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Temporal compression by stimulated Brillouin scattering of Q-switched pulse with fused-quartz and fused-silica glass from 1064 nm to 266 nm wavelength

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Abstract

We have designed a compact solid compressor by stimulated Brillouin scattering (SBS), which consists of two right angle prisms and a fused silica glass block. A 13–16 ns Nd:YAG laser pulse has been temporally compressed to 1 ns or less phase conjugation pulse in a fused-quartz and fused-silica glass at four different wavelengths. Maximum reflectivity of SBS was 90–95% without damage. The brightness of the compressed pulse was about ten-fold higher than that of the incident pulse. Damage-free operation using fused quartz glass as a better phase conjugation material could lead to the construction of a more compact, laser-diode-pumped, and all-solid-state laser system.

Keywords: Fused-silica glass; Phase conjugation; Pulse compression; Stimulated Brillouin scattering

1. INTRODUCTION

The stimulated Brillouin scattering (SBS) as a phase-conjugation mirror (PCM) using liquid or gaseous material can improve the performance of high-average-power laser system (Rockwell, 1988; Dane *et al.*, 1994; Yoshida *et al.*, 1997*a*, 1997*b*; Kong *et al.*, 2005*a*, 2005*b*, 2006, 2007; Meister *et al.*, 2007; Kappe *et al.*, 2007). The phase conjugation mirror can restore the phase and improve the image quality of laser, and thus is a good tool for compensation of wave front distortion of a high-power laser beam. Some SBS materials are often dangerous because of their toxicity and high-pressure conditions. The advantages of using solid media are their compactness, harmlessness, and easy handling. Crystalline quartz was used as the nonlinear medium in the first practical demonstration of SBS (Chiao *et al.*, 1964). In the case of optical fibers, the long path length results in a sufficient SBS effect even at a low power level (Ippen & Stoien, 1972; Cotter, 1982; Eichler *et al.*, 1997). However, the incident energy is limited to a few mJ to avoid the incident surface damage.

The study of the SBS process in optical glasses such as fused quartz and fused silica glass is important for applications such as PC mirror. The SBS gain coefficient of fused quartz glass has been previously reported (Eggleston & Kushner, 1987; Fairs *et al.*, 1990, 1993). On the other hand, bulk fused quartz glass has been verified as a highly damage-resistant SBS mirror with high reflectivity (Yoshida *et al.*, 1997*a*, 1999*a*, 1999*b*). Furthermore, the advantages of bulk glass as a phase-conjugating medium are compact, harmless, and easy to handle. The SBS compression of laser pulse has been investigated theoretically and experimentally for various wavelengths of lasers and active SBS media (Dane *et al.*, 1994; Schiemann *et al.*, 1997; Kmetik *et al.*, 1998; Neshev *et al.*, 1999). The SBS compressor provides enhancements in peak intensity of pulses while maintaining its high energy, and makes available laser pulse duration from about 500 ps to 1 ns. It is difficult to generate mode-locked pulses without damage at high peak power. On the other hand, this method of short-pulse generation is very simple, and can be used to achieve high brightness that is calculated from SBS reflectivity, and the compressed pulse width. And the study of the SBS process in the fused silica glass is important for such applications as a phase conjugation mirror. We previously reported that 8 ns Nd:YAG laser pulse has been temporally compressed to less than 1 ns phase conjugation pulse in a 1.2-m long fused quartz glass at three different wavelengths (Yoshida *et al.*, 2004). SBS maximum reflectivity was about

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40–45% without any damage. The brightness of the compressed pulse was about four-fold higher than that of the incident pulse. However, the handling was inconvenient because of a long cell. Thus, we have designed two cell SBS compressor system with a fused-silica glass. A compact solid compressor by SBS combined two right angle prisms and fused silica glass block. For two cell SBS system, the nonlinear process including optical breakdown, self-focusing, and thermal heating can entirely disrupt the SBS process at higher laser powers.

We demonstrated the efficient compression of 13–16 ns pulse duration to 1 ns or less of an Nd:YAG laser at its second, third, and fourth harmonics. The fused silica glass and quartz glass can also be used as phase conjugator for high-average-power lasers instead of the gaseous or liquid SBS materials.

