Vol 16 No 1, January 2007
1009-1963/2007/16(01)/0154-05

Chinese Physics

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A method to measure the Brillouin frequency shift of the medium through Brillouin amplification ratio*

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(Received 2 June 2006; revised manuscript received 25 June 2006)

In order to measure the Brillouin frequency shift (BFS) of the medium, this paper proposes a method using mixtures in a two-cell stimulated Brillouin scattering system, which uses a medium to be measured as amplifier medium and a mixture medium as generator medium. The seed light from the generator gains effective amplification in the amplifier and the amplification ratio changes with the mixing fraction. Only when the BFS of the mixture medium is equal to that of the medium in the amplifier does the seed light obtain the maximum amplification ratio. The method has the advantage of independence of the wavelength of the incident light.

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

1. Introduction

Stimulated Brillouin scattering (SBS) has the characteristic of phase conjugation, which can eliminate the phase distortion during the propagation and improves the laser beam quality.[1] So the SBS phase conjugation theories and experiments have been researched extensively in the past several decades. It is found in experiments that the characteristics SBS medium have significant influence on SBS performance, so the measuring SBS parameters is especially important.[2−4] Fabry–Perot etalon (F–P) has been used to measure the Brillouin frequency shift (BFS).[5] The F–P has the advantages of high resolution and high accuracy, but is limited by the bandwidth, since one kind of F–P can only measure the BFS in the case of a fixed incident light. When the BFS is needed to be measured in the case of different incident lights, several kinds of F–P are needed, and thus great inconveniences are brought about. That is why the BFS of most media has only been measured when the wavelength of the incident light is 694.3nm (given off by the ruby laser).[6]

In this paper, a method using mixtures in a two-cell SBS system is proposed to measure the BFS of the medium, which has the advantage of independence of the wavelength of the incident light. The medium to be measured is used as amplifier medium and mixture medium as generator medium. The seed light from the generator interacts with the pump light and gains effective amplification in amplifier.[7] As a result, the width of Stokes pulse becomes narrow and the energy enhances. The amplification ratio of the seed light is decided by the exponential gain coefficient $G = gIL$ (g is the gain coefficient of the medium, I is the intensity of the incident light, L is the amplifier length). For a fixed intensity of incident light and a fixed amplifier length, the amplification ratio of the seed light is decided by the gain coefficient of the medium. The amplification ratio of the seed light has a connection with the difference of BFS. The BFS of the mixture medium varies with its mixing fraction and accordingly the difference of BFS as well as the amplification ratio of the seed light varies. The seed light obtains the maximum amplification ratio only when the BFS of the medium in the amplifier is equal to that of the medium in the generator. Therefore, we can measure the BFS of the medium through calculating that of the mixture medium when the seed light obtains the maximum amplification ratio.

2. Theories

2.1. Brillouin amplification

Considering that the small-absorption-rate medium is used as amplifier, we can obtain the gain coefficient g [8,9]

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

*Project supported by the National Natural Science Foundation of China (Grant Nos 10476009 and 60478020).
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where g^{e} is the electrostrictive gain factor, $\Delta\nu$ is the difference of BFS ($\nu = |\nu_1 - \nu_2|$, ν_1 and ν_2 are the BFS of the amplifier and generator respectively), and Γ is the FWHM (full width at half maximum) of the amplifier, as shown in Fig.1.

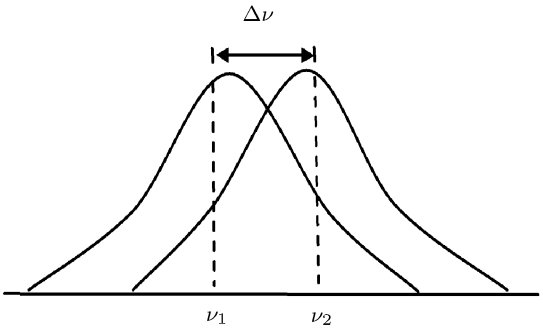


Fig.1. The difference in Brillouin line shapes.

