A new method for measuring the threshold of stimulated Brillouin scattering*

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A new method for measuring the threshold of stimulated Brillouin scattering (SBS) based on the generation location of a Stokes beam is proposed for the first time to our knowledge. The length of the medium cell is selected to be longer than the free gain length of pump pulses in the Brillouin medium. The reflected light from a certain mirror in front of the medium cell is chosen as the reference beam, and the SBS threshold is measured by the "jump" of the delay between the Stokes beam and the reference beam. An 8-ns Q-switched single-longitudinal-mode pulse is used as the pump and the typical SBS medium FC-72 is selected as the nonlinear medium in our experiment. The SBS threshold intensity is measured to be 173–178 mW/cm^2, which is consistent with existing results measured with the transmitted energy limiting method.

Keywords: stimulated Brillouin scattering (SBS), threshold, amplified Brillouin scattering (ABS), delay

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1. Introduction

During the past decades, stimulated Brillouin scattering (SBS) has attracted attention owing to its broad applications, such as the maintenance of the beam front distortion with SBS phase conjugation mirror,[8] pulse compression,[9,10] laser beam combination,[12–14] Brillouin amplification,[15,16] optical limiting applied for the high power protection,[17,18] slow light effect in the fiber,[19,20] distributed temperature/strain optical fiber sensing,[23–25] and optical signal restoration.[21] Among various parameters which affect the SBS characteristics, the SBS threshold value is very important and lots of work has been done to find how to determine this value in recent years.[1–3,6,7] The initial definition of the threshold is the pump intensity at which the gain of Stokes signal exceeds its loss. However, many SBS media are characterized by weak loss, leading to the difficulty in determining the SBS threshold with this method. In practical applications, the threshold is commonly regarded to be achieved when the reflectivity of Stokes energy relative to the pump energy is raised to some certain value (usually 1%–5%).[1–7] Nevertheless, this is an ambiguous definition because different threshold values will be obtained when different percentages are chosen as the criteria.

Recently, researchers indirectly detected the SBS threshold by characterizing the transmitted beam. This method can overcome the drawbacks of methods of directly measuring the reflected beam, because the reflected Stokes power is too weak to be detected with the threshold pump power. Bai *et al.* proposed a method to measure the SBS threshold with different attenuation coefficients of broadband and narrowband lasers in the Brillouin medium.[1] This method is effective for many kinds of materials, but it is not practical when some media such as FC-72 and FC-75 since the SBS can also be induced effectively with a broadband pump.[3] Hasi *et al.* assumed that the threshold can be measured by investigating the optical limiting effect of the transmitted waveform. They defined the SBS threshold as the pump power at which the limiting shoulder begins to arise owing to the reflection of Stokes beams. This method is practically simple, but at some certain condition the obtained value is not accurate and depends on the stability of the pump waveform. Gao *et al.* reported that the SBS threshold

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can be measured by energy limiting of the transmitted beam.[3] They linearly fit the transmitted energy below and above the threshold, and defined the pump energy with respect to the intersection point of the two lines as the SBS threshold. This method can be used in almost all kinds of materials and is independent of the waveform stability. However, there are also some disadvantages to be taken into consideration. The SBS derives from the spontaneous Brillouin scattering of thermally induced refractive modulation. The spontaneous scattering Stokes beam is amplified by the acoustic field and pump beam to become amplified Brillouin scattering (ABS). When the pump intensity is increased to the level of the SBS threshold, the SBS effect arises. In other words, the whole generation process of SBS evolves from spontaneous Brilouin scattering to SBS through ABS. The SBS can never be distinguished from ABS with Gao's method because the cross point may stay in the ABS region.

In this paper, a new method is proposed to accurately measure the SBS threshold. This method is mainly based on the spatial generation location of the Stokes light in the medium cell with the pump intensity being lower or higher than the SBS threshold. The principle of this novel method and the experiment results will be described in this paper. This method is very simple to be operated, the whole measurement time is shorter than other methods, and most importantly, this method is more accurate than Gao's method because the SBS can be distinguished clearly from the ABS.

