Stimulated Brillouin scattering pulse compression to 175 ps in a fused quartz at 1064 nm

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Stimulated Brillouin scattering pulse compression of a 2.5 ns laser into a 175 ps pulse using a fused quartz is demonstrated without optical damage. The synchronization and the time jitter between the initial and the compressed pulses were measured ($\sigma < 80$ ps) and analyzed numerically.
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I. INTRODUCTION

Subnanosecond and picosecond lasers are essential in many applications such as high-harmonic generation with high spectral purity for atomic and molecular spectroscopy[1,2] and as efficient pump sources for optical-parametric amplifiers.[3,4] Picosecond pulses are most commonly created by mode locking. However, mode-locked lasers operate at nonvariable repetition rates and require sophisticated techniques to be synchronized to a specific event. The other option is to start with a *Q*-switched nanosecond laser and to compress the pulse by Raman and/or Brillouin pulse compression. Pulse compression through stimulated Raman scattering dates back to the early days of lasers.[5] By early 1980s, it was discovered that the stimulated Brillouin scattering (SBS) phenomena are more suitable for pulse compression of powerful lasers,[6,7] offering higher quantum efficiency, higher gain, and the correction of abberations by phase conjugation.[8,9] For both SBS phase-conjugating mirriors and SBS pulse compressors, two types of cell arrangements exist (a) The single cell SBS generator where a long focal length lens is used to focus the laser into the SBS cell or into a tapered waveguide containing the SBS medium. (b) The multiple cell SBS amplifier where the entire chain is seeded by a single cell SBS generator. As the single cell compressor operates at high conversion efficiencies only at low input energies, it is not suitable for use with high-energy pulses.[6,10,11]

SBS compression can occur in both liquid and solid media. Although, liquid media, such as heavy fluorocarbons and tetrachlorides, are widely used in pulse compression applications, they have several disadvantages. These liquids require fine filtration to remove dissolved impurities and must be handled with caution as they are toxic. On the other hand, solid SBS media, while compact and harmless, are vulnerable to bulk breakdown damages.[12] The first experiment to measure SBS properties in crystalline quartz and sapphire was done as early as 1964 by Chiao *et al.*[12] Since then, the use of solid-state materials as a SBS medium was abandoned for a long time due to its vulnerability to bulk damages. Recently, Yoshida and co-workers showed that by using a long focal length lens to initiate the SBS, it is possible to safely use bulk fused silica and fused quartz as a SBS medium for pulse compression without causing a damage.[13–15]

SBS pulse compression is a passive process that does not require any cumbersome electronics and it can occur in low-cost materials. Consequently, SBS pulse compression is the most simple and inexpensive method, whereby a short pulse of about 100–200 ps is synchronized with a few nanosecond pulse. Such synchronization can serve as a diagnostic tool for a plasma that has been initiated by the nanosecond laser pulse. Here, we report successful compression of a 2.5 ns laser pulse at a wavelength of 1064 nm, down to 175 ps in a fused-quartz compressor, and the subsequent measurement of the timing jitter between the initiating pulse and the compressed pulse.

II. EXPERIMENTAL SETUP AND RESULTS

The laser pulse we used was generated by slicing a single-longitudinal-mode cw laser with an AM fiber modulator (EOSpace 12 GHz, 30 dB extinction ratio), producing a 10 pJ, 2.5 ns pulse. This pulse was then injected into a Nd:YAG (yttrium aluminum garnet) regenerative amplifier which amplified it to about 0.5 mJ, followed by a two pass Nd:YAG amplifier which further amplified the pulse to 200 mJ. At the output, we had a near Gaussian profile beam with 2.6 mm width ($1/e^2$) and beam quality of $\sim$1.2 diffraction limit. For the pulse compression, we used the multiple SBS amplifier configuration seeded by a single SBS generator cell, as was first suggested by Dane *et al.*[16] for the compressing of high-energy laser pulses. The experimental layout of the generator-amplifier pulse compressor is shown in Fig. 1. The distribution of the pump energy between the different amplifiers and the generator was done through a series of polarizers and wave plates, which allow us to finely tune the energy in each step and to avoid damages. The laser passes through a $\lambda/2$ wave plate after which polarizer P1 is used to split 6 mJ for the SBS generator with the remainder serving as a pump for the next amplifiers. The 6 mJ pulses are reflected by the polarizer P2 toward the SBS generator, going through a $\lambda/4$ wave plate to create a circularly polarized beam which is further focused into the 20 cm long quartz rod with a $f=300$ mm lens. The beam waist is located about 15 cm inside the rod and the beam diameter is $\sim$110 μm. SBS is initiated near the focus and, after being