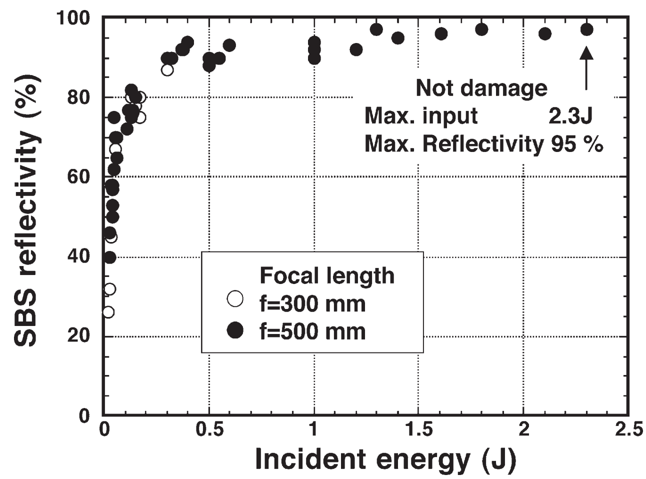

Fig. 1. SBS reflectivity of a bulk fused-quartz glass as a function of the incident pulse energy at 16-ns pulse duration using the focal length of 300 mm and 500 mm.

2. SBS REFLECTIVITY OF FUSED-SILICA GLASS

The used laser is a linearly polarized Q-switched Nd:YAG oscillator at single-frequency and TEM_{00} mode of operation. The full width at half maximum (FWHM) of the laser pulse is 16 ns and its shape is quasi-Gaussian. The beam profile at the lens position is close to a Gaussian shape of 2.8 cm in diameter. The beam quality is 1.5 times diffraction-limited. The used sample is Type Heralux-E (Shin-Etsu Quartz Products Co. Ltd., Tokyo Japan; 20-mm$^{\phi}$ × 300-mm^{l}) that shows a strong striation. The circularly polarized laser beam is focused at the point of 250-mm inside the glass by a lens of focal length 300 or 500 mm. The distance between the lens and the incident surface of the glass is about 130 mm. The beam diameter on the surface of the glass is about 1.6 mm. Figure 1 shows the SBS reflectivity of a bulk fused-quartz glass as a function of the incident pulse energy at 16-ns pulse duration using the lens of focal length 300 mm and 500 mm. Figure 2 shows the oscilloscope traces of the typical incident and reflected waveforms at several incident energies. As the incident energy increases, the SBS reflectivity increases monotonically. Using single transverse-mode for the pump light, a fused-quartz glass can be used for higher pumping energy of a few J, without laser induced damage with the lens $f = 500$ mm. We previously reported that the SBS reflectivity reached the maximum value of 95% at the input energy of 2.3 J, which was approximately 153 times larger than the SBS threshold of about 15 mJ (Yoshida *et al.*, 2003). The transmitted energy is about 130 mJ at the maximum incident energy of 2.4 J (48 GW/cm^2) under the SBS reflectivity of 95%. The maximum transmitted fluence at the focus is estimated to be over 760 J/cm^2 with an assumption of uniform focusing. However, because the transmitted pulse shape becomes shape near the trapezoid, the peak intensity is estimated to be 25 GW/cm^2 at 30 ns pulse width. In the experiment, the focusablity into a fused-quartz might be reduced due to a poor optical homogeneity by a strong striation. The focal spot-size in the sample measured by a He-Ne laser is about three times larger than that in air, and the transmitted wave front distortion is about 30λ at 0.63-μm wavelength. The intrinsic transmitted intensity seems to be 85 J/cm^2, which does not exceed the damage threshold of 120 J/cm^2. The incident energy was limited by the incident surface damage. As the incident energy increases, the temporal profile of the reflected high-energy pulse shows a smooth and un-modulated envelope with a moderately steep leading edge. The damage threshold at a longer pulse

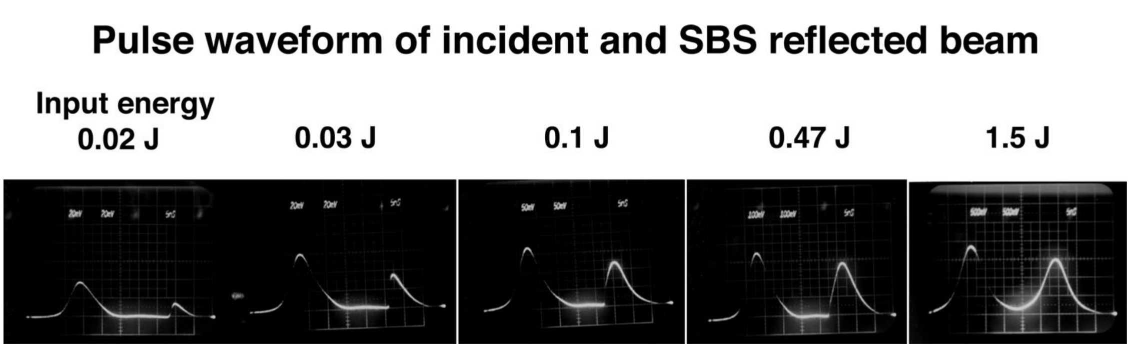

Fig. 2. The oscilloscope traces of the typical incident and reflected waveforms at several incident energies.