2. Operation principles

The principle of our method is based on the following three points. Firstly, it has been verified theoretically and experimentally that the reflected beam from the medium cell is only SBS light when the pump energy is controlled in a certain range.[1] When the laser pulse width is longer than the phonon lifetime of the material, the threshold of SBS is far lower than that of the stimulated Raman scattering (SRS). The threshold of stimulated thermal scattering is far higher than that of the SRS. Meanwhile, other nonlinear effects such as self focusing can be suppressed effectively.[1,3] The Rayleigh scattering beam features no frequency shift so that it cannot be amplified by interacting with the subsequent pump pulse. Thus, when the pump intensity reaches the SBS threshold, the backscattered light features Brillouin scattering only.

Secondly, when a high power single-mode laser beam irradiates directly on the windows of the Brillouin cell, it will be reflected and guided in the opposite direction of the pump beam. If a broadband light is chosen as the pump, the sideband of the power spectrum may overlap with the Brillouin gain spectrum of the medium. Then the reflected beam can be amplified by the pump to some degree, just like a seed guided into the medium cell in the opposite direction of the pump beam. This is the so-called self seeding scattering model.[22]

Thirdly, the Brillouin cell contains randomly distributed thermal noise, which can induce spontaneous Brillouin scattering. The Stokes beam of the spontaneous scattering is amplified to form ABS, and the evolution from ABS to SBS occurs with the increase of pump intensity.

The schematic diagram of the principle of our threshold evaluation method is shown in Fig. 1, where L is the length of the cell filled with a Brillouin medium, A and B represent the two window mirrors of the medium cell, and C denotes the location, from which to the front mirror A is equal to the free gain length[1,3] (FGL, $l_{\rm FG} = \tau_{\rm p}c/2n$, where $\tau_{\rm p}$ is the pulse width of the pump, n represents the refractive index of the Brillouin medium, and c is the light velocity in the vacuum) of the pump pulses. The FGL may change in a small range with the average length corresponding to half of the pulse width when a Gaussian-shaped laser pulse is used as a pump. That is to say, position C, as the center, is changed in a small range. It can be seen clearly from Fig. 1 that the length of the medium cell is larger than the FGL of the laser pulses.

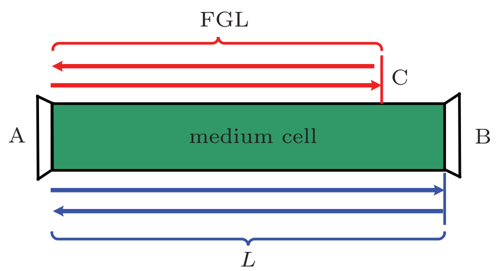

Fig. 1. (colour online) Schematic diagram of the SBS threshold measurement.

The reflection from mirror B provides a seed, which is much stronger than spontaneous Brillouin scattering, and the detected back scattered beam originates mainly from location B if the input energy is below the SBS threshold. However, when the pump intensity is increased to the level of SBS threshold, the Stokes beam generated at location C propagates in the opposite direction of the pump beam and is amplified greatly by the stimulated scattering process. The generation point of the detected Stokes beam evolved from point B to point C. The reflected pump beam from the window mirror A was chosen to be the reference beam, and the delay between this reference beam and the reflected beam from the Brillouin cell was measured. At a low pump intensity, the measured delay is expressed as $\Delta t_1 = 2nL/c$. The delay remains constant with the increase of the pump intensity in a certain range below the SBS threshold. The delay "jumps" to $\Delta t_2 = 2nL_{\rm FG}/c$ when the pump intensity approaches the threshold level. In this paper, the pump intensity at which the measured delay "jumps" from Δt_1 to Δt_2 is defined as the pump intensity threshold.

3. Experimental setup

The experimental setup is shown in Fig. 2. The laser system used in our experiment is an injected–seeded Nd:YAG laser (continuum powerlite precision II 9010) with a line width of 90 MHz, a pulse width of 7–8 ns, and a diffraction angle of 0.45 mrad. The laser wavelength used is 1064 nm, the repetition rate is 1 Hz, and the beam diameter is 8 mm. The pulse energy can be adjusted by rotating the angle of the half-wave plate with respect to the polarizer P. Initially, the laser beam is s-polarized. It passes through a half-wave plate and is split into two parts by the polarizer P. The reflected part is guided into an optical dump. The transmitted p-polarized beam becomes circularly polarized after passing through a quarter-wave plate and is divided into two beams by a beam-spliter with a small reflectivity of k. The reflected beam from the beamspliter is detected with an ED (PE50DIF-ER, Ophir). Suppose that the reflected energy detected by an ED is E_0, the pump energy injected into the medium cell can be deduced simply as $E_{\rm p} = (1-k)E_0$. The generated backward Stokes light becomes s-polarized after passing the quarter-wave plate again and is reflected by the polarizer P. This design forms an isolator, preventing the backward Stokes light from entering the laser source. The waveform of the reflected beam is detected by a PIN photodiode, and recorded by a digital phosphor oscilloscope TDS3032B. The reflected energy is measured by an ED (PE50DIF-ER, Ophir). The distance between the quarter-wave plate and the front window of the medium cell is denoted as L_1, and the length of the cell is denoted as L_2.

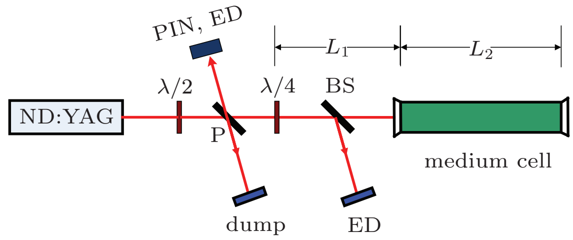

Fig. 2. (colour online) Schematic diagram of the experimental setup.

In our experiment, FC-72 was chosen as the Brillouin medium, and the cell length $L_2 = 113$ cm. The refractive index of FC-72 is 1.251.[11] In the case of Gaussian pulses with a pulse width of 8 ns, the FGL is equal to 96 cm in this material, which is in consistent with our design principle (smaller than L_2). It can be seen from Fig. 2 that the light beam transmitted from polarizer P may be reflected backward by the $\lambda/4$plate and the two window mirrors of the medium cell. To eliminate the effect of the reflected beam of the window mirrors, a small angle was made for detuning the cell axis from the direction of the pump light. The distance between the $\lambda/4$ plate and the front window is 123 cm (i.e., $L_1 = 123$ cm). As shown in Fig. 3, the backward output beam from the polarizer P contains two components, which is recorded by a CCD camera. The left part I is the beam reflected by $\lambda/4$ plate, showing the characteristic of the pump beam, and the right part II is the Stokes beam generated in the medium cell. To separate the reference beam and the Stokes beam, we adjust the direction of $\lambda/4$ plate by a very small angle to detune from the light path, and the CCD camera was placed at about 2 meters

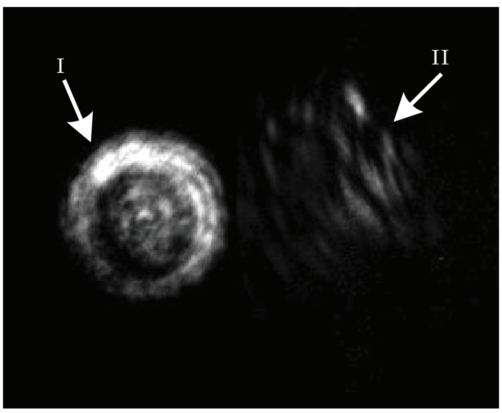

Fig. 3. The transverse intensity distribution of the reflected beam (I represents the reference beam and II denotes the Stokes beam).

away from the polarizer. The reflected pump beam was chosen as the reference beam, and the delay between the reference and the Stokes beam is investigated to evaluate the SBS threshold.

4. Results and discussion

The pulse shape of the reflected beam recorded in our experiment is shown in Fig. 4. It can be seen from Fig. 4 that a single shot of the laser radiation contains two peaks. The earlier one is attributed to be the pump component (reference beam) and the later one stems from the Stokes light. Their delay is measured to be 17.2 ns with the pump energy lower than 330 mJ, and keeps good stability. However, when the pump energy was increased to 340 mJ, the delay became 15.9 ns. The delay decreases with the increase of the pump energy when the energy is beyond the SBS threshold. According to the principle of our method, the SBS threshold energy for FC-72 under our experiment condition is in the range of 330–340 mJ, and the threshold intensity is in the range of 172.9–178.1 MW/cm^2.

