Laser and Particle Beams (2009), *27*, 733–737.

doi:10.1017/S0263034609990437

Investigation on effect of medium temperature upon SBS and SBS optical limiting

W.L.J. HASI, X.Y. GUO, H.H. LU, M.L. FU, S. GONG, X.Z. GENG, Z.W. LU, D.Y. LIN, AND W.M. HE

Institute of Opto-electronics, Harbin Institute of Technology, Harbin, China; National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin, China

(RECEIVED 9 July 2009; ACCEPTED 8 September 2009)

Abstract

The effect of medium temperature upon characteristic of stimulated Brillouin scattering (SBS) and SBS optical limiting is investigated. The physical mechanism behind is analyzed theoretically and experimentally verified in Continuum's Nd: YAG Q-switched laser system using FC-72 as the SBS medium. The temperature affects the electrostrictive coefficient, refractive index, density and acoustic velocity of the medium weakly. In contrast, the kinematic viscosity, which is inversely proportional to the temperature, is related to gain coefficient and phonon lifetime and thus greatly affects the SBS characteristics. Therefore, in the low temperature, the kinematic viscosity is usually high, which can lead to a small gain coefficient and a short phonon lifetime. Therefore, the SBS characteristic can be changed by controlling the temperature to a great extent.

Keywords: Medium temperature; Phonon lifetime; SBS optical limiting; Stimulated Brillouin scattering

INTRODUCTION

Stimulated Brillouin scattering (SBS) has been regarded as an effective way to recover beam front and can be exploited to improve beam quality. The SBS phase conjugation exhibits several advantages in terms of small frequency shift, simple configuration, high fidelity, and high energy reflectivity. Therefore, it has been a focus of theoretical and experimental investigation during the past several decades (Kong *et al.*, 2007; Yoshida *et al.*, 2007; Ostermeyer *et al.*, 2008; Bai *et al.*, 2008; Grofts *et al.*, 1991; Wang *et al.*, 2007, 2009; Hasi *et al.*, 2007). A great deal of research has demonstrated medium is a crucial factor for improving the SBS performance (Yoshida *et al.*, 1997; Hasi *et al.*, 2008*a*; Park *et al.*, 2006; Chalus & Diels, 2007; Gong *et al.*, 2009). In the previous investigations, SBS phase conjugation experiments are usually carried out in room temperature and the effect induced by temperature change is seldom considered. In reality, the medium temperature may be changed due to the absorption of pump light with a high power and repetition rate. Therefore, investigation on the effect of medium temperature upon SBS and SBS optical limiting is a meaningful issue (Hasi *et al.*, 2008*b*, 2008*c*).

In this paper, the effect of medium temperature upon characteristic of SBS and SBS optical limiting is investigated. The physical mechanism behind is analyzed theoretically and experimentally verified in Continuum's Nd: YAG Q-switched laser system using FC-72 as the SBS medium. The temperature affects the electrostrictive coefficient, refractive index, density and acoustic velocity of the medium weakly. In contrast, the kinematic viscosity, which is inversely proportional to the temperature, is related to gain coefficient and phonon lifetime, and thus greatly affects the SBS characteristics. Therefore, in the low temperature, the kinematic viscosity is usually high, which can lead to a small gain coefficient, and a short phonon lifetime. Therefore, the SBS characteristic can be changed by controlling the temperature to a great extent.

