Experimental investigation on the improvement of SBS characteristics by purifying the mediums

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The influence of optical breakdown on stimulated Brillouin scattering (SBS) process is investigated with purified CCl_4, acetone, and CS_2 mediums which are obtained through 0.22-μm pore-size filter. Experiments are conducted with a Nd:YAG *Q*-switched laser system. The optical breakdown threshold, the reflectivity and the stability of SBS in both purified and unpurified mediums are determined and compared. The improvement of optical breakdown threshold is observed more or less in all purified mediums. In the condition that optical breakdown does not occur after the medium purified, the energy reflectivity and the stability of SBS both show improvement. Therefore, the characteristics of SBS can be improved by purifying the mediums to obtain higher optical breakdown threshold which reduces the influence of optical breakdown on SBS process.

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Stimulated Brillouin scattering (SBS) has long been the focus of extensive theoretical and experimental investigation for its phase conjugation ability which can be used to compensate the phase aberrations during light transmission and thus improve the beam qualities[1,2]. Experimental study has shown a correlation between the optical breakdown effect and the characteristics of SBS such as phase conjugation fidelity, energy reflectivity and stability[3,4]. The threshold of optical breakdown is found not only dependent on the chemical structure of the medium but also on the size of indissolvable dust particles in the medium. It is believed that particles ranging from several to several tens of micrometers strongly absorb the photons in the light path. Some of the particles ionize and cause micro explosion due to the heating effect of light, and optical breakdown is likely to occur in such environment. According to this concept, purification of the medium could increase the threshold of optical breakdown and therefore improve SBS performance. Unfortunately, although great manufacturing effort has been paid to improve the chemical purity of the solvents, many commercially available solvents still contain too many unwanted particles. Therefore, it is suggested to purify the medium before SBS experiment with filtration[5] and distillation[6].

In this paper, we report our work on the improvement of SBS characteristics by purification of mediums. We used filtration method to purify several types of medium and examined the optical breakdown threshold, the energy reflectivity and the stability of SBS induced by a Nd:YAG *Q*-switched laser before and after purification. The influence of optical breakdown on the SBS characteristics was also discussed.

Figure 1(a) shows a filtration device which uses a micro-pore membrane to separate solid particles from liquid. The device comprises a cup, a funnel, a collector, a clip, and a vacuum pump. The filter membrane whose pore-size may be 0.22, 0.45, 0.8, 1.2 μm, etc. separates the device into two parts, namely the upper and the lower part. The unfiltered solvent is added into the upper part, under the pressure of graviton, the solvent passes through the membrane into the lower part and becomes filtrate, the particles held by the membrane form residue.

Figure 1(b) shows a distillation device in which liquid is heated and becomes vapor, and then the vapor returns to liquid state through a condensation process. The device comprises a distillation flask, a condensation tube, a receiver, and a heater. When it is working, liquids that have lower boiling point are vaporized, liquids that have higher boiling point and non-volatile particles are held in the flask. Therefore the liquid is purified. High purity medium can be obtained by repeating this distillation procedure or by fractionation[7].

In the experiment, the device shown in Fig. 1(a) was adopted to purify CCl_4, acetone, and CS_2 liquids. Because no significant increase in optical breakdown threshold was observed when the pore-size of filter membrane was greater than 0.45 μm, we chose 0.22-μm pore-size membrane instead which proved much better. The parameters of the chosen liquids are listed in Table 1. All data are given for 1.064-μm wavelength at 20 °C. Parameters marked by "*" are given by our experiments,

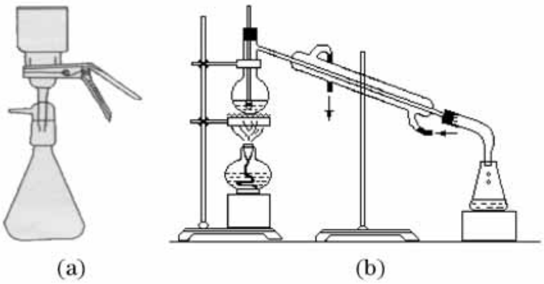

Fig. 1. Purification device. (a): Filtration method; (b): distillation method.

