Measurement of Brillouin gain coefficient in fluorocarbon liquid

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We report the measurements of Brillouin gain coefficients in FC-770, FC-40, FC-43, and FC-70 using a Brillouin oscillator and amplifier system. In contrast to the traditional way, the novel method provides direct measurements of these coefficients with the medium electro-strictive coefficient or with the phonon lifetime absent. Additionally, the Brillouin gain coefficient of FC-70 in this experiment is different from the theoretical work.

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Stimulated Brillouin scattering (SBS) has broad applications, such as in phase conjugation mirrors[1,2], optical limiting[3], optical sensing[4,5], and high-efficiency signal amplification[6,7]. Pulse compression from nanoseconds to sub-nanoseconds[8–12] can also be commonly achieved by SBS. The selected SBS medium plays an important role in SBS amplification. Excellent SBS media can help improve the conjugation fidelity, energy transferring reflectivity, and pulse compression ratio.

Up until now, many kinds of gases, liquids, and solids have been investigated to find an efficient SBS medium. Fluorocarbon is now widely used as a new series of SBS media. It has many advantages, such as a high gain coefficient, high damage threshold, and short photon lifetime, all of which contribute to higher energy reflectivity and a short Stokes pulse[13,14].

The gain coefficient is essential for the SBS medium, which has a great relationship with the scattering threshold and Brillouin amplification. So far, the reported Brillouin gain coefficient values of fluorocarbon are mainly calculation results[15]. This method, however, suffers the disadvantages of the uncertainty of the electrostriction coefficient and the bandwidth. In order to obtain an accurate value, an experimental method is presented[16,17] based on small-signal Stokes amplification in a Brillouin amplifier.

In this Letter, we report the experiment results of the Brillouin gain coefficient measurement with a pump light wavelength of 532 nm, and demonstrate the theoretical basis of the method. Four kinds of different fluorocarbons are measured. Compared to the theoretical values, the experimental results have a higher reliability.

In the small-signal situation ($I_L \gg I_S$), the intensity of the Stokes radiation from a Brillouin amplifier can be expressed as

$$I_S(z) = I_S(0)\exp(g_B I_L L), \tag{1}$$

where $I_S(0)$ is the input Stokes intensity, $I_S(z)$ is the output Stokes intensity, I_L is the pump intensity, and g_B is the Brillouin gain coefficient. L is the interaction length in the Brillouin media. In the small-signal situation, the gain of the Stokes energy depends linearly on I_L, so the Stokes amplification can be written as

$$E_S(z) = E_S(0) + g_B L \iint I_S(0) I_L \mathrm{d}A\mathrm{d}t, \tag{2}$$

where $E_S(0)$ is the input Stokes energy, $E_S(z)$ is the output Stokes intensity, and I_L is the pump energy. E_L is the injected pump energy. Taking the Taylor expansion of the second term on the right, with the first-order expansion terms on the left, the following equation can be obtained

$$\frac{E_S(\mathrm{z}) - E_S(0)}{E_S(0) E_L} = \frac{g_B L}{\bar{A}\,\bar{\tau}}, \tag{3}$$

$$\frac{1}{\bar{A}} = \frac{\iint I_S(0) I_L \mathrm{d}A}{\int I_S(0)\mathrm{d}A \int I_L \mathrm{d}A}, \tag{4}$$

$$\frac{1}{\bar{\tau}} = \frac{\iint I_S(0) I_L \mathrm{d}t}{\int I_S(0)\mathrm{d}t \int I_L \mathrm{d}t}. \tag{5}$$

If the pulse duration and the beam area of the Stokes are smaller than the pump, the interaction beam area $\bar{A}$ and pulse duration $\bar{\tau}$ can be interpreted with the pump:

$$g_B = \frac{\bar{A}\,\bar{\tau}}{L} \cdot \frac{E_S(\mathrm{z}) - E_S(0)}{E_S(0)} \cdot \frac{1}{E_L}. \tag{6}$$

Through the linear fit of the Stokes energy gain to the pump energy, the Brillouin gain coefficient can be obtained.

