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Measurement of stimulated Brillouin scattering (SBS) threshold based on waveform variation of SBS optical limiting*

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This paper proposes a method for measuring the stimulated Brillouin scattering (SBS) threshold based on waveform variation of SBS optical limiting. The output waveforms for different pump power densities are numerically simulated, and validated in the Nd:YAG seed-injected laser system. The results indicate that SBS does not take place in the case of a low pump power density and thus the output power scales up linearly with pump power. Once the pump power density exceeds the SBS threshold, SBS takes place and thereby the energies are transferred from pump to Stokes. As a result, a small shoulder appears in the trailing edge of the output waveform, which provides another method to determine the SBS threshold.

Keywords: stimulated Brillouin scattering (SBS), SBS optical limiting, SBS threshold, waveform

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1. Introduction

During the past several decades, stimulated Brillouin scattering (SBS) has been a focus of theoretical and experimental investigations in the field of nonlinear phase conjugation, which is regarded as an effective way to recover beam front and thus can be exploited to improve beam quality greatly.[1−6] The SBS phase conjugation exhibits several advantages in terms of small frequency shift, simple configuration, high fidelity and high energy reflectivity. Research has demonstrated that the SBS medium plays a key role in optimizing the SBS performances.[7−12] In Refs.[11] and [12] the correlations between matter structure and SBS characteristics of perfluoro-compound (PFC) and perfluoropolyether (PFPE), which have low absorption coefficient and high power-load abilities, have been analysed. These series of PFCs and PFPEs can thus be used in the SBS phase conjugation mirror in the high-power laser system. The SBS parameters, including SBS threshold, gain coefficient, absorption coefficient, phonon lifetime, etc., show great importance in terms of the application of SBS.[13,14] Among these parameters, the determination of SBS threshold is very important and has been investigated in Ref.[15]. The SBS threshold value is experimentally defined to be the pump energy when the energy reflectivity is 2%, 3% or 5%, depending on the experimental condition.[16] In experiment, we found that the Stokes energy is usually very low with reflectivity below 5% and the backward reflection from optical components also affects the detection to a certain extent. Therefore, it may bring some inconvenience to the measurement when we use an energy detector with normal sensitivity.

In this paper, a method for measuring the SBS threshold according to the variation of the output waveform induced by SBS optical limiting is proposed. The output waveforms for different input power densities are numerically simulated, and validated in the Nd:YAG seed-injected laser system. When pump power density is low, SBS does not occur and the output power increases linearly with the input power. However, when the pump power slightly exceeds the SBS threshold, SBS takes place and leads to a quick

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energy transfer from pump to Stokes. As a result, a small shoulder appears in the back of the output waveform.[17−20] This shoulder is just the indication of SBS occurrence and can be used to determine the threshold value.

2. Theory

In the case of negligible absorption, SBS energy reflectivity is decided by the exponential gain coefficient G of the system[21,22]

$$G = gIL, \tag{1}$$

where g is the Brillouin gain coefficient, I is input power density, and L is the effective interaction length. The SBS threshold is often theoretically defined to be the input power density when $G = 25$.[21,22] The SBS threshold is defined in terms of power density rather than energy to facilitate the comparison between different experimental conditions. The system exponential gain coefficient is proportional to the input power density, which is related to the input energy by[23]

$$I = E/\tau_{\mathrm{p}}\pi\omega^2 = 4E/\tau_{\mathrm{p}}\pi f^2\theta^2, \tag{2}$$

where E is the input energy, $\omega = \theta f/2$ is the waist radius of the Gaussian beam, θ is the far-field divergence angle, τ_{p} is the pulse width and f is the focal length. Thus, the input power density is affected by the pulse width, divergence angle and focal length.

According to the theoretical model of SBS optical limiting given in Ref.[24], the transmitted waveforms are simulated with pump power density varying from 6.2 GW/cm^2 to 7.4 GW/cm^2, as shown in Fig.1. In the simulation, the incident light wavelength is 1064 nm, with a repetition rate of 1 Hz, pulse width of 8 ns, spot diameter of 10 mm, and divergence angle of 0.45 mrad. The cell length and focal length of the lens are 40 cm and 20 cm, respectively. The SBS medium is HT-230 with gain coefficient of 4.1 cm/GW and absorption coefficient of 10^{-3} cm^{-1}.

Figure 1(a) shows that when the input power density is 6.2 GW/cm^2, the output waveform is almost the same as the pump pulse. Figures 1(b) and 1(c) show that a small shoulder and an obvious shoulder can be observed in the back of output waveforms when the input power density increases to 6.8 GW/cm^2 and 7.4 GW/cm^2, respectively. This is because that when the pump power density is lower than the SBS threshold, the SBS process does not occur and the output power scales up linearly with the input power. However, when the input power density is 6.8 GW/cm^2, which is barely above the SBS threshold, the SBS process takes place, leading to the energy transfer from pump to Stokes. As a result, a small shoulder appears in the back of the output waveform. When the input power density increases to 7.4 GW/cm^2, a strong SBS process takes place and the shoulder is more obvious. The pump power density corresponding to the onset of the small shoulder in the transmitted waveform can be regarded as the SBS threshold, and thus the SBS threshold of HT-230 is 6.8 GW/cm^2.

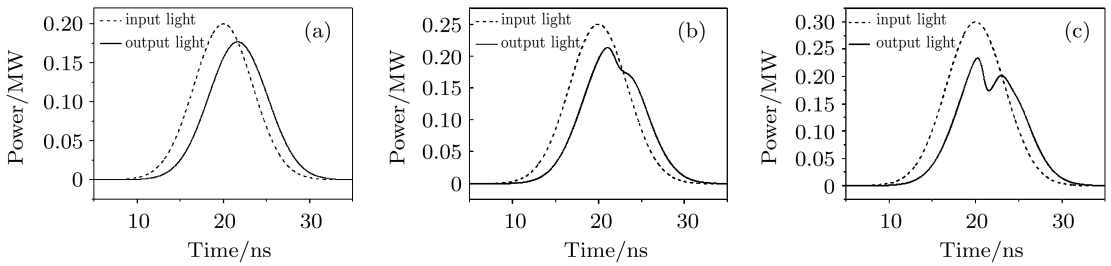


Fig.1. The output waveforms of SBS optical limiting with different pump power densities, (a) 6.2 GW/cm^2, (b) 6.8 GW/cm^2, (c) 7.4 GW/cm^2, respectively.

3. Experiment

The experimental setup is provided in Fig.2. The continuum's Nd:YAG seed-injected laser outputs s-polarized light, which becomes p-polarized after passing a 1/2 wave plate and then circularly polarized after passing a 1/4 wave plate. The SBS system comprises a generator cell and a focal lens L. The pump light is focused into the generator cell to produce Stokes light. Polarizer P together with the 1/4 wave plate forms a

light isolator, preventing the backward SBS light from entering the YAG oscillator. The Stokes light becomes s-polarized after passing the 1/4 wave plate, and is reflected by polarizer P. The pump energy can be adjusted by a 1/2 wave plate. The energies of the pump pulse, output pulse, and Stokes pulse are measured with an energy meter OPHIR. The pulse shapes are detected with a PIN photodiode, and recorded with a digital oscilloscope TDS684A.

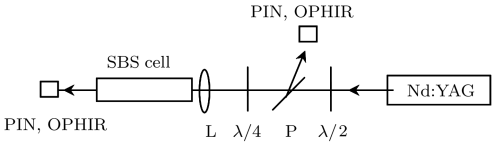


Fig.2. Experimental setup.

The experimental parameters are identical to those in the simulation. The output waveforms are shown in Fig.3, and agree well with the simulation results. From Fig.3, we can see that when the input power density is increased to 7.2 GW/cm^2, a small shoulder appears in the back of the output pulses. Therefore, we can regard the SBS threshold value of HT-230 to be 7.2 GW/cm^2. The measured SBS threshold is a bit higher than that of the theoretical simulation, which is caused by the energy loss induced by optical components. We also measured the thresholds of other media with this method and the results are listed in Table 1.[8,12,25]

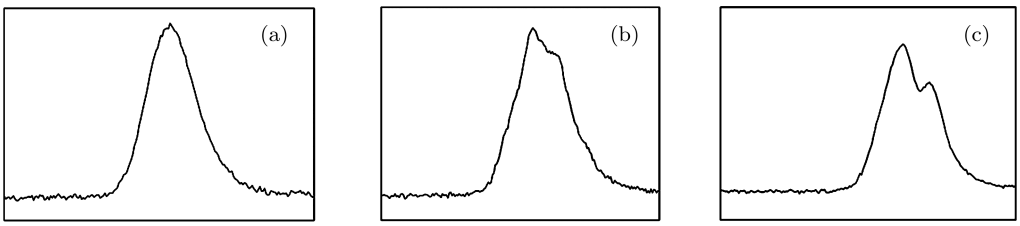


Fig.3. Experimental results of the output waveforms with different input power densities, the input power densities are (a) 6.2 GW/cm^2, (b) 7.2 GW/cm^2, (c) 8.2 GW/cm^2, respectively.

Table 1. SBS parameters of some new media.

liquid	absorption coefficient (cm^{-1})	optical breakdown threshold (GW/cm^2)	threshold power density (GW/cm^2)	Brillouin frequency shift (GHz)	SBS gain coefficient (cm/GW)	phonon lifetime (ns)
FC-72	$< 10^{-3}$	> 100	2.2	1.10	6.0	1.2
FC-75	$< 10^{-3}$	> 100	3.0	1.34	5.0	0.9
FC-43	$< 10^{-3}$	> 100	5.7	1.42	3.6	0.2
HT-70	$< 10^{-3}$	> 100	3.8	1.17	5.7	0.9
HT-230	$< 10^{-3}$	> 100	7.2	1.52	4.1	0.1

4. Analysis and discussions

The absorption to the pump is an important factor related to the SBS threshold value. For example, the gain coefficients of water, acetone and ethanol are higher than that of CCl_4; however, their thresholds are not smaller than that of CCl_4 because of their large absorption coefficients.[26,27] The influence of absorption on the focal length can be denoted as

$$I = I_0 \, \mathrm{e}^{-\alpha L}, \tag{3}$$

where I is the power density at focus, I_0 is the input power density just at the front facet of the cell, α is the absorption coefficient. L is the effective interaction length and can be approximated by Eq.(4) when the lens is put close to the cell[28]

$$L = nf, \tag{4}$$

where n is the refractive index, f is the focal length. From Eqs.(3) and (4), we can see that a long focal length will result in large energy absorption since a long effective interaction length is preserved. Therefore, the power density at the focus is low and the measured SBS threshold is comparatively high.

Another aspect in the experiment and simulation we should pay attention to is that how big the shoulder should be in order to call it a signature of the SBS threshold. In fact, it is the same question as what percentage should be chosen when we use energy reflectivity to determine the SBS threshold, since different choices result in different threshold values. Actually, we can add the pump energy gradually, i.e., by a small interval of 0.1 mJ every time in the simulation and experiment. Once the transmitted waveform varies in comparison with the pump, we can say that it reaches the threshold value and the SBS process occurs.

5. Conclusions

In this paper, a method for measuring the SBS threshold according to the waveform variation based on SBS optical limiting is proposed. Both the simulation and experiment indicate that SBS does not occur when the input power density is low. Therefore the output pulses have almost the same waveforms as the input pulses. However, when the pump power density exceeds the SBS threshold, a small shoulder appears in the back of the output waveform, which can be used to judge the occurrence of SBS.

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