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Experimental measurement of bulk viscosity of water based on stimulated Brillouin scattering

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ABSTRACT

This paper presents a new method for measuring water bulk viscosity directly by using stimulated Brillouin scattering (SBS). The relationships among shear viscosity, bulk viscosity, thermal capacity, and the line-width were deduced theoretically. The line-width and the bulk viscosity in water with different temperatures were investigated experimentally, and the error of experimental result was analyzed. The results obtained demonstrate that the proposed way is an accurate method for measuring bulk viscosity of water.

1. Introduction

Stimulated Brillouin scattering plays a key role in nonlinear optics, some of its characteristics, such as phase conjugation, pulse width compression and amplification, etc., have been widely applied in related fields [1–3]. Frequency shift and line-width of SBS, which are two important parameters of SBS spectrum, have been applied to measure the temperature and sound velocity, and some remarkable progress has been made [4–13]. Xu et al. [14] once presented a method to measure the bulk viscosity of water by using spontaneous Brillouin scattering. This method has a greater success in real-time monitoring and high precision measurement of bulk viscosity. Compared with spontaneous Brillouin scattering, SBS possesses some important characteristics, for example, threshold value, high gain, conjugation and tunable and so on [15]. In practical applications, the signal intensity of SBS is stronger than that of spontaneous Brillouin scattering, so the signal can be used to probe easily; furthermore, compared with spontaneous Brillouin scattering, SBS possesses higher measurement accuracy, hence it can reduce errors. We have explored the relationships among the line-width of SBS and shear viscosity, bulk viscosity and thermal capacity theoretically. The relationship between the line-width of SBS and bulk viscosity in water with different temperatures have also been investigated experimentally.

2. Theoretical analysis

Brillouin scattering is caused by the density fluctuations of the medium, and the SBS is obtained on the basis of Spontaneous Brillouin scattering, which occurs on condition that the incident light energy density exceeds a certain threshold. When the frequency shift of SBS is far less than incident light frequency, the relationship between scattering intensity and frequency can be expressed as [16]

$$I(\omega) = I_{ad}\frac{\sigma/2\pi}{(\omega-\Omega_0)^2+\sigma^2} \tag{1}$$

where I_{ad} is the scattering intensity of adiabatic density fluctuations, $\sigma=\Gamma q^2/2$, $\Omega^2=\upsilon^2 q^2, q=\frac{4n\pi}{\lambda}\sin\left(\frac{1}{2}\right)$, ω is the angular frequency of scattering light, υ is the frequency of scattering light, Γ is the function of thermodynamics variables, $\Gamma=\frac{1}{\rho}\left[\frac{4}{3}\eta_s+\eta_b+\frac{\kappa}{C_p}(\gamma-1)\right]$, is the shear viscosity, η_s is the bulk viscosity, κ is coefficient of heat conduction, and $\gamma=C_P/C_V$.

From the formula above, we know Brillouin peak is a peak with Lorentz line-shape, the line-width of SBS can be given by

$$(\omega b) = 2\delta = \Gamma q^2 = \frac{1}{\rho}\left[\frac{4}{3}\eta_s+\eta_b+\frac{k}{C_p}(\gamma-1)\right]q^2 \tag{2}$$

Considering that, in the liquid, the magnitude of the first and second terms on the right side of the equation are much larger than that of the third term (more than two orders), we obtain:

$$(\omega b) = \frac{1}{\rho}\left(\frac{4}{3}\eta_s+\eta_b\right)q^2 = \frac{1}{\rho}\left(\frac{4}{3}\eta_s+\eta_b\right)\frac{4\pi^2\upsilon_B^2}{\mathrm{v}} \tag{3}$$

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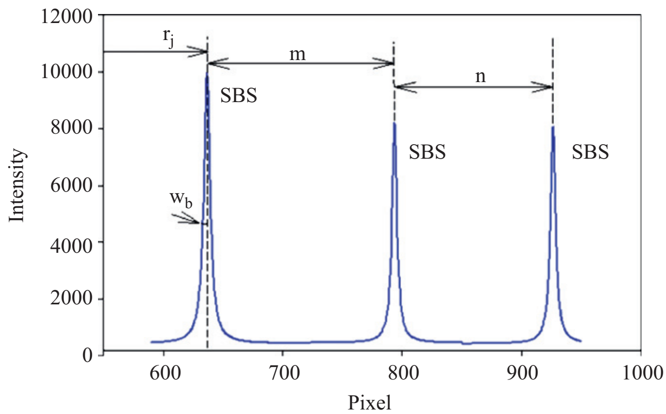

Fig. 1. Schematic diagram of the line-width of SBS.

So the bulk viscosity can be calculated through the following equation:

$$\eta_b = \frac{(\delta\omega)_B \nu^2 \rho}{4\pi^2 \nu_B^2} - \frac{4}{3}\eta_s \tag{4}$$

The relationship between frequency shift and sound speed of Brillouin scattering is [17]:

$$\nu_B(S,T) = \frac{2n(S,T)}{\lambda}\nu(S,T)\sin(\theta/2) \tag{5}$$

Substituting Eq. (4) into (5), we get the relationship between bulk viscosity and Brillouin scattering line-width as follows:

$$\eta_b = \frac{(\delta\omega)_B \lambda^2 \rho}{16\pi^2 n^2(S,T)} - \frac{4}{3}\eta_s \tag{6}$$

where η_s is the shear viscosity, can be obtained from Handbook of Chemistry and Physics, or by theoretical calculation, $(\delta\omega)_B$ is Brillouin scattering line-width measured by experiment.