THEORY

The gain coefficient of medium can be expressed by (Park *et al.*, 2006; Erokhin *et al.*, 1986; Pohl & Kaiser, 1970)

$$g = \frac{4\pi^2\gamma^2\tau}{nc\upsilon\rho\lambda^2}, \tag{1}$$

Address correspondence and reprint requests to: Z.W. Lu, Institute of Opto-electronics, Harbin Institute of Technology P.O. Box 3031, Harbin 150080, China. E-mail: zw_lu@sohu.com

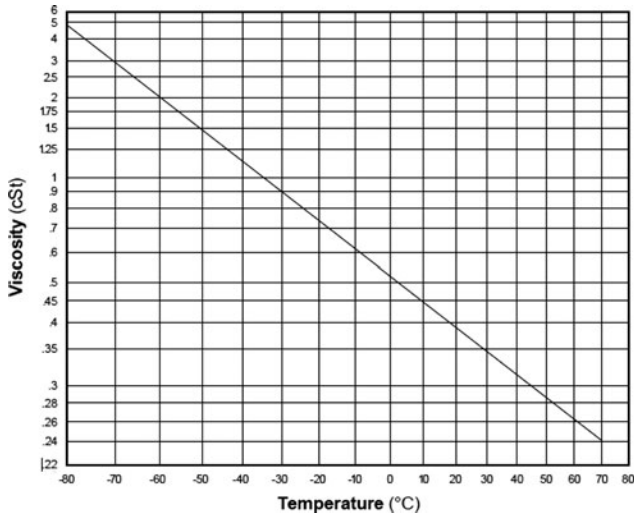

Fig. 1. The kinematic viscosity of FC-72 *versus* medium temperature (3M Specialty Materials, 2000).

where g is the gain coefficient, n is the refractive index, γ is the electrostriction coefficient, which is related to n by $\gamma = (n^2-1)(n^2+2)/3$, τ is the phonon lifetime, c is the light velocity in the vacuum, υ is the acoustic velocity, ρ is the density and λ is the wavelength of incident light.

Table 1. *The density and kinematic viscosity of SBS medium at different temperature*

Medium		FC-72	FC-87	FC-77	FC-84
Density (g/cm^3)	25°C	1.68	1.63	1.78	1.73
	−54°C	1.90	1.84	1.97	1.93
Kinematic viscosity (cSt)	25°C	0.4	0.4	0.8	0.55
	−54°C	1.9	1.1	6.9	4.0

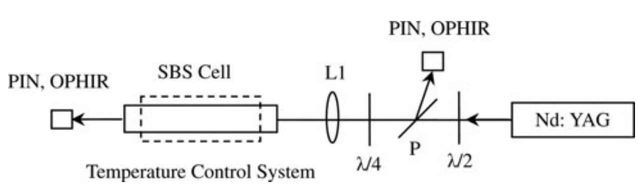

Fig. 2. Experimental setup.

The phonon lifetime τ of medium can be expressed by (Park *et al.*, 2006; Erokhin *et al.*, 1986)

$$\tau = \frac{\lambda^2}{4\pi^2\eta}, \tag{2}$$

where η denotes the kinematic viscosity. Eq. (2) shows that when the phonon lifetime τ is inversely proportional to the kinematic viscosity η.

Substituting Eq. (2) into Eq. (1), the gain coefficient g can be related to kinematic viscosity η by:

$$g = \frac{\gamma^2}{nc\upsilon\rho\eta}. \tag{3}$$

Eq. (3) shows that the gain coefficient is also inversely proportional to kinematic viscosity.

The temperature change has a little effect on the refractive index, density, and acoustic velocity. However, for the kinematic viscosity, it varies greatly with the temperature (Weaver, Patent (IPC8 Class: AF21V2900FI); Lagemann *et al.*, 1948; 3M Specialty Materials, 2000; Grassi & Testi, 2008), as shown in Figure 1.

Table 1 lists the density and kinematic viscosity of SBS medium perfluoro-compound at 25°C and −54°C, respectively. The density of FC-72 increases from 1.68 g/cm^3 at 25°C to 1.90 g/cm^3 at −54°C, and the relative change is only 13%; however, the kinematic viscosity increases from 0.4 cSt at 25°C to 1.9 cSt at −54°C (3M Electronics Markets Materials Division, 2003).

