Laser and Particle Beams (2013), *31*, 301–305.
©Cambridge University Press, 2013 0263-0346/13 $20.00
doi:10.1017/S0263034612001097

Research on the compression properties of FC-3283 and FC-770 for generating pulse of hundreds picoseconds

W.L.J. HASI, X.Y. WANG, S.X. CHENG, Z.M. ZHONG, Z. QIAO, Z.X. ZHENG, D.Y. LIN, W.M. HE, AND Z.W. LU
National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin, China

(RECEIVED 23 October 2012; ACCEPTED 10 November 2012)

Abstract

This paper gives out two kinds of novel well-behaved stimulated Brillouin scattering (SBS) mediums, FC-3283 and FC-770. Numerical calculation and experimental measurements show these two mediums both having lower absorption, higher optical loads and short phonon lifetime, which making them good candidate mediums for high-energy high-power SBS. Using them as the mediums in the compacted two-cell SBS phase-conjugation mirror, it is easily to generate ultrashort phased-conjugated Stokes pulses just with hundreds picoseconds. When the incident light energy is beyond 200 mJ, the pulse width of 8 ns can be compressed to 200 ps or less in both mediums. Especially, the FC-770 is very suitable to be chosen for generating the SBS picosecond pulses with the narrowest compression pulse width of 109 ps and the highest energy reflectivity of 80%.

Keywords: SBS hundreds picoseconds pulse compression; SBS mediums; Stimulated Brillouin scattering

INTRODUCTION

Inertial confinement fusion (ICF) has drawn people's attention because of its vital application prospect in solving the energy crisis and national defense. Betti *et al.* (2007) from the University of Rochester proposed the shock ignition scheme for ICF. As a new shock ignition scheme for ICF, it presents a new challenge for accelerating ICF scientific research because of its lower comprehensive requirements of laser driver scale and spatial and temporal character. It has become a challenge to generate the laser pulse that can be used for driven source of ICF, with pulse-width of 200 ps, energy of several kilojoules and a pulse peak power of 10 terawatts.

The research on the stimulated Brillouin scattering (SBS) mediums for generating pulse of hundreds picosecond is the main task, which presents a new challenge for amplification technology of the high power laser. Pulse compression by SBS is to use SBS effect leading to a quick energy transfer from pump to the Stokes whose pulse front edge is prior to be amplified. Since it is non-linear exponential growth process, the compressed pulse with high efficiency is very suitable to amplify the Stokes as pulse signal with high energy efficiently (Damzen *et al.*, 1983*a*; 1983*b*; Hon *et al.*, 1980; Gao *et al.*, 2012; Shin *et al.*, 2010; Omatsu *et al.*, 2012), and the Stokes pulse peak power could increase to dozens of times. We could make use of this process to obtain picoseconds laser pulse with high power. In the latest ICF ignition program for shock ignition, we could obtain stable Stokes seed pulses with picoseconds by the pulse compression technology based on the SBS. We can also use SBS amplification technology with high conversion efficiency leading to a full energy transfer from pump pulse width of nanosecond to the Stokes seed of short-pulse, and then obtain Stokes pulses with a width of hundred picoseconds, a pulse peak power of terawatts, energy of several kilojoules. And this is the most direct and cost-saving method in shock ignition research right now.

Although many people studied the pulse compression technology by SBS, they mainly focused on low-energy nanoseconds pulse (Yoshida *et al.*, 2007*a*; 2004; Dane *et al.*, 1994). Because the picosecond pulses have some defects, such as low conversion efficiency, low load capacity, poor stability, short incident wavelength, repeated compression, and rather complexed experiment devices (Neshev *et al.*, 1999; Yoshida *et al.*, 2007*b*; Marcus *et al.*, 2008). In 2009, Yoshida *et al.* (2009) used FC-40 as the SBS medium in a compact two-cell SBS system. The sequence is reversed

---

Address correspondence and reprint requests to: W.L.J. Hasi, National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin, China. E-mail: hasiwuliji@sohu.com; or to: Z.W. Lu, E-mail:zw_lu@sohu.com

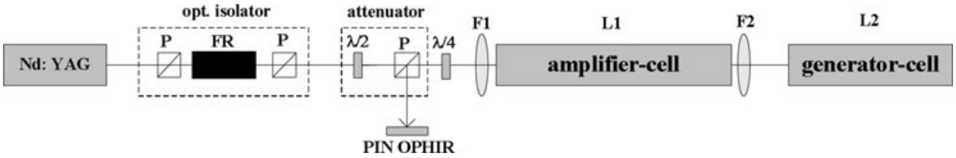

Fig. 1. Schematic diagram of the experimental set-up.

(13 ns was compressed to 160 ps) and the maximum energy reflectivity was about 80%, which have been the highest pulse compression ratio and energy reflectivity can be got from the lab condition so far. However, they focused on the influence of structural parameters (cell length and focal length) on the efficiency of SBS pulse compression instead of medium parameters. Actually, the medium parameters have great influences on SBS pulse compression properties (Park *et al.*, 2006; Hasi *et al.*, 2008; Dong *et al.*, 2012; Yoshida *et al.*, 1997), especially phonon lifetime is the main factor affecting SBS pulse compression limit (Velchev *et al.*, 1999; Gorbunov *et al.*, 1983; Damzen *et al.*, 1983*a*; 1983*b*; Fedosejevs & Offenberger 1985; Schiemann *et al.*, 1997). Therefore exploring the mediums with excellent SBS property and relatively short phonon lifetime is the first condition for hundreds picoseconds pulse compression SBS system.

This paper gives out two kinds of novel well-behaved SBS mediums, FC-3283 and FC-770. Numerical calculation and experimental measurements show these two mediums both having lower absorption, higher optical loads, and short phonon lifetime, which making them good candidate mediums for high-energy high-power SBS. The research on the compression properties for generating pulse of hundreds picoseconds is carried on in the two-cell SBS compact structural system. It turns out that these two mediums not only indicate the good properties of SBS but also show excellent compression properties for generating pulse of hundreds picoseconds. When the incident light energy is beyond 200 mJ, the pulse width of 8 ns can be compressed to 200 ps or less in both mediums, especially the FC-770 is very suitable to be chosen for generating the SBS picoseconds pulses. Both the highest energy reflectivity could reach about 80%.

EXPERIMENTAL STUDY

Schematic diagram of the experimental set-up is shown in Figure 1. We use a single mode injection seeded Q-switched Continuum Nd: YAG laser with *s*-polarization whose bandwidth is 50 MHz. Here we adopt the compact two-cell SBS system, which consists of a generator cell, an amplifier cell and lens F_1, F_2. The *s*-polarized light is turned into *p*-polarized by a 1/2 wave plate, and then becomes circularly polarized after a 1/4 wave plate. And the polarizer *P* and 1/4 plate is operated as an optical isolator to prevent the backward Stokes returning to the Nd: YAG laser. The convex lens F_1 is placed in front of the amplifier cell, which can increase the pump power intensity in the amplifier cell so that the Stokes light can be amplified effectively, and the focus of F_1 is located out of amplifier cell. The pump light injected into the generator cell could generate Stokes light through the convex lens F_2. The Stokes light could couple with the pump light in the amplifier cell and then would be amplified effectively. The backward Stokes light, through a 1/4 wave plate, becomes *s*-polarized, and is then reflected by the polarizer *P*. The pulse width of Stokes is detected by detection system and we can change the energy of the pump light by adjusting the 1/2 wave plate. The detection system consists of a PIN photodiode, a digital oscilloscope and a MIN-E1000 energy meter. The energies of incident and Stokes light are detected by PE50BB-DIF-V2 (OPHIR) energy meter. The pulse waveforms are detected by PIN photodiode whose response time is 18.5 ps (New Focus, 1454) and recorded by a digital oscilloscope DPO7254 (bandwidth is 2.5 GHz).

In the experiment, the pulse width of pump beam is 8 ns, far-field divergence angle is 0.45 mrad, beam diameter is 9.5 mm, and incident energy is 220 mJ. Here we adopt the compact two-cell SBS system whose structural parameters are as follows: the amplifier cell length $L_1 = 80$ cm, the convex lens $F_1 = 150$ cm, the generator cell length $L_2 = 80$ cm, the convex lens $F_2 = 60$ cm. We choose FC-3283 and FC-770 as scattering medium whose parameters are list in Table 1. The phonon lifetime, gain coefficient and SBS Brillouin frequency shift are calculated according to the formula in Refer (Park *et al.*, 2006). The absorption coefficient and optical breakdown threshold (OBT) are measured directly in the experiment.

In order to eliminate the tiny particles on the influence of optical breakdown threshold, we use the filter with a pore size of 0.2 μm to purification (Hasi *et al.*, 2004), and then carry out the measurement of the absorption coefficient

Table 1. *Parameters of liquid SBS Media*

Medium	FC-3283	FC-770
Refractive index	1.281	1.27
Average molecular weight	521	399
Density (g/cm^3)	1.83	1.793
Kinematic viscosity (cSt)	0.75	0.79
Boiling point (°C)	128	95
Absorption coefficient (cm^{-1})	0.0009	0.0011
OBT(GW/cm^2)	179	198
Phonon lifetime (ns)	0.59	0.57
SBS gain coefficient (cm/GW)	4.0	3.5
Brillouin shift (MHz)	1080	1081

and optical breakdown threshold. When measuring optical breakdown threshold (defined as the average of the highest power density of the incident light and the lowest when the optical breakdown phenomenon does not occur within the medium), we choose a lens of focal length 15 cm and loaded SBS sample cell (having a thickness of 40 cm) placed in the optical path of the lens at the focus. We use He-Ne laser to irradiate the focus of SBS medium pool side vertically with changed-coupled device detecting the changes of transmitted light spot to determine whether optical breakdown occurs in the medium (Guo *et al.*, 2012*a*; 2012*b*).

Both FC-3283 and FC-770 belong to PFCs in which the hydrogen of hydrocarbons, ethers and amines connected with carbon atoms are all replaced by fluorine atoms. The molecular formula of FC-3283 is $(C_3F_7)_3N$. FC-770 is a mixture of perfluoromorpholine compounds, mainly composed of C_4F_9NO and its isomer, which can be classified as perfluorinated ethers (3M Fluorinert™ Electronic Liquid FC-770). The molecular structures of FC-3283 and FC-770 are shown in Figure 2.

As can be seen from Table 1, both FC-3283 and FC-770 have properties of low absorption, high load and a relatively short-lived phonon lifetime. The molecular absorption in the near-infrared regime mainly corresponds to combined acoustic frequency of the X-H bond (X stands for C, N, O, S, P) and the double frequency (Wang *et al.*, 1994). Thereby PFCs and PFPE mediums comparatively have rather small absorption coefficient to the infrared light owing to the band of C-C, C-F, C-N and C-O instead of X-H bonds (X stands for C, N, O, S, P). Fluorine possesses the least atomic radius and its Van der Waals radius is merely 0.135 nm, so in the perfluorocarbon molecules the carbon chain skeleton is tightly wrapped by the fluorine atoms, which play a good protective effect for the carbon chain skeleton (Xia & Luo, 2005), so they have high OBT. In addition, when the wavelength of incident light is stable, the phonon lifetime of the medium is inversely proportional to the kinematic viscosity (Hasi *et al.*, 2009). And as the kinematic viscosity of both mediums is relatively large, their phonon lifetime is relatively short.

Figure 3 shows the experimental trend of the SBS pulse compression width under different input energies in these two mediums. We can see that as the incident energy increases, the pulse widths generated in the FC-3283 and FC-770 become narrow rapidly at the beginning and then the trend decline down gradually. It can be explained by the fact that the system exponential gain coefficient ($G = gIL$, where g is the gain coefficient of the medium, I is the power density of incident light, L is the length of the effective role) (Lee *et al.*, 2005), becomes larger as the incident energy increases and then the pulse width is getting narrower. However, with the further increase of the incident light energy, the SBS pulse compression tends to the limit, so the width of the pulse becomes narrower gradually.

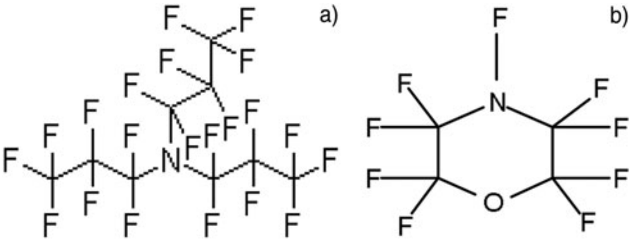

Fig. 2. The molecular structures of (a) FC-3283 and (b) FC-770.

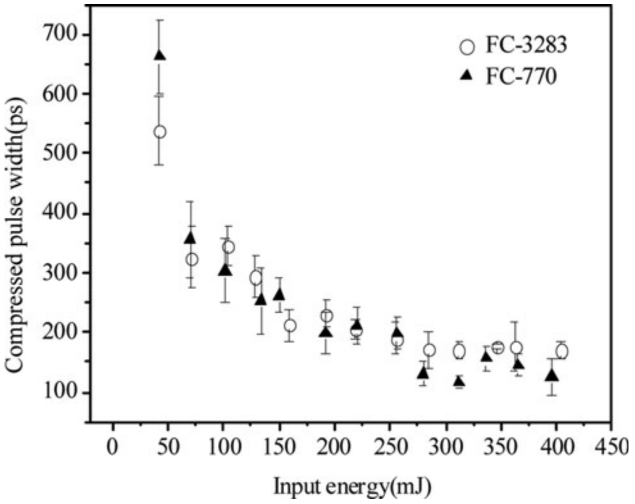

Fig. 3. The experimental curve of the SBS pulse compression width with two different mediums under different input energies.

Furthermore, it also can be seen from Figure 3 that the pulse width of 8 ns can be compressed to 200 ps or less in both mediums when the incident light energy is beyond 200 mJ. When it increases to about 310 mJ, the narrowest width of compression pulse is achieved with the highest stability; continuously increasing the incident energy, the pulse compression waveform width will be widened with lower stability; this may be due to beginning to appear the weak optical breakdown in the mediums occasionally (Hasi *et al.*, 2012).

Figure 4 shows the compression pulse waveforms of FC-3283 and FC-770 when the incident energies are 190 mJ. The pulse widths measured are 202 ps and 190 ps, respectively. In the experiment, we can observe that the compressed pulse width of the FC-770 is narrower and higher stability than that of FC-3283 with the energy of incident light increasing, which may be because optical breakdown threshold of FC-3283 is lower than FC-770, it appears relatively strong. Figure 5 shows when the incident energy is 310 mJ, the compression pulse waveform is narrowest with the width of 168 ps and 109 ps, respectively.

The SBS energy reflectivity of these two mediums under different driven energies is shown in Figure 6. Obviously, both energy reflectivities are very similar with rather low incident light energy; but with the higher incident energy, the energy reflectivity of FC-770 is higher than that of FC-3283.

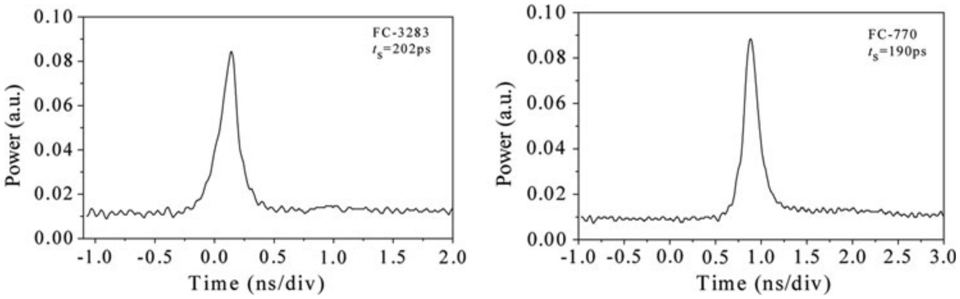

Fig. 4. The compression pulse waveforms of FC-3283 and FC-770 when the incident energies are 190 mJ.

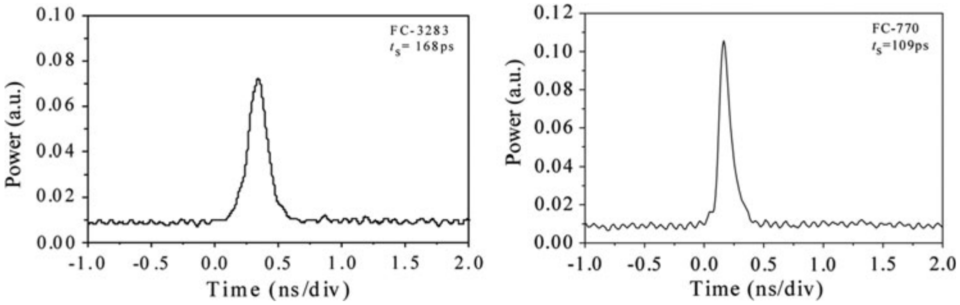

Fig. 5. The narrowest pulse waveforms of FC-3283 and FC-770 when the incident energies are 310 mJ.

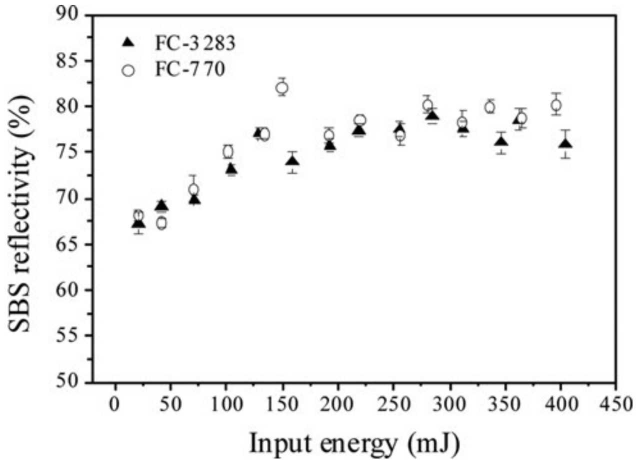

Fig. 6. The SBS compression reflectivity of two mediums under different input energies.

This is because the gain coefficient and absorption coefficient of the FC-3283 and FC-770 are very close, when the incident energy is small their energy reflectivity is also similar; but when the incident light energy is much higher, the optical breakdown of FC-3283 is relatively stronger, so its energy reflectivity is lower than that of FC-770.

CONCLUSION

In this paper, FC-3283 and FC-770 are chosen to study the compression properties for generating pulse of hundreds picoseconds in the structure of SBS compact two-cell system. It turns out that these two mediums not only indicate the good properties of SBS but also show excellent compression properties for generating pulse of hundreds picoseconds. When the incident light energy is beyond 200 mJ, the pulse width of 8 ns can be compressed to 200 ps or less in both mediums; the narrowest width of compression pulse is achieved with the highest stability when the incident light energy is about 310 mJ. When the incident light energy is much higher, FC-770 can get more compressed pulse also a higher stability. Therefore the FC-770 is more competitive as the SBS medium to generate picoseconds pulses. The optical breakdown of the mediums has great influence on width for generating compression pulse of hundreds picoseconds and their stability, therefore to explore the mediums with greater optical breakdown threshold is the next objective of the study.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Grant Nos. 61138005), the Program for New Century Excellent Talents in University (Grant No. NCET-08-0173), and the Fundamental Research Funds for Central Universities (Grant No. HIT.BRET2.20100/2).

REFERENCES

Betti, R., Zhou, C.D., Anderson, K.S., Perkins, L.J., Theobald, W. & Solodov, A.A. (2007). Shock ignition of thermonuclear fuel with high areal density. *Phys. Rev. Lett.* **98**, 155001.

Damzen, M.J. & Hutchinson, M.H.R. (1983*a*). High-efficiency laser-pulse compression by stimulated Brillouin scattering. *Opt. Lett.* **8**, 313–315.

Damzen, M.J. & Hutchinson, H. (1983*b*). Laser pulse compression by stimulated Brillouin scattering in tapered waveguides. *IEEE J. Quantum Electron.* **19**, 7–14.

Dane, C.B., Neuman, W.A. & Hackel, L.A. (1994). High-energy SBS pulse compression. *IEEE J. Quan. Electr.* **30**, 1907–1915.

Dong, Y.K., Zhang, H.Y., Chen, L. & Bao, X.Y. (2012). 2-cm-spatial-resolution and 2-km-range Brillouin optical fiber sensor using a transient differential pulse pair. *Appl. Opt.* **51**, 1229–1235.

Fedosejevs, R. & Offenberger, A.A. (1985). Subnanosecond pulses from a KrF laser pumped SF6 Brillouin amplifer. *IEEE J. Quan. Electr.* **21**, 1558–1562.

Gao, W., Hu, X.B., Sun, D. & Li, J.Y. (2012). Simultaneous generation and Brillouin amplification of a dark hollow beam with a liquid-core optical fiber. *Opt. Express* **20**, 20715–20720.

Gorbunov, V.A., Paperny, T.S.B., Petrov, V.F. & Startsev, V.R. (1983). Time compression of pulses in the course of stimulated Brillouin scattering in gases. *Sov. J. Quan. Electr.* **13**, 900–905.

Guo, X.Y., Hasi, W.L.J., Zhong, Z.M., Jin, C.Y., Lin, D.Y., He, W.M. & Lu, Z.W. (2012). Research on the SBS mediums used in high peak power laser system and their selection principle. *Laser Part. Beams*. **31**, 525–530.

Hasi, W.L.J., Lu, Z.W., Gong, S., Liu, S.J., Li, Q. & He, W.M. (2008). 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., Guo, X.Y., Lu, H.H., Fu, M.L. Gong, S., Geng, X.Z., Lu, Z.W., Lin, D.Y. & He, W.M. (2009). Investigation on effect of medium temperature upon SBS and SBS optical limiting. *Laser Part. Beams.* **27**, 733–737.

Hasi, W.L.J., Zhong, Z.M., Qiao, Z., Guo, X. Y., Li, X., Lin, D.Y., He, W.M., Fan, R.Q. & Lu, Z.W. (2012). The effects of medium phonon lifetime on pulse compression ratio in the process of stimulated Brillouin scattering. *Opt. Commun.* **285**, 3541–3544.

Hasi, W.L.J., Lu, Z.W., He, W.M., Wang, S.Y. & Liu, S.N. (2004). Experimental investigation on the improvement of SBS characteristics by purification. *Chin. Opt. Lett.* **2**, 718–721.

Hon, D.T. (1980). Pulse compression by stimulated Brillouin scattering. *Opt. Lett.* **5**, 516–518.

Lee, S.K., Lee, D.W., Kong, H.J. & Guo, H. (2005). Stimulated Brillouin scattering by a multi-mode pump with a large number of longitudinal modes. *J. Korean Phys. Soc.* **46**, 443–447.

Marcus, G., Pearl, S. & Pasmanik, G. (2008). Stimulated Brillouin scattering pulse compression to 175 ps in a fused quartz at 1064 nm. *J. Appl. Phys.* **103**, 103105.

Neshev, D., Velchev, I., Majewski, W.A., Hogervorst, W. & Ubachs, W. (1999). SBS pulse compression to 200 ps in a compact single-cell setup. *Appl. Phys. B* **68**, 671–675.

Omatsu, T., Kong, H.J., Park, S., Cha, S., Yoshida, H., Tsubakimoto, K., Fujita, H., Miyanaga, N., Nakatsuka, M., Wang, Y., Lu, Z., Zheng, Z., Zhang, Y., Kalal, M., Slezak, O., Ashihara, M., Yoshino, T., Hayashi, K., Tokizane, Y., Okida, M., Miyamoto, K., Toyoda, K., Grabar, A.A., Kabir, Md.M., Oishi, Y., Suzuki, H., Kannari, F., Schaefer, C., Pandiri, K.R., Katsuragawa, M., Wang, Y.L., Lu, Z.W., Wang, S.Y., Zheng, Z.X., He, W.M., Lin, D.Y., Hasi, W.L.J., Guo, X.Y., Lu, H.H., Fu, M.L., Gong, S., Geng, X.Z., Sharma, R.P., Sharma, P., Rajput, S., Bhardwaj, A.K., Zhu, C.Y. & Gao, W. (2012). The current trends in SBS and phase conjugation. *Laser Part. Beams* **30**, 117–174.

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.

Schiemann, S., Ubachs, W. & Hogervorst, W. (1997). Efficient temporal compression of coherent nanosecond pulses in a compact SBS generator-amplifier setup. *IEEE J. Quan. Electr.* **33**, 358–366.

Shin, J.S., Park, S. & Kong, H.J. (2010). Compensation of the thermally induced depolarization in a double-pass Nd:YAG rod amplifier with a stimulated Brillouin scattering phase conjugate mirror. *Opt. Commun.* **283**, 2402–2405.

Velchev, I., Neshev, D., Hogervorst, W. & Ubachs, W. (1999). Pulse compression to the sub-photon lifetime region by half-cycle gain in transient stimulated Brillouin scattering. *IEEE J. Quan. Electr.* **35**, 1812–1816.

Wang, J., Sowa, M.G., Ahmed, M.K. & Mantsch, H.H. (1994). Photoacoustic near-infrared investigation of homo-polypeptides. *J. Phys. Chem.* **98**, 4148–4155.

Xia, S.Z. & Luo, Y.M. (2005). *Organic Chemistry*. Wuhan: Huazhong University of Science and Technology Press.

Yoshida, H., Fujita, H., Nakatsuka, M., Ueda, T. & Fujinoki, A. (2007*a*). Compact temporal-pulse-compressor used in fused-silica glass at 1064 nm wavelength. *Jpn. J. Appl. Phys.* **46**, 80–82.

Yoshida, H., Fujita, H., Nakatsuka, M. & Fujinoki, A. (2004). Temporal compression by stimulated Brillouin scattering of Q-switched pulse with fused quartz glass. *Jpn. J. Appl. Phys.* **43**, 1103–1105.

Yoshida, H., Fujita, H., Nakatsuka, M., Ueda, T. & Fujinoki, A. (2007*b*). 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., Hatae, T., Fujita, H., Nakatsuka, M. & Kitamura, S. (2009). A high-energy 160-ps pulse generation by stimulated Brillouin scattering from heavy fluorocarbon liquid at 1064 nm wavelength. *Opt. Express* **17**, 13654–13662.

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.* **16**, 3739–3744.