Table 1. SBS Parameters in Liquid Mediums

Parameter	CCl_4	Acetone	CS_2
Refractive Index	1.460	1.358	1.595
Absorption Coefficient (cm^{-1})	0.003^*	0.022	0.003^*
SBS Threshold (mJ)	3	7	6
SBS Gain Coefficient (cm/GW)	6	15.8	68
Phonon Lifetime (ns)	0.6	2.67	6.4
Unpurified Optical Breakdown Threshold (GW/cm^2)	8^*	16^*	20^*

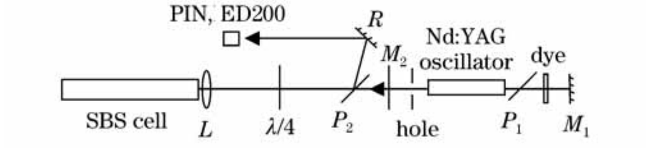

Fig. 2. Experiential setup of SBS.

others are quoted from Refs. [8,9].

The experimental setup is shown in Fig. 2. The Nd:YAG Q-switched laser system comprised a full reflection mirror M_1, a Q-switch dye plate, a polarizer P_1, a Nd:YAG rod, a hole, and a partial reflection mirror M_2. Polarizer P_2 was placed in parallel to P_1 so that P_2 and the 1/4 waveplate formed an isolator, which could stop the backscattered SBS light from entering the YAG oscillator. The p polarized light output by the oscillator became circular polarized light when passing through the 1/4 waveplate and then entered the SBS system. The SBS system consisted of a focus lens and a generator cell of 400-mm length. The Stokes light became s polarized light when passing through the 1/4 waveplate and was reflected to mirror R by polarizer P_2. The incidence light and SBS light were detected by energy meter ED200. The pulse duration and pulse shape were detected by PIN photoelectric diode and recorded by oscilloscope TDS684A. CCD camera was used to capture the sparkles caused by optical breakdown. In order to demonstrate the influence of focus lens on optical breakdown effect, we used two lenses, the focus of which were 50 and 150 mm, respectively.

The wavelength of the pump light output by the Nd:YAG Q-switched laser was 1.064 μm, the laser operated at 1-Hz repetition rate, 10.0-ns pulse duration, 50.0-mJ peak energy, and 1.6-mrad beam divergence. The pulse energy was controlled by placing attenuators in the light path.

Defined as the input light intensity at which value the probability of seeing sparkles and flares in the medium is 50% using 50-mm focus lens[10], the optical breakdown threshold was measured before and after purification. It was observed that the optical breakdown threshold of CCl_4 increased from 8 to 20 GW/cm^2, that of acetone increased from 16 to larger than 100 GW/cm^2 (no visible optical breakdown was observed even if the pump energy reached 50 mJ), and that of CS_2 increased from 20 to 24 GW/cm^2. The difference between the increase rates could be explained by the difference in particle size and density in the medium which were produced by different manufacturers.

The optical breakdown is a complex process which is caused by avalanche ionization and generates plasma in the medium. The avalanche ionization starts from a few free electrons in the medium. When the plasma area is formed, sparkles and flares could be seen. The process of optical breakdown in CCl_4 medium can be described as follows[3]: the dust particles in the medium absorb light and release a small number of free electrons. Those electrons combine with CCl_4 molecules to form CCl_4^- molecular ions, which soon become Cl^- ions and CCl_3 free radicals, the Cl^- ions tend to loose their electrons easily at the presence of strong light, so a large number of electrons accumulate in the medium and whereby the avalanche ionization initiates.

The threshold of optical breakdown is dependent on the size and density of the particles. In addition, it is also dependent on the chemical structure of the medium[5]. The closer the chemical bonds are surrounded by the outer atoms, the higher ionization energy (the minimum amount of energy required to remove the least strongly bound electron from a gaseous atom or ion is called the ionization energy), the lower electron affinity (electron affinity of an atom (molecule or radical) is defined as the energy difference between the lowest (ground) state of the neutral and the lowest state of the corresponding negative ion in the gas phase), and the higher bond dissociation energy (the bond dissociation energy (enthalpy change) for a bond $A-B$ which is broken through the reaction $AB \to A+B$ is defined as the standard enthalpy change for the reaction at a specified temperature, here at 298 K) are needed, the more difficultly the molecule ionizes or breaks up, and therefore the higher the optical breakdown threshold is. On the other hand, the higher absorption rate the medium has, the stronger attenuation the pump light will experience before reaching the focus area, and thus the less possibility of the optical breakdown will occur. In CS_2 molecules, for example, the C=S is a double bond, whereas in CCl_4 molecules the C−Cl is a single bond, and C=S bond energy is higher than C−Cl bond (578 and 327 kJ/mol, respectively), so the optical breakdown threshold of CS_2 medium is higher than that of CCl_4. As for the acetone, its absorption rate is ten times more than that of CCl_4 and CS_2, so its optical breakdown occurs less likely when the density of particles is small.