Since the gain coefficient and phonon lifetime are both related to the kinematic viscosity, the temperature change will greatly affect the two parameters. In the low temperature, the gain coefficient and phonon lifetime are small. Increasing the temperature will lead to the increase in the gain coefficient and phonon lifetime.

EXPERIMENT

The experimental setup is shown in Figure 2. Continuum's Nd: YAG Q-switched laser outputs single mode s-polarized light with line-width 90 MHz, which becomes p-polarized after passing the 1/2 wave plate, and then circular polarized after passing the 1/4 wave plate. The SBS system comprises a generator cell and a focus lens L1 ($f =$

Table 2. *The SBS parameters of some media at room temperature*

Medium	Absorption coefficient (cm^{-1})	SBS gain coefficient (cm/GW)	Density (g/cm^3)	SBS threshold (mJ)	Phonon lifetime (ns)
FC-72	$<10^{-3}$	6.0	1.68	2.5	1.2
FC-87	$<10^{-3}$	6.6	1.65	2.2	1.1
FC-77	$<10^{-3}$	5.1	1.78	4.3	0.7
FC-84	$<10^{-3}$	6.0	1.73	4.0	0.9

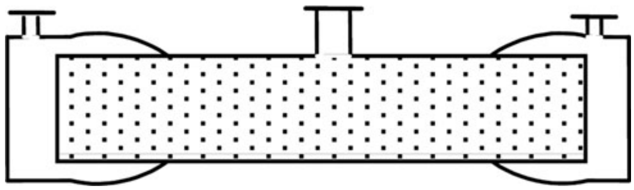

Fig. 3. SBS cell with double window plates, the cell length is 60 cm and inside diameter is 5 cm.

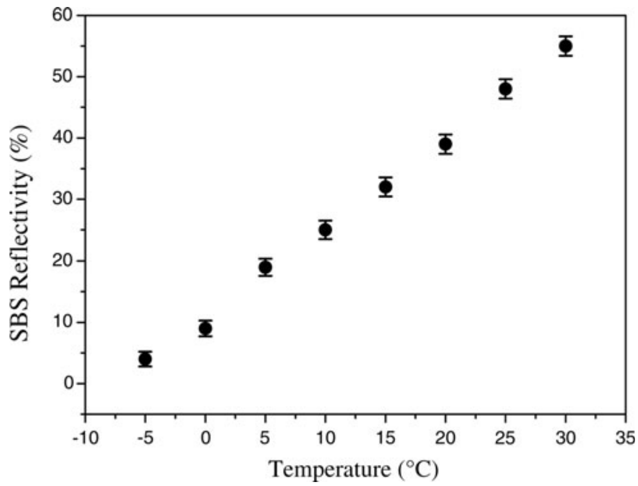

Fig. 4. The dependence of SBS reflectivity on medium temperature as pump energy fixed at 40 mJ.

30 cm). The pump light is focused into a generator cell to produce Stokes light. Polarizer P together with a $1/4$ wave plate forms a light isolator, preventing the backward SBS light from entering YAG oscillator. The Stokes light becomes s-polarized after passing the $1/4$ wave plate, and is reflected by polarizer P. The pump energy can be adjusted through a $1/2$ wave plate. The energy of pump pulse, Stokes pulse, and transmitted pulse are measured with energy meter OPHIR. The pulse shape is detected with PIN photodiode, and recorded with digital oscilloscope TDS684A.

The output wavelength of Continuum's Nd: YAG Q-switched laser is 1064 nm, with a repetition rate of 1 Hz, pulse width 8 ns, and divergence angle 0.45 mrad. FC-72 is adopted as the SBS medium. The medium temperature is altered by resistance heating films and semiconductor-refrigerating chips. Table 2 lists the parameters of some SBS media. In order to eliminate the water droplet formed on the cell window plate due to the temperature difference between air and medium at low temperature, SBS cell with double window plates is designed, as shown in Figure 3. The interspace between the two window plates is vacuum-pumped; therefore no water droplet can be formed while the light can propagate freely.