The experimental optical path is shown in Fig. 1. The Q-switched Nd:YAG laser with a single longitudinal mode

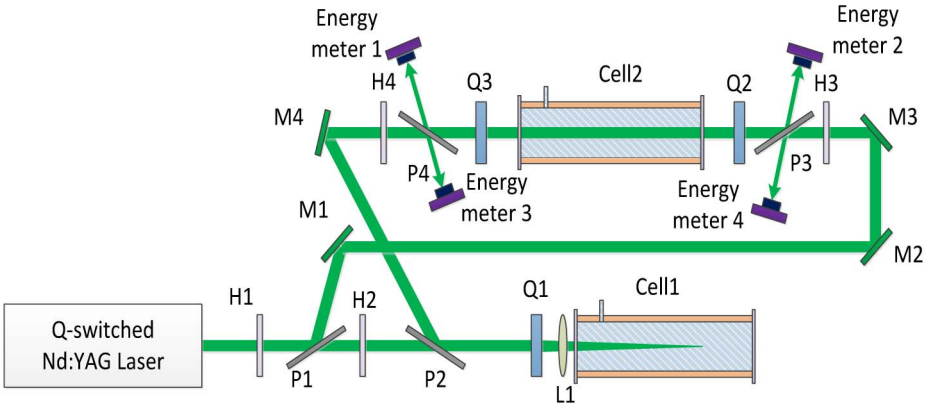

Fig. 1. Optical path used for Brillouin gain coefficient measurements, M1–M4, 532 nm reflection mirrors; H1–H4, half-wave plates; Q1–Q3, quarter-wave plates; P1–P4, Polarizers; L1, lens, focal length 400 mm; Cell 1, SBS oscillator; Cell 2, SBS amplifier.

and the Gaussian baseband is employed in the experiment. Before the output, the frequency of the laser is doubled by a BBO crystal. The laser beam is separated into two parts. One is used to produce the Stokes light through an SBS oscillator, while the other part is used as a pump light in a Brillouin amplifier. The length of both cells is 50 cm, and they are filled with the same liquid medium to ensure the frequency shift matching.

These media all belong to perfluorinated amines; they all have chemical structure $(C_nF_{2n+1})_3N$. Here, FC-770 is composed of C_4F_9NO, FC-43 is composed of $(C_3F_7)_3N$, FC-70 is composed of $(C_5F_{11})_3N$, and FC-40 is composed of $(C_4F_9)_3N$ and $(C_4F_9)_2NCF_3$.

In the amplifier cell, we make sure that the meeting position of the Stokes pulse and the pump pulse is in the middle of the cell. A 50 cm cell limits the interaction length in amplification. There is a difference in the pulse width overlap. It should take a bounded integration in the separation of the pulse peaks:

$$\frac{1}{\bar{\tau}} = \frac{\int_{-\tau_L/2}^{-\tau_L/2} I_S(0) I_L \mathrm{d}t}{\int_{-\tau_L/2}^{-\tau_L/2} I_S(0) \mathrm{d}t \int_{-\tau_L/2}^{-\tau_L/2} I_L \mathrm{d}t}. \tag{7}$$

Data from the energy meters, which measure the input pump energy (meter4), the output pump energy (meter1), the input Stokes energy (meter3), and the output Stokes energy (meter2), are all recorded by a computer at the same time. In all cases, the optical phonon lifetime is much smaller than the pulse width of the Stokes light so that transient effects can be ignored. In experiments, the pump energy is two orders of magnitude higher than the Stokes light. Taking FC-770 as an example, a number of samples are recorded at different pump energies, and these recordings are depicted as a measurement figure (shown in Fig. 2). All measurement devices have been calibrated.

The waveforms of the input Stokes light and the pump light are detected by a photodiode (Ultrafast Photodetectors, UPD-40-UVIR-P, rising time 40 ps). Their pulses can be viewed on an oscilloscope (LeCroy Wave Master 806Zi-A) with a bandwidth of 6 GHz and a resolution of 40 GS/s, so $\bar{\tau}$ can be calculated (Fig. 3). After the measurement of the energy, the amplification cell in the optical path can be removed. A CCD camera (GYD-SG1024B12GA, a 1024 pixel × 1024 pixel CCD) with a 13 μm × 13 μm resolution is added at this position to acquire the near field of the Stokes and the pump. Using this method, the area overlap $\bar{A}$ can be calculated according to the individual pixels sum.

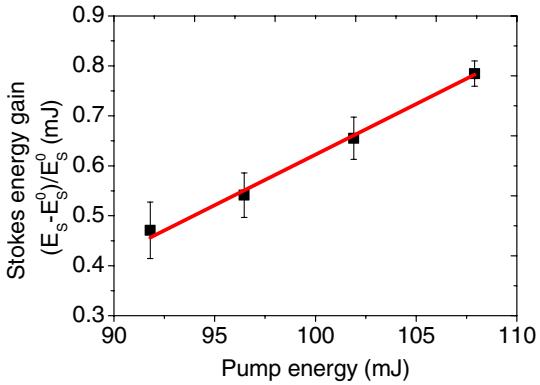

Fig. 2. Typical dependence of Stokes energy gain on pump energy at 532 nm for FC-770. The red line is the linear fit.