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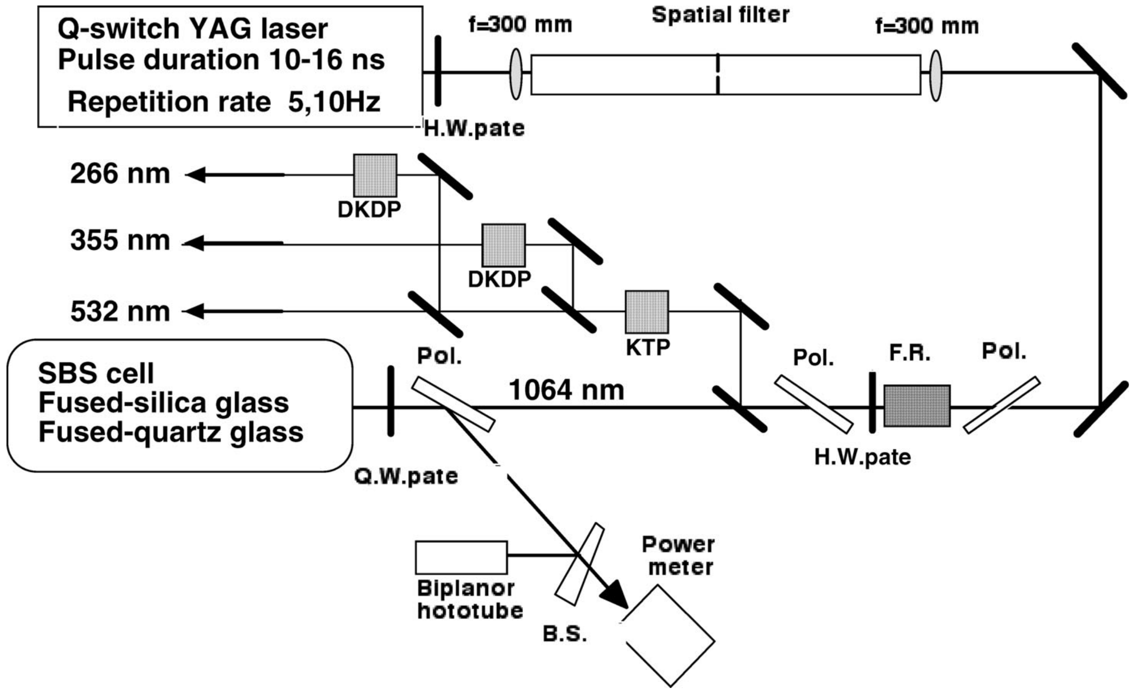

Fig. 3. The experimental layout of temporal SBS compression.

operation depends on the SBS reflectance. These results are consistent with so-called empirical scaling law, which indicates that the damage threshold intensity is inversely proportional to the square root of the pulse duration. This behavior has been ascribed to the thermal diffusion of the temperature rise during a pulse width. As the reflectivity grows above the threshold, the reflecting point of the incident laser is expected to move toward the source from the focus point. The bulk damage will be induced by the considerable transmitted focusable power through a reflection point at a focus when the reflectivity by SBS process is low, for example, at a multi-mode operation.

3. EXPERIMENT OF SBS TEMPORAL COMPRESSION

The experimental layout of temporal SBS compression is shown in Figure 3 and the SBS compressor with fused silica glass is shown in Figure 4. The laser used in experiments was a linearly polarized Q-switched Nd:YAG