Figure 4 provides the dependence of SBS energy reflectivity on the medium temperature for fixed pump energy. The reflectivity scales is almost linearly with the temperature. This is because small kinematic viscosity due

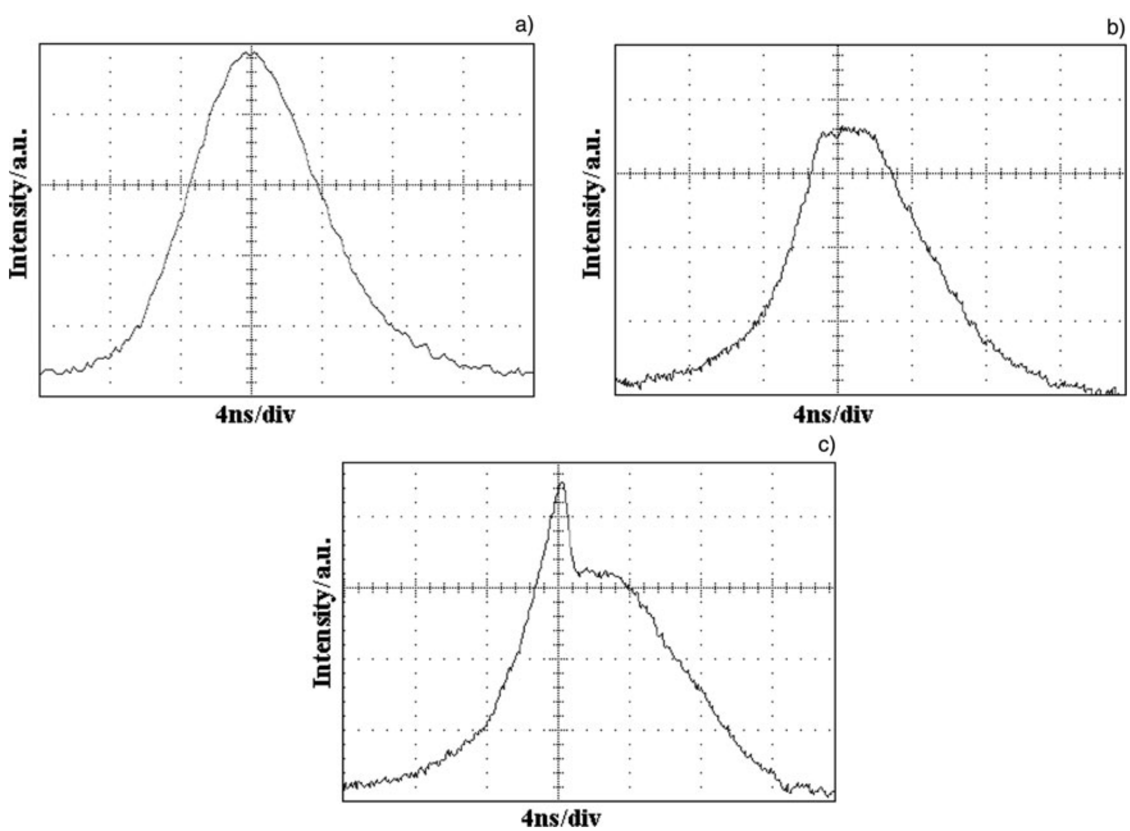

Fig. 5. (**a**) Pump waveform and transmitted waveforms of SBS at different temperature (**b**) 8°C, and (**c**) 15°C, respectively.

to a high temperature can lead to a large gain coefficient, thus enhancing the energy coupling efficiency between the pump and Stokes (Boyd & Rzazewski, 1990). Therefore, a proper choose of temperature increase can lead to improved SBS energy reflectivity. For the output energy of SBS optical limiting, it will turn high at a low temperature (Hasi *et al.*, 2009).

