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Research on the enhancement of power-load of two-cell SBS system by choosing different media or mixture medium

W.L.J. HASI, Z.W. LU, Q. LI, AND W.M. HE
Institute of Opto-Electronics, Harbin Institute of Technology, Harbin, China

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Abstract

In order to enhance the power-load of two-cell stimulated Brillouin scattering (SBS) system, methods of using different media and mixed medium are proposed. In theory, the amplification function of two-cell system of different medium with close vicinity in the Brillouin frequency shift (BFS) is analyzed. Also the variation of BFS of the mixed medium with the mixing ratio is analyzed. In the two-cell SBS system pumped by Q-switched Nd:YAG laser, the SBS system performance characteristics are investigated with different media and mixed medium. The experimental results indicate that the Stokes can be sufficiently amplified by choosing different medium with close vicinity in the BFS; the power-load performance is enhanced as well as the maximum amplification efficiency the Stokes by choosing mixed medium.

Keywords: Brillouin frequency shift; Power-load; Stimulated Brillouin scattering

1. INTRODUCTION

For the past several decades, stimulated Brillouin scattering (SBS) has been a focus of theoretical and experimental investigation (Kong *et al.*, 2005*a*, 2005*b*, 2006; Lu *et al.*, 2006; Lontano *et al.*, 2006). An important property of SBS is phase conjugation which can be exploited to recover the phase front of a beam, and thus improve the beam quality (Zel'dovich *et al.*, 1972). An experimental setup that utilizes the SBS phase conjugation property is often referred to as the phase conjugation mirror (PCM). In practice, PCM can take on different forms. For example, focused single cell, compact two-cell system, and independent two-cell system are all typical configurations. The last two can be further generalized as a generator-amplifier two-cell system, since both of them consist of a generator and an amplifier (Crofts *et al.*, 1991; Hull *et al.*, 1989; Miller *et al.*, 1989). This paper will focus on the generator-amplifier two-cell system. In a generator-amplifier two-cell system, a Stokes seed light is generated by the generator, and then progarates through the amplifier where it interacts with the pump light and is amplified. The Stokes wavefront always receives the greatest amplifcation, thus PCM output a narrow Stokes pulse with significantly enhanced instantaneous power density.

Until recently, most experiments used the same medium for the generator and the amplifier. Besides simplicity, another important reason for choosing the same medium is that the frequency difference between the pump light and Stokes seed light would match the Brillouin frequency shift (BFS) of the amplifier medium. In the case of matched BFS, the pump wave and Stokes wave would drive a third accoustic wave which out performed its competing accoustic modes generated through noise, thus SBS setup more quickly over unmatched cases. However, for certain applications, the one-medium system may exhibit several short comings. For example, many SBS mediums which are commonly used as generators have large absorption rate, and low optical breakdown threshold, thus they are not suitable for high power-load amplifiers. The irony is that, although some mediums have small absorption rate, the optical breakdown threshold is too low to be used as amplifiers. Therefore, when the pump wave has a high power desnisty, optical breakdown will occur frequently, and SBS performance is compromised. It is suggested that an attenuation plate be placed between the generator and the amplifier to lower the power intensity incident on the generator. This method works to some extent, but an inevitable side effect is that the plate also attenuates the Stokes seed, which in turn lowers the energy conversion efficiency (Dane *et al.*, 1994). In order to solve this problem, two approaches have been proposed: (1) choosing different media for different cells, i.e., medium with small absorption rate as amplifier,

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Address correspondence and reprint request to: Zhiwei Lu, Institute of Opto-Electronics, Harbin Institute of Technology P.O. Box 3031, Harbin 150080, China. E-mail: zw_lu@sohu.com

and medium with high optical breakdown threshold as the generator, to enhance the power-load of the generator cell, while keeping the attenuation loss of the amplifier acceptably low (Hasi *et al.*, 2005*a*); (2) choosing medium with small absorption rate as amplifier and mixed medium as generator. The mixed medium preferrably have high optical breakdown threshold which is the same as the BFS of the amplifier (Hasi *et al.*, 2007).

The reason for considering a mixed medium as a generator is that, BFS is adjustable to match that of the amplifier, since as aforementioned, the energy conversion is less efficient when there is a mismach of BFS between the generator and the amplifier. The BFS of a mixed medium varies with the mixing ratio (Andreew, 1982), which provides an opportunity to minimize the mismach of BFS, thus achieving optimal amplification of the Stokes seed light.

In this paper, we studied experimentally several two-cell SBS systems that use mixed medium as a generator and a different media for generator and amplifier. The SBS systems are pumped by the same Q-switched Nd:YAG laser. A theoretical model is provided and analyzed. The experimental results show that, when compared with one-medium SBS systems, both the mixed-medium and different-medium SBS systems exhibit significant enhancement in the amplification rate of Stokes wave, when the medium BFS is matched, the power-load performance is enhanced as well. These improvements are obtained without the attenuation of the Stokes seed, as compared with the attenuation-plate method.

2. THEORY

2.1. Brillouin amplification

The SBS gain coefficient is composed of two parts. The first part is the contribution of electrostriction, which occurs in pure and absorptive mediums. The second part describes medium absorption, which is applicable only for absorptive mediums. We assume that low-absorption medium is used as the amplifier, thus the second part is neglible, and the gain coefficient, g, can be written as follows (Arecchi & Schulz-Dubois, 1972):

$$g = g^{e}_{(\max)} \frac{1}{1 + (2\Delta\nu/\Gamma_{\mathrm{B}})^2},$$

where $g^{e}_{(\max)}$ is the electrostriction factor; $\Delta\nu$ is the difference of BFS ($\Delta\nu = |\nu_1 - \nu_2|$, ν_1 and ν_2 are the BFS of the amplifier and generator, respectively); Γ_B is the full width at half maximum (FWHM) of the amplifier.

Eq. (1) shows that $g = g^{e}_{(\max)}$ for $\Delta\nu = 0$ and $g < g^{e}_{(\max)}$ for $\Delta\nu \neq 0$, that is, when the BFS of the amplifier equals to that of the generator, the largest gain coefficient can be obtained. A noticable fact is that, when $\Delta\nu$ is small, g differs from $g^{e}_{(\max)}$ only by a small value. This fact has signficant meaning that different mediums with different but close BFS will still exhibit SBS amplification so long as there is an overlap in the Brillouin spectrum.

2.2. BFS

The BFS can be written as follows (Erokhin *et al.*, 1986):

$$\nu = 2nv/\lambda,$$

where n is the refraction index of the medium, v is the sound velocity in the medium, and λ is the wavelength of the pump light.

Eq. (2) shows that for a fixed incident pump light, the BFS of the medium exhibits both refraction index and sound velocity dependence. The refraction index and sound velocity of the binary mixed medium varies with the mixing ratio. The refraction index of the CCl_4/C_3H_6O mixture exhibits a monotonic dependence on the mixing ratio, while there exists an extremum for the sound velocity when it varies with the mixing ratio. The physical explanations for the existence of extremum for the sound velocity was extensively researched by Bergmann (1964).

Figure 1 shows the BFS of CCl_4/C_3H_6O vs. CCl_4 volume fraction (Andreew, 1982). It can be seen that when the CCl_4 is about 25% of the total mixture volume (point A), the BFS of the mixture equals to that of pure CCl_4. According to Eq. (1), $g = g^{e}_{(\max)}$ and the Stokes seed generated in the mixed medium gains maximum amplification.

3. EXPERIMENT

3.1. Experimental setup

The experimental setup is shown in Figure 2. The Q-switched Nd: YAG laser output p-polarized light, polarizer P together with a one-quater wave plate forms a light isolator and prevents the backscattered SBS light from entering the laser. The SBS system comprises an amplifier cell, a generator cell, two lenses, L_1 and L_2. Convex lens L_1 ($f = 80$ cm) is put before