Equation (1) shows that $g = g^{\mathrm{e}}$ for $\Delta\nu = 0$, that is, when the BFS of the amplifier equals to that of the generator, the gain coefficient achieves the maximum. According to Eq.(1) we can obtain the gain coefficient as a function of the difference of BFS, as plotted in Fig.2.

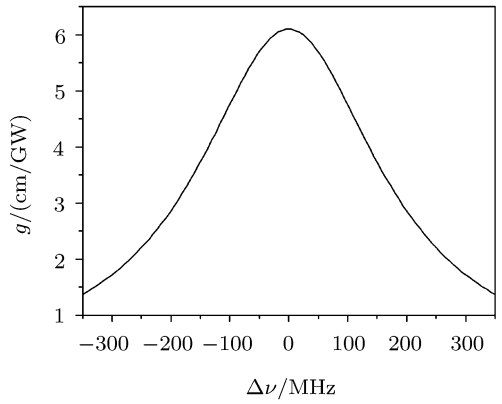


Fig.2. The gain coefficient g vs the difference of BFS $\Delta\nu$. The Brillouin line width of C_2Cl_4 is 376 MHz, the gain coefficient is 6.1 cm/GW.

2.2. Brillouin frequency shift

The BFS is given by[10]

$$\nu = 2n\upsilon/\lambda, \tag{2}$$

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

The refractive index of the liquid mixture can be calculated by [11]

$$n = \left\{ \frac{1 + 2(\varphi_1\rho_1 + \varphi_2\rho_2)\left[\dfrac{\varphi_1(n_1^2-1)}{\rho_1(n_1^2+2)} + \dfrac{\varphi_2(n_2^2-1)}{\rho_2(n_2^2+2)}\right]}{1 - (\varphi_1\rho_1 + \varphi_2\rho_2)\left[\dfrac{\varphi_1(n_1^2-1)}{\rho_1(n_1^2+2)} + \dfrac{\varphi_2(n_2^2-1)}{\rho_2(n_2^2+2)}\right]} \right\}^{1/2}, \tag{3}$$

where n is the refractive index of the mixture medium, n_1 and n_2 are the refractive index of each component, ρ_1, ρ_2 are the density of each component, φ_1, φ_2 are the volume fraction of each component, $\varphi_1 = V_1/(V_1+V_2)$, $\varphi_2 = V_2/(V_1+V_2)$, and V_1, V_2 are the volume of each component.

The sound velocity of the mixture medium can be deduced according to the mixing rule.[12] For the mixture medium with weak interaction, the sound velocity can be calculated by [13]

$$\upsilon = \Big(\sum_{i=1}^{2} M_i X_i/\rho_i\Big) \Big/ \sqrt{\Big(\sum_{i=1}^{2} M_i X_i\Big)\Big(\sum_{i=1}^{2} M_i X_i/\rho_i^2\upsilon_i^2\Big)}, \tag{4}$$

where M_i, X_i, ρ_i and υ_i are the molecular weight, molar fraction, density and sound velocity for each component respectively.

By substituting Eqs.(3) and (4) into Eq.(2), we can obtain the BFS of the mixture

$$\nu = \frac{2}{\lambda}\left\{ \frac{1 + 2(\varphi_1\rho_1 + \varphi_2\rho_2)\left[\dfrac{\varphi_1(n_1^2-1)}{\rho_1(n_1^2+2)} + \dfrac{\varphi_2(n_2^2-1)}{\rho_2(n_2^2+2)}\right]}{1 - (\varphi_1\rho_1 + \varphi_2\rho_2)\left[\dfrac{\varphi_1(n_1^2-1)}{\rho_1(n_1^2+2)} + \dfrac{\varphi_2(n_2^2-1)}{\rho_2(n_2^2+2)}\right]} \right\}^{1/2}$$

$$\times \Big(\sum_{i=1}^{2} M_i X_i/\rho_i\Big) \Big/ \sqrt{\Big(\sum_{i=1}^{2} M_i X_i\Big)\Big(\sum_{i=1}^{2} M_i X_i/\rho_i^2 \upsilon_i^2\Big)} \,. \tag{5}$$

It can be concluded from Eq.(5) that the BFS changes with the mixing ratio.[14]

3. Experiments

3.1. Experimental setup

The experimental setup is shown in Fig.3. The Nd:YAG Q-switched laser contains a 100% reflective mirror M_1, a Q-switched plate, a polarizer P_1, a 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. The SBS system comprises an amplifier cell, a generator cell, two focus lens L_1 and L_2. The oscillator outputs p-polarized light, which becomes circular polarized when 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 light 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 light in the amplifier and is amplified dramatically. SBS light becomes s-polarized after passing the 1/4 wave plate and be reflected off polarizer P_2. The distance between the two cells is 10 cm. Both the lens L_1 and L_2 are close to the cell and placed behind each cell. 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.

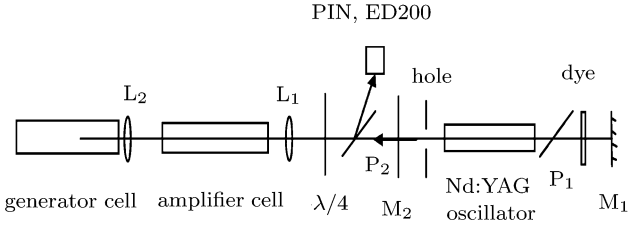


Fig.3. Experimental setup.

3.2. The choice of mixture medium

In order to obtain a broad measure range, CCl_4/C_6H_6 mixture is chosen in the experiment. Both CCl_4 and C_6H_6 are non-polar liquids, and thus the interaction between the components of the mixture is weak.[15] Therefore, the BFS of the mixture versus the volume fraction of CCl_4 can be calculated according to Eq.(5), as shown in Fig.4.[16] Both the gain coefficient and the absorption coefficient of CCl_4 are smaller than those of C_6H_6. Therefore, the energy of seed light generated by the mixture medium is nearly a constant. The SBS parameters of some media are listed in Table 1.

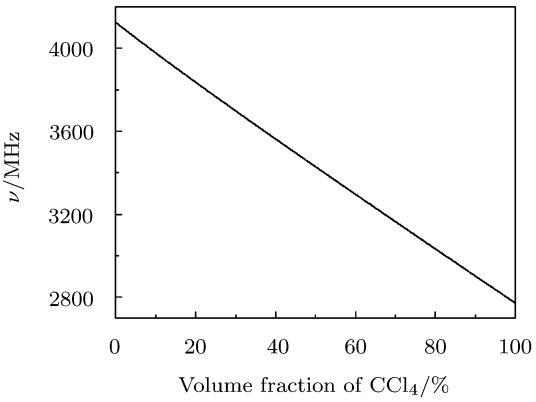


Fig.4. The BFS of the CCl_4/C_6H_6 vs the volume fraction of CCl_4.

Table 1. Some related parameters of liquid media.

medium	n	α/cm^{-1}	ν/MHz	Γ/MHz	g/(cm/GW)	υ/(m/s)
C_2Cl_4	1.505	0.003	3016*	376*	9*	1066
CS_2	1.632	0.003	3760	50	68	1246
CCl_4	1.460	0.004	2792	528	6	1012
C_6H_6	1.501	0.018	4130	228	9.6	1359

Notes: parameters with a asterisk are calculated according to equations given by Ref.[10] and others are quoted from Refs.[10, 15, 17].

3.3. Results and discussions

The wavelength of the pump wave is 1.064 μm with repetition rate of 1 Hz, pulse duration 8 ns, maximum energy 50 mJ, and beam divergence angle 1.6 mrad (5 times diffractive limit). The input energy is controlled by inserting attenuators into the light path. The generator medium is always CCl_4/C_6H_6, the amplifier media are C_2Cl_4 and CS_2 respectively.

We denote the above two cases with A: C_2Cl_4+G: CCl_4/C_6H_6 and A: CS_2+G: CCl_4/C_6H_6 respectively. In order to obtain the optimal amplification ratio of the seed light, we should strike a balance between choosing the amplifier cell length and the absorption coefficient of the amplifier medium. The experimental results indicate that when the absorption coefficient is small and the pump pulse width is about 10 ns, the Stokes gains optimal amplification when the amplifier cell length is about 60 cm.

Figure 5 shows the amplification ratio of the seed light versus the volume fraction of CCl_4, with C_2Cl_4 and CS_2 in the amplifier respectively. The amplification ratio of the seed light rises correspondingly with volume fraction of CCl_4 initially. After the amplification ratio reaches the peak value, it begins to decrease. As the volume fraction of CCl_4 increases, the BFS of the mixture medium becomes small, and the difference of BFS decreases. This leads to the increases in both the gain coefficient of the amplifier and the amplification ratio of the seed light. When the BFS of the mixture medium is equal to that of the medium in the amplifier, the difference of BFS is reduced to zero. At this time, the gain coefficient of the amplifier and the amplification ratio of the seed light reach the maximum. However, as the volume fraction of CCl_4 increases further, the difference of BFS increases, so the gain coefficient of the amplifier and the amplification ratio of the seed light decrease. As shown in Fig.5, when the volume fraction of CCl_4 is 83% and 26% respectively, the amplification ratio of A: C_2Cl_4+G: CCl_4/C_6H_6 system and A: CS_2+G: CCl_4/C_6H_6 system reach the maximum. Thus, the BFSs of C_2Cl_4 and CS_2 can be calculated. The results are shown in Table 2.

Table 2. BFS measured by experiments.

medium	φ_1	ν/MHz	
		experiment	published
C_2Cl_4	83%	2993±18	3016
CS_2	26%	3752±23	3760

Table 2 shows that the BFS measured in this way approach those given by references quite well. If the influence of temperature can be reduced, the comparative errors can be reduced.[18] While the temperature has less impact on the refractive index, the velocity changes greatly with it. Besides, the velocity–temperature indices of some liquids are negative, so their velocities decrease with the temperature.[19] Two means can be used to reduce the influence caused by temperature: (1) put both the generator and the amplifier in thermostat; (2) correct the velocity by means of utilizing the velocity-temperature index.[20]

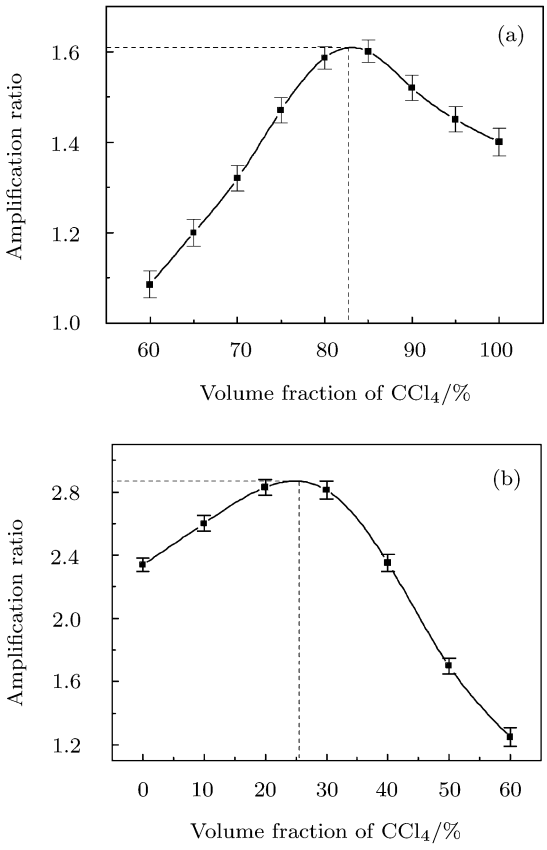


Fig.5. The amplification ratio vs volume fraction of CCl_4, the amplifier medium is (a) C_2Cl_4, (b) CS_2.

4. Conclusions

A method of measuring the BFS of the medium by using mixtures in a two-cell SBS system is proposed, which uses the medium to be measured as amplifier and a mixture medium as generator. The maximum amplification ratio can be obtained by adjusting the mixing ratio of the mixture until the BFS of the mixture medium is equal to that of the medium in amplifier. Therefore, we obtain the BFS of C_2Cl_4 and CS_2. The results measured in this way approach those given by references quite well. The method has the advantage of independence of the wavelength of the incident light. So it promises to be a new method for measuring the BFS of the medium.

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