Figure 3 shows SBS energy reflectivity as a function of input pulse energy in CCl_4 medium before and after purification. In the condition that a 50-mm focus lens was used, optical breakdown occurred in both purified and unpurified CCl_4 medium, this could explain why they have similar energy reflectivity and tendency. When the pulse energy was lower than 25 mJ, only weak optical breakdown was observed (weak sound and dim sparkles as shown in Fig. 4(a)), and its influence on energy reflectivity was small. As the pulse energy increased, energy reflectivity increased nonlinearly, it was because the light intensity in the focus area increased with the pulse energy, which enhanced the SBS energy conversion efficiency. However, when pulse energy grew larger than 25 mJ, optical breakdown became stronger (louder sound

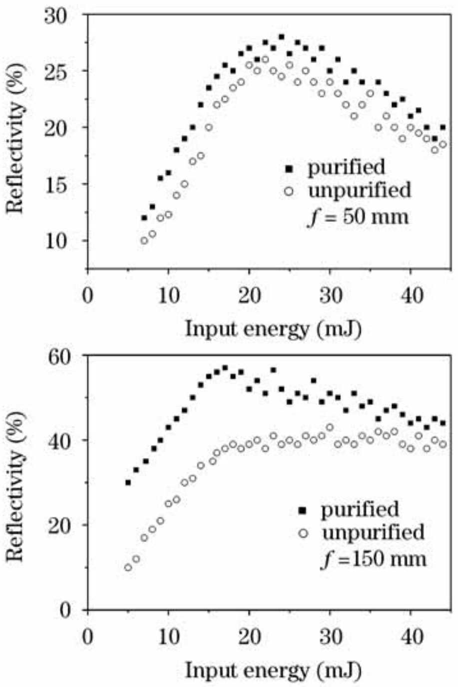

Fig. 3. Dependence of reflectivity on the input laser pulse energy in purified and unpurified CCl_4.

(a) 10 mJ (b) 30 mJ

Fig. 4. The sparkles caused by optical breakdown in CCl_4.

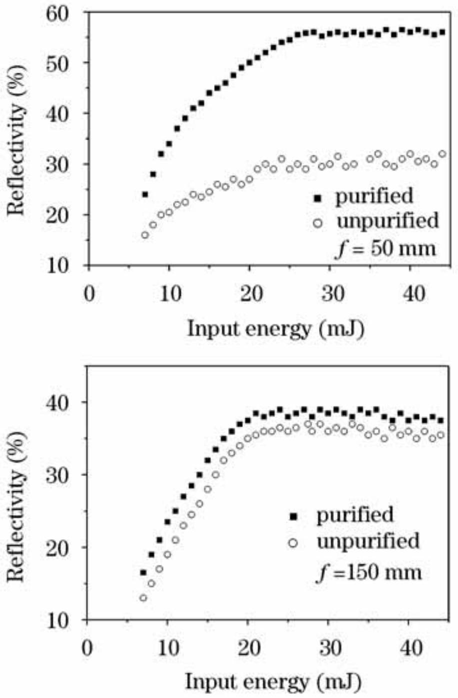

Fig. 5. Dependence of reflectivity on the input laser pulse energy in purified and unpurified acetone.

(a) 10 mJ (b) 30 mJ

Fig. 6. The sparkles caused by optical breakdown in acetone.

and brighter sparkles could be seen, as shown in Fig. 4(b)), its influence on energy reflectivity became larger, therefore the energy reflectivity began to decrease as input pulse energy increased. Severe optical breakdown acted as a limiting factor of the maximum energy reflectivity and stability (defined as the ratio of mean square value to arithmetic mean value of the measured data), which were 28% and 7% respectively. In the condition that a 150-mm focus lens was used, no optical breakdown was observed at first in purified CCl_4 medium when pulse energy was smaller than 20 mJ, whereas distinct optical breakdown was observed in unpurified CCl_4 medium, which showed that purified medium had better SBS characteristics in terms of energy reflectivity and stability. Experimental data showed that the maximum energy reflectivity had increased from 40% to 60%, and stability improved from 6% to 4%. However, when the input pulse energy grew larger than 20 mJ, optical breakdown occurred in purified CCl_4 medium, and energy reflectivity as well as stability began to decrease until reaching the same level of the unpurified CCl_4 medium.

