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Capillary compressor of femtosecond laser pulses with nonlinear rotation of polarisation ellipse

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Abstract. **The process of nonlinear rotation of the polarisation ellipse of laser radiation, occurring simultaneously with the broadening of the pulse spectrum due to nonlinear self-phase modulation in a gas-filled capillary, is studied. It is shown that the maximal rotation of the polarisation ellipse is experienced by the spectral components, shifted towards the short-wavelength side with respect to the central wavelength of the initial laser pulse. Using the effect of polarisation ellipse rotation, an eightfold increase in the energy contrast ratio of a 28-fs light pulse, obtained by compression of the radiation pulse from an ytterbium laser with the duration 290 fs, is implemented.**

Keywords: *femtosecond pulses, compression of pulses, capillary, nonlinear rotation of polarisation ellipse.*

1. Introduction

Time compressors of femtosecond laser pulses using the pulse spectrum broadening upon propagation through a capillary filled with noble gas are widely used due to the simplicity of construction, high efficiency and reliability. The energy efficiency of such compressors reaches 50 % [1, 2], and the degree of compression, i.e., the input-to-output ratio of the pulse durations may be as large as 15 [3, 4].

In capillary compressors the spectrum broadening and the pulse frequency chirping, which allow further temporal compression of the pulse, occur due to nonlinear self-phase modulation [5], in which the shift of the frequency ω of the pulse output from the capillary with respect to the frequency ω_0 of the input pulse is determined by the variation in the laser radiation intensity I in time, $\omega - \omega_0 \sim - n_2\partial I/\partial t$, where n_2 is the nonlinear part of the refractive index of the gas, filling the capillary [6]. Figure 1 presents a typical laser pulse shape and the corresponding time variation in the instantaneous radiation frequency due to nonlinear self-phase modulation. One can see that during the pulse the sign of the frequency chirp is changed. The chirp is negative at the leading and trailing edges of the pulse, while in the central part of the pulse, where the intensity is maximal, the chirp is positive.

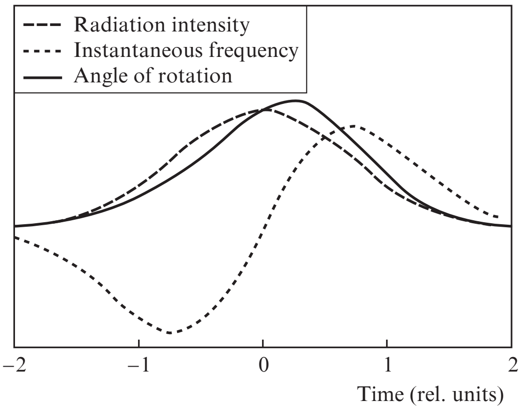

Figure 1. Calculated time dependences of the frequency variation due to self-phase modulation and of the polarisation ellipse rotation angle (parameter $\alpha = 0.2$) for a Gaussian pulse.

The pulse compression at the output from the capillary is implemented by passing the pulse through a dispersive optical element that allows compensation for the chirp with definite sign. That is why the central part of the pulse is compressed, while the duration of the pulse fronts is not reduced, due to which a low intensity pedestal is formed with a compressed pulse on it. The duration of the pedestal is approximately equal to that of the initial pulse. The fraction of energy in the pedestal reaches 40 % of the total pulse energy.

The low-intensity pedestal was observed in the experiments on femtosecond pulse compression. For example, in Ref. [1] the pedestal energy fraction amounted to ~50 %. Naturally, such a low contrast essentially limits the field of application of capillary compressors. In this connection it is important to develop the methods for increasing the contrast in order to get ‘pure’ femtosecond pulses. At present, the most investigated and widely used methods are the second harmonic generation [7] and the generation of orthogonally polarised light waves [8]. In both methods a nonlinear transformation of the compressed pulse is accomplished in nonlinear crystals mounted after the compressor. The additional stage of nonlinear transformation complicates the optical scheme and reduces the stability of the compressor performance; hence, it is urgent to get ‘pure’ femtosecond pulses directly at the output of the compressor.

