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Investigation on improving characteristics of two-cell SBS system with CCl_4/C_2H_5OH liquid mixture*

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In order to improve the performance of the two-cell stimulated Brillouin scattering (SBS) system, this paper proposes the methods of using mixtures, which require amplifier media to have small absorption rate, and generator media to have high optical breakdown threshold and Brillouin frequency shift equal to that of the amplification media. The characteristics of the two-cell SBS system are studied experimentally by using CCl_4 as amplifier medium and CCl_4, C_2H_5OH and CCl_4/C_2H_5OH liquid mixture as generator medium pumped by Nd:YAG Q-switched laser. The obtained results show that liquid mixture in generator cell improves the power load ability, phase conjugation fidelity, energy reflectivity (ER) and ER stability.

Keywords: stimulated Brillouin scattering, Brillouin frequency shift, liquid mixture
PACC: 4265C, 4265F

1. Introduction

The stimulated Brillouin scattering (SBS) phase conjugation (PC) mirror has several configurations such as focused single cell, compact two-cell system and independent two-cell system. The last two configurations can be called generator–amplifier two-cell system, because they all comprise a generator and an amplifier. The Stokes seed light generated in the generator enters the amplifier where it interacts with the pump light and is amplified dramatically. Thus the Stokes pulse width is narrowed and energy reflectivity (ER) enhanced. Until recently, most experiments use the same medium in generator and amplifier so that the frequency difference between the pump light and Stokes seed light matches the Brillouin frequency shift of the amplifier medium. However, this use of one medium also causes problems. For example, the SBS parameters such as the absorption rate, optical breakdown threshold (OBT), etc., often limit the SBS performance.[1] First, most media have large absorption rate, so that in the long amplifier cell the energy loss can be significant; second, although some media have small absorption rate, the OBT is comparatively low, therefore, when the pump is strong, optical breakdown occurs and SBS performance is deteriorated in terms of PC fidelity, ER and ER stability.[2] It is suggested that an attenuation plate can be put before the generation cell to lower the incident pump intensity.[3] However, the plate also attenuates the Stokes seed light, which in turn lowers the ER. Another approach proposed is to use different pure media that have similar Brillouin frequency shift in generator and amplifier respectively.[4] This method enhances the power load ability but lowers the system gain because of the mismatch of the Brillouin frequency shift of the media. In this paper, we propose an approach that eliminates the drawbacks of the above mentioned methods while keeping their advantages. The basic concept is to use small-absorption-rate medium in amplifier and high OBT mixture medium in generator, and both media have the same Brillouin frequency shift (which is achieved by adjusting the mixing fraction of the generator medium),[5] so that the performance of two-cell SBS system can be improved significantly.

In the two-cell SBS system studied by us, CCl_4 medium is used in amplifier, and CCl_4, C_2H_5OH, CCl_4/C_2H_5OH mixture (CCl_4:10% of total volume) are used in generators. The system performances with the media are investigated with an Nd:YAG Q-switched laser. The results show that when CCl_4/C_2H_5OH mixture is used in generator, the ER

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is improved effectively in comparison with the case that uses different pure media (CCl_4 in amplifier and C_2H_5OH in generator); the power load ability, PC fidelity, the ER and ER stability are improved effectively in comparison with the case that uses one medium (CCl_4 for both cells) when the pump light energy is higher than 35 mJ.

2. Theories

2.1. Brillouin amplification

When the laser beam enters the SBS medium by one way (for example, through focused lens or tapered waveguide), an ultrasonic wave will set up due to electrostriction effect in the area where the pump intensity is higher than the SBS threshold value. The ultrasonic wave forms a spatial grating which scatters the incident pump wave and generates the backscattered Stokes wave (for the generator case). When the incident pump intensity is lower than the threshold value and Stokes seed light with appropriate energy is fed into the medium, the Stokes wave, the ultrasonic wave and the incident pump wave will couple with each other and the energy of the pump transfers to the Stokes wave. This process is called Brillouin amplification. In the amplification process, the leading edge of the Stokes pulse rises up quickly and dramatically due to gain saturation. When the amplification is complete, most pump energy is transferred to the very narrow backscattered Stokes pulse. This process is called pulse compression (for the amplifier case).