Figure 5 shows the transmitted waveforms of SBS optical limiting at different temperatures. The top of the transmitted pulse is almost a platform at 8°C, while a peak appeared at 15°C. This can be explained as follows: at a high temperature, kinematic viscosity is small and leads to a long phonon lifetime; thus the energy transfer is incomplete and the peak appears. In contrast, at a low temperature, the phonon lifetime is comparatively short and the complete energy transfer can lead to the generation of flat-top waveform (Hasi *et al.*, 2008*d*). Therefore, a low temperature is preferred to be chose for the generation of flat-top pulse in time domain.

CONCLUSIONS

The effect of medium temperature upon characteristic of SBS and SBS optical limiting is investigated. The physical mechanism behind is analyzed theoretically and experimentally verified in Continuum's Nd: YAG Q-switched laser system using FC-72 as the SBS medium. The temperature affects the electrostrictive coefficient, refractive index, density and acoustic velocity of the medium weakly. In contrast, the kinematic viscosity, which is inversely proportional to the temperature, is related to gain coefficient and phonon lifetime, and thus greatly affects the SBS characteristics. Therefore, in the low temperature, the kinematic viscosity is usually high, which can lead to a small gain coefficient and a short phonon lifetime. Therefore, the SBS characteristic can be changed by controlling the temperature to a great extent.

ACKNOWLEDGEMENTS

This work is supported by National Natural Science Foundation of China (Grant Nos. 60778019, 60878005), the Program for New Century Excellent Talents in University (Grant No. NCET-08-0173), and the Program of Excellent Team in Harbin Institute of Technology.

REFERENCES

3M Electronics Markets Materials Division. (2003). 3M Center, Building 220-9E-11 St. Paul, MN 55144-1000.

3M Specialty Materials. (2000). 3M Center, Building 223-6S-04 St. Paul, MN 55144-1000.

Bai, J.H., Shi, J.W., Ouyang, M., Chen, X.D., Gong, W.P., Jing, H.M., Liu, J. & Liu, D.H. (2008). Method for measuring the threshold value of stimulated Brillouin scattering in water. *Opt. Lett.* **33**, 1539–1541.

Boyd, R.W. & Rzazewski, K. (1990). Noise initiation of stimulated Brillouin scattering. *Phys. Rev. A* **42**, 5514–5521.

Chalus, O. & Diels, J.C. (2007). Lifetime of fluorocarbon for high-energy stimulated Brillouin scattering. *J. Opt. Soc. Am. B* **24**, 606–608.

Erokhin, A.I., Kovalev, V.I. & Faïzullov, F.S. (1986). Determination of the parameters of a nonlinear response of liquids in an acoustic resonance region by the method of nondegenerate four-wave interaction. *Sov. J. Quan. Electr.* **16**, 872–877.

Gong, S., Hasi, W.L.J., Lu, Z.W., Dong, F.L., Lin, D.Y., He, W.M., Zhao, X.Y. & Fan, R.Q. (2009). Study on the choosing principles of SBS new medium perfluoro-compound for phase conjugation mirror and optical limiter. *Acta Phys. Sin.* **58**, 304–308.

Grassi, W. & Testi, D. (2008). Transitional mixed convection in the entrance region of a horizontal pipe. *5th European Thermal-Sciences Conference*, The Netherlands.

Grofts, G.J., Damzen, M.J. & Lamb, R.A. (1991). Experimental and theoretical investigation of two-cell stimulated-Brillouin-scattering systems. *J. Opt. Soc. Am. B* **8**, 2282–2288.

Hasi, W.L.J., Gong, S., Lu, Z.W., Lin, D.Y., He, W.M. & Fan, R.Q. (2008*b*). Generation of flat-top waveform in the time domain based on stimulated Brillouin scattering using medium with short phonon lifetime. *Laser Part. Beams* **26**, 511–516.