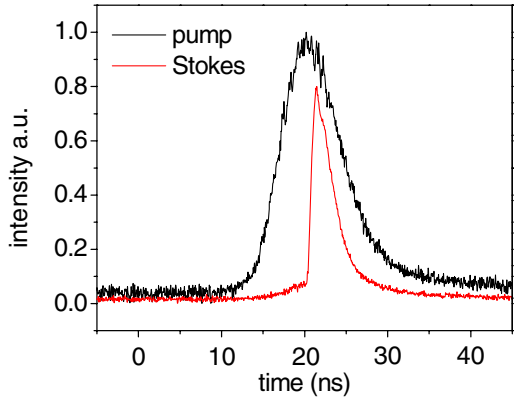

Fig. 3. Typical waveform of the pump light (black) and Stokes light (red) recorded by a photodiode (in FC-770).

Table 1. Measurement Values of Brillouin Gain Coefficient

	Brillouin gain coefficient (cm/GW)	
Type of medium	This work	Theoretical work
FC-40	2.06 ± 0.20	1.8[15]
FC-770	3.7 ± 0.28	3.5[19]
FC-43	1.035 ± 0.13	1.3[21]
FC-70	0.895 ± 0.11	0.2[21]

According to the theoretical analysis, the Brillouin gain coefficient values are calculated by Eq. (6). In Eq. (6), the cell length is measured easily with high accuracy. The accuracy of $\bar{A}$ and $\bar{\tau}$ is mainly dependent on the measuring equipment. Deviations mainly come from the linear fit of the Stokes energy gain to the pump energy.

The measured values of the Brillouin gain coefficients of a few kinds of fluorocarbons are shown in Table 1. Our measurement results for FC-40 and FC-770 are in agreement with theoretical work. While the value of FC-43 is a little bit smaller than the theoretical work[18–20], the gain coefficient of FC-70 is measured to be higher[21].

It is reported that the Brillouin gain coefficient can be calculated by a well-known formula, as follows:

$$g_B = \frac{4\pi^2\gamma^2}{ncV\rho\lambda^2\Gamma_B} \cdot \frac{1}{1+\left(\frac{2\Delta\omega}{\Gamma_B}\right)^2}, \tag{8}$$

where γ is the electrostriction coefficient, λ is the optical wavelength of the Stokes light, Γ_B is the rate of acoustic intensity, ρ is the medium's density, and V is the sonic speed in the medium. If $\Delta\omega$ is ignored, the Brillouin gain coefficient can be expressed as

$$g_B = \frac{4\pi^2\gamma^2}{ncV\rho\lambda^2\Gamma_B}. \tag{9}$$

Under the condition of resonance, the formula is the maximum value estimation used for the Brillouin gain coefficient calculation. Due to the existence of frequency broadening caused by the Doppler effect or collision effect, the calculation formula of the Brillouin gain coefficient is not appropriate anymore. The direct measurement method circumvents the problem that the frequency broadening brings irreparable errors to the calculation results.

In a previous work, the SBS energy reflectivity of different pump energies in FC-70 was seen to be similar as that in FC-43. However, according to the calculated results of the Brillouin gain coefficient, the value of FC-70 is 0.2 cm/GW, which is much lower than FC-43. On the basis of the SBS characteristic investigation of FC-70[18], we believe that 0.895 cm/GW is much closer to the true Brillouin gain coefficient of FC-70.

The motivation for measuring the Brillouin gain coefficient depends on the needs in designing the Brillouin pulse compressor, which is required by pulse compression from nanoseconds to sub-nanoseconds. Based on the measurement results, the suitable amplification medium can be chosen with a relatively high SBS energy efficiency.

In conclusion, we measure the value of the Brillouin gain coefficient of a few kinds of fluorocarbons (FC-40, FC-770, FC-70, and FC-43) at 532 nm experimentally through the process of Brillouin amplification. The measured values of FC-40, FC-770, and FC-43 are in agreement with the previously calculated values. However, FC-70 is different from the previous work. Our work provides a method of measuring the Brillouin gain coefficient values under varying experiment conditions.

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