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SBS pulse compression to 200 ps in a compact single-cell setup

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Abstract. Temporal compression of nanosecond pulses from a commercial Q-switched Nd:YAG laser at second and third harmonic into the sub-nanosecond regime is demonstrated. In a geometry consisting of a single cell only, compression in several liquid media is investigated. For both 532 and 355 nm smooth and reliable operation is obtained with output pulses as short as 200 ps. A new concept is proposed to separate SBS pulses from the pump beam at low optical losses.

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Stimulated Brillouin scattering (SBS) is a nonlinear optical process, discovered in the first decade of laser physics, i.e. in the 1960s. For an introduction to the physics underlying SBS we refer to the book of Boyd [1]. Since its discovery the main application of SBS has been in optical phase conjugation. In the past two decades the use of SBS for the compression of laser pulses has been investigated theoretically and experimentally [2–6] for various types of lasers and active media. Dane et al. [7] demonstrated pulse compression at very high energies, and Fedosjevs and Offenberger [8] achieved compressibility by a factor of 60. As a third application of SBS we mention its use to filter spontaneous emission from a laser beam [9].

Various geometries of SBS laser-pulse compressors have been proposed, usually showing the features of a generator for a SBS-backscattered wave followed by amplification in one or more stages. Damzen and Hutchinson [10] investigated the special design of a tapered waveguide. Recently Schiemann et al. [11] reported on a compact generator–amplifier setup (CGAS) in which efficient compression of 532-nm pulses from a Nd:YAG laser was achieved. Following up on the CGAS design we present a simplified SBS scheme consisting of a single cell and using a limited number of optical components only. In this setup we demonstrate efficient compression of pulses of 4–5 ns duration from an injection-seeded Nd:YAG laser at its second and third harmonics. The SBS behaviour in water, methanol, ethanol, and CCl_4 is investigated. Particularly the relation between the phonon lifetime, i.e. the relaxation damping time of hypersound in the liquid, and optimum compressibility has been studied. The phonon lifetime τ_p is a material property of the medium, which scales with wavelength as [1, 5]:

$$\tau_p = \tau'_p(\nu'/\nu)^2. \tag{1}$$

Hence at shorter wavelengths as well as in CCl_4 with the shortest phonon lifetime, the highest compression is expected.

At both wavelengths, 532 and 355 nm, we provide a prescription to achieve pulse durations of 200 ps, which may turn Nd:YAG lasers, available in many laboratories, into more versatile tools for dynamical and nonlinear optics studies. Also we propose an alternative method for separating the compressed Stokes pulses from the incident pump beam. Usually the beams are separated by polarization; we suggest taking advantage of the frequency shift of the SBS output.

1 Experimental setup and measurement methods

The geometries of relevance for the present experiments are schematically depicted in Fig. 1. In our previous work SBS-pulse compression was demonstrated in a compact generator–amplifier setup (CGAS) [11], depicted in Fig. 1a. The CGAS consists of two separate cells filled with liquid: one for the generation of the SBS-Stokes pulse and the other for amplification, without use of attenuators. The underlying concept of this approach is that the necessary attenuation of the pump beam propagating towards the oscillator results from pump depletion induced by the SBS amplification. In Fig. 1b we introduce a simplified geometry based on a single cell involving a concave mirror, coated for high reflectivity at 532 or 355 nm, that redirects the generated SBS-pulse through

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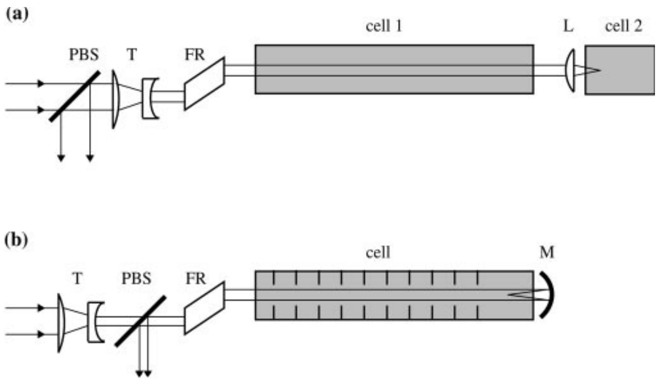