When F-P etalon and ICCD are used to measure the frequency shift of SBS, corresponding calculating formula is given below:

$$\nu_B \approx \frac{r_{j-1}^2 - r'_{j-1}{}^2}{r_j^2 - r_{j-1}^2} FSR \tag{7}$$

where ν_B is the frequency shift of SBS, FSR is the free spectral range of F-P etalon. Fig. 1 is a graph used to analyze and calculate the line-width of SBS, the FSR of F-P etalon can be expressed by the distance between the two adjacent peaks of SBS, and hence we get Eqs. (8) and (9).

$$(r_j+m)^2 - r_j{}^2 = (r_j+m+n)^2 - (r_j+m)^2 \tag{8}$$

$$(\delta\omega)_B = \frac{(r_j+w_b)^2 - (r_j-w_b)^2}{(r_j+m)^2 - r_j{}^2} FSR \tag{9}$$

3. Experimental scheme and result discussion

The schematic diagram of experimental apparatus is shown in Fig. 2. As, in water, the line-width of SBS is very narrow (only 1 GHz or so), it presents a high stability requirements to the laser and the receivers. In our experiment, an injection-seeded Q-switched Nd:YAG laser (Continuum Power Lite 8000) was used; it operated in a single longitudinal mode at 532 nm wavelength. Pulse frequency was 10 Hz, pulse width was 8 ns. Since, near the threshold value, the excited states of SBS is not very stable, which leads to the Stokes spectrum line being not stable, the laser energy that we used was a little higher compared with the threshold value of SBS. Laser exports vertical polarized light, and after going through a half-wave plate, it becomes horizontal and passes through the polarizer BS with a transmittance. After passing through a quart-wave plate, the transmitted light becomes circularly polarized light and was converged into sink in the position of one meter from its side, which accords with the freedom gain length of SBS in the water [19]. What should be noticed is that, to increase the measured signal-to-noise ratio (SNR), a cylindrical lens was placed in front of the F-P etalon. In this case, the energy distributed on a whole circle will be concentrated to two spots so that the SNR can be increased obviously. Finally, the scattering spectra were analyzed and recorded by ICCD (PI-MAX ST-type 133, Princeton Instruments). The FSR of F-P etalon that we used was 20.1 GHz, which can meet the demand of frequency shift of SBS. The pixel size of ICCD is 26 × 26 μm, resolution is 256 × 1024, and gray output bit depth is 216 levels (16 bits). The water temperature was adjusted by a temperature controlled circulator with the accuracy of 0.02 °C.

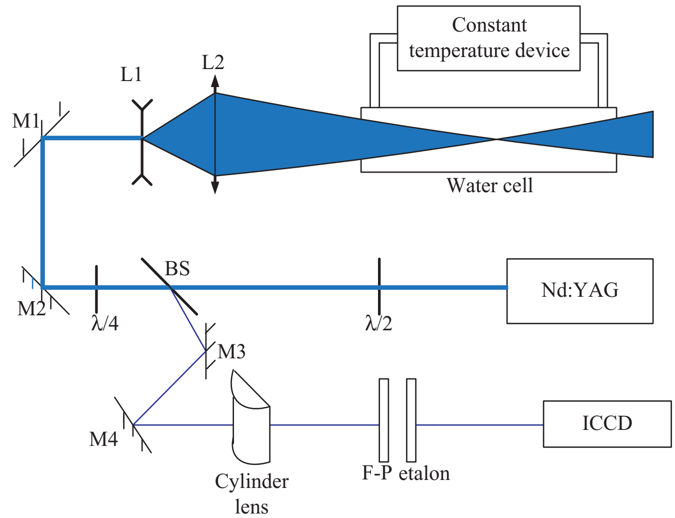

Fig. 2. Schematic diagram of experimental setup (λ/2: half-wave plate, λ/4: quarter-wave plate, BS: polarizer, M1-M4: mirrors, L1 and L2: lens group).

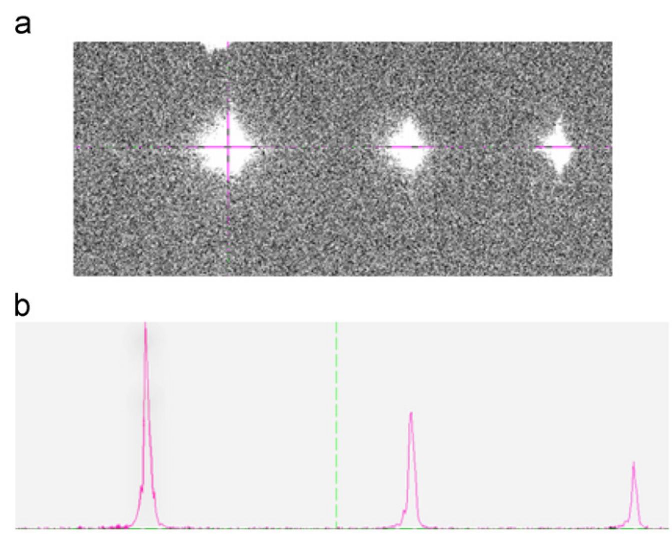

Fig. 3. Measured spectra of SBS. (a) Point-like spectrum obtained by using cylindrical lens and F-P etalon. (b) Planar section of point-like spectrum.

Fig. 3 is a measured spectrum of SBS, in which the three peaks are all SBS peaks. According to interference theory, the distance