

$$\langle f(z,t)\rangle=0, \tag{4a}$$

$$\langle f(z,t)f^*(z,t)\rangle=Q\delta(z-z')\delta(t-t'), \tag{4b}$$

where Q is estimated from the thermal dynamic equation: $Q=2k_{\mathrm{B}}T\rho_0\Gamma/v^2\sigma$, ρ_0 is the average density of SBS medium, v is the acoustic speed, σ is interaction cross section. In order to approach the problem of nonlinear propagation in the SBS medium, we should solve the coupled Eqs. (1), (2) and (3). Firstly, we integrate the Eq.(3) and substitute the result into Eqs.(1) and (2). Equations (1) and (2) then turn into the following equations

$$\begin{aligned}&\left(\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)A_1+\frac{1}{2}\alpha A_1\\&=\frac{g\Gamma}{2}A_1\int_0^t A_1A_s^*\exp[-\Gamma(t-\tau)]\mathrm{d}\tau\\&\quad+\mathrm{i}kA_s\int_0^t f\exp\left[-\frac{1}{2}\Gamma(t-\tau)\right]\mathrm{d}\tau,\end{aligned} \tag{5}$$

$$\begin{aligned}&\left(-\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)A_s+\frac{1}{2}\alpha A_s\\&=\frac{g\Gamma}{2}A_1\int_0^t A_1^*A_s\exp[-\Gamma(t-\tau)]\mathrm{d}\tau\\&\quad+\mathrm{i}kA_1\int_0^t f\exp\left[-\frac{1}{2}\Gamma(t-\tau)\right]\mathrm{d}\tau,\end{aligned} \tag{6}$$

where $g=4k\Lambda/\Gamma$ is SBS gain coefficient of steady state. We numerically solve equations by an implicit finite difference in time and a backward difference scheme in space. Eqs.(5) and (6) can be solved with an efficient numerical algorithm, so a numerical simulation of the quasi-transient SBS process is set up in which dynamic properties of optical limiting by SBS can be shown. The wavelength of laser is 1064nm and SBS parameters of CCl_4 are listed in Table 1.

Table 1. SBS parameters of CCl_4.

Medium	n	$\rho_0/(\mathrm{g/cm^3})$	$\tau_\mathrm{l}/\mathrm{ns}$	γ^e	ω/MHz	$g/(\mathrm{cm/GW})$	$\alpha/\mathrm{cm^{-1}}$
CCl_4	1.452	1.595	0.6	1.35	17417	6	0

The initial laser field (laser pulses was input at $z = L$,the end of the SBS cell)is known. We assume quasi-Gaussian spatial and temporal intensity profiles of the incident laser pulses, which are closely matched to the intensity profiles of the laser pulses used in our experiments. Stokes field builds up from random noise field $f(z,t)$, whose shape is suggested Gaussian and configuration varies stochastically from 0 to 2π. Boundary condition and initial condition in time and space are given as: $P_\mathrm{l}(L,t) = P_\mathrm{max}\exp\{-4\ln 2[(t - t_0)/t_\mathrm{p}]^2\}$, $A_\mathrm{s}(0,t) = 0$, $A_\mathrm{s}(z,0) = 0$, $f(z,0) = f_i$.

Now we present numerical solutions of nonlinear propagation under these conditions.

2.2. Temporal limiting and power limiting analysis of SBS

The phenomenon of SBS in liquid is nowadays widely used to compress nanosecond laser pulses down to the sub-nanosecond region with remarkable conversion efficiency in back-scattering radiation.[14,15] Because the reshaping of temporal profile of pulse determines its power characteristics directly, it is valuable to investigate the variations of the temporal profiles of transmitted pulses in a SBS process. As for temporal distribution, we can obtain the simulation solutions of propagated beam by solving the wave Eqs. (5) and (6). The results include the temporal parts which are considerably more complicated than those for a stationary case. The time-dependent solutions are correlative with pump intensity and pump pulse width mostly. Simulations with time dependence of transmitted pulses in SBS nonlinear optical process are given by numerical calculations. The temporal profiles of transmitted pulses at various pump pulse-widths are analysed graphically. As Fig.1 shows, the input pulses are reshaped and their width is narrowed. The reason why the shapes become narrow in this way is that when input pulses enter the medium, the leading edge of the pulse firstly interacts with the medium, it keeps the shape of the input pulse before the occurrence of SBS. Once the power of the input pulses exceeds the SBS threshold, the output power reduces, thus the following edge descends sharply and the transmitted pulse is narrowed, and the falling edge ends in a low step. The temporal profiles of transmitted pulses look like being truncated, so the temporal distribution shows narrowing or temporal limiting characteristics by SBS. The temporal limiting is connected strictly with the width of pump energy and pump duration according to our calculations: (1) The higher the pump energy, the narrower the output profile. (2) When the pump pulse-width is wide and energy is high enough, the temporal profiles of transmitted pulses display decaying oscillations in the falling time. In contrast, it is difficult to generate decaying oscillations for shorter pump pulse width or lower pump energy. So for 2ns short pump pulse-width at our experimental energy level, the decaying oscillations almost disappear. These decaying oscillations have been analysed by Raijun *et al.*,[12] they pointed out that these decaying oscillations have a period of $2L/C$ (L is the length of SBS cell, C is the velocity of light in vacuum). It can be seen in our theoretical envelope of the transmitted pulse train in Figs.1(a) and 1(b). Because the width of the transmitted pulse for 2ns input laser pulse is much smaller than the period, the decaying oscillation disappear in Fig.1(c) and then we have a good shape of transmitted pulse.

Based on temporal profile analysis, we can obtain the power limiting behaviour[13] by the SBS nonlinear effect. From the temporal profile of transmitted pulses with different duration of pump pulses of Figs.1(a)–1(c), we can see power limiting behaviour as a result of process of SBS when pump pulses propagate in CCl_4. At lower power below SBS threshold, the pump pulse is transmitted without intensity attenuation; but further growing power can influence the output pulse due to SBS process, this higher power part is back-scattered to build Stokes field. Then transmitted power level becomes well below the input power level, so this system has the power limiting characteristics. When the succeeding part of the pump pulse comes, the remnant power, not high enough to reach the SBS threshold, propagates without SBS effect and gives the low power step. Figure 2 gives the variations of output peak power with input pump peak power. When input power is low, the output peak power increases at the same rate of that of pump. When input power is higher, the peak power of input pulse is depleted by SBS, so the output peak power raise up slowly. With

further increase of input peak power, the output peak power increases much slower than pump pulse. This shows the characteristics of saturation and means that the output peak power could tend to a stable value of power in the end. Thus nonlinear power loss of the pump pulse surely leads to power limiting.

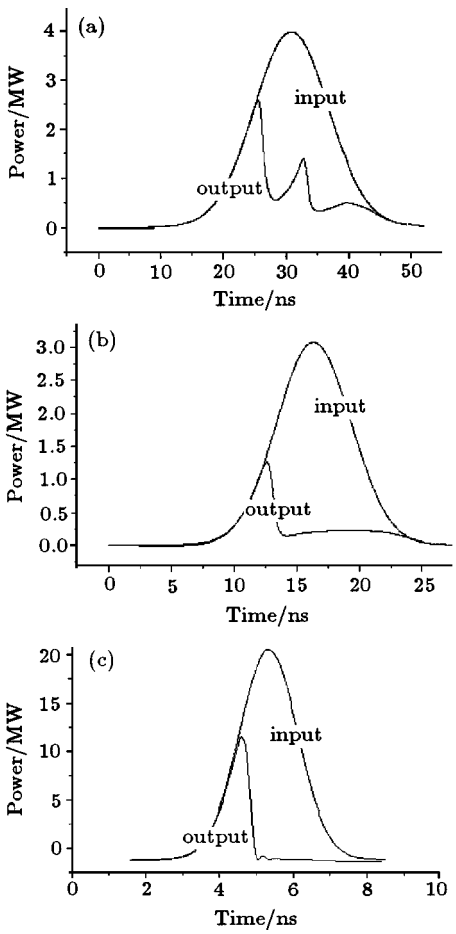


Fig.1. Theoretical pump profiles and transmitted profiles for various pump pulse-widths ((a) 16nm, (b) 7ns, (c) 2ns).

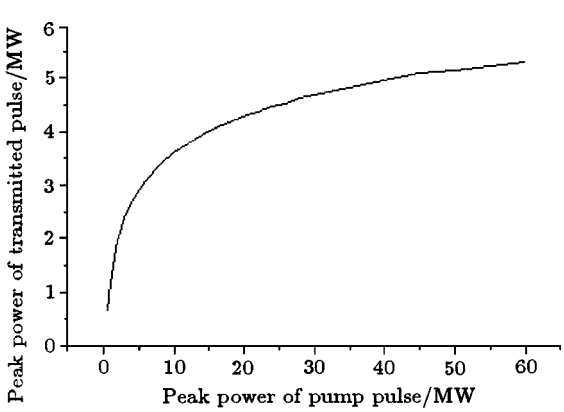


Fig.2. Calculated transmitted peak power varying with pump peak power (L=50cm, pump pulse-width 7ns).

2.3. Energy limiting and transmission characteristics of SBS

Next, the energy limiting characteristics in SBS are considered. We analysed energy aspects of optical limiting by SBS according to the theoretical integration of temporal profile. Emphasis is given to the aspect of dependence of limiting performance on major pump parameters such as width of laser pulses. We expect to obtain good optical limiting behaviour by choosing proper physical parameter configurations such as the separation between lens and cell, length of cell and focus of lens and so on. In Fig.3, the curves show the output energy varying with input energy with different pulse-widths. It can be seen that when input energy is low, the output energy increases linearly, when input energy exceeds the limiting threshold, the increasing rate of output energy remarkably slows down, thus the system shows an optical limiting effect. The three curves show optical limiting behaviour in different pulse duration regions. They surely all have limiting characteristics but have different limiting thresholds and different limiting amplitude. We can say that the shortest laser pulse has the best limiting behaviour in which the output energy almost keeps a constant value and the limiting effect begins much earlier. This can be explained by the fact that for a given pulse energy, a shorter pulse has higher intensity, so the intensity threshold is reached at lower energy and limiting performance begins at lower energy level for a shorter pulse. In this regime, the SBS effect is more intensive than the others, and gives more smooth curve of output energy, so we can safely say this is the best theoretical limiting regime.

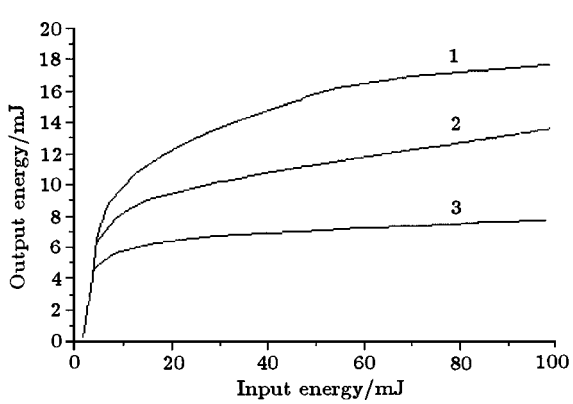


Fig.3. Theoretical simulations of optical limiting behaviour in CCl_4 for various pump pulse-widths 1—16ns, 2—7ns and 3—2ns.

