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Temporal compression of pulses from a 100-kHz-repetiton-rate femtosecond ytterbium laser

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Abstract. **We report the temporal compression a femtosecond ytterbium laser pulse at a pulse repetition rate of 100 kHz using the effect of nonlinear self-phase modulation in a gas-filled capillary. A 260-fs laser pulse is compressed down to 17 fs with an energy efficiency of 40%. An average radiation power at the compressor output is 2 W. At a second compression stage, the time contrast is increased and the pulse duration is reduced in the process of the second harmonic generation in a KDP crystal. The obtained pulses have a duration of 11 fs at an efficiency of 35%.**

Keywords: *femtosecond pulses, ytterbium laser, capillary, pulse compression.*

1. Introduction

High-power femtosecond laser systems on crystals doped with ytterbium ions are presently widely used due to their high energy efficiency, compactness, reliability and low cost as compared to other femtosecond lasers. Usually, ytterbium lasers have a master oscillator–regenerative amplifier scheme. The active medium in the master oscillator is a silica fibre, and in the regenerative amplifier it is a crystal doped with ytterbium ions. A sufficiently narrow gain in crystals prevents such laser systems from generating pulses shorter than 200 fs. If necessary, pulses of shorter durations can be obtained by using methods of nonlinear compression, in particular, pulse compression in a gas-filled capillary [1].

Nonlinear compression of femtosecond pulses in a scheme with a gas-filled capillary was studied in our papers [2, 3]. A 300 fs, 150 μJ pulse of the ytterbium laser was compressed down to a 30 fs pulse at an energy efficiency of ~ 50%. The pulse repetition rate (PRR) was 3 kHz, which corresponded to an average radiation power of ~ 0.2 W after the compressor.

In some experiments (for example, with generation of higher-order harmonics and attosecond light pulses in gas media), laser pulses with a power of at least 1 GW and duration of several periods of the light wave are required [4]. For increasing sensitivity and accuracy of the experiment, it is desirable to ensure the highest PRR. Modern femtosecond ytterbium laser systems can operate at a PRR of several hundred kilohertz. Investigation of nonlinear compression in such laser systems for obtaining high-power light pulses with a duration of several light-wave periods is an actual problem. In the present work, we study compression of laser pulses in a gas-filled capillary at a pulse repetition rate of 100 kHz.

2. Capillary choice

The main problem in developing a scheme for a capillary compressor is the choice of capillary dimensions. In broadening the emission spectrum of a laser pulse in a gas-filled capillary in the process of self-phase modulation, it is necessary to avoid ionisation of the active gas, which can reduce the operation efficiency and stability. If the active gas is xenon that has the highest nonlinear refractive index, the radiation intensity inside the capillary should not exceed 10^{13} W cm^{-2} [5]. Hence, at laser pulse parameters specified above, the diameter of fundamental mode in the capillary should be greater than 60 μm. Since the diameter of the fundamental mode is 0.6 of the internal capillary diameter [6], the latter should be greater than 100 μm.

As shown in [3], at the prescribed value of capillary transmission T that is determined by the length and internal diameter of the capillary, the spectrum broadening $F = \Delta\omega_{\rm out}/\Delta\omega_{\rm las}$ (where $\Delta\omega_{\rm las}$ and $\Delta\omega_{\rm out}$ are the spectral widths of laser radiation and of radiation at the output from the capillary, respectively) weakly depends on the capillary length L: $F \sim L^{1/3}$. Thus, the capillary length is chosen issuing mainly from the maximal possible dimension of the compressor. In our experiments, the capillary length was 60 cm.

The maximal spectral broadening depends on the capillary transmission and length, as well as on the wavelength of laser radiation λ as follows [3]:

$$F = \left[1 + k\left(\frac{L}{\lambda}\right)^{2/3} \frac{(1 - T)^2}{(-\ln T)^{2/3}}\right]^{1/2}, \qquad (1)$$

where k is a constant.