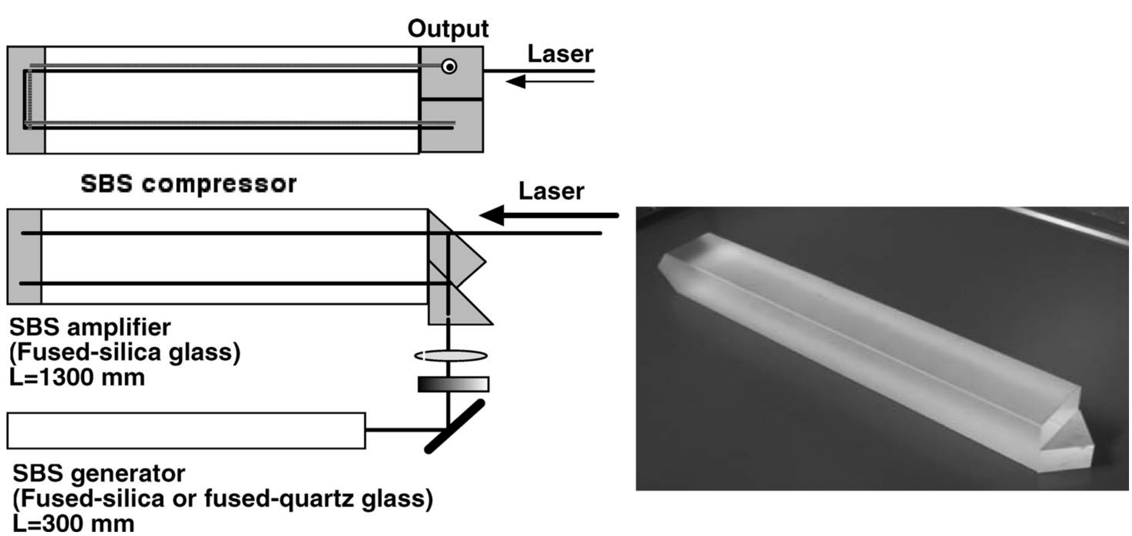

Fig. 4. The SBS amplifier consists of two right angle prisms and fused silica glass block.

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oscillator at single-frequency and TEM_{00} mode of operation. The amplified output was 13–16 ns pulse of approximately 500 mJ at 10 Hz repetition rate. The beam quality was 1.5 times diffraction-limited. The laser light was focused into an SBS-glass through a variable attenuator using a combination of a half-wave plate and a thin-film polarizer. The reflected laser beam was separated using a dielectric thin-film polarizer and a quarter-wave plate.

The used fused silica glass was Suprasil-P12 (4-cm × 4-cm × 30-cm^1) made by Shin-Etsu Quartz Products Co. Ltd. This fused silica glass can be used with wide wavelength because the absorption coefficient of the fused-silica glass from 266 nm to 1064 nm was $> 1 \times 10^{-4}$ cm^{-1}. The incident and output surfaces of the fused-silica glass were uncoated. Experiments on SBS compression was performed for the combination of a generator-amplifier system. The SBS amplifier consists of two right angle prisms and a fused silica glass block as shown in Figure 4. The boundary of each fused silica glass has very high transmittance because of the optical contact. The circularly polarized laser beam was transmitted through 132 cm (four pass length) long glass, and was focused to a 30-cm long generator by a lens (focal length = 50 cm). The occurrence of damage in the sample was determined with the naked eye and with the scattering of a He-Ne laser beam. The pulse shapes of the pump and both the reflected and transmitted beams were monitored using a Hamamatsu R1193 biplanar phototube and a Tektronix 7104 oscilloscope with a temporal resolution of 300 ps. The incident energy was monitored by a calibrated biplanar phototube. The reflected and transmitted energies were directly measured using joule meters. The SBS backward reflectivity from the fused silica was also compared with the total reflection from a 99.8% conventional thin-film mirror. Experiments on SBS compression were measured at four wavelengths of 1064, 532, 355, and 266 nm.

Table 1 shows the expected pulse width for shortening until the relaxation time before and after pulse compression at four wavelengths. The maximum output pulse energy of a commercial 10-n Q-switched Nd:YAG laser system was about 2 J. The output energies at its second, third, and fourth harmonics were 1.2, 0.8, and 0.5 J, respectively. The phonon lifetime τ_B is roughly proportional to the square of the pump wavelength assuming that τ_B, λ_p^2. Shorter wavelengths tend to produce better pulse compression because the phonon lifetime. The τ_B value at 1064, 532, 355, and 266 nm for fused silica glass were approximately 4, 1, 0.44, and 0.25 ns, respectively and the corresponding $\Delta\nu_B$ values were approximately 40, 160, 360, and 640 MHz, respectively. The expected pulse width at each wavelength can be compressed up to the pulse width until the phonon relaxation time. The brightness of the compressed pulse was reported about fourfold higher than that of the incident pulse at a1064-nm wavelength (Yoshida *et al.*, 2003). The brightness by the SBS compression at a 266- nm wavelength was obtained about 32-fold higher than that of the incident pulse. The brightness doesn't consider the reflected beam quality and was calculated from SBS reflectivity and the compressed pulse width. The SBS gain coefficient of fused-silica glass is independent of the pumping wavelength in the transparent medium, and was reported to be 2.9 cm/GW (Fairs *et al.*, 1990) to 4.3 cm/GW (Ippen *et al.*, 1972) at 532 nm.