The gain coefficient g is given by Eq.(1)[6,7]

$$g = g^{\mathrm{e}} \frac{1}{1 + (2\Delta\nu/\Gamma)^2} + g^{\mathrm{a}} \frac{4\Delta\nu/\Gamma}{1 + (2\Delta\nu/\Gamma)^2}. \qquad (1)$$

The gain coefficient is composed of two parts. The first part is due to the electrostriction, it occurs in pure and absorptive media. The second part is due to absorption, it occurs only in absorptive media. We assume that small absorption rate medium is used in the amplifier, therefore the second part is small and can be ignored, thus Eq.(1) is reduced to

$$g = g^{\mathrm{e}} \frac{1}{1 + (2\Delta\nu/\Gamma)^2}, \qquad (2)$$

where g^{e} is electrostriction factor, $\Delta\nu$ is the Brillouin frequency shift difference between the amplifier and generator ($\Delta\nu = |\nu_1 - \nu_2|, \nu_1, \nu_2$, is the Brillouin frequency shift of the amplifier and generator respectively), Γ is the FWHM (full width at half maximum) of the amplifier.

Equation (2) shows that $g = g^{\mathrm{e}}$ for $\Delta\nu = 0$ and $g < g^{\mathrm{e}}$ for $\Delta\nu \neq 0$, that is, when the Brillouin frequency shift of the amplifier equals to that of the generator, we obtain the largest gain coefficient. According to Eq.(2) we can obtain the gain coefficient as a function of the Brillouin frequency shift difference between the amplifier and generator.[8]

2.2. Brillouin frequency shift

The Brillouin frequency shift is given by Eq.(3).[9]

$$\nu = 2nv/\lambda, \qquad (3)$$

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

Equation (3) shows that for a specified pump light, the Brillouin frequency shift of the medium is dependent on its refractive index and sound velocity. On the other hand, the refractive index and sound velocity of the mixture medium are determined by those of its component as well as the mixing fraction. The sound velocity of CCl_4/C_2H_5OH mixture as a function of the volume fraction of CCl_4 is shown in Fig.1(a),[10] and the correlation between the refractive index and the volume fraction of CCl_4 is given by Lorentz–Lorenz equation,[11] as plotted in Fig.1(b). Therefore, the correlation between the Brillouin frequency shift and the volume fraction of CCl_4 can be derived through Eq.(3), as plotted in Fig.1(c). It can be seen that when the CCl_4 is about 10% of the total mixture volume, the Brillouin frequency shift of the mixture (point A in the figure) equals that of pure CCl_4 (point B). According to Eq.(2), $g = g^{\mathrm{e}}$ and the Stokes seed generated in the mixture medium gains maximum amplification.

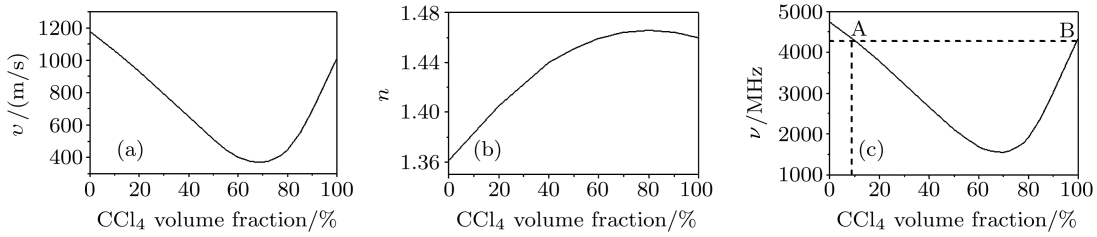


Fig.1. (a) Sound velocity, (b) refractive index and (c) Brillouin frequency shift of CCl_4/C_2H_5OH mixture vs CCl_4 volume fraction.

3. Experiments

3.1. Experimental setup

The experimental setup is shown in Fig.2. The Nd:YAG Q-switched laser contains a 100% reflective mirror M_1, a Q-switch plate, a polarizer P_1, an Nd:YAG rod, a small hole, and a partial reflective mirror M_2. Polarizer P_2 is parallel to P_1, it forms a light isolator together with a 1/4 wave plate, preventing the backscattered SBS light from entering the oscillator. The SBS system comprises an amplifier cell, a generator cell, two focus lens L_1 and L_2. The Nd:YAG oscillator outputs p-polarized light, which becomes circular polarized light after passing the 1/4 wave plate. Convex lens L_1 (f=80 cm) is put before 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 30cm) 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 light after passing the 1/4 wave plate and is reflected off polarizer P_2.

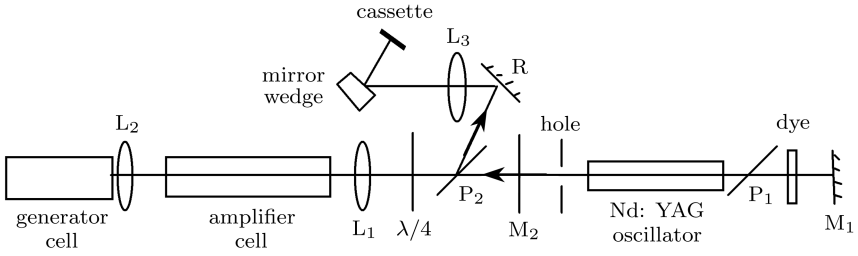


Fig.2. Experimental setup.

The wavelength of the pump wave is 1.064 μm with repetition rate of 1Hz, pulse duration 8 ns, maximum energy 50 mJ, and beam divergence angle 1.6mrad (5 times diffractive limit). The pump energy is controlled by inserting attenuators into the light path. The energy of the pump and SBS light is measured with energy meter ED200, the pulse shape is detected with PIN photodiode and recorded with digital oscilloscope TDS684A. The CCD camera is used to shoot the sparkles caused by optical breakdown. The PC fidelity (which is defined as the ratio of the energy transmitted through the divergence angle equal to that of the pump light to the total energy transmitted through the divergence angle of the Stokes light, normalized by the far-field transmission of the pump beam 86%[12,13]) is measured with the mirror-wedge method, measuring the far-field energy distribution of the Stokes light by using array camera technology.[14,15] The array camera comprises focus lens L_3 (f=50 cm), the mirror wedge and a cassette. The mirror wedge which is composed of a 100% reflective mirror and a 50% reflective mirror splits a beam into a fan of beams of progressively greater attenuation. The ultraviolet oscillographic paper is used to record the series of light spots with decreasing radiuses (shown in Fig.3), which is read through a microscope. Thereby, the PC fidelity can be gained by making a program to work out the dependence of radiation angle on the energy distribution.[16]

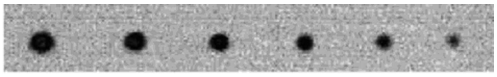


Fig.3. The series of decreasing light spots recorded by the ultraviolet oscillographic paper.

3.2. Results and discussion

The amplifier medium is always CCl_4, the generator media are CCl_4, C_2H_5OH, and CCl_4/C_2H_5OH mixture (CCl_4: 10% of total volume), respectively. We denote the above three cases with A:CCl_4+G:CCl_4, A:CCl_4+G:C_2H_5OH and A:CCl_4+G: CCl_4/C_2H_5OH, respectively.

In order to eliminate optical breakdown induced by the dust particles, we use 0.22 μm pore-size membranes to filter the liquids.[17] We have measured the OBTs (OBT is defined to be the pump power density at which the possibility of observing sparkles caused by optical breakdown in the medium is 50%) for three cases. It is found that the OBT of CCl_4 medium rises from 8 GW/cm^2 to 20GW/cm^2; C_2H_5OH from 15GW/cm^2 to higher than 100GW/cm^2 (no optical breakdown is observed when the energy is as high as 50 mJ, the upper limit for the laser we used). The OBT of filtered CCl_4/C_2H_5OH mixture is also measured, which is also higher than 100GW/cm^2. This is because the OBT of filtered C_2H_5OH is much higher than that of CCl_4, so that when the volume fraction of CCl_4 medium is not large enough, the overall OBT is determined mainly by that of the C_2H_5OH. Table 1 gives the SBS parameters of CCl_4 and C_2H_5OH when the wavelength of incident light is 1.064 μm.

Table 1. SBS parameters of CCl_4 and C_2H_5OH.

	CCl_4	C_2H_5OH
Refractive index n	1.46	1.361
Absorption rate α/cm^{-1}	0.003	0.119
SBS gain coefficient g/(cm/GW)	6	12
Frequency shift ν/MHz	2772	2970
Line width Γ/MHz	520	353
Sound velocity v/(m/s)	1012	1161

Notes: parameters are quoted from Ref.[9,18,19].

Figure 4 shows the ER of the three systems as a function of pump energy under the same condition. When the pump energy is lower than 25 mJ, the ER of all systems rises correspondingly with the pump energy. When the pump energy is higher than 25mJ, the ER of A: CCl_4+G:CCl_4 system begins to decrease, while those of A:CCl_4+G:CCl_4/C_2H_5OH system and A:CCl_4+G:C_2H_5OH system are still increasing.

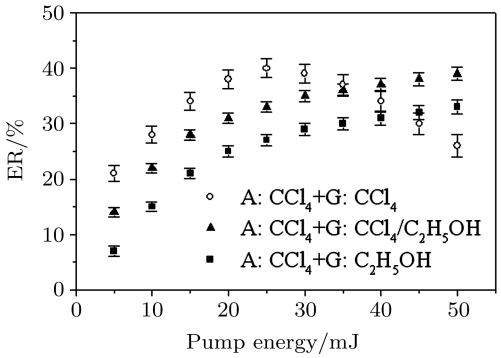


Fig.4. ER vs the pump energy.

The differences of the variation tendency of the ER for the above three systems can be interpreted by the optical breakdown. As the pump energy increases, the power density becomes stronger, and SBS energy conversion efficiency becomes more efficient, so that the ER of the three systems increases. When the pump energy is lower than 25mJ, optical breakdown occurs in the A:CCl_4+G:CCl_4 system. The optical breakdown is weak (small sound and faint light spots as seen in Fig.5(a)) and has little negative influence on the Stokes seed. Thus, the ER increases all the time. However, when the energy is higher than 25mJ, severe optical breakdown (large sound and bright light spots as seen in Fig.5(b)) occurs in the A:CCl_4+G:CCl_4 system, which leads to a rapid decrease in the ER.[20] No optical breakdown occurs in the A:CCl_4+G:CCl_4/C_2H_5OH system and A:CCl_4+G:C_2H_5OH system, so the ER of these systems keeps increasing.



Fig.5. The sparkles caused by optical breakdown in CCl_4.

The differences of the ER between the above three systems result from the differences in the Stokes seed energy and the seed amplification efficiency as well as the optical breakdown. Despite the gain coefficient of C_2H_5OH being twice that of CCl_4, the absorption rate of C_2H_5OH is 40 times larger than that of CCl_4. Thus, when the optical breakdown is weak, the Stokes seed energy and the ER of the A:CCl_4+G:CCl_4 system are larger than those of A:CCl_4+G:CCl_4/C_2H_5OH

system and A:CCl_4+G:C_2H_5OH system. For the A:CCl_4+G:CCl_4/C_2H_5OH system and the A:CCl_4+G:C_2H_5OH system, the seed amplification efficiency is different despite of the small difference between their Stokes seed energy. For the A:CCl_4+G:CCl_4/C_2H_5OH system, the seed light gains the maximum amplification (the gain coefficient of the amplifier is 6 cm/GW), while the amplification is less effective for the A:CCl_4+G:C_2H_5OH system due to the difference of Brillouin frequency shift (the gain coefficient of the amplifier medium is 3.7 cm/GW). Therefore, the ER of A:CCl_4+G:CCl_4/C_2H_5OH system is larger than that of A:CCl_4+G:C_2H_5OH system under the same condition. It can be predicted that the difference of the ER increases as the pump energy increases further.