Fig. 1a,b. Geometrical configurations for SBS compressors. **a** Two-cell compact generator-amplifier setup (CGAS) as used previously by our group [11] with circularly polarized light. **b** Single-cell geometry used in the present study. (T – telescope; PBS – polarizing beam splitter; FR – Fresnel rhomb; L – lens; M – mirror)

the same cell for amplification. Again, as discussed in [11] two basic ideas determine the choice of focal length of the reflecting mirror and the cell length. The focusing in the oscillator part may be chosen as tight as possible, such that the very leading edge of the pump beam reaches SBS threshold in the focus. A lower limit to the focal length is, however, determined by the restriction that optical breakdown in the medium must be prevented. With available cleaning methods to filter solid particulates from the liquid (pore size 200 nm) focal lengths of 10 cm can be combined with pulse energies of up to 300 mJ, while avoiding optical breakdown for more than 99% of the pulses. The cell length is chosen such that the phase-conjugate SBS-pulse folds on to the entire counterpropagating pump beam for amplification. At the same time scattering losses of both pump and Stokes beams are minimized by keeping the cell as short as possible. Since SBS oscillation starts from the leading edge of the propagating pulse an optimum is expected for a spatial length of the pulse of $(c/n)\tau$, where τ is the pulse duration at full-width-half-maximum (FWHM) and n the index of refraction of the liquid medium. For a pulse duration of 5 ns (FWHM) and a typical index of refraction of $n = 1.3$–1.5 the cell length was taken at 1.1 m. The linearly polarized beam from the laser passes through a Fresnel rhomb to transform the beam pumping the SBS process into a circular polarization state. The generated SBS-beam can be separated from the pump beam using a thin-film polarizing beam splitter, under optimized angles (60° for 532 nm and 50° for 355 nm). To preserve the circular polarization the beams pass the window surfaces of the cell under normal incidence.

A telescope is used to resize the laser beam diameter. In this way the optimal energy density is adjusted to achieve maximum compression of the input pulse as discussed in [11]. The peak intensity of the pump pulse in the collimated arm should be kept below the SBS threshold to avoid diffuse SBS, which perturbs proper pulse compression. A further improvement in the setup involves ten diaphragms inserted in the cell preventing Rayleigh-scattered light to be guided from the cell walls into the interaction region. This resulted in a considerable decrease of scattered photons from the cell, hampering the data acquisition.

Pulse compression was investigated for two different wavelengths. Both the second and third harmonics of an injection-seeded, Q-switched Nd:YAG laser (Spectra-Physics Quanta-Ray GSR 330-10) were used to pump the SBS process. Injection-seeded operation of the Nd:YAG laser is necessary to prohibit mode-beating, which gives rise to competing nonlinearities and optical breakdown. The experiments were performed at a repetition rate of 10 Hz. Measurements of the spatial beam profile were performed using photosensitive paper, and a CCD camera (Hitachi VK-M98E) with a large active area window was used for online monitoring. An investigation of SBS pulse compression as a function of spatial position in the transverse profile was performed by extracting part of the beam using a short, multimode optical fiber of $\approx 100\ \mu$m core diameter. It was verified, by monitoring fs pulses at various input intensities, that the dispersion and nonlinear effects in this fiber are negligible.

Temporal characteristics of the pulses were measured with three different techniques. First, a fast oscilloscope (Tektronix TDS 680B - 1GHZ, 5Gs) combined with a fast photodiode (Hamamatsu G4176 - 100 ps) was employed for online registration of pulse durations. The temporal resolution of this system was evaluated by monitoring pulses (100 fs) from a fs laser to be 430 ps. It was also used to measure pump-pulse durations. Secondly, a sampling oscilloscope (Tektronix 7904 equipped with 7S11 sampler and S6 sampling head) was used in combination with a 100-ps photodiode. Because of the low repetition rate of the laser source and the time jitter of the trigger this measurement gives a relatively low signal-to-noise ratio; moreover the sampling oscilloscope does not provide single-shot pulse information. An advantage of this device is the absolute accuracy of its time base.