Table 1. *The expected pulse width before and after pulse compression at four wavelengths*

Wavelength(nm)		1064	532	355	266
10 ns Q-SW pulse	Energy(J)	2	1.2	0.8	0.5
	Intensity(GW)	0.2	0.12	0.08	0.05
Compressed pulse	Relaxation (ns)	4	1	0.44	0.25
	Efficiency (%)	90	90	80	80
	Reflected energy (J)	1.8	1.08	0.64	0.4
	Intensity (GW)	0.45	1.08	1.45	1.6
Ratio of brightness		2.3	9	18	32

4. EXPERIMENTAL RESULTS

An optimum reflection is expected for an interaction length $L = (c/2n)\tau_\pi$ of the pulse because SBS begins from a leading edge of the propagating pulse. Where τ_π is the pulse width (FWHM) and n is the refractive index of the fused quartz glass. For a 10 ns fundamental pulse and a refractive index $n = 1.45$, the interaction length was 103 cm. The SBS reflectivity and pulse duration was measured at1064, 532, 355, and 266 nm.

The bandwidth of the laser oscillator used here is 200–250 MHz and so that the coherence length L_c is about 120–150 cm. The interaction length L in the SBS amplifier block was over 191 cm ($L = 132$ cm, $n = 1.45$). The SBS reflectivity using several attenuation mirrors at 1064-nm wavelength is shown in Figure 5. The Brillouin generator-amplifier system could be optimized by the insertion of partial reflectance mirrors between two fused silica glasses.

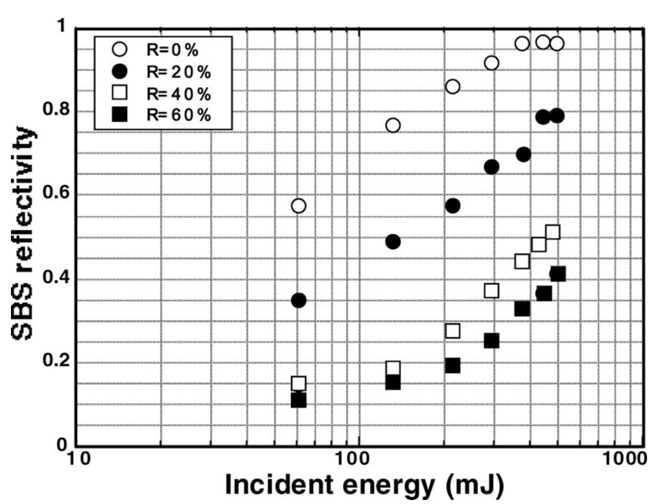

Fig. 5. SBS reflectivity measured at 1064 nm pumping.

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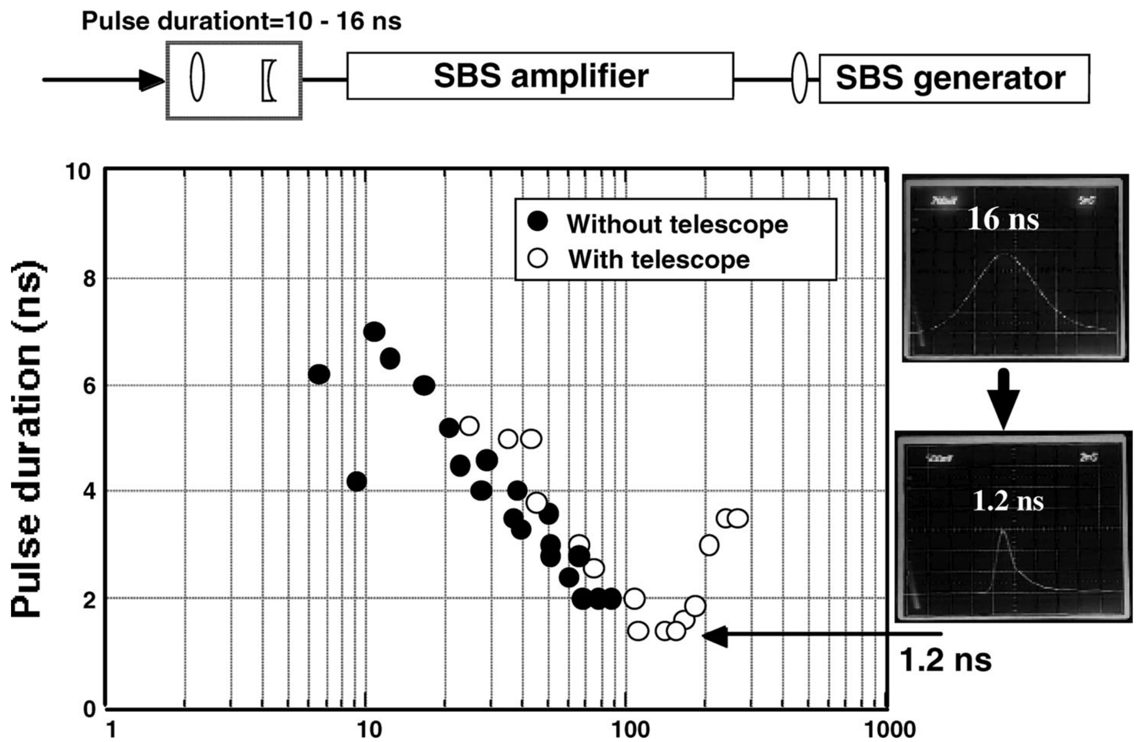