The maximal broadening is attained in the regime, when, at a fixed power of the output laser pulse, the gas pressure is chosen a bit lower than the pressure, at which higher-order modes arise in the capillary [3] and, as a consequence, the capillary transmission reduces. This value of the gas pressure is close to the pressure corresponding to a self-focusing threshold for the laser beam. The value of k in (1), which depends on a capillary material, was found in [3] issuing from an analysis of available experimental data. For a quartz capillary we have $k = 17$.

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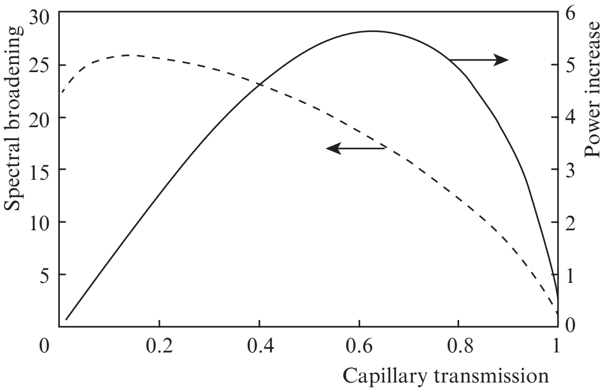

Figure 1. Calculated dependences of spectrum broadening F (dashed curve) and power increase M (solid curve) for a pulse vs. capillary transmission T.

Figure 1 shows the dependence of the spectrum broadening on the capillary transmission for a 60-cm-long quartz capillary. The maximal broadening is attained at $T = 16\%$. In addition to the spectrum broadening, which determines the degree of laser pulse compression, the power of the compressed pulse is also important. In Fig. 1, one can also see the dependence of a power increase M, determined as the ratio of the pulse power after compression to that of the input pulse, on the capillary transmission. In the case of ideal pulse compression, the increase M at the capillary output can be presented in the form

$$M = baFT. \tag{2}$$

Here, the factor b determines the efficiency of radiation coupling into the capillary (usually $b \approx 0.8$), and the coefficient a is the fraction of the pulse energy subjected to compression.

It is known that a frequency chirp of the pulse broadened in the nonlinear process of self-phase modulation changes the sign during the pulse evolution [7]; the most intensive part of the pulse, which is subjected to compression, has a positive chirp, whereas low-intensity edges of the pulse acquire a negative chirp. For a Gaussian pulse, we have $a \approx 0.6$ [7]. Hence, $M \approx 0.5\,FT$.

From Fig. 1, one can see that at the shortest pulse duration (large spectrum broadening), a close-to-maximal power of the compressed pulse can be obtained in the range of capillary transmission from 0.5 to 0.6. In this case, it is possible to obtain approximately twenty-fold time compression of the pulse and increase its power by 5 times and more as compared to the initial pulse power.

Since the attenuation factor for the fundamental mode α in the quartz capillary depends on the internal capillary radius r as $\alpha = 0.42\,\lambda^2/r^3$ [6], for obtaining the optimal compression regime we have chosen a capillary with a length of 60 cm and internal radius of 75 μm. The calculated transmission T for such a capillary is 0.55.

3. Capillary compressor

The scheme of the experiment on time compression of radiation of a femtosecond ytterbium laser (TETA, Avesta) is presented in Fig. 2. It was possible to vary the laser PRR in the range 25–250 kHz keeping an average power of output radiation equal to 5 W. In the experiments, the highest PRR reached 100 kHz. Higher frequencies have not been studied because a higher gas pressure and other designs of the gas cell are needed. The radiation pulse had a duration of 260 fs and a spectral width of 6 nm.

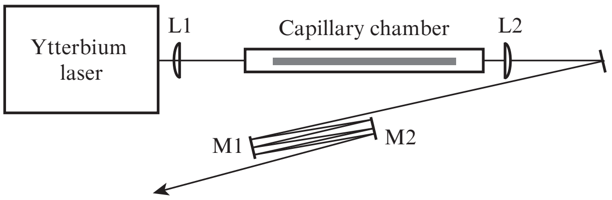

Figure 2. Optical scheme of the capillary compressor: (M1, M2) chirped mirrors; (L1, L2) lenses.