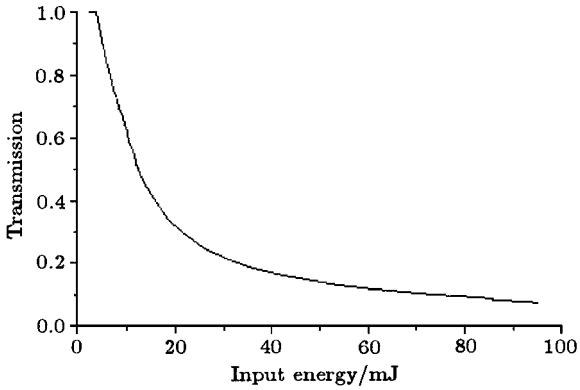


Fig.4. Theoretical transmission as a function of input energy (L=50cm, pump pulse-width 7ns).

Based on energy propagation characteristics shown by the above analysis of SBS process, we give computed numerical calculation of transmission graphically in Fig.4. This theoretical curve gives theoretical transmission as a function of input energy, which shows good optical limiting effect of CCl_4 to nanosecond laser pulses. As expected, the optical system shows optical limiting performance such that: at low input energy, laser pulses transmit in the medium linearly; the transmission can be almost as high as 100%, so the energy of transmitted pulse is about the same as the input energy. Once the input energy reaches a certain level, with increasing input energy the output energy declines sharply. We name this value of input energy as "limiting threshold $E_{\rm th}$". With the further increasing of input energy, the output energy begins to level off and keeps almost a constant value. We name the constant value of the output energy as "the limiting amplitude $E_{\rm am}$". Through theoretical analysis, we find that if input energy satisfies the condition $E_{\rm in} > E_{\rm th}(E_{\rm in} \geq 3E_{\rm th})$, the output energy will be sure to enter a good limiting regime. A good limiting regime means a high constant output energy for a wide range of input energy variations. The transmission becomes nonlinear and decreases sharply with increasing input signal energy. The above studies show that this optical system has good optical limiting effect. In view of the fact that not only time and power limiting but also energy limiting have been achieved here, we conclude that optical limiting effect can be realized on the basis of the process of SBS in CCl_4.

3. Experimental set-up

Figure 5 shows our experimental set-up for optical limiting studies based on SBS in liquid CCl_4. It consists of the following components: the Q-switch Nd:YAG laser provides a series of polarized laser pulses with single-longitudinal mode. The spatial beam profile is close to a quasi-Gaussian and 2.5mm in diameter. The parameters of the input laser beam are 1064nm wavelength, 90mJ input pump energy before attenuation. A variable optical attenuator consists of a rotatable half- wave plate and a polarizing prism, which can attenuate the laser beam intensity continuously without changing the temporal and spatial structure of the laser radiation. An isolator consisting of quarter-wave plate and a polarizing plate is used to prevent backward scattering beam from coupling into the laser system.

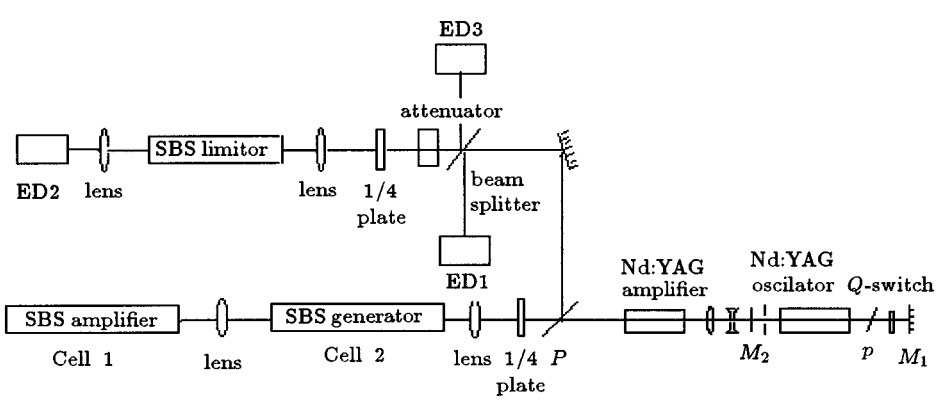


Fig.5. Experiment set-up.

In order to obtain laser pulses with widths varying from 16ns to 2ns, we use two SBS cells (1, 2) to control the pulse duration by adjusting the cell separation. The changeable laser beam is focused into a 50cm-long cell by a lens of focal length f=15cm. The pulse waveform is measured by a fast photodiode detector and pulse energy is detected by ED200 (ED200 is an energy detector used in visible and infrared). The signals both waveforms and energy are recorded by a digital oscilloscope (TDS684A). As can be seen from Fig.5, we first narrow the width of the laser pulse by SBS from 16ns to 7ns then to 2ns. We measure the output energy, temporal waveform nearfield of incident pulse and transmitted pulse. Then we establish the energy relationship between the output and input signals, and record the temporal waveform of both the input pulse and the transmitted pulse in our experiment.

4. Experimental results and discussions

In some applications, good pulses free from temporal oscillations may be required. In this case, it is better to obtain a temporally clean pulse with stabilization. So we pay much attention to experimental output of temporal profiles. The measured shape of the envelope of the transmitted pulse train are given in Figs.6 (a)–6(c). The envelope of the transmitted pulse train keeps the shape of the input pulse in the leading edge and the following edge descends sharply and ends with a low step. The reasons why the transmitted pulse shapes change in such way are discussed in the theoretical analysis. Ten selected pulse profiles are superimposed on the same graph. They only roughly agree with the theoretical curve when the pulses are wide as shown in Fig.6(a), while for short pulses the agreement is fairly good as shown in Fig.6(c). The reason can be explained as that when the input pulses are wide, all kinds of nonlinear effects can occur besides SBS during the interaction duration, such as the optical breakdown effect and nonlinear absorption, which produce additional oscillations for these transmitted signals. Measured transmitted pulses agree quite well with theoretical curve and oscillation almost disappears in transmitted pulse with 2ns input laser pulses, therefore the most stable waveform is obtained in this regime.

Our transmitted temporal waveforms for wide pulses (16ns) are just the same as other research results,[16,17] their research on SBS have also given broad and wide output pulse shape in nonlinear medium. Those SBS processes are in a regime close to steady state, the width of pulse is larger than the period of decaying oscillation, so there are more decaying oscillations in the duration of 16ns. When the duration of laser pulse is reduced to a level comparable with the period of decaying oscillation, decaying oscillations do not show up evidently, therefore the transmitted pulse shape becomes better with the width of input pulse becoming shorter (2ns).

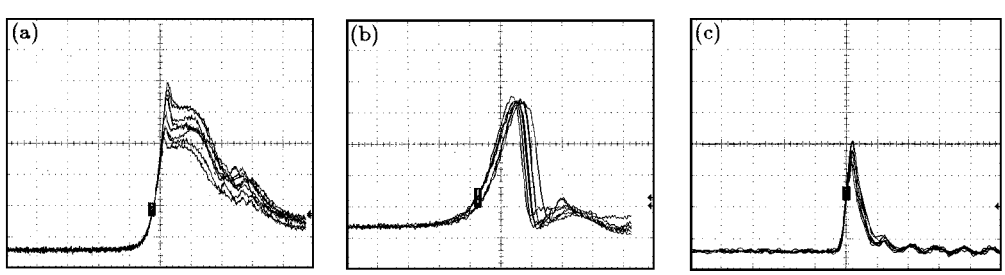


Fig.6. Experimental transmitted profiles for various pump pulse-widths ((a) 16ns, (b) 7ns, (c) 2ns).

The experimental energy data are given in Table 2, and plotted in Fig.7. The good optical limiting responses were obtained under the experimental conditions as shown. When the input signal is small, the energy of the output pulse depends directly upon the energy of the input pulse, increasing linearly with that of the input pulse. As soon as the energy of input pulse is raised up to the threshold level of SBS, the increasing rate of output energy begins to slow down. So the whole curve may be divided into two regions: a linear region and a limiting region. Because our experimental energy level is above the SBS threshold, our research has been focused on the latter region in which saturated output signal is essentially achieved. Optical limiting performance is optimal in short pulsewidth regime. Figure 7 also gives the fluctuation for

both transmitted and input signals. For laser pulses with energy varying from 14mJ to 88mJ and pulse-width of 2ns and the repetition rate 2Hz, the measured output energy is limited in a narrow range of 4.5 to 5.5mJ, which is much smaller than that of the input energy. It is obvious that the optical limiting effect has been achieved in our experimental range based on SBS in CCl_4. The reason why the experimental dots in the Fig.7 fall below the theoretical curves may be that we neglected absorption in the calculation, as well as other nonlinear optical effect such as optical breakdown. So much more energy will be lost in fact, resulting in lower transmitted energy level.

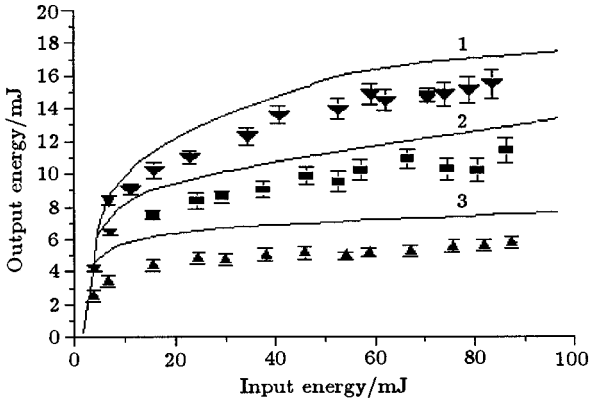


Fig.7. Input-output characteristic for CCl_4: the solid curves are theoretical curves and the dots are experimental results: 1—16ns, 2—7ns, 3—2ns.

Table 2. Experimental data (E_1, pump energy, E_2, transmitted energy).

E/mJ(2ns)	E_1	4.5	7.2	15.2	24.3	29.5	38.4	47.6	53.7	58.3	67.9	76.2	82.6	88
	E_2	2.9	3.4	4.5	4.7	4.1	5.2	4.9	5.1	5.5	5.5	5.4	5.3	5.5
	ΔE_2	0.19	0.20	0.18	0.21	0.22	0.23	0.24	0.25	0.28	0.24	0.23	0.29	0.30
E/mJ(7ns)	E_1	4.5	7.2	15.2	24.3	29.5	38.4	47.6	53.7	58.3	67.9	76.2	82.6	88
	E_2	4.4	6.8	6.9	6.3	6.4	6.8	7.5	7.3	7.7	8.3	7.8	7.4	8.7
	ΔE_2	0.20	0.22	0.20	0.34	0.29	0.39	0.41	0.46	0.46	0.50	0.62	0.68	0.69
E/mJ(16ns)	E_1	8.7	15.2	22.1	26.3	32.4	41.6	47.6	57.3	62.5	65.4	75.2	78.6	85
	E_2	8.5	9.6	11.0	11.4	12.1	13.0	14.2	14.3	14.9	15.1	14.6	15.2	15.4
	ΔE_2	0.18	0.22	0.21	0.37	0.30	0.39	0.39	0.40	0.45	0.47	0.55	0.68	0.7

5. Conclusions

In this paper, nonlinear propagation process of laser pulses in SBS medium has been investigated. We explored the optical limiting effect by analysing the nonlinear transmission behaviour of Nd:YAG nanosecond laser pulses based on SBS, both theoretically and experimentally. We made a detailed comparison of experiment and theory to determine the optimal condition for the optical limiting effect behaviour. For nanosecond excitation pulses, we observed both energy limiting and power limiting of the input signal. Our experimental results are in good agreement with the predictions of our theoretical analysis. A great deal of information on the optical limiting effect has been analysed, and an interesting suggestion for optical limiting based on SBS has been put forward. SBS is a promising mechanism for high-threshold optical limiter, which can be used as an optical protecting device for laser systems against unexpected accidents.

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