Effect of water temperature on pulse duration and energy of stimulated Brillouin scattering

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The water temperature has a strong effect on the kinematic viscosity, which is inversely proportional to the phonon lifetime and the gain coefficient. The higher the temperature is, the smaller the kinematic viscosity is, and the larger the phonon lifetime is. At a low pump power and a short focal length, we can derive a single-peak stimulated Brillouin scattering (SBS) pulse. The duration of this single-peak SBS pulse depends mainly on the phonon lifetime of water. With the increase of the water temperature, the duration of such a single-peak SBS pulse will become longer, and the SBS energy will become higher for the gain coefficient, which is related to the phonon lifetime. Therefore, varying the medium temperature can lead to the changes of SBS pulse duration and SBS energy.

Keywords: stimulated Brillouin scattering, pulse duration and energy, water temperature, phonon lifetime

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1. Introduction

Stimulated Brillouin scattering (SBS) is a nonlinear process which has been widely studied because of its specific properties in optical phase conjugation,[1,2] beam combination,[3–6] and pulse compression.[7,8] Since then, the enormous potential of SBS has been realized, and commercial lasers employing internal pulse compression are now available.[9,10] The use of SBS for the compression of laser pulse has been investigated theoretically and experimentally in various types of lasers and active media.[11]

The SBS pulse duration is a key factor for many applications, especially in the Brillouin laser. The SBS pulse duration or the shape of SBS is sensitive to the changes of pump power, focal length, and active medium. When the pump energy is low and the focal length is short, we can get a single-peak SBS pulse that has a good temporal profile.[12,13] In this paper, the relationship between the medium (water) temperature and the SBS pulse duration is determined. By changing the medium temperature, we are able to vary the phonon lifetime, thereby the characteristics of SBS are investigated.

2. Theory

Brillouin scattering refers to the scattering of a light wave by an acoustic phonon. Stimulated Brillouin scattering is initiated by Stokes photons created by spontaneous Brillouin scattering. When the pump power exceeds the SBS threshold, the Stokes light intensity can be derived by solving the wave equation[14,15]

$$\frac{\mathrm{d}I_{\mathrm{L}}}{\mathrm{d}z} = -gI_{\mathrm{L}}I_{\mathrm{S}}, \quad \frac{\mathrm{d}I_{\mathrm{S}}}{\mathrm{d}z} = -gI_{\mathrm{L}}I_{\mathrm{S}}. \tag{1}$$

The Stokes intensity is characterized by an exponential amplification

$$I_{\mathrm{S}} = I'_{\mathrm{S0}}\exp(G), \tag{2}$$

where I_{L} is the incident light intensity, I_{S} and I'_{S0} are the SBS intensity and the initiated weak Stokes intensity, respectively. Here G can be written as $G = g_0 I_{\mathrm{L}} L$, where L is the interaction length in the medium. The g_0 is the gain coefficient of the SBS material and can be expressed as[16]

$$g_0 = \frac{\gamma_{\mathrm{e}}^2\omega^2}{\rho_0 nc^3 v\Gamma_{\mathrm{B}}}, \tag{3}$$

where γ_{e}, ω, ρ_0, n, c, v, and Γ_{B} denote the electrostriction coefficient, the Stokes angular frequency, the density, the refractive index, the light velocity in vacuum, the acoustic velocity, and the line width (in angular frequency) of the spontaneous Brillouin scattering, respectively. For phonon lifetime $\tau_{\mathrm{B}} = 1/\Gamma_{\mathrm{B}}$, we find that the gain coefficient is given by

$$g_0 = \frac{\gamma_{\mathrm{e}}^2\omega^2\tau_{\mathrm{B}}}{\rho_0 nc^3 v}. \tag{4}$$

The phonon lifetime at the backward can be written as[16]

$$\tau_{\mathrm{B}} = \frac{\rho_0 c^2}{\eta\omega^2 n^2}. \tag{5}$$

The density, refractive index, and acoustic velocity vary little with the change of temperature, however, the kinematic viscosity changes greatly with the temperature, which is the key factor for the phonon lifetime and the gain coefficient. In a high temperature, the kinematic viscosity is small, so the phonon lifetime and the gain coefficient are large. Decreasing

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the temperature will cause the reduction of the phonon lifetime and the gain coefficient.[17,18] The changes of phonon lifetime and gain coefficient have an effect on the pulse duration and the intensity of SBS. In our experiment, we measure the SBS pulse duration and the SBS energy in different medium temperatures to find out how the medium temperature influences the phonon lifetime and the gain coefficient.

3. Experiment and results

3.1. Experiment

The experimental arrangement for SBS pulse duration and SBS intensity measurements is presented in Fig. 1. An injected-seeded *Q*-switched pulsed Nd:YAG laser is operated at 532 nm (Contimuum Powerlite PrecisionII 8000) with the pulse duration of 8 ns. The line width is about 120 MHz, and the repetition rate is 10 Hz. The linearly polarized beam becomes circular polarized after passing through a half-wave plate, a polarization beam splitter (PBS), and a quarter-wave plate, and is focused into an SBS generation cell to excite Stokes light. We use fresh water as the SBS active medium with a phonon lifetime of the order of a nanosecond. The backwards Stokes light becomes s-polarized after passing the quarter-wave plate, and is reflected by the polarization beam splitter. The SBS pulse shape is detected by a probe (Electro-Optics Technology model ET 2000 with the rising time of 200 ps) and recorded by an oscilloscope (Agilent model DSO 7104A with the band width of 1 GHz).

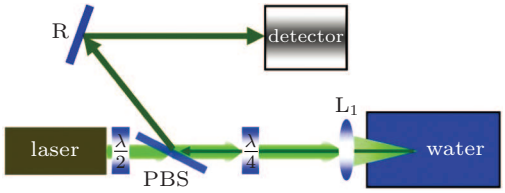


Fig. 1. (color online) Experimental setup, where PBS is a polarization beam splitter, and detector is a PIN photodiode.

3.2. Results

3.2.1. The change of water temperature affects the pulse duration of SBS

In our experiment, we kept the pump energy at 1.8 mJ and the focal length at 30 cm, and the water temperature was adjusted by a temperature controlled circulator with the accuracy of 0.02 °C. Then we measured the pulse durations of single-peak SBS at different water temperatures. The average values of SBS pulse duration at different water temperatures are shown in Table 1. In Table 1, PD stands for pulse duration.

Table 1. SBS pulse durations at different water temperatures.

Temperature/°C	5	10	15	20	25	30	35	40
PD/ns	1.69	2.0	2.25	2.40	2.60	2.70	2.75	2.85

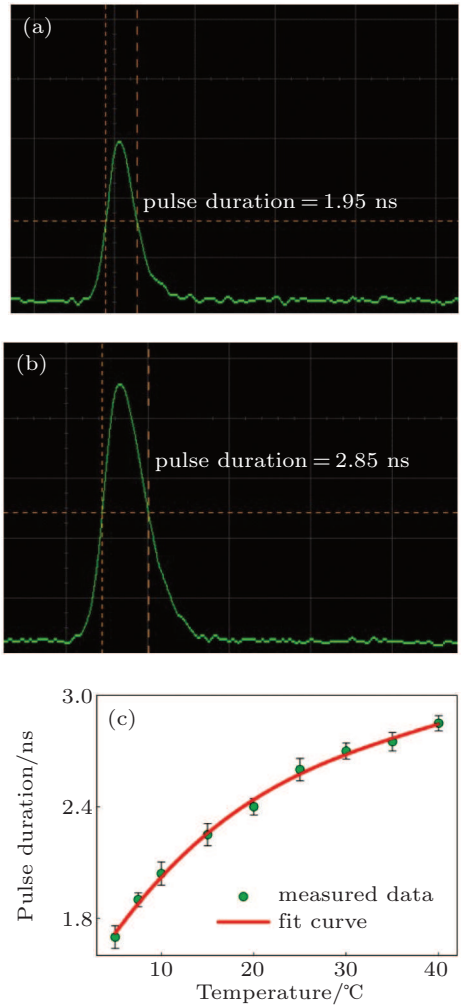


Fig. 2. (color online) Single-peak SBS pulse durations at different water temperatures: (a) single-peak SBS pulse duration at 10 °C, (b) single-peak SBS pulse duration at 40 °C, (c) single-peak SBS pulse duration changed with temperature.