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To obtain high-contrast pulses at the output of a capillary compressor one may use the effect of nonlinear rotation of the polarisation ellipse of radiation, which consists in rotation of the axes of the polarisation ellipse with respect to the initial elliptical polarisation of the light wave in the course of passing through a nonlinear medium. The rotation of the polarisation ellipse axes is a consequence of the optical path difference between the linear orthogonal polarisations along the ellipse axes. The difference of optical paths is caused by different values of the nonlinear refractive index for different intensities of linearly polarised light fields, forming the elliptically polarised light. The use of the effect of polarisation ellipse nonlinear rotation in a gas-filled capillary for increasing the pulse contrast was demonstrated in [9]. However, in this work the radiation intensity in the capillary was not high and no significant broadening of the spectrum was observed. The process of nonlinear rotation of the polarisation ellipse, taking place simultaneously with the process of spectrum broadening due to self-phase modulation, was not investigated.

The aim of the present work is to study experimentally the possibility of increasing the contrast of a compressed femtosecond pulse by two nonlinear processes, simultaneously occurring in the gas-filled capillary, namely, the polarisation ellipse rotation and the self-phase modulation.

2. Experimental setup

The optical scheme of a capillary compressor is presented in Fig. 2. We studied the compression of pulses from the ytterbium TETA-3 laser (Avesta Ltd) having the energy 160 μJ and the duration 290 fs. The central wavelength was 1028 nm, the generated spectrum bandwidth was 6 nm. The pulse repetition rate was 3 kHz. The light beam with a Gaussian intensity distribution had the diameter 4.7 mm at the $1/e^2$ intensity level, the divergence 0.9 mrad, and the beam quality parameter $M^2 = 1.05$.

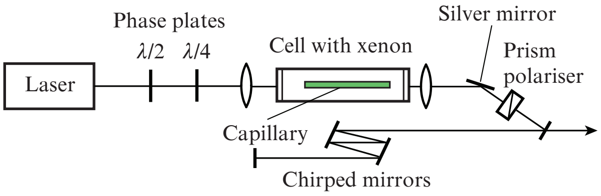

Figure 2. Optical scheme of a compressor with nonlinear rotation of the polarisation ellipse.

The laser radiation was focused into a silica capillary with the inner diameter 150 μm and the length 30 cm, placed in a chamber filled with xenon. The measured transmission of the capillary was 60% and did not change in the course of experiments.

To form an elliptically polarised light wave, a half-wave ($\lambda/2$) and a quarter-wave ($\lambda/4$) phase plates were installed before the lens, focusing the radiation into the capillary. The eccentricity of the polarisation ellipse for the input radiation was varied by rotating the half-wave plate. At the output of the chamber with the capillary the radiation was collimated by a lens and directed at angle 70° onto the surface of a silver mirror, which under the present conditions played the role of a quarter-wave phase plate [10]. Its necessity was caused by the wide radiation spectrum output from the capillary. The quarter-wave plate at the capillary input was oriented such that in the absence of nonlinear processes in the capillary the polarisation of the radiation, reflected from the silver mirror, coincided with that of the radiation, incident on the quarter-wave plate. The pulse, reflected from the silver mirror, was directed to the prism polariser (Glan–Taylor prism) that blocked the radiation having the polarisation, coincident with that of the radiation after the half-wave plate. Thus, the polariser transmitted only the radiation whose polarisation was rotated in the capillary.

The radiation passed through the polariser was directed into the time compressor, based on the chirped mirrors with the group delay dispersion of –250 fs^2. The scheme with double passes through the chirped mirrors was used with the total number of reflections equal to eight. The compressed pulse was then coupled into the registration system, including the spectrometer and the autocorrelator, based on noncollinear second harmonic generation in a crystal.

3. Experimental results and discussion

Before starting the experiments on compression of pulses of elliptically polarised radiation, the compression of linearly polarised pulses was studied. In this case the prism polariser at the output of the compressor was oriented at the maximal transmission of the polarisation, coincident with that of the input radiation. Figure 3a shows the emission spectrum at the output from the capillary compressor at the xenon pressure 3.2 atm. The spectrum possesses a jagged structure typical of

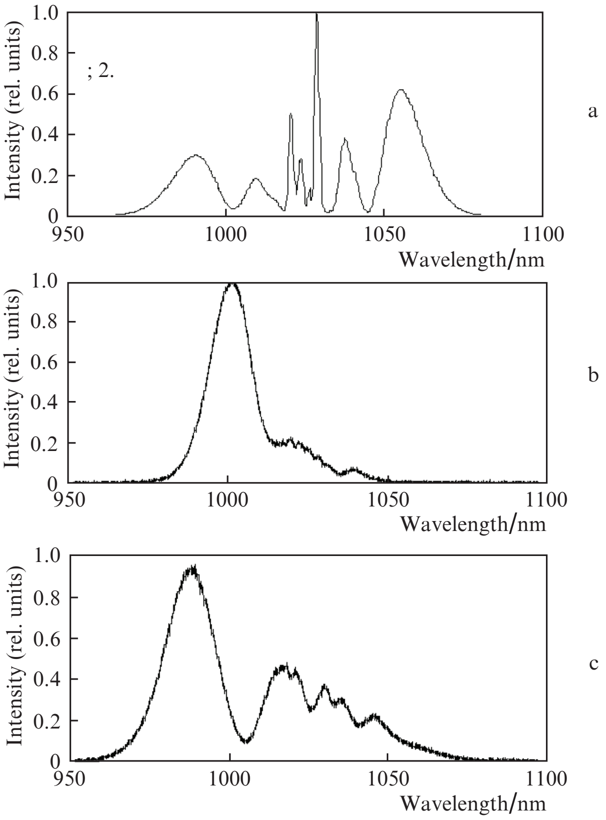

Figure 3. Emission spectra at the output from the capillary compressor in the case of linear polarisation (a) and elliptical polarisation with the aspect ratio of ellipse axes 1.1 (b) and 1.35 (c)

the spectra, broadened in the process of self-phase modulation [5, 6]. Deep modulation of the spectrum appears due to the interference of light waves with similar frequencies, emitted at different moments of time. One can see from Fig. 1 that the waves with equal frequencies are emitted in the regions of both a negative and a positive frequency chirp. The autocorrelation function of the compressed pulse is shown in Fig. 4a. The duration of the central peak corresponds to the light pulse with the duration 28 fs. The central peak is situated on a low-intensity pedestal having the duration close to that of the pulse at the compressor input and equal to ~300 fs. The measured fraction of energy in the low-intensity pedestal amounts to ~40% of the total pulse energy. As already mentioned above, just this fraction of energy is carried by the non-compressed (negative-chirp) part of the Gaussian pulse.

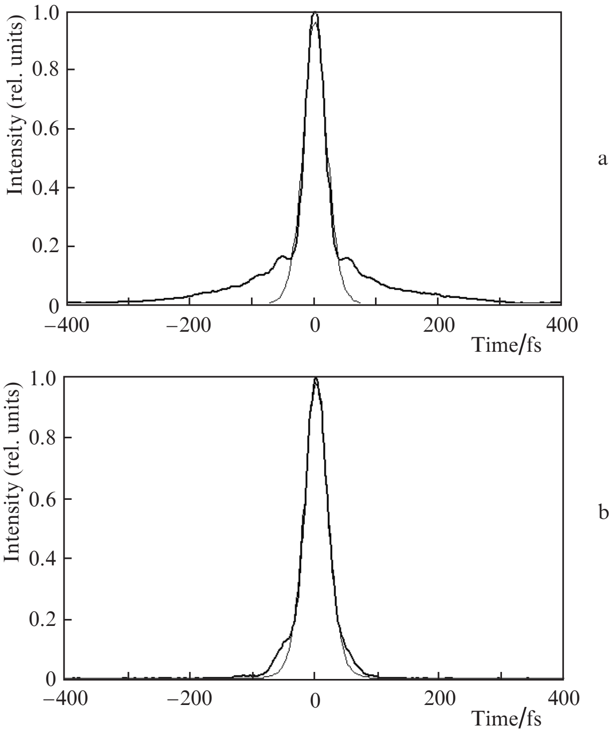

Figure 4. Autocorrelation function of the pulse at the output from the capillary compressor (thick curve) and autocorrelation function for the sech^2 pulse (thin curve) in the absence of nonlinear rotation of the polarisation ellipse (a) and in the presence of rotation (b).

Proceeding to the elliptically polarised laser radiation, delivered into the capillary, we observe that the shape of the emission spectrum after the prism polariser that blocks the radiation, whose polarisation coincides with that of the light wave after the half-wave phase plate, acquires a qualitatively different appearance. Figures 3b and c show the output spectra for different aspect ratios of the radiation polarisation ellipse at the capillary input under the xenon pressure 4 atm. For the spectra presented, the ratio of intensities of the orthogonally polarised light waves, differing in phase by $\pi/2$, amounts to 1.1 (Fig. 3b) and to 1.35 (Fig. 3c). The total intensity is the same in both cases. It is seen that when the polarisation insignificantly differs from circular (Fig. 3b), the spectrum possesses smooth shape and is shifted towards the short-wavelength side with respect to the central wavelength of the initial laser radiation.