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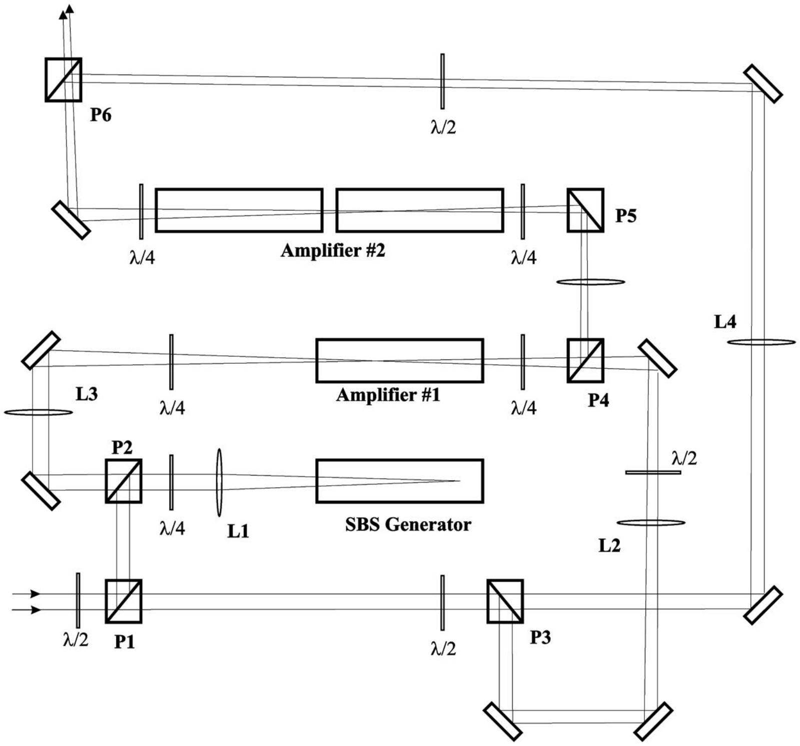

FIG. 1. Compressor setup.

reflected back, it is gradually compressed to 700–1100 ps as it gains energy from the tail of the pump. The pulse duration is very sensitive at this stage to the pump pulse energy and to the diameter and location of the beam waist inside the slab. The reflected SBS pulse is phase conjugated with the pump,[9] and as such, it has the same circular polarization. Hence, when the reflected SBS passes through the $\lambda/4$ wave plate, its polarization will be rotated by 90° relative to the pump and will pass through polarizer P2 toward the first amplifier. Amplification occurs using an 11 mJ beam split from the main beam by polarizer P3 which is counterpropagating with the seed beam in amplifier 1. Again, we used a 20 cm long fused-quartz rod as the amplifier. The waist size of both the pump and the SBS seed in the amplifier is ~350 μm, and are located about 15 cm from the SBS entrance facet. At the output of amplifier 1, we had 2–3 mJ, 400–500 ps pulses. Typical pulse shapes of the SBS generator and of amplifier 1 pulses are presented in Figs. 2 and 3. From amplifier 1, the pulse goes to amplifier 2 for further amplification and pulse compression. We experimentally determined that, for the second stage amplification, a dual slab amplifier using 20 cm slabs outperforms a single slab amplifier. The pump energy at this amplification was ~19–20 mJ and the beam waist ~500 μm. The output energy from amplifier 2 was as high as ~12–14 mJ and pulse duration as short as ~175 ps. At this amplification stage we observed that the pulse temporal shape tends to break into a short pulse (~175–230 ps), followed by a long hump [see Figs. 4(a) and 4(b)] and it required careful alignment to produce a single pulse. Also, we observed that, although the beam had a nice Gaussian shape, at different locations in the beam cross section, diverse temporal shapes are obtained. For pump probe experiments, where the long pulse is used to induce plasma and the short pulse is used as a probe, it is essential to know the time jitter between these two pulses, and to find the parameters that minimize it. In our experiment, we tried to measure the jitter between the pump and SBS signal after the SBS generator. Pump energy fluctuations (20%) caused huge fluctuation in the SBS signal from the generator and it was extremely hard to collect enough statistics for jitter analysis. After amplifier 1, the SBS signal was stabilized and it was possible to measured the jitter between the pump and the SBS signal. Because our pump source had energy fluctuation of about 20%, we recorded both Δt between pump and SBS peaks, and the pump energy. After compensating for the energy fluctuation, we found a time jitter of 78 ps.