The results of our experiment are also shown in Fig. 2. As can be seen in Fig. 2, the pulse duration of SBS at 40 °C is 2.85 ns, which is longer than that at 10 °C. Figure 2(c) shows that with the increase of water temperature, the pulse duration of SBS becomes longer, which indicates that the phonon lifetime alters with the change of water temperature: the higher the water temperature, the longer the phonon lifetime. When the pump energy and the focal length are kept constant, the pulse duration of single-peak SBS is mainly dependent on the phonon lifetime of the medium. The longer the phonon lifetime is, the slower the response of the medium to the rapid changes in the Stokes and laser field is, and the wider the SBS pulse duration is. Inversely, a shorter phonon lifetime will lead to a narrower SBS pulse. The phonon lifetime is so sensitive to the change of the medium temperature that we can get different pulse durations of single-peak SBS by varying the medium temperature, which can be used in laser pulse compression.

3.2.2. The change of water temperature affects the energy of SBS

Comparing Fig. 2(a) with Fig. 2(b), we can also notice that the SBS intensity at 40 °C is higher than that at 10 °C. The reason is that the gain coefficient increases as the phonon lifetime becomes longer, which is in accord with Eq. (3). In order to prove that the gain coefficient varies with the change of water temperature, we measured the energy of SBS at four different water temperatures and ten different pump energies for each temperature. Figure 3(a) shows that the energy of SBS grows with the increase of the pump energy. At the same pump energy, the change of the water temperature affects the energy of SBS, raising the temperature will increase the energy of SBS. This phenomenon is obvious when the temperature is high, which can be explained by Eq. (2): the intensity of SBS is proportional to $\exp(gIL)$, the change of the temperature makes little difference on the gain coefficient, so the change of the SBS intensity is not obvious when the pump intensity is weak, which can be seen in Fig. 3(a) as the pump energy is below 30 mJ; at a strong pump intensity, the little change of the gain coefficient caused by temperature will lead to a great increase of the index factor $\exp(gIL)$, so the alteration of the SBS intensity will be obvious.

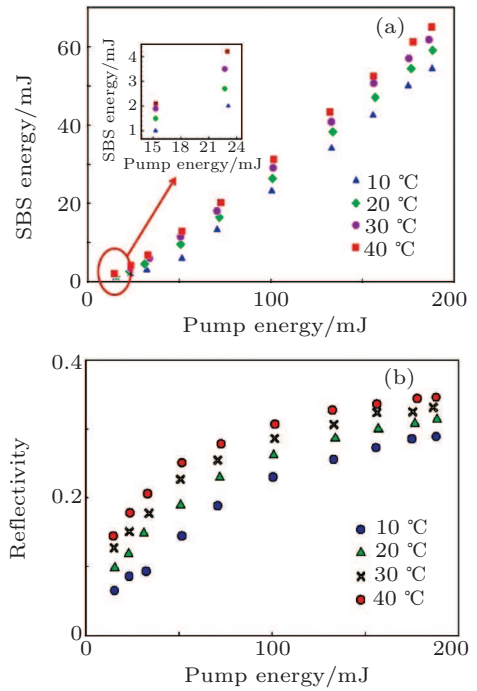


Fig. 3. (color online) (a) SBS energy and (b) SBS reflectivity at different pump energies and temperatures. The inset shows the SBS energy at low pump energy.

In Fig. 3(b), we replace the SBS energy by reflectivity as the y axis. The reflectivity is defined as the SBS energy divided by the pump energy. The dependence of SBS reflectivity on temperature can be seen clearly. The SBS reflectivity will increase as the water temperature rises.

4. Conclusion

At high temperature, the duration of single-peak SBS pulse is long and the energy of SBS is high, which are in accord with the theory that the high temperature leads to a longer phonon lifetime and a larger gain coefficient.

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