Fig. 6. The compressed pulse duration measured at 1064 nm pumping.

Thereby this system can control the energy that enters the Brillouin generator to prevent bulk-damage. A maximum intrinsic SBS reflectivity of over 95% without attenuation was obtained at incident energy of about 500 mJ. However, SBS reflected energy is estimated to be about 350 mJ, to get about 70% transmittance with total surface loss of about 22% of the fused silica glass, and other losses of 8%. The maximum reflectivity of over 66% was obtained experimentally. If the anti-reflection coating is given to all surfaces, the SBS reflectivity will be over 95%. No optical damage was observed during the experiment. With a 60% reflectance mirror (transmittance 40%), the maximum SBS reflectivity reached about 40% at a 500-mJ incident energy.

In Figure 6, the temporal pulse width was experimentally compressed from 10–16 ns to 1.2 ns. The Stokes pulse duration depends on the pumping intensity, and the compressed minimum pulse width at over 100 MW/cm^2 reached 1.2 ns or less. However the Stokes pulse showed substantially wider pulses as the incident intensity increased to 300 MW/cm^2. This results from the leading edge of the amplifier Stocks incident pulse interacting with the low energy leading edge of the Gaussian pumping pulse. The SBS-compressed pulse was shorter than the reported phonon time of 4 ns. The compressed pulse width can simply be calculated $\tau_s = 2.3\ \tau_B / I_p g_B L$, where I_p is the pump pulse intensity, g_B and L correspond to the SBS gain coefficient and interaction length, respectively (Fedosejevs & Offenberger, 1985). For maximum pump intensity, the predicted pulse width of about 1.2 ns is in agreement with the measured value (1 ns). The laser intensity of the compressed pulse increased approximately 10 times that of the incident pulse. In Figure 6 an incident pulse and typical shapes of compressed pulses are presented. A slow falling time of compressed pulse was observed due to the reduced intensity at the wings of the spatial profile. The pump beam was highly compressed near the center of the beam, while the compression effect was much less at the wings. The pulse shape of the reflected beam was a mixed pulse that combines the fast rising time at the center and the slow falling time at the wing of the pulse.

At a 532 nm wavelength, the maximum SBS reflectivity reached about 85% at about 100 mJ incident energy with several pulse widths as shown in Figure 7. The SBS threshold

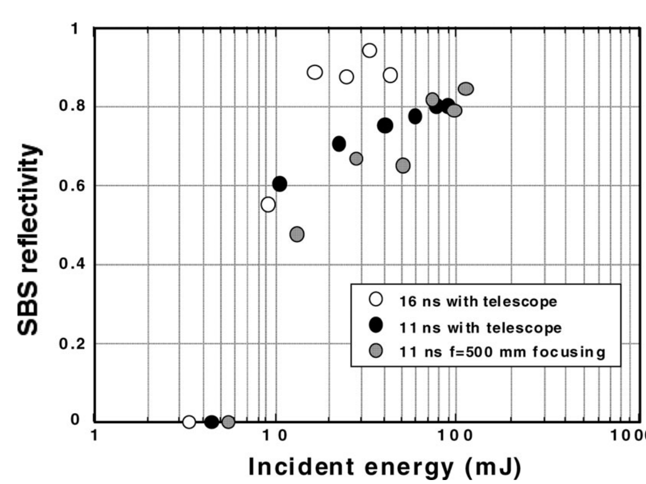

Fig. 7. SBS reflectivity measured at 532 nm pumping.

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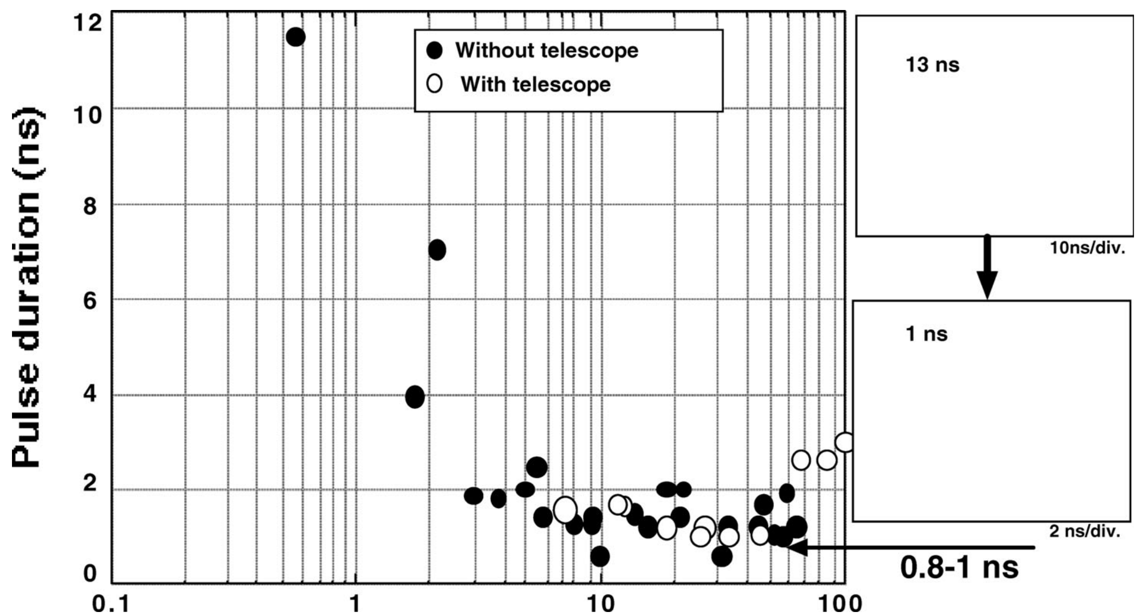

Fig. 8. The compressed pulse duration measured at 532 nm pumping.

is 3–5 mJ, which is about three-fold lower than the fundamental pumping. Figure 8 shows the compressed pulse duration as a function of the pump intensity. The temporal pulse width is experimentally compressed from 13 ns to 0.8 ns at over 50 MW/cm^2. The phonon lifetime at 532 nm is estimated to be about 1 ns. The brightness of the compressed pulse was about 14-fold higher than that of the pump pulse.

In the ultraviolet region at 355 nm, a shorter pulse is expected to compress what due to the shorter phonon lifetime. The phonon lifetime at 355 nm is estimated to be about 0.44 ns. At 355 nm pumping wavelength as shown in Figure 9, the compression pulse was experimentally demonstrated with over 80% reflectivity at 30 mJ input energy. However, the SBS reflectivity was decreased to 60% at about 80 mJ input energy. The compressed

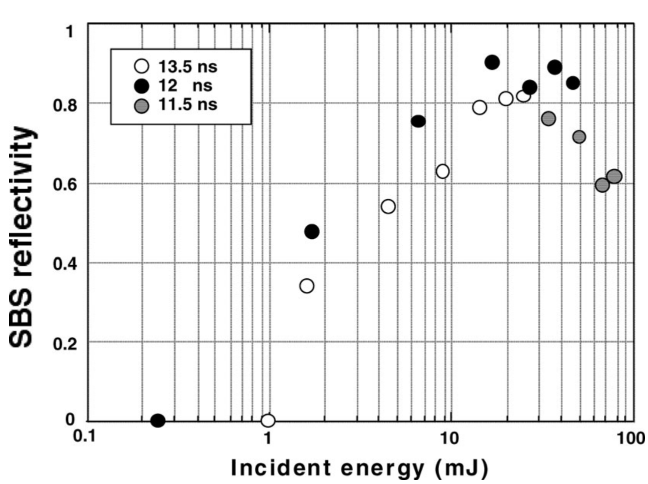

Fig. 9. SBS reflectivity measured at 355 nm pumping.

minimum pulse width reached 0.6 ns or less at 30 to 50 MW/cm^2 pump intensity as shown in Figure 10. The fused quartz glass turned blue after a longer irradiation with 355 nm pulse giving rise to a minimal absorption, and hence, prohibiting the SBS compression. Ionization and multi-photon absorption is more likely to occur at ultraviolet wavelength region. The measured pulse width of 0.6 ns was longer than the phonon lifetime of 0.44 ns because of the pump bandwidth of 700 MHz, which is larger than the Brillouin bandwidth of 360 MHz.

The SBS reflectivity and pulse duration was also measured at 266-nm. The maximum SBS reflectivity reached about 20% at 10 mJ incident energy. However, the damage has occurred at over 12 mJ input energy because of the ionization and multi-photon absorption. The compressed pulse width reached 0.6 ns or less. The SBS threshold at 266 nm pumping was higher than that at 355 nm because of the multi-photon absorption. If the input energy increases too few 10mJ, the predicted pulse width can reach to about 0.3 ns.

In Figures 6, 8, and 10 typical shapes of compressed pulses at 1064, 532, and 355 nm pumping wavelengths are presented. The temporal profiles were recorded on the large-area biplanar phototube covering the total spatial beam diameter. A slow falling time of compressed pulse was observed due to the reduced intensity in the wings of the spatial profile. The pump beam was highly compressed near the center of the beam, while at the wings; the compression effect was much less. The pulse shape of the reflected beam is a mixed pulse that combines the fast rising time at the center of the beam and the slow falling time at the wing of the pulse. SBS fidelity of the reflected beam was defined by the spot size of the far-field pattern

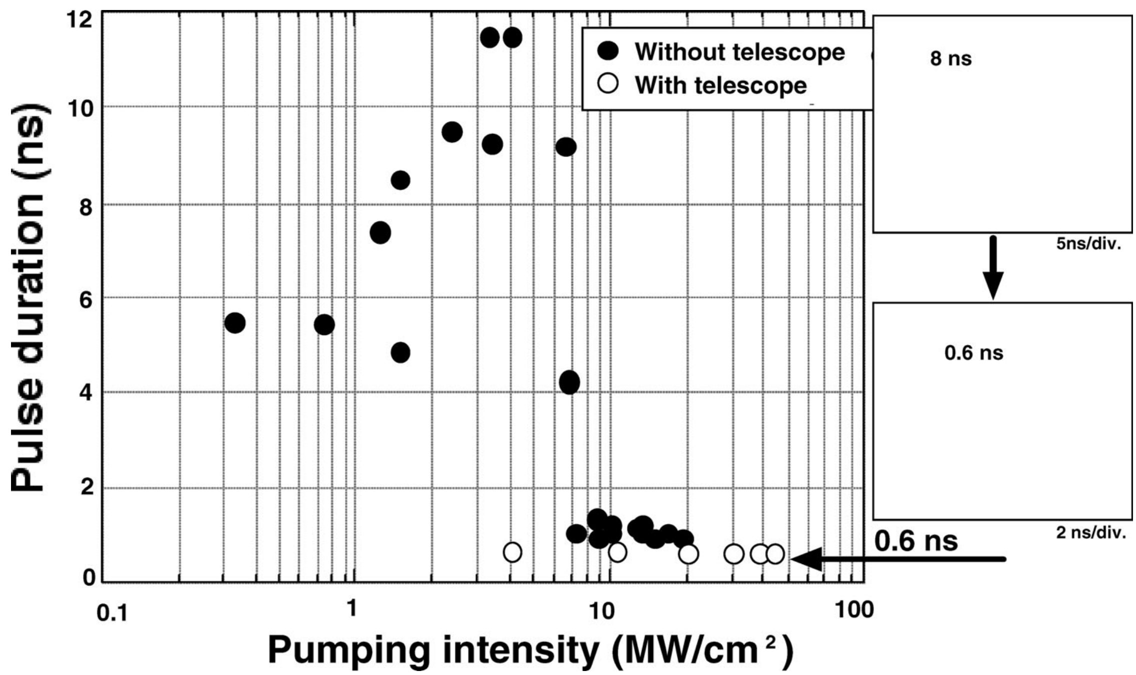

Fig. 10. The compressed pulse duration measured at 355 nm pumping.

of the SBS-return pulse. A typical spot size for the SBS-PC return beam was 1.5 times diffraction-limited and similar to that of the incident beam. The near field pattern of reflected beam results in very smooth without the higher spatial components.

5. CONCLUSION

We have designed a compact and high efficient solid compressor by SBS, which consists of two right angle prisms and a fused silica glass block. A 13–16 ns Nd:YAG laser pulse has been temporally compressed to 1 ns or less phase conjugation pulse in a fused-quartz and fused-silica glass at four wavelengths. Maximum reflectivity of SBS at 1064, 532, and 355 nm was over 90, 85, and 80% without damage, respectively. The brightness of the compressed pulse was over ten fold higher than that of the incident pulse.

Damage-free operation using two cell system of fused-silica glass as a better phase conjugate material could lead to the construction of a more compact, laser-diode pumped all-solid-state laser system. The generation of sub-ns pulse is useful for precise material processing and EUV lithography.

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