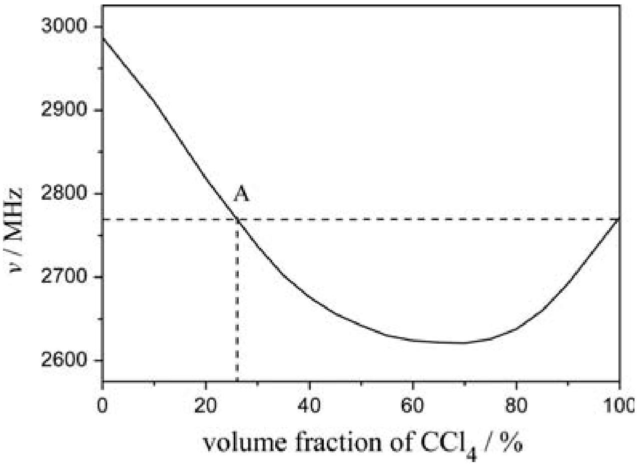

Fig. 1. The BFS of the CCl_4/C_3H_6O vs the volume fraction of CCl_4.

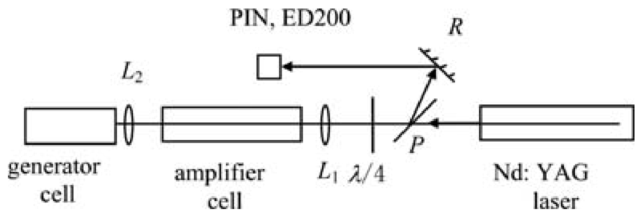

Fig. 2. Experimental setup.

the amplifier (cell length is 60 cm) in order to increase the pump intensity in the amplifier cell by reducing the beam diameter. Pump wave is focused into the generator (cell length 30 cm) through lens L_2 ($f = 5$ cm), and excites SBS seed, which couples with the pump wave in the amplifier and is amplified dramatically. SBS wave becomes *s*-polarized after passing the one-quater wave plate, and is reflected off polarizer *P*. The energy of the pump and SBS light is measured with the energy meter, the pulse shape is detected with photodiode, and recorded with digital oscilloscope TDS684A.

3.2. Results and discussion

The wavelength of the pump wave is 1.064 μm with a repetition rate of 1 Hz, pulse duration 10 ns, maximum energy 50 mJ, and beam divergence angle 1.6 mrad (five times diffractive limit). The pump energy incident into the amplifier cell is adjustable by placing an attenuators. Table 1 lists the SBS parameters of some typical SBS media at pump wavelength 1.064 μm. It shows that most common mediums have large absorption rate except CCl_4 and CS_2.

In order to show the amplification of different-media two-cell SBS systems, we chose mediums from Table 1 in our experiements. The results showed that the amplification function exists between the five media in the first group listed in the table. Also, this is the same for the second group. However, two-cell systems with media chosen from the first and the second group, respectively, do not exhibit SBS amplification. This observation agreed with the model prediction that only the media with close vicinity in BFS can possess amplification function.

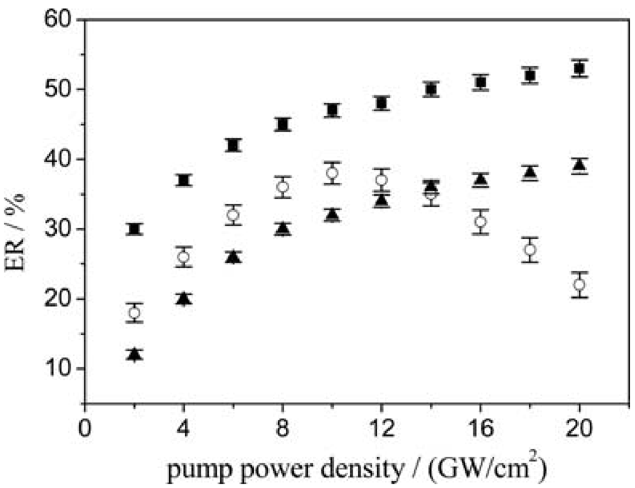

Fig. 3. ER vs the pump power density for three systems, ■ A: CCl_4 +G: CCl_4/C_3H_6O, ▲ A: CCl_4 + G: C_3H_6O, ○ A: CCl_4 + G: CCl_4.