Hasi, W.L.J., Lu, Z.W., Gong, S., Li, Q., Lin, D.Y. & He, W.M. (2008*c*). Investigation on output energy characteristic of optical limiting based on the stimulated Brillouin scattering. *Appl. Phys. B* **92**, 599–602.

Hasi, W.L.J., Lu, Z.W., Fu, M.L., Lu, H.H., Gong, S., Lin, D.Y. & He, W.M. (2009). Improved output energy characteristic of optical limiting based on double stimulated Brillouin scattering. *Appl. Phys. B* **95**, 711–714.

Hasi, W.L.J., Lu, Z.W., Gong, S., Liu, S.J., Li, Q. & He, W.M. (2008*a*). Investigation on new SBS media of Perfluoro-compound and Perfluoropolyether with low absorption coefficient and high power-load ability. *Appl. Opt.* **47**, 1010–1014.

Hasi, W.L.J., Lu, Z.W., Li, Q. & He, W.M. (2007). Research on the enhancement of power-load of two-cell SBS system by choosing different media or mixture medium. *Laser Part. Beams* **25**, 207–210.

Hasi, W.L.J., Lu, Z.W., Liu, S.J., Li, Q., Yin, G.H. & He, W.M. (2008*d*). Generation of flat-top waveform in the time domain based on stimulated Brillouin scattering. *Appl. Phys. B* **90**, 503–506.

Kong, H.J., Yoon, J.W., Beak, D.J., Shin, S., Lee, S.K. & Lee, D.W. (2007). Laser fusion driver using stimulated Brillouin scattering phase conjugate mirrors by a self-density modulation. *Laser Part. Beams* **25**, 225–238.

Lagemann, R.T., Woolf, W.E., Evans, J.S. & Underwood, N. (1948). Ultrasonic Velocity in Some Liquid Fluorocarbons. *J. Am. Chem. Soc.* **70**, 2994–2996.

Ostermeyer, M., Kong, H.J., Kovalev, V.I., Harrison, R.G. & Fotiadi, A.A. (2008). Trends in stimulated Brillouin scattering and optical phase conjugation. *Laser Part. Beams* **26**, 297–362.

Park, H., Lim, C., Yoshida, H. & Nakatsuka, M. (2006). Measurement of stimulated Brillouin scattering characteristics in heavy fluorocarbon liquids and perfluoropolyether liquids. *Jpn. J. Appl. Phys.* **45**, 5073–5075.

Pohl, D. & Kaiser, W. (1970). Time-resolved investigations of stimulated brillouin scattering in transparent and absorbing media: Determination of phonon lifetimes. *Phys. Rev. B* **1**, 31–43.

Wang, S.Y., Lu, Z.W., Lin, D.Y., Ding, L. & Jiang, D.B. (2007). Investigation of serial coherent laser beam combination based on Brillouin amplification. *Laser Part. Beams* **25**, 79–83.

Wang, Y.L., Lu, Z.W., He, W.M., Zheng, Z.X. & Zhao, Y.H. (2009). A new measurement of stimulated Brillouin scattering phase conjugation fidelity for high pump energies. *Laser Part. Beams* **27**, 297–302.

Weaver, M.A.S.E. (2009). Efficient cooling of lasers, LEDs and photonics devices. Patent (IPC8 Class: AF21V2900FI).

Yoshida, H., Fujita, H., Nakatsuka, M., Ueda, T. & Fujinoki, A. (2007). Temporal compression by stimulated Brillouin scattering of Q-switched pulse with fused-quartz and fused-silica glass from 1064 nm to 266 nm wavelength. *Laser Part. Beams* **25**, 481–488.

Yoshida, H., Kmetik, V., Fujita, H., Nakatsuka, M., Yamanaka, T. & Yoshida, K. (1997). Heavy fluorocarbon liquids for a phase-conjugated stimulated Brillouin scattering mirror. *Appl. Opt*. **36**, 3739–3744.