Such shape of the spectrum can be explained as follows. The intensity of the light wave, which passed through a prism polariser, is proportional to the angle Θ of rotation of the polarisation ellipse in the capillary. The angle of rotation is determined by the ratio of the optical path difference for the orthogonally polarised waves to the instantaneous value of the wavelength $\lambda(t)$. Since the difference of the optical path lengths is proportional to the radiation intensity $I(t)$, we have $\Theta(t) \sim I(t)/\lambda(t)$. Due to nonlinear self-phase modulation the wavelength at the capillary output varies following the law [6]

$$\lambda(t) \approx \lambda_0 \left(1 - \frac{n_2 L}{c}\frac{\partial I}{\partial t}\right)^{-1},$$

where λ_0 is the central wavelength; L is the capillary length. Since the instantaneous wavelength is reduced at the trailing edge of the pulse due to self-phase modulation, for pulses with a smooth top the maximal angle of rotation of the polarisation ellipse is attained after the intensity of the light wave passes the maximal value, i.e., for laser radiation with a shorter wavelength as compared to the input one. Figure 1 presents the results of calculations of relative polarisation ellipse rotation versus time for a Gaussian pulse having the duration 300 fs and the intensity in the capillary 4×10^{12} W cm^{-2}, the xenon pressure being equal to 4 atm in the 30-cm-long capillary. For a Gaussian pulse the dimensionless quantity that determines the shift of the maximum of the rotation angle is the parameter $\alpha = n_2 IL/(c\tau)$, where τ is the pulse duration. It is seen that the maximal rotation angle is attained at the trailing edge of the laser pulse in the region of shorter wavelengths (higher frequencies). Therefore, when passing from circular to elliptical polarisation of the light wave, the shorter-wavelength components should be first observed in the spectrum of the pulse, transmitted through the prism polariser, which actually occurs in the experiment.

When the intensity difference between the orthogonally polarised waves is increased (i.e., at greater eccentricity of the polarisation ellipse), there occurs first the growth of energy passing through the polariser and the broadening of the pulse spectrum. Then, the growth of energy becomes slower and the spectrum acquires a jagged shape, similar to that for linear polarisation. This is due to the fact that the angle of rotation of the polarisation ellipse at the maximum of intensity becomes greater than $\pi/2$. Under the conditions of our experiment the optimal regime was achieved when the ratio of intensities of the orthogonally polarised components was equal to 4 : 3 (Fig. 3c). The estimates show that in this case the difference $\pi/2$ between the orthogonally polarised light waves, forming the elliptically polarised light beam, is attained at a nearly maximal intensity value. The energy efficiency of the compressor under the optimal conditions amounted to 16% which is nearly three times lower that the efficiency of compressor performance at linear polarisation of radiation in the capillary.

The nonlinear polarisation selection of the most intense part of the pulse, spectrally broadened in the capillary, allowed obtaining a sufficiently smooth spectrum of radiation and, therefore, a more contrast pulse after compression. The autocorrelation shape of the compressed pulse having the duration 28 fs is shown in Fig. 4b. In this case, the central peak contains 95% of the total energy. The insignificant difference (~5%) of this correlation function from that for the pulse, whose shape is described by the function sech^2, is due to the residual modulation of the spectrum. In our opinion, a more uniform spectral shape and higher-contrast pulses may be obtained by equipping the optical scheme with polarisers having higher extinction coefficients than those used in the present work. In particular, the silver mirror may be replaced with a broadband $\lambda/4$ phase plate.

In conclusion, we note that the use of the nonlinear polarisation ellipse rotation effect in a capillary compressor allowed the pulse energy contrast to be increased by eight times. We showed that under the simultaneous nonlinear rotation of the polarisation ellipse and chirping of the pulse frequency via the self-phase modulation, the maximal value of the polarisation ellipse rotation angle is attained for the radiation spectral components, shifted to the short-wavelength side with respect to the central wavelength of the input laser radiation.

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