III. NUMERICAL SIMULATION

Our numerical simulation followed those given by Velchev *et al.*[17] We first simulated the SBS generator and

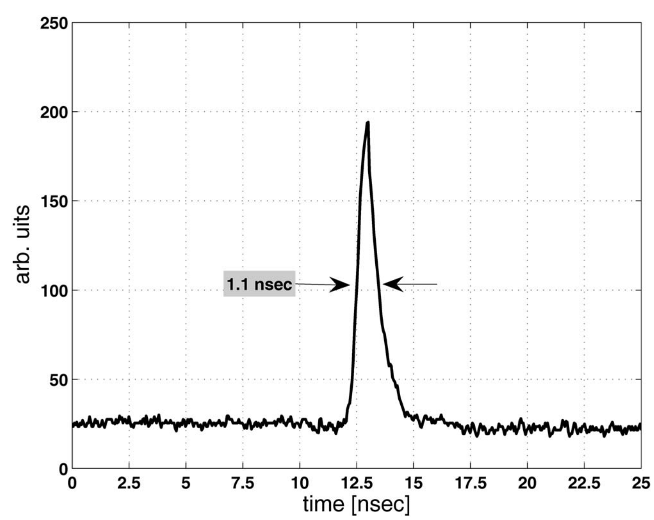

FIG. 2. Temporal pulse shape at the output of the SBS generator.

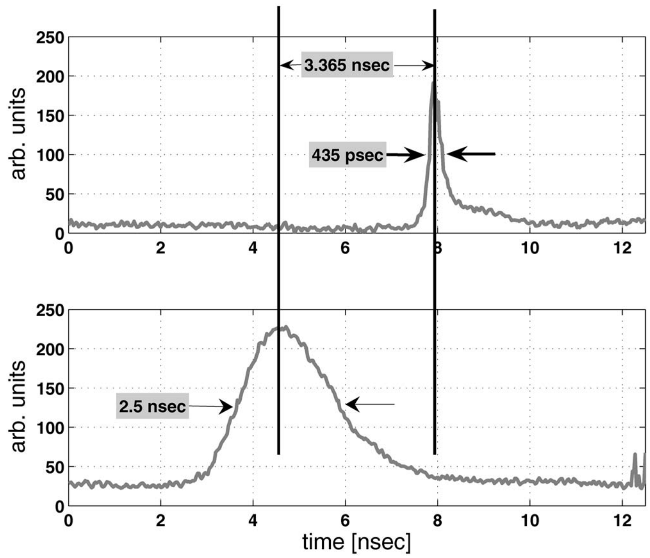

FIG. 3. Temporal pulse shape at the output of the first SBS amplifier and the pump. The vertical bars were placed manually at the peaks of both pulses and were used to measure the time jitter between the pump and the resultant short SBS pulse.

