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Compression of pulses during their amplification in the field of a focused counterpropagating pump pulse of the same frequency and width in media with electrostriction nonlinearity

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***Abstract*.** **Efficient compression of focused ~ 0.9-ns pulses of a miniature Nd : YAG laser to less than 60 ps is experimentally obtained at their interaction with counterpropagating pulses of the same carrier frequency and width in CCl_4. In this case, electrostriction interaction (amplification) begins not from the level of spontaneous-scattering noise; therefore, the counterpropagating pulses can be compressed at pump pulse energies below the stimulated Brillouin scattering (SBS) threshold energies. When counterpropagating seed pulses are used, the energy and temporal stability of compressed pulses are several times higher, and their time jitter is smaller than that for SBS compression from the level of spontaneous-scattering noise.**

Keywords: *electrostriction nonlinearity, amplification and compression of short pulses.*

1. Introduction

Currently, the basic properties in the formation of spatiotemporal structures of light waves upon stimulated backscattering (SB), including the formation of compressed pulses, in the generation regime from the level of spontaneous-scattering noise are known quite well (see [1 – 3] and references therein). In this case, the degree of compression $N_\tau = \tau_{\rm las}/\tau_{\rm S}$ in one cascade of an SB compressor ($\tau_{\rm las}$ and $\tau_{\rm S}$ are the widths of the pump and Stokes pulses, respectively) does not generally exceed the stimulated scattering threshold increment $G \sim 25$. Therefore, to obtain short highly compressed pulses, we experimentally implemented cascade compression of pulses for the first time [4] and, using master oscillator (MO) pulses with $\tau_{\rm las} \approx 12$ ns, obtained compressed Stokes pulses with $\tau_{\rm S} \approx 200$ ps. Using SB cascade compression of pulses [2, 5], one can obtain few-picosecond pulses in the spectral ranges where standard mode-locked lasers are difficult to operate.

When using lasers with $\tau_{\rm las} \sim 5$ ns, the widths $\tau_{\rm S}$ of SBS-compressed pulses reach generally 0.3 ns [3]. To obtain shorter pulses in a single-cascade SBS compressor, one must use shorter pump pulses. To this end, single-mode passively and actively *Q*-switched lasers have been developed to generate pulses with $\tau_{\rm las} \sim 2$ ns [6 – 8]. However, even at $\tau_{\rm las} < 2$ ns, the compressed-pulse width exceeded 100 ps [6, 9]. To reduce it to $\tau_{\rm S} < 100$ ps, we applied trailing-edge cut off at optical breakdown (OB) in air using a Kepler telescope [6, 10].

The numerical simulation [11 – 13] showed that the complex dynamics of SBS compression, taking into account the inertia of the medium and the beam diffraction at an optimally chosen pump focusing geometry and spatial selection of Stokes pulses, makes it possible to obtain much shorter pulses. However, to implement SBS compression of short pulses, it is necessary to use high-intensity pump pulses, which provoke many competing effects, such as stimulated Raman scattering (SRS), bulk OB, self-phase modulation (SPM), and light self-focusing (SF). These effects complicate the compression dynamics and limit the minimum attainable widths of Stokes pulses in the generally used SBS media of the CCl_4 type.

Schemes of the SBS oscillator – amplifier type [1 – 3] are preferred, because they allow one to vary the pump energy from relatively low [14] to rather high [15]. It is noteworthy that, using the oscillator – amplifier scheme, we experimentally demonstrated amplification of short signal pulses without a Stokes frequency shift in both collimated and slightly focused pump pulses ~ 5 ns wide [14]. Based on our previous studies of the excitation of hypersonic oscillations by close-to-counterpropagating picosecond pulses [16], we classified the results of [14] as different regimes of time-dependent amplification in transparent media with electrostriction nonlinearity for short pulses, including those without a Stokes shift or even with an anti-Stokes shift of the carrier frequency of amplified signal with respect to the frequency of the counterpropagating focused pump.

As a matter of fact, the possibility of wave-to-wave energy transfer at time-dependent interactions in dynamic holograms has been known for long [17]. It was actively investigated, but generally in the approximations of plane waves or collimated beams. As far as we know, a significant reduction of the pulse width for interacting waves has not been reported. We noted a possibility of compressing signal pulses in focused beams when investigated the phase conjugation in time-dependent electrostriction four-wave mixing [18]. In this paper, we report the results of studying the compression of short (with a width close to the relaxation time of hypersonic waves) signal pulses during their amplification in the field of focused counterpropagat-

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ing pump of the same carrier frequency and width in media with electrostriction nonlinearity.

2. Experimental

Counterpropagating interaction of pulses with identical carrier frequencies can be implemented in different ways, for example, as in [14], where the Stokes pulses formed by reflection from SBS mirrors interact with the same medium. However, it should be noted that no particular attention has been paid to the change in the spectrum of SBS-compressed pulses until recently [19, 20]; therefore, the aforementioned technique may cause some shift of carrier frequencies for counterpropagating pulses. Apparently, the simplest way of implementing counterpropagating interaction in an active medium without shifting the carrier frequency is to partially reflect a laser pulse (*1a*) by a conventional plane mirror (*9*), located behind an SBS medium (*8*) (Fig. 1). In this case, to prevent reflected radiation from penetrating the laser cavity, one can use standard polarisation isolation, composed of a dielectric polariser (*4*) and a quarter-wave plate (*5*). This isolation, in combination with a half-wave plate before it, makes it possible to gradually control the energy of linear polarised pulses arriving at the system. To perform gradually controlled beam focusing into cell (*8*), it is convenient to use a system of lenses (*6*) and (*7*). Behind the medium-containing cell (*8*) [in front of mirror (*9*)], one can place lens (*14*) to collimate the transmitted beam; an attenuating filter (*13*); and, when necessary, screen (*15*) to eliminate reflection from mirror (*9*), which can be displaced along the beam propagation direction.

A miniature passively modulated *Q*-switched Nd : YAG laser with longitudinal diode pumping (*1*), generating pulses with a width of about 0.9 ns and energy up to 2 mJ was used as a pump source. When necessary, a lamp-pumped amplifier was additionally applied, which generated pulses with energy up to 10 mJ at a pulse repetition rate of 10 Hz. The energies of the laser and compressed pulses were measured by a Scientech Vector H410 power meter with a Scientech Astral$^{\mathrm{TM}}$ Calorimeter AC2501 photodiode, and their widths were determined using fast Newport D-15ir (*10*) and Thorlabs DET01CFC/M (*11*) photodiodes, connected to a broadband digital four-channel TDS6124C oscilloscope (*12*). The measured pulses were focused [using lenses (*2*) and (*3*)] to single-mode optical fibres and applied to photodiodes (*10*) and (*11*). Oscilloscope (*12*) made it possible to record pump and compressed pulses (Fig. 2) separately and with different time resolutions. Along with typical oscillograms, the results of statistical treatment (for a specified number of pulses) of the values measured (specifically, the amplitudes and widths of pulses, as well as the widths of their leading and trailing edges, with indication of means and variances) could also be displayed on the oscilloscope screen. In addition, we could display simultaneously both pulses on the screen and measure, for example, the laser pulse width and the relative (depending on the optical paths of the signals measured to the corresponding detectors) delay of compressed pulse, calculated at the 50 % level on the pulse leading edges (shown by arrows in Fig. 3).

The oscilloscope-measured width τ_{m} can be described by the formula [21]

$$\tau_{\mathrm{m}} = (\tau_{\mathrm{r}}^2 + \tau_{\mathrm{d}}^2 + \tau_{\mathrm{o}}^2)^{1/2}, \tag{1}$$

where τ_{r} is the real (true) pulse width; τ_{d} is the detector signal (response) rise time; and τ_{o} is the oscilloscope signal (response) rise time. For example, when the above-described system was used to detect short ($\tau_{\mathrm{r}} \leqslant 30$ ps) picosecond laser pulses with the same wavelength ($\lambda = 1064$ nm), the measured pulse width was 50 ps. Hence, the joint response time of the detector and oscilloscope can be estimated as $\tau_{\mathrm{do}} = (\tau_{\mathrm{d}}^2 + \tau_{\mathrm{o}}^2)^{1/2} \approx$ 40 ps. Thus, the real pulse width can be reconstructed from the measured width using the formula

$$\tau_{\mathrm{r}} = (\tau_{\mathrm{m}}^2 - \tau_{\mathrm{do}}^2)^{1/2}. \tag{2}$$

To obtain compressed Stokes pulses of minimum width in the regime of standard SBS compression [experimental

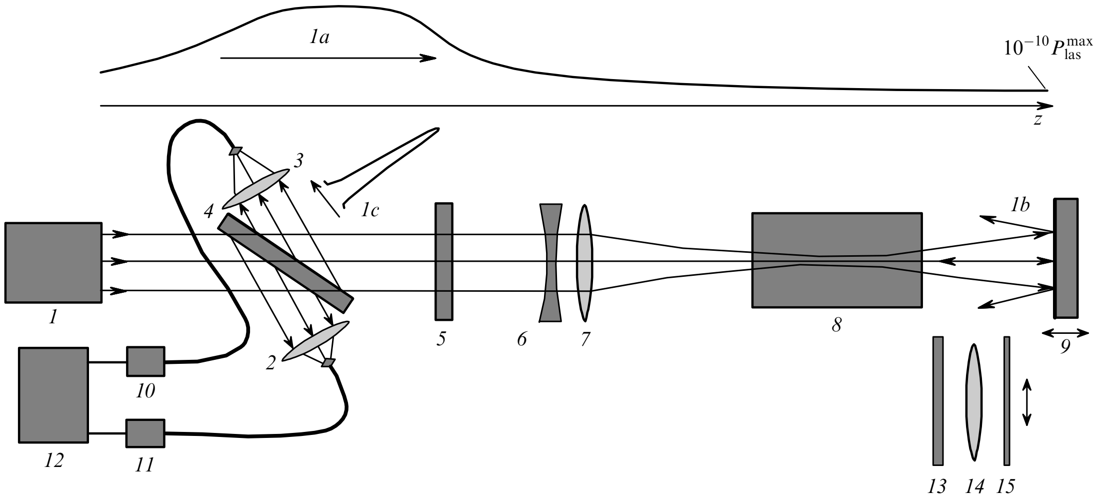

Figure 1. Schematic of the experimental setup: (*1*) diode-pumped solid-state miniature laser; (*1a*) spatial shape (length) of the pump pulse power; (*1b*) pump radiation reflected by a plane mirror; (*1c*) compressed pulse; (*2, 3*) lenses focusing the pump and compressed pulses into an optical fibre; (*4*) dielectric polariser; (*5*) quarter-wave plate; (*6, 7*) lenses of the system focusing pump radiation; (*8*) cell with an electrostriction (SBS) medium; (*9*) reflecting mirror; (*10, 11*) fast photodiodes; (*12*) broadband digital oscilloscope; (*13*) neutral filter; (*14*) collimating lens; (*15*) screen.

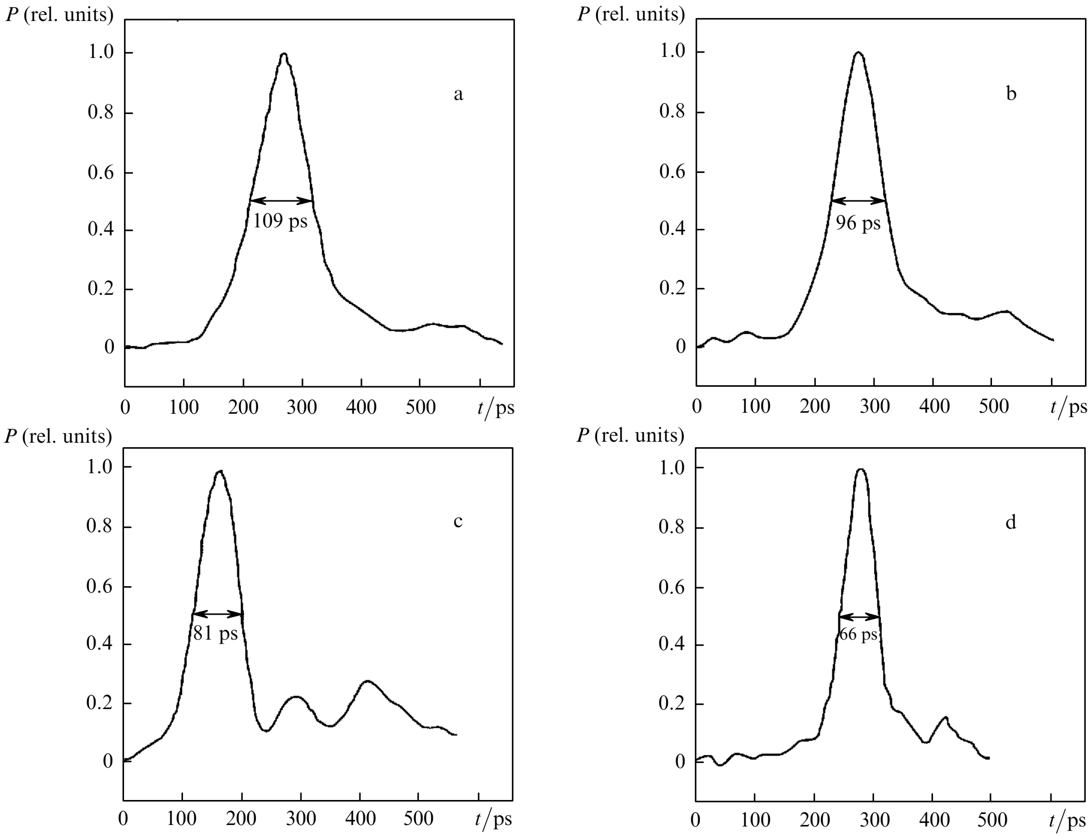

Figure 2. Oscillograms of compressed pulses (a) in the standard SBS-compression regime from the noise level; (b) in the presence of a seed pulse due to the transmitted-pump reflection by an additional mirror; (c) in the presence of a seed pulse due to the pump scattering by the cell walls and windows; and (d) with introduction of a seed pulse of the same width, counterpropagating with respect to the pump.

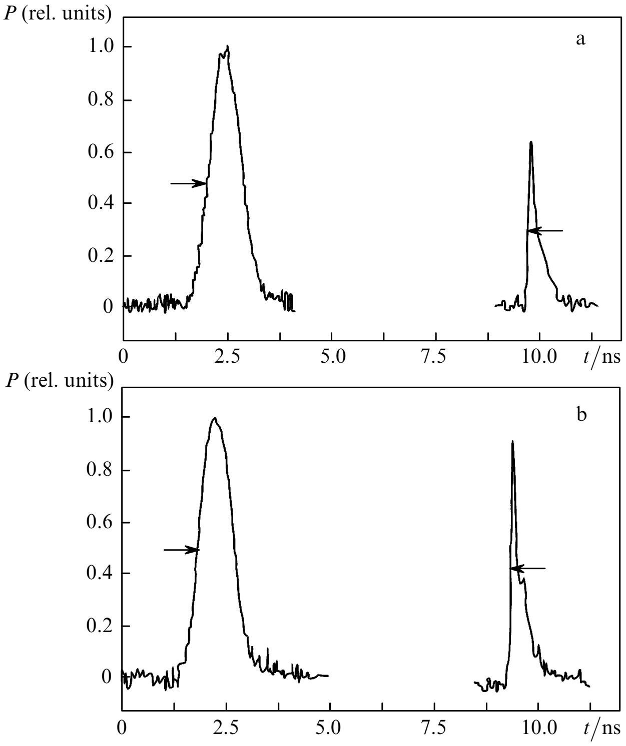

Figure 3. Oscillograms of the pump pulses (on the left) and compressed pulses (on the right) (a) in the conventional SBS compression regime from the noise level and (b) in the presence of a seed pulse due to the transmitted-pump reflection by an additional mirror.

scheme without mirror (*9*) or with screen (*5*)] from the spontaneous-scattering noise level, we first chose focusing conditions close to optimal (based on the known considerations [2 – 14]), which were then corrected by measuring the compressed-pulse width at different energies of miniature laser pulses. At optimal focusing and laser pulse energy the compressed-pulse width was measured to be $\bar{\tau}_{\rm m} = 109$ ps at an rms variance $\sigma_{\rm m} = 9$ ps (Fig. 2a) Thus, the real mean width $\bar{\tau}_{\rm r}$ of compressed Stokes pulses is close to 100 ps. The standard SBS compression regime with $\rm CCl_4$ retained a fairly high efficiency for pulse repetition rates up to ~ 200 Hz, without applying additional procedures, for example, cell displacement in the transverse direction, etc.

To clarify the situation with the use of the reflecting mirror (*9*) behind cell (*8*), we present the power distribution for a laser pulse (1*a*) with a FWHM of 1 ns, emitted by the miniature laser (*1*), along the propagation direction (Fig. 1, top). To estimate the characteristic distances, the shape of the pulse power envelope (Fig. 3) can be approximated by a Gaussian:

$$P_{\rm las}(t) = P_{\rm las}^{\rm max} \exp\left[-4\ln 2\left(\frac{t-t_0}{\Delta t_{1/2}}\right)^2\right],$$

where $\Delta t_{1/2}$ is the Gaussian pulse FWHM and t_0 is the pulse peak position on the time axis. Then, the pulse width Δt at a level of 10^{-10} of the maximum power, which exceeds the spontaneous-scattering noise level e^{-G} in the pump beam direction (the threshold gain increment G is generally assumed to be ~ 25) is $\Delta t_{10^{-10}} = (10\ln 10/\ln 2)^{1/2}\ \Delta t_{1/2} \approx$

$\approx 5.8\Delta t_{1/2}$, and the spectral width $\Delta\nu_{10^{-10}}$ exceeds the spectral width at half maximum, $\Delta\nu_{1/2} = 2\ln 2(\pi\Delta t_{1/2})^{-1}$ by the same number of times. Thus, at this level in vacuum, the length of a 1-ns pulse is larger than 170 cm and its spectral width is 0.085 cm^{-1}. Therefore, for a mirror placed directly behind the cell, the seed-signal level exceeds the scattering-noise level even when the pump pulse peak is at a distance of about 60 cm from the cell input window and an extra time of 2 ns is necessary for it to reach the window. Note that this spectral width is close to the Stokes backscattering shift $\nu_{\text{B}} = (2nV_l/c)\nu_{\text{las}} \approx 0.092\ \text{cm}^{-1}$ in CCl_4 [3], where n is the refractive index, V_l is the hypersonic velocity in the medium, c is the speed of light in vacuum, and ν_{las} is the pump carrier frequency. One should also take into account that, because of rather high intracavity intensities, a short pulse generated in a miniature laser can be spectrally broadened due to the Kerr nonlinearity in the active element and other optical elements of the laser.

In Fig. 1 the cell length $L = 20$ cm is correlated with the spatial length of the envelope of pulse (*1a*). Thus, when light with power $P = 10^{-10}P_{\text{las}}^{\max}$ is incident on mirror (*9*), the main part of the pulse is still far from the cell; however, the power of pulse (*1b*), reflected from the mirror, is already much higher than the level of spontaneous Brillouin scattering. Therefore, the power of the counterpropagating seed signal (at the laser frequency) at the cell input may significantly exceed that of the backscattered spontaneous Stokes radiation at fairly large distances between mirror (*9*) and cell (*8*). Electrostriction interaction of counterpropagating pulses is inertial ($\tau_{\text{B}} = 0.6$ ns is the decay time of hypersonic oscillations in CCl_4 [3]) for short ($\tau_{\text{las}} \sim 1$ ns) pulses. Hence, this interaction can be not only effectively enhanced in cell (*8*) but also effectively compressed (under focused pumping); i.e., the gained-pulse width can be reduced (Fig. 3b). Obviously, to obtain effective interaction between pulses, it is necessary to provide their good spatial overlap, which can be done by aligning mirror (*9*). The light reflected from mirror (*9*) can be used more efficiently by collimating the beam transmitted through the cell with an additional lens (*14*). However, in this case mirror (*9*) must be aligned much more precisely: the reflected beam should return in exactly opposite direction.

It should be emphasised that here the main thing is not the decrease in the mean (measured) width of compressed pulses from 109 to 96 ps but much higher stability of their parameters, which can be characterised by the ratio $\delta_j = \sigma_j/\mu_j$ of the corresponding variances σ_j to the mean values μ_j. For example, when passing from the SBS-compression regime from the noise level to the compression regime with a seed laser pulse, the stabilities of the pulse widths and amplitudes changed from $\delta_\tau^{\text{SBS}} = 0.08$ and $\delta_A^{\text{SBS}} = 0.09$ to $\delta_\tau^{\text{ES}} = 0.03$ and $\delta_A^{\text{ES}} = 0.02$, respectively. Thus, the introduction of a feedback through a reflecting mirror improved the stability of the parameters by a factor of 3–4, with a significant reduction in the pulse width. In addition, in the former regime (at a pulse repetition rate of 10 Hz), a compressed pulse arose at the minimum laser pulse energy $W_{\text{las}}^{\text{SBS}} = 0.89$ mJ, whereas in the latter regime this occurred at $W_{\text{las}}^{\text{ES}} = 0.52$ mJ. The oscillograms in Figs 2a and 2b were recorded at the laser pulse energy $W_{\text{las}} = 1.3$ mJ.

Simultaneous observation of both pulses on the oscilloscope screen (Fig. 3) makes it possible to measure the time jitter for compressed pulses with respect to the laser pump pulses. For example, in the case of generation of compressed Stokes pulses from the spontaneous-scattering noise level (Fig. 3a), their time jitter $\Delta t_{\text{jit}}^{\text{SBS}} = 39$ ps, whereas the mirror feedback (Fig. 3b) reduced the jitter to $\Delta t_{\text{jit}}^{ES} = 12$ ps, i.e., by a factor of more than 3. In addition, the data in Fig. 3 indicate that in the presence of a mirror compressed pulses of a larger amplitude arise earlier than without a mirror.

With an increase in the mirror–cell distance, the mean delay time $\Delta t_{\text{d}}^{\text{ES}}$ of compressed pulses with respect to the pump pulses increases from zero at $\Delta s = 1.6$ cm to ~ 200 ps at $\Delta s = 30$ cm (Fig. 4). When the mirror is absent or screened, a compressed pulse arises $\Delta t_{\text{t}}^{\text{SBS}} = 350$ ps later than for a mirror closely adjacent to the cell (at the same pump pulse energy $W_{\text{las}} \approx 1.2$ mJ). It can also be seen that the time jitter of the compressed pulse occurrence barely changes when the mirror is displaced along the axis by a distance up to 30 cm but increases by a factor of more than 3 when the mirror is misaligned, screened, or absent. Figure 4 shows also the results of studying the dependence of the change in the energy efficiency of compression and the compressed pulse stability on the mirror position. At a minimum distance from the mirror to the cell the conversion efficiency of the pump pulse energy to the compressed pulse energy was 45%. With an increase in the mirror–cell distance, as a result of the decrease in the amplitude and increase in the delay of seed signals, their gain reduced, as well as the energy stability: $\delta_W = \sigma_W/\mu_W$. The latter increased from $\delta_W^{\text{ES}} \leqslant 0.02$ at a small distance from the mirror to the cell to $\delta_W^{\text{ES}} \approx 0.2$ at a fairly large distance. In this case, the energy efficiency and stability were almost the same as in the absence of mirror feedback.

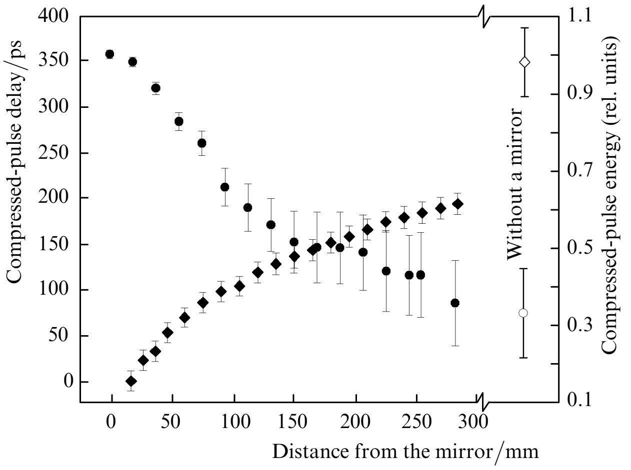

Figure 4. Dependences of the (◆) delay and (●) energy of compressed pulses on the distance from the mirror.

Thus, the use of a conventional plane mirror to form (by reflection) a weak (but exceeding the spontaneous-scattering level) counterpropagating (with respect to the focused pump pulse) seed pulse of the same width and frequency not only increases the degree and energy efficiency of pulse compression but also increases significantly (by a factor of 3–4) the stability of the main parameters (amplitude and width) of compressed pulses with the same considerable decrease (by a factor of more than 3) in their time jitter.

The scheme with an external mirror behind the cell does not make it possible to implement the entire possible range of delays for weak counterpropagating pulses. However, in some cases amplification may start from the level of laser pump radiation scattered by the internal elements of the cell: its lateral walls and output and input windows. This possibility of forming a random loop feedback was previously discussed in [22]. With this feedback, one can obtain shorter ($\bar{\tau}_{\rm m}^{\rm ES} = 81.5$ ps) compressed pulses (Fig. 3c) with a small spread ($\sigma_{\tau}^{\rm ES} = 1.85$ ps) of width ($\delta_{\tau}^{\rm ES} = 0.02$). Unfortunately, intracell-scattering configurations are implemented randomly and rarely. Therefore, the separation of laser pulse into pump and seed pulses with their subsequent counterpropagating overlap in the cell is the most convenient way for studying the possibility of compressing seed pulses at their amplification in counterpropagating focused pump pulses. Obviously, it is necessary to ensure the corresponding polarisations and a sufficiently good overlap of the counterpropagating pulses in this case. Not going into details of this (more complex) scheme, we will only report the results of the experiments on studying the dependences of the width and energy of amplified pulse on its delay (Fig. 5). At a zero delay the instantaneous power peaks of counterpropagating pulses coincide in the pump beam waist. A negative delay indicates how much earlier the weak-pulse power peak crosses the waist in comparison with the pump peak. One can see in Fig. 5 that the optimal delays are close to zero, a situation where both pulses arrive at the waist almost simultaneously. In this case, pulses with a measured minimum mean width $\bar{\tau}_{\rm m}^{\rm ES} \approx 66$ ps and standard deviation $\sigma_{\tau}^{\rm ES} \approx 4.4$ ps (Fig. 2d) were obtained. Taking into account the proximity of the measured widths to the measurement resolution limit, the real width of the thus compressed pulses can be estimated as $\tau_{\rm r}^{\rm ES} \approx [(\tau_{\rm m}^{\rm ES})^2 - \tau_{\rm do}^2]^{1/2} \approx 52$ ps.

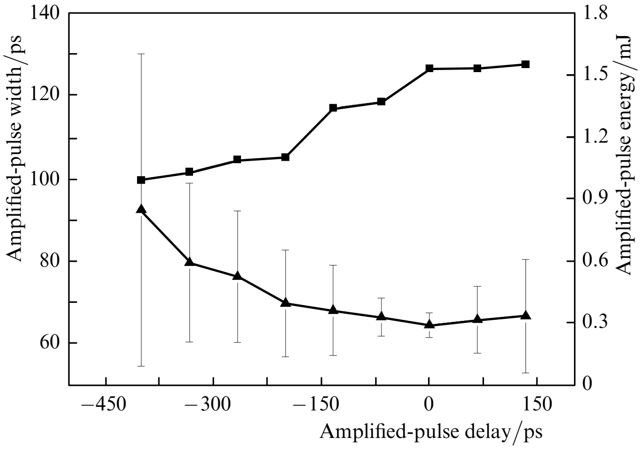

Figure 5. Dependences of the (▲) width and (■) energy of amplified pulses on the delay with respect to the pump pulse.

Using a lamp amplifier, we could obtain laser pulses of higher energy and investigate the dependences of their characteristics not only on the time delay but also on the pump energy. The data in Fig. 5 correspond to close-to-optimal conditions: a pump pulse energy of 3.2 mJ and a seed pulse energy of 0.26 mJ. Here, we obtain the energy gain $K_W \geqslant 6$ and the degree of compression $N_{\tau}^{\rm ES} \geqslant 18$ at a maximum power of compressed pulses $P_{\rm max}^{\rm ES} \sim 30$ MW.

3. Results and discussion

The search for schemes similar to the aforementioned ones, which was performed after these experiments, showed that such schemes are only rarely used. Focusing of light through a cell with subsequent reflection from a mirror was applied by Lavrent'ev et al. [15]. However, they used a conventionally compressed Stokes pulse propagating in an individual cell. This pulse was reflected before the arrival of the pump pulse, and the reflected signal was sent toward it and then amplified in the cell upon interaction with the pump. Focusing mirrors were placed behind SBS cells in [23] to monitor phases and preserve the time envelope of reflected pulses with a width of ~ 7 ns.

The presence of a feedback, which arises as a result of pump scattering by the cell reflecting surfaces [22] or is specially formed using loop cavities [24], leads (due to the electrostriction) to the formation of density and refractive index gratings, which significantly affect the pump scattering. Note that this study was stimulated by the detection of enhanced stability of the parameters of compressed pulses at random approach of a focused pump beam to the SBS cell walls.

The presence of feedback due to the pump-formed grating affects both the propagation and amplification of spontaneous radiation at the Stokes frequency. For long (~ 10 ns) pump pulses with a narrow spectrum, a Stokes shift (conventional for the SBS medium used) was observed in reflected light [22, 24]. A study of the instability of counterpropagating plane waves with the same carrier frequencies in media with electrostriction nonlinearity [25] showed that the threshold instability in counterpropagating waves is much lower in comparison with the generation of Stokes radiation in one pump beam. When the threshold is slightly exceeded, the output wave intensities oscillate with a frequency of the Brillouin shift, and an increase in the input wave intensity reduces this frequency to 1/4 of the Brillouin shift or even less. It was reported about the formation of a Bragg grating due to the weak Rayleigh scattering of pulses with a width of about 10 ns in the recent review [26]. This grating can then be amplified by other mechanisms of nonlinearity (for example, two-photon absorption in dye solutions), which leads to effective pump backscattering without a frequency shift. This type of scattering was referred to as stimulated Rayleigh – Bragg scattering [26].

Here, we did not investigate the compressed-pulse spectrum; therefore, the question of the change in the external counterpropagating signal under amplification and the spectrum compression remains open, anyhow, as well as the question of the compressed-pulse spectrum in the conventional SBS compression regime. Our previous calculations [27] showed that, because of the characteristic shape of compressed pulses, the product of the spectral width (at the half-intensity level) by the pulse width is much smaller (by a factor of almost 2) than the corresponding product for Gaussian pulses. It was recently shown [19, 20] that an increase in the pump intensity shifts the compressed-pulse spectrum toward the pump spectrum, as a result of which the Stokes shift decreases. At the same time, Gao et al. [28] stated (based on numerical calculations in the specified-pump-field approximation) that, in the case of amplification of a signal with a spectral width close to the spontaneous scattering linewidth $\Delta\nu_{\rm B} = 1/(2\pi\tau_{\rm B})$, which is determined by the relaxation time τ_B of hypersonic waves, the peak of the amplified-signal spectrum shifts by the Stokes frequency of Brillouin scattering, ν_B. For liquid tetrachloride CCl_4, the corresponding parameters were reported in [3]: $\tau_B = 0.6$ ns, $\Delta\nu_B = 265.4$ MHz ($0.0088\ \mathrm{cm}^{-1}$), and $\nu_B = 2.76$ GHz ($0.092\ \mathrm{cm}^{-1}$). Pulses with a shape similar to Gaussian were used in the experiments; therefore, their spectral width can be estimated from the formula $\Delta\nu_{\rm las} = 2\ln 2/(\pi\tau_{\rm las})$. For the laser pulse widths that were used in the experiments ($\tau_{\rm las} \approx 0.9$ ns) the spectral width at half maximum, $\Delta\nu_{\rm las} \approx 488.3$ MHz ($0.016\ \mathrm{cm}^{-1}$), exceeds the Lorentzian width of the spontaneous scattering line, $\Delta\nu_B$. For compressed pulses one should expect a spectral width $\Delta\nu_r^{\rm ES} \approx \ln 2/(\pi\tau_r^{\rm ES}) \approx 4.2$ GHz, which exceeds not only the spontaneous scattering linewidth but also the Stokes shift frequency. As a whole, we believe it necessary to study in more detail the changes in the spectrum of compressed pulses, especially in the regime of seed-pulse amplification and compression.

Note also that the energy transfer from a more intense beam to a less intense one may occur at different mechanisms of nonlinearity of the medium. As was noted above, this transfer was observed in the cases of thermal nonlinearity [17] and electrostriction (in our previous studies [14, 16, 18] and here). Effective energy transfer from a pump pulse to a weaker pulse can also be implemented in the femtosecond range using the Raman mechanism of nonlinearity [29], where the pump and seed beams cross at an acute angle in air; in this case, the seed pulse width decreases from 52 to 27 fs and the energy increases from 6 to 31 μJ at an initial pump pulse energy of 610 μJ. Recently Lancia et al. [30] demonstrated a possibility of transferring the energy from a longer (3.5 ps) pump pulse to an almost counterpropagating shorter (400 fs) seed pulse of the same frequency at their interaction in a laser plasma excited by an additional ionising ($W_i = 30$ J) chirped 400-ps pulse; as a result, a short-pulse energy of 60 mJ was obtained at a gain $K_a = 32$.

4. Conclusions

We experimentally studied the change in the shape and width of short signal pulses at their amplification in the field of focused counterpropagating pump pulses with the same carrier frequency and width in a medium with electrostriction nonlinearity. One of the simplest ways to implement counterpropagating interaction of such pulses is to place a plane mirror behind the SBS cell. It was shown that, using pulses of Nd:YAG and other solid-state miniature lasers with a width of about 1 ns, signal pulses can be efficiently compressed to widths below 70 ps in media of the CCl_4 type, where the relaxation time of hypersonic waves is close to the duration of interacting pulses. With allowance for the fact that the measurement response time is about 40 ps, the real width of compressed pulses is close to 50 ps. Since the amplification does not begin from the noise level, the external seed pulse can be compressed at pump pulse energies below the SBS energy threshold. For practical applications it is very important that in this case their energy and temporal stability increase significantly (several times), whereas the time jitter of compressed pulses decreases in comparison with the SBS compression from the level of spontaneous scattering noise. In addition, the occurrence time of compressed pulses depends on the delay time and seed-pulse intensity, due to which it can be gradually varied in a range of about 200 ps. In the case of SBS compression from the noise level a compressed pulse is generated with a delay of about 350 ps in comparison with the reverse reflection by a mirror placed directly behind the SBS cell. Therefore, having optimised the intensity and delay time of seed pulses, one can significantly extend the range of focused pulse energies at which the energy can be efficiently transferred to compressed counterpropagating pulses, and the influence of such competing effects as SRS, self-focusing, and optical breakdown is relatively small.

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