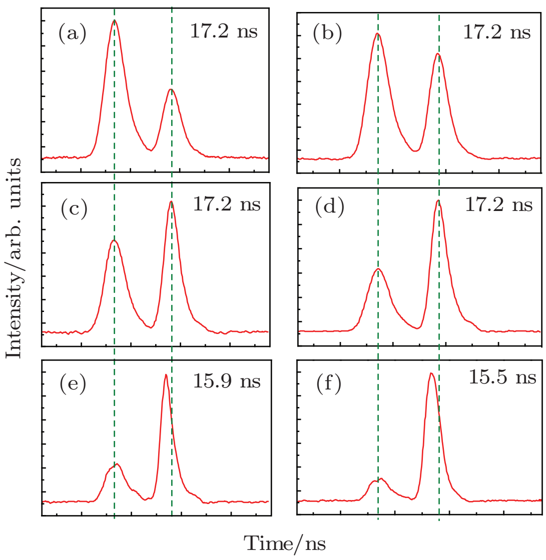

Fig. 4. (colour online) Waveform of the reflected beam with a pump energy of (a) 260, (b) 300, (c) 320, (d) 330, (e) 340, and (f) 350 mJ.

According to Section 2, the backward Stokes light is generated from the rear window of the medium cell when the pump energy is below the threshold level. That is to say, the measured delay is the double pass time of the light between $\lambda/4$ plate and the end window mirror of the cell. Given that the refractive index of FC-72 is 1.251, the delay can be calculated: $\Delta t_{\mathrm{bth}} = 2(L_1 + nL_2)/c = 17.62$ ns. When the pump energy approaches the threshold level, the delay is the double pass time of FGL, which is expressed as $\Delta t_{\mathrm{th}} = 2(L_1 + nl_{\mathrm{FG}})/c$, and equals 16.2 ns. Here, we use the subscription "bth" and "th" to distinguish delays with pump energy below and close to the threshold.

The measured delay is in good agreement with theoretical calculations. However, there is still a deviation which is due to the following reasons: first, the refractive index used in the calculation may not be the real index of FC-72, which depends on the accuracy of the index measurement; second, the discrepancy may be caused by the assumption of FGL which actually represents a certain range, while the above calculation is based on the location of point C.

The SBS energy reflectivity around the threshold was also measured in our experiment. We detected the reflected Stokes energy after filtering the pump component out. The Stokes energy was measured to be about 7.3 mJ while the pump energy is 340 mJ, with the reflectivity being 2.2%, which is in accordance with the general criteria of threshold reflectivity.

To further validate the accuracy of our method, the transmitted energy limiting method reported in Ref. [3] was used to be compared. The experimental setup was identical to that described in Ref. [3] and the material was also FC-72. The relationship of the transmitted and input intensities is shown in Fig. 5. It can be seen that the threshold intensity is 174.4 MW/cm^2 (with respect to the threshold energy of 331.4 mJ), which is in good agreement with the result of our newly proposed method.

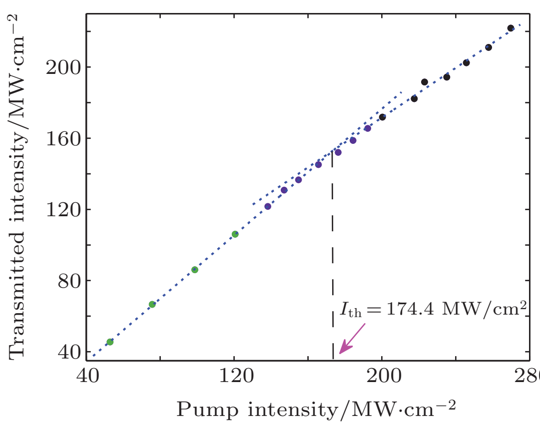

Fig. 5. (colour online) The relationship between the transmitted and pump intensities.

5. Conclusions

In summary, a new method of determining the SBS threshold based on the generation location of the backward Stokes beam is proposed, with which the SBS threshold of FC-72 was measured experimentally. The principle of this measurement is described as follows. When the pump intensity is beyond the SBS threshold, the Stokes beam generates originally in the leading edge of a Gaussian pulse. That is to say, the effective interaction length equals the FGL of the laser pulses in the medium while the length of the material cell is designed to be longer than FGL. However, when the incident pump intensity is lower than the threshold intensity, the reflected Stokes beam may originate from the rear window of the medium cell. The pump intensity at which the generation location "jumps" from the rear end of the Brillouin cell to the inside of the medium cell was defined as the threshold intensity, and this critical point can be found out by measuring the delay between the Stokes light and the reflected pump beam from the front window. The SBS threshold intensity of FC-72 was measured to be in the range of 173–178 MW/cm^2 with this newly proposed method. For comparison, the threshold was measured under the same condition with the method of transmitted energy limiting reported in Ref. [3], and the obtained value was 174.4 MW/cm^2 which is in good agreement with that of our new method.

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