In order to study the power load performance, we investigated the following three SBS systems: (1) CCl_4/C_3H_6O (CCl_4: 25% of total volume) as the generator and CCl_4 as the amplifier; (2) C_3H_6O as the generator and CCl_4 as the amplifier; (3) CCl_4 as both generator and amplifier. We denote the three cases as (1) A: CCl_4 + G: CCl_4/C_3H_6O, (2) A: CCl_4 + G: C_3H_6O, and (3) A: CCl_4 + G: CCl_4, respectively.

Figure 3 shows the energy reflectivity (ER) of the three systems as a function of the pump energy under the same experimental conditions. The general trend is briefed as follows. In the beginning, the ER of all systems increases monotonously with the pump energy. As the pump energy increases further, the growth speed of ER of (3) A: CCl_4 + G: CCl_4 system slows down and eventually begins to decrease, but those of (1) A: CCl_4 + G: CCl_4/C_3H_6O system and (2) A: CCl_4 + G: C_3H_6O system never show a decrease.

It is observed experimentaly that no optical breakdown occurs in the (1) A: CCl_4 + G: CCl_4/C_3H_6O system and (2) A: CCl_4 + G: C_3H_6O system, whereas it occurs in the (3) A: CCl_4 + G: CCl_4 system all the time and deteriorates as the pump power density enhances (Hasi *et al.*, 2005*b*).

Table 1. *The SBS parameters of some medium (Erokhin et al., 1986)*

	n	α/cm	v/MHz	Γ/MHz	g/(cm/GW)	τ/ns	υ
CCl_4	1.460	0.004	2772	520	6	0.6	1012
Acetone	1.358	0.018	2987	224	15.8	2.67	1168
n-Hexane	1.375	0.047	2779	222	26	3.24	1085
Methanol	1.328	0.156	2683	250	13	1.27	1121
Ethanol	1.361	0.119	2873	353	12	0.9	1241
CS_2	1.632	0.003	3761	52.3	68	6.4	1250
Benzene	1.501	0.018	4124	289	9.6	1.4	1359
Toluene	1.496	0.028	3799	250	13	1.27	1327
Cyclohexane	1.426	0.058	3568	774	6.8	0.41	1313
Water	1.324	0.171	3703	317	3.8	1.87	1482

Analysing the experimental data, we found that these data can be well explained by the theorerical model. As the pump power density increases, energy conversion efficiency becomes more efficient, and consequently the ER increases for (1) A: CCl_4 + G: CCl_4/C_3H_6O and (2) A: CCl_4 + G: C_3H_6O system. However, the ER rises slowly because of the saturation of the energy conversion efficiency, when the pump power density increases further. Under the same conditions, the ER for the (1) A: CCl_4 + G: CCl_4/C_3H_6O system is larger than that for A: CCl_4 + G: C_3H_6O system for the reason that the Stokes gains maximum amplification due to the BFS match between two cells. It can be predicted that this difference will be boosted when the pump energy increases. For the (3) A: CCl_4 + G: CCl_4 system, the ER rises rapidly with the pump energy despite the weak optical breakdown, which has an comparatively small impact on the ER when the pump power density is small. However, severe optical breakdown leads to the decrease in the ER when the pump power density increases (Wang *et al.*, 2004). The phase conjugation fidelity for the A: CCl_4 + G: CCl_4/C_3H_6O system and the A: CCl_4 + G: C_3H_6O system are obviously higher than that for the A: CCl_4 + G: CCl_4 system.

4. CONCLUSIONS

In order to enhance the power-load of two-cell SBS system methods for using different media and mixted medium are proposed. Both the theoretical and experimental results indicate that the amplification function exists when choosing different media with close vicinity of the BFS and superposition on the Brillouin profile. This configuration will not only diversify the medium used in two-cell system, but also optimize the system performances. Choosing medium with small absorption coefficient in the amplifier cell and mixted medium in the generator cell, which has high optical breakdown threshold, and the same BFS as that of the amplifier cell, can lower the energy loss and enhance the system power load. The BFS of mixture medium varies with the mixing ratio, so the mismach of BFS can be eliminated, thereby enhancing the power load while simultaneously keeping the maximum of the Stokes amplification ratio.

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