Figure 5 shows SBS energy reflectivity as a function of input pulse energy in acetone medium before and after purification. In the condition that a 50-mm focus lens was used, optical breakdown occurred in unpurified medium but did not occur in purified medium. The SBS energy reflectivity and stability showed significant improvement using purified acetone medium. The maximum reflectivity increased from 30% to 60%, and stability improved from 5% to 3%. Although optical breakdown occurred in unpurified acetone medium, the effect was weak regardless of the pump energy (as shown in Fig. 6), and had only weak influence on energy reflectivity. As the input pulse energy grew stronger, the energy reflectivity increased nonlinearly until reaching a maximum value which indicated the saturation of energy conversion efficiency. It was predicted that if the input pulse energy became even stronger and optical breakdown was significant, the energy reflectivity would drop. In the condition that a 150-mm focus lens was used, no optical breakdown occurred in both purified and unpurified acetone mediums, and the energy reflectivity and stability were similar. However, the maximum energy reflectivity was lower than that using 50-mm focus lens, this was mainly because the acetone medium absorbed more pump and Stokes light energy when the focus length was longer.

Figure 7 shows SBS energy reflectivity as a function of input pulse energy in CS_2 medium before and after purification. No significant improvement in optical breakdown threshold was observed after the purification of CS_2 medium, so the energy reflectivity and stability were similar before and after purification. In the condition that a 50-mm focus lens was used, optical breakdown occurred in both purified and unpurified medium. Although optical breakdown occurred, it was weak for all pump energy

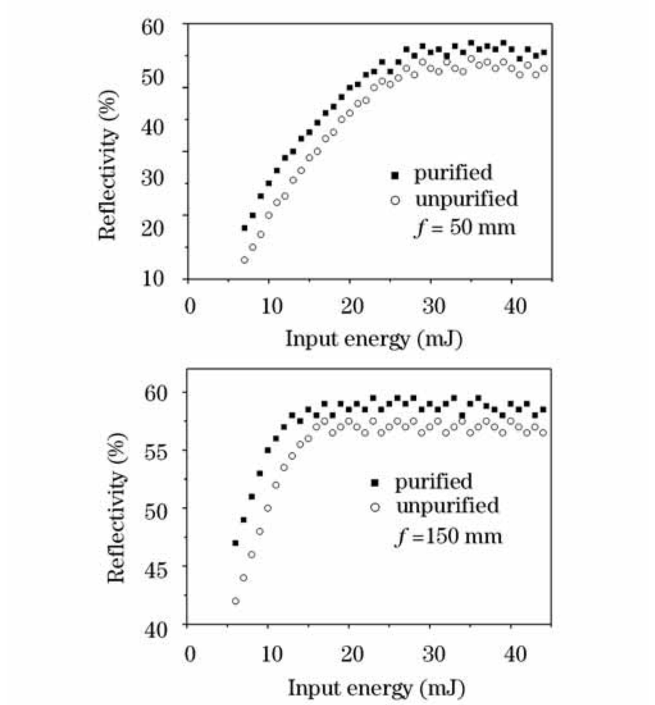

Fig. 7. Dependence of reflectivity on the input laser pulse energy in purified and unpurified CS_2.


(a) 10 mJ (b) 30 mJ

Fig. 8. The sparkles caused by optical breakdown in CS_2.

(as shown in Fig. 8), so it produced little influence on SBS energy conversion efficiency. As the input pulse energy grew stronger, the energy reflectivity increased nonlinearly until reaching a certain value which indicated the saturation of energy conversion efficiency. In the condition that a 150-mm focus lens was used, no optical breakdown occurred in both mediums and the energy reflectivity and stability were similar. Because CS_2 has a large gain coefficient and a small absorption rate, its maximum energy reflectivity was high.

The optical breakdown threshold of a medium is dependent not only on the chemical structure of the medium but also on the size of the indissolvable dust particles in the medium. Because most commercially available chemical solvent contains dust particles which are different in size and density, the optical breakdown threshold of a medium could be increased by purification, and the improvement depends on the size and density of the particles. Optical breakdown is a limiting factor of the SBS energy reflectivity and stability. If the optical breakdown is successfully prevented by purification of the medium in which optical breakdown will occur without purification, the SBS energy reflectivity and stability will show significant improvement. On the other hand, different mediums have different optical breakdown threshold and produce different influence on SBS characteristics. In this paper, the influence of optical breakdown on SBS phase conjugation fidelity is not discussed, but we predict that there must be a correlation between them.

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