The actual data on SBS compression delivering the shortest pulses were taken with a streak camera (Hadland IMACON 500 – 20 ps). The two-dimensional streak images on the phosphor were monitored with a CCD camera and fed, via a frame-grabber, into a PC for data analysis. Temporal calibration of the streak camera was performed by comparing measurements with those of the sampling oscilloscope. The intensity scale of the streak camera was calibrated by simultaneously measuring long laser pulses with the 1 GHz oscilloscope.

Prior to the measurements of SBS pulse compression some spatial and temporal characteristics of the pump beam were determined. The spatial profile at the entrance of the amplifier cell corresponds to a super-Gaussian shape (third power) with FWHM of 6.6 mm for the second harmonic (532 nm), whereas the third harmonic is closer to Gaussian. The pulse has a Gaussian temporal profile with a FWHM ≈ 5.0 ns for the green and slightly shorter (≈ 4.6 ns) for the UV. Due to the injection seeding the Nd:YAG laser runs in a single longitudinal mode with a frequency spectrum close to Fourier-transform limited.

2 Results and discussion

Experiments on SBS pulse compression were performed for four different liquid media: water, methanol, ethanol and carbon tetrachloride (CCl_4), and for two wavelengths (532 and 355 nm). Refractive indices for these substances and values for the phonon lifetimes, extracted from [1] and corrected for

Table 1. Indices of refraction n, at temperatures of 25 °C, and values for the phonon lifetimes τ_p (in ps) at two relevant wavelengths. Values of τ_p are obtained from [1] after wavelength scaling

Liquid	n	τ_p (532 nm)	τ_p (355 nm)
water	1.333	295	131
ethanol	1.359	265	118
methanol	1.326	374	166
CCl_4	1.460	180	80

the wavelength dependence following (1), are presented in Table 1.

2.1 Tranverse beam profile effect in SBS

In the theoretical investigation of SBS compression usually a plane-wave approximation is considered. This simplification of the problem to a single dimension implies a uniform compression over the transverse profile of the laser beam. We studied the effect of the varying intensity over the spatial beam profile experimentally, using a short multimode optical fiber to extract light from a specific point in the beam and a photodiode combined with the 1 GHz oscilloscope (time resolution 430 ps) for registration. In this way we measured the local compression factor for green pulses (532 nm) of FWHM = 6.6 mm using water as SBS medium; only for this specific measurement pump pulses of 6 ns duration were used. We reduced the laser intensity to a level where compression yields pulses not shorter than 1 ns. The results of measurements on the transverse beam profile dependence are presented in Fig. 2. It is clearly seen that the beam is highly compressed in the vicinity of the center, while in the wings the compression is much less. Figure 2 shows that the central part, defined by the inner 4 mm of the diameter, is compressed close to the minimum pulse duration. When we operate the laser closer to the optimum compression energy (see below) the region of shortest pulse duration is even broader than 4 mm. In previous work [12] we have investigated the dependence of compressibility on averaged beam intensity. The theoretical prediction, that at pump intensities below an optimum value compression is less efficient, was experimentally verified. With the model of [11, 12] the present results on the dependence of compressibility on local intensity can be understood in a quantitative sense.

Spatial beam profiles of the incident pump beam as well as the SBS-reflected beam were measured in the form of single-shot imprints in photosensitive paper. These imprints show, in a qualitative sense, that the beam quality is preserved by the compression process. In the following we present only data pertaining to the central part of the beam.

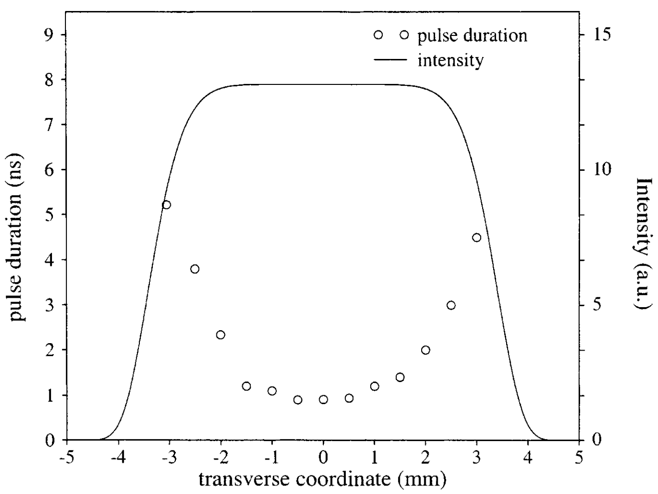

Fig. 2. Compression of the laser pulse vs. transverse coordinate; data taken for water as SBS-medium and pump pulse at 532 nm with 6-ns duration. The *solid line* is a fit through the measured pump beam profile. The *circles* are experimental data on pulse durations of compressed pulses. Temporal resolution of the detection system for this measurement is 430 ps; therefore the energy density in the compressor was adjusted for a Stokes pulse duration not shorter than 1 ns

2.2 Pulse compression at 532 nm *for various liquids*

In Fig. 3 some *typical* results on pulse compression at 532 nm are presented; the pictures correspond to single-shot measurements taken with the streak camera. Measurements of SBS threshold, optimal energy, energy of the SBS compressed beam, and the reflectivity of the setup for four different liquids are presented in Table 2. Energies and intensities of the pulses can be related by accounting for the beam diameter of FWHM = 6.6 mm. As shown previously [11, 12] optimum compressibility is obtained at a certain pump beam intensity. For a fixed beam diameter (as in the present study) this

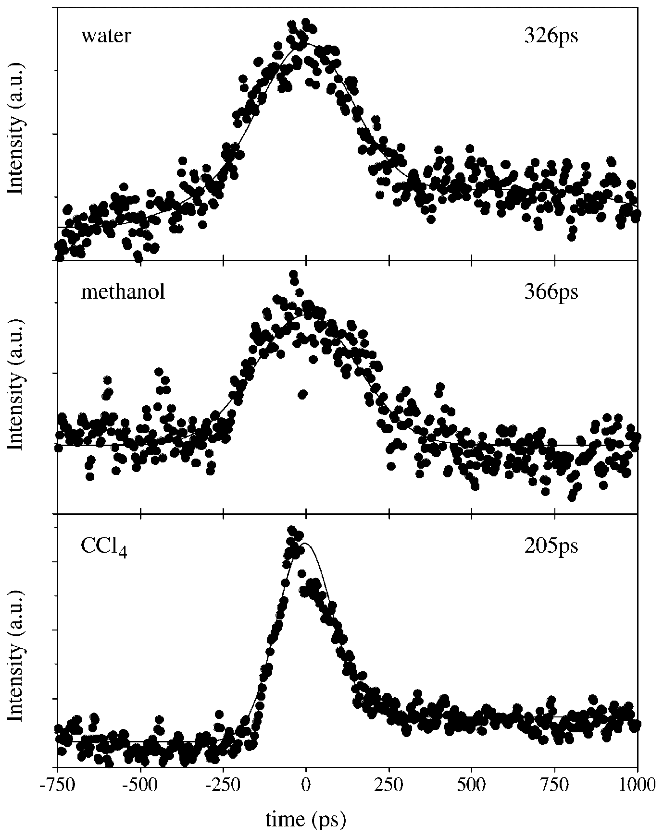

Fig. 3. Streak-camera recordings of *typical* SBS-Stokes pulses measured for a pump wavelength at 532 nm using three different media

Table 2. Results of the SBS processes studied; E_{th} is the threshold energy for the formation of a phase-conjugated SBS-Stokes pulse; E_{opt} is the pulse energy for which SBS compression is optimal (both E_{th} and E_{opt} given for spatial beam of FWHM = 6.6 mm); Reflectivity R holds for energy E_{opt} (including 35% optical losses); τ_t refer to *typical* (i.e. average) observation of Stokes pulse durations

Liquid	E_{th}/mJ	E_{opt}/mJ	R/%	τ_t/ps
		SBS at 532 nm		
water	1.75	180 (10)	57.9	325
methanol	0.62	84 (5)	54.0	366
ethanol	0.63	67 (5)	56.7	–
CCl_4	1.0	65 (5)	56.9	200
		SBS at 355 nm		
water	1.9	87 (5)	43.5	200
methanol	0.5	39 (3)	41.9	–

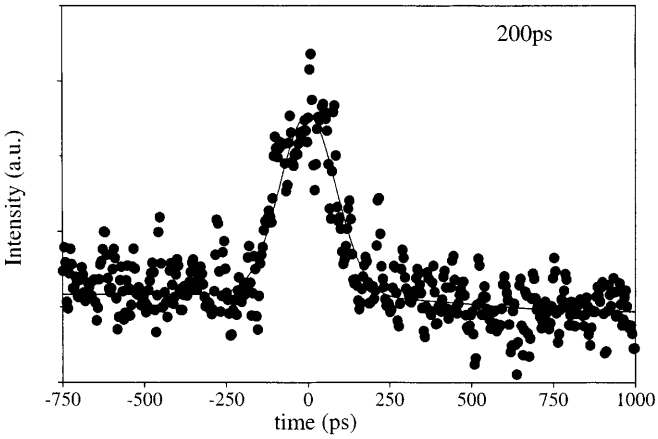

Fig. 4. Streak-camera recording of a typical pulse measured in water for a pump wavelength at 355 nm

corresponds to a certain optimum energy (E_{opt}); in practical applications the beam diameter can be adjusted such that E_{opt} matches the pump intensity for optimum compression. A combination of maximum energy and optimum compression (for the fixed beam of FWHM = 6.6 mm) is achieved in water, whereas the shortest pulses were obtained in CCl_4. In the experiments on pulse compression in water and ethanol the process of stimulated Raman scattering (SRS) competes with SBS. In the case of water at optimum incident energy SRS is weak and does not influence SBS pulse compression. However in the case of ethanol intense red SRS-flashes were observed, accompanied by temporal fragmentation of the SBS back-scattered pulse. This makes ethanol an unreliable SBS medium, in contrast to water and methanol. The optimum reflectivities, of about 57%, seem to be small. However, the optical losses in the setup, where no anti-reflection-coated optics was used, were estimated to be 35% so that the intrinsic SBS reflectivity is evaluated to be more than 90%.

An important finding in the pulse duration measurements is the spread in the output pulse durations. The results presented in Fig. 3 and the values for the pulse duration (FWHM) listed in Table 2 are *typical*, i.e. averaged over a large number of measurements. Although in methanol the most probable pulse duration obtained was 366 ps (Fig. 3b), we did observe pulses as short as 330 ps. The same holds for the other liquids. An exceptionally short pulse (of 110 ps) was observed in CCl_4, where the average value is 200 ps (Fig. 3c). Apparantly there is a statistical spread in pulses emanating from a SBS compressor. This spread is likely to be related to the origin of the pulses, a buildup from acoustic noise induced by the laser pulse or by temperature fluctuations. This issue, first addressed by Buzelis et al. [13], remains a subject for future experimental and theoretical studies.

Although the issue is debated in the literature [2–4, 6, 10, 11] the phonon lifetime is often considered as a lower limit to pulse compression in SBS. Here we find experimentally SBS-compressed pulses with duration notably shorter than the phonon lifetime. The typical averaged values for the pulse duration as experimentally observed indeed are limited by the phonon lifetime. When comparing the results of minimum Stokes pulse duration in the various liquids (cf. Table 2) the trend indeed follows the phonon lifetimes (cf. Table 1).

2.3 *Pulse compression at* 355 nm

In the UV region at 355 nm shorter pulses are expected from the SBS compressor due to the shorter phonon lifetime at higher frequencies (cf. (1)). Some practical restrictions may be expected from enhanced Rayleigh scattering and from photochemistry induced by the high-intensity UV laser beam. A practical problem encountered during the measurements was the low transmittivity for UV of the streak-camera optics, which gave rise to an increased noise in the data.

The experiments were performed in water and methanol and the results for the SBS threshold, optimum energy and reflectivity are included in Table 2. The values of the optimum energy were derived from measurements using the 1 GHz oscilloscope. Streak camera pictures could only be measured for compression in water where the output energy is just sufficiently high to extract a curve form the noise. A typical example is shown in Fig. 4. In methanol smooth operation of the SBS compressor was verified with measurements using the photodiode; however, due to the lower value of E_{opt} the output energy was insufficient to determine a value for the optimum compression with the streak camera. While in water the average pulse duration was 200 ps, pulses as short as 180 ps were observed, again indicating a spread in the Stokes pulse durations. The expectation that in the UV region shorter pulses may be generated is confirmed in this experiment.

Although the experiments in water and methanol produced smooth SBS pulses with reasonable pulse-to-pulse fluctuations no reliable measurements could be performed on CCl_4 in combination with 355-nm pulses. In the latter case the liquid turned yellow after irradiation with UV giving rise to strong absorption and hence prohibiting proper SBS-compression measurements. Whether this is caused by UV-induced photochemistry in the CCl_4 liquid, or by the effects of the intense Rayleigh scattered light on to the viton O-rings sealing the cell could not unambiguously decided.

2.4 *Proposal for a simplified low-loss SBS geometry*

In Fig. 1b a compact single-cell configuration was presented, which is demonstrated to be a useful tool for SBS compression. In Fig. 5 we propose another single-cell setup for

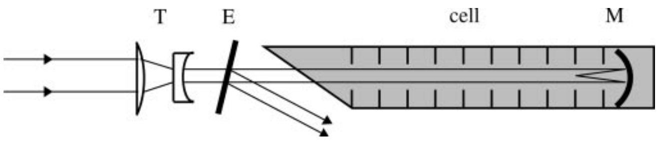

Fig. 5. Proposal for a simplified single-cell SBS configuration to be used with linearly polarized light and low optical losses; T – telescope; M – mirror; E – etalon

SBS, that has not been tested yet, but may have some advantages over the design presently used. The optical losses in the present setup can be further reduced by mounting the concave retroreflecting mirror, which in fact separates the oscillator from the amplifier, inside the liquid, therewith reducing the number of optical elements. We have not attempted this in the setup of Fig. 1b, since we do not have access to a highly reflecting concave mirror fulfilling the more rigourous demands with respect to damage threshold for operation inside a liquid.

To our knowledge, in all setups reported in the literature for SBS pulse compression the Stokes beam is separated from the pump beam by its polarization; hence a number of polarization components are usually required. Now, for a new separation method, we propose to take advantage of the frequency shift over several GHz (depending on the medium) of the Stokes beam. An etalon may be inserted under a specific angle (again depending on the Stokes shift) in the beam to fully transmit the pump wave and reflect the Stokes wave. Demands on the damage threshold and optical quality of the etalon coating are high; in an attempt to demonstrate this method with a commercial etalon it was severely damaged. In principle this scheme possesses intrinsically low optical losses and could be succesfully applied where high reflectivity is required. An advantage is that the polarization of incident and Stokes pulse may remain linear; this will allow for the use of a Brewster-cut window at the entrance of the compressor. An additional feature is that the SBS process occurs on a single transverse mode giving rise to a higher SBS gain than for circularly polarized light.

3 Conclusion

A new setup for SBS pulse compression has been demonstrated, providing pulses as short as 200 ps at two different wavelengths. The pulse compression in different liquids was investigated. Laser pulses at 532 and 355 nm of 4–5 ns duration may by compressed to 200 ps for reliable and smooth operation at 10-Hz repetition rates. We have shown that optimum SBS compression occurs in a flat-topped inner region of the transverse beam profile; for applications of compressed pulses the outer wings of the beam may be filtered away. For the third harmonic at 355 nm water appears to be the appropriate medium, whereas at the second harmonic at 532 nm CCl_4 may be favorably used. In previous work [12] we have demonstrated the possibility of continuously tuning the pulse duration between the duration of the lower limit (now 200 ps) and the duration of the incident pump beam, by varying the diameter of the pump beam. These experiments on SBS pulse compression provide a recipe for equipping commercially available Q-switched injection-seeded Nd:YAG lasers, in use in many laboratories around the world, with an extension of a short-pulse option. Such an option, consisting of a single cell filled with liquid and some polarization optics, transforms common lasers into more versatile tools for dynamical and nonlinear optics studies.

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