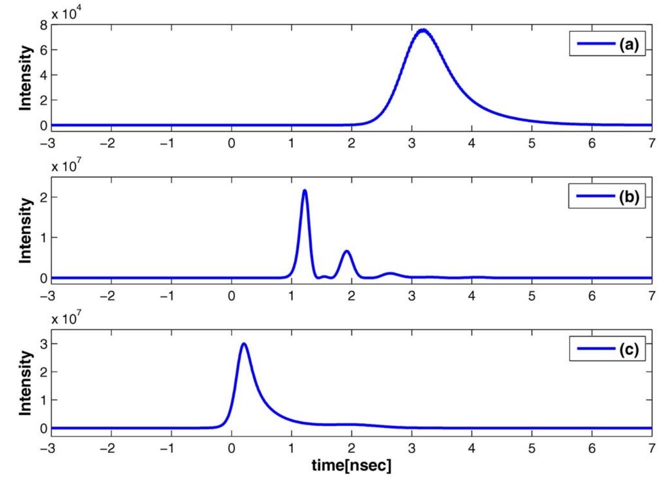

FIG. 5. (Color online) Representative results of our simulations. (a) The output from the SBS generator pumped with 5.5 mJ, $\tau_{ph}=4$ ns. Pulse duration at the output from SBS generator of ~890 ps. (b) The output from first amplifier pumped with 11 mJ, $\tau_{ph}=4$ ns. One can see a series of narrow oscillations ~170 ps each. (c) Same simulation as in case (b) but with $\tau_{ph}=0.15$ ns.

then used these results as a seed for the amplifier simulation. The parameters we used in our simulation were as follows:

(1) $\Omega_B=2\pi(23 \text{ GHz})694/1064$,[18] where Ω_B is the Brillouin frequency;
(2) $\tau_{ph}=4$ ns,[14] where τ_{ph} is the phonon relaxation time;
(3) pulse length of the pump laser is 2.5 ns;
(4) beam waist at SBS generator—110 μm located 15 cm from the front surface; and
(5) beam waist at amplifier 1—350 μm located 15 cm from the front surface.

The simulation prediction agree with the experimental results from the SBS generator (see Figs. 2 and 5) but fail to duplicate the experimental results from amplifier 1 [see Fig. 5(b)]. The simulation results for amplifier 1 showed a train of very short pulses, which we did not observed experimentally, and the total energy was not conserved. Applying a predictor-corrector scheme to our simulation solved this energy nonconservation problem but did not reproduced the pulse shape from the experiment. One of the reasons for this discrepancy could be a spectral broadening of the pump laser in the regenerative amplifier. Such broadening may occur due to the fact that the regenerative cavity was not stabilized and may support multilongitudinal mode while the seed is a single mode. It is well known that when the laser linewidth is comparable to $1/\tau_{ph}$, the pulse compression efficiency is reduced. Phenomenologically, to account for this spectral width in our simulation, we gradually reduced the phonon lifetime until it reproduced the experimental results. With a new phonon lifetime $\tau_{ph}^{new}=150$ ps, it reproduced our experiment very well [see Figs. 5(c) and 3]. We ran our simulation in two stages in order to find the situation with minimum pulse width and

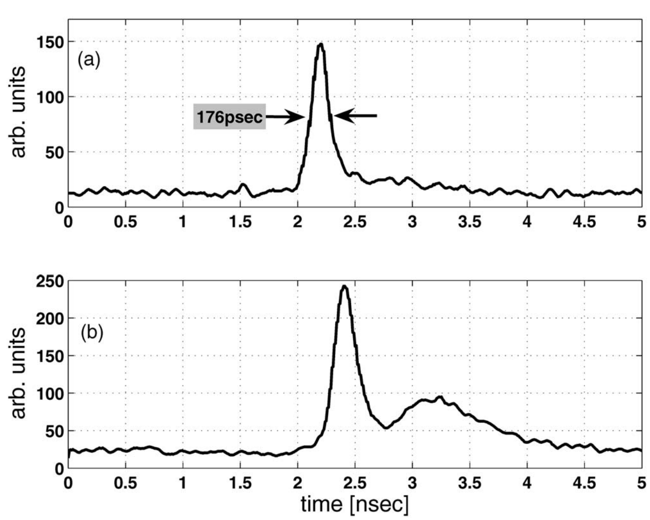

FIG. 4. Temporal pulse shape at the output of the second SBS amplifier: (a) Single pulse with a pulse width of 176 ps. (b) A short pulse (230 ps), followed by long hump. With a careful alignment and selection of a portion of the beam, it was possible to get single pulse.

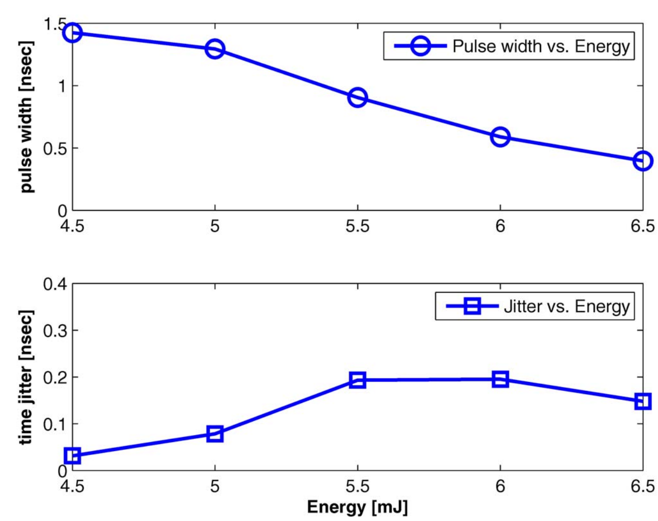

FIG. 6. (Color online) Pulse width and jitter as a function of the pump energy after the SBS generator stage.

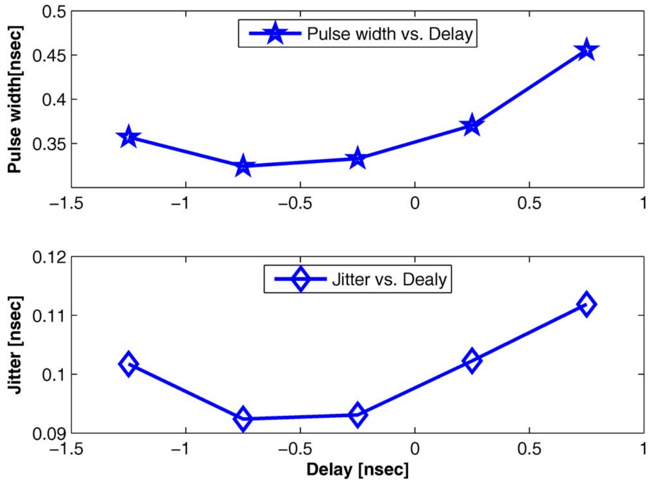

FIG. 7. (Color online) Pulse width and jitter after the first amplifier stage as a function of the delay between the pump and the seed pulses.

minimum jitter. First, we ran the SBS generator simulation at different pump energies and observed the effect on the pulse length and jitter. The results are shown in Fig. 6. At energies below 5.5 mJ, the pulse duration was too long (and the reflectivity was very low), and above 6.5 mJ, we were too close to the damage threshold of the quartz. Therefore, we choose to take the results of the 5.5 mJ simulations and seed them into the amplifier simulations. We see from Fig. 6 that we are starting with pulses of about 900 ps and jitter time of about 200 ps. The aim of the second stage is to find the best delay time between the pump and the seed in order to get lowest jitter and shortest pulse duration. We set the delay equal to zero when the two peaks of the pump and the seed temporally overlap at the focal plane. Positive delay means that the pump lags behind the seed. The results of the second stage are shown in Fig. 7. We observed that both the pulse width and the jitter are optimized for a negative delay of 750 ps.

IV. CONCLUSIONS

We reported on the compression of a 2.5 ns pulse down to 175 ps using a quartz slab as a SBS medium. We have shown both experimentally and by numerical simulations that the addition of amplification stages can increase the yield efficiency, reduce the pulse duration, and reduce the time jitter between the pump and the compressed pulses. This is the shortest pulse ever attained with SBS compression in solid-state medium. The 175 ps pulse can be used as a probe for pump-probe experiments with nanosecond laser initiated plasma. For that purpose, we have measured the timing jitter between the pump pulse and the SBS pulse to be less than 80 ps. We have found, by numerical simulations, that the time jitter is reduced when the seed pulse lags behind the pump pulse.

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