Moreover, the leading edge rises rapidly as a result of the gain saturation. When the amplification is complete, the energy is almost transferred to the very narrow backscattered Stokes pulse, thus realizing the pulse compression.[21−23] Figure 6 shows the pulse shapes of A:CCl_4+G:CCl_4/C_2H_5OH system (5ns/div).

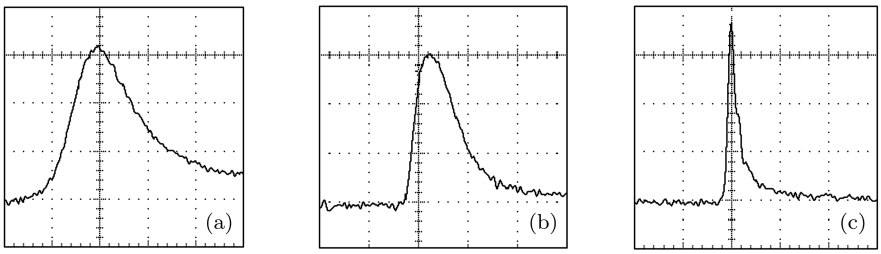


Fig.6. Pulse shapes of A: CCl_4+G: CCl_4/C_2H_5OH system. (a) the pump pulse (pulse width 8.2 ns, rise time 4.0 ns), (b) the Stokes seed pulse (pulse width 4.9 ns, rise time 1.3 ns), (c) the output Stokes pulse (pulse width 1.1 ns, rise time 0.5 ns).

The optical breakdown lowers the power load ability of the system, and produces negative influence on the PC fidelity and ER stability (defined as the ratio of mean square value to arithmetic mean value of the measured data).[24] Table 2 lists the ER stability and the PC fidelity of the three systems with the pump energy at 15 mJ and 45 mJ respectively. The PC fidelities for the A:CCl_4+G:CCl_4/C_2H_5OH system and the A:CCl_4+G:C_2H_5OH system are above 90% and the ER stabilities are below 3%. However, the PC fidelity for the A:CCl_4+G: CCl_4 system is below 80%, and the ER stability is above 5%. Thus we can conclude that the A:CCl_4+G:CCl_4/C_2H_5OH system has the best performance when the pump energy is more than 35mJ. Also it can be predicted that its superiority will be displayed further for higher pump energy.

Table 2. The ER stability and the PC fidelity for three two-cell SBS system when the pump energy is 15 mJ and 45 mJ respectively.

Pump energy	System	ER stability/%	PC fidelity/%
15 mJ	A: CCl_4+G: CCl_4	5.4	75.0
	A: CCl_4+G: C_2H_5OH	2.2	97.6
	A: CCl_4+G: CCl_4/C_2H_5OH	2.1	98.4
45 mJ	A: CCl_4+G: CCl_4	5.7	72.5
	A: CCl_4+G: C_2H_5OH	2.6	95.0
	A: CCl_4+G: CCl_4/C_2H_5OH	2.5	96.2

4. Conclusions

In this paper, a two-cell SBS system is investigated experimentally. The system uses small-absorption-rate CCl_4 in amplifier and high OBT CCl_4/C_2H_5OH mixture (CCl_4:10% of total volume) which has the same Brillouin frequency shift as that of CCl_4 in generator. The results show that when CCl_4/C_2H_5OH mixture is used in generator, the ER is improved effectively in comparison with the case that

uses different pure media (A:CCl_4+G:C_2H_5OH system); the power load ability, PC fidelity, the ER and ER stability are improved effectively in comparison with the case that uses one medium (A:CCl_4+G:CCl_4 system) when the pump light energy is higher than 35 mJ.

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