Linearly polarised laser radiation was focused by lens L1 with a focal distance $F = 50$ cm to the entry of a capillary placed in a 1-m-long stainless steel chamber with an internal diameter of 1 cm and filled with xenon. The internal diameter of the capillary was 150 μm and its length was 60 cm. Radiation at the output from the capillary was collimated by lens L2 ($F = 15$ cm) and passed to a time compressor comprised of chirped mirrors. Having been reflected from the chirped mirrors with a second-order dispersion of -1500 fs^2 (six reflections), the pulse was directed to an autocorrelator (ACF-20, Avesta) for duration measurements.

The measured ratio of the output energy to the pulse energy at the capillary input in the vacuum chamber was 0.42. Since the efficiency of radiation coupling into the capillary was 0.8, the measured capillary transmission was $T_{\text{meas}} = 0.53$, which negligibly differs from the calculated value ($T = 0.55$).

For choosing the optimal compression regime, we measured the capillary transmission versus xenon pressure in the chamber at a constant laser pulse energy of 50 μJ. At xenon pressures above 10 atm, a sharp fall in the capillary transmission was observed, which was related with exceeding the generation threshold for higher capillary modes [8]. Therefore, further experiments were carried out at a xenon pressure of 10 atm, in which case the capillary transmission reduced by 2% as compared to the transmission of the evacuated chamber.

Figure 3 shows a spectrum of the pulse broadened in the gas-filled capillary and an autocorrelation function of the pulse after temporal compression on chirped mirrors. The spectral width is 130 nm; hence, the pulse broadening exceeds 20, which agrees with calculations (see Fig. 1). A higher intensity of the short-wavelength part in the spectrum is related to a lower attenuation of shorter-wavelength radiation in propagating through the capillary. The spectrum presented in the figure corresponds to a transform-limited pulse with a duration of 16 fs. The measured autocorrelation function yields a duration of the compressed pulse of 17 fs (Fig. 3b) assuming that the pulse has a Gaussian shape. The sub-pulse that is observed on the autocorrelation function we explain by the third-order dispersion uncompensated by the chirped mirrors.

At a compressed pulse energy of 20 μJ and the main pulse (comprises about 60% of energy) duration of 17 fs, the power of the main pulse was ~0.7 GW. Since the power of the initial laser pulse is 0.19 GW (50 μJ and 260 fs), the power increase M reaches 3.7. The lower value of M as compared to the calculation result (5.5) is related to the fact that the shape of the compressed pulse is distinct from the Gaussian shape assumed in the calculations. An average radiation power at the output from the compressor was 2 W at the PRR of 100 kHz.

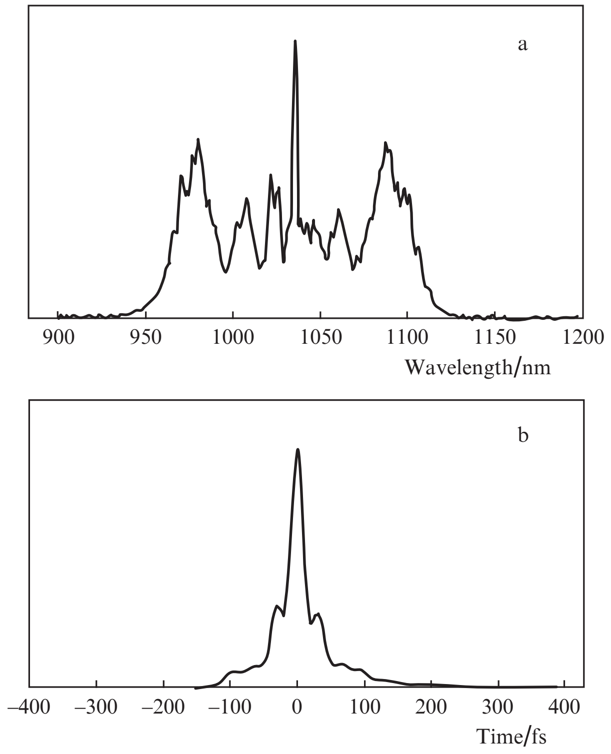

Figure 3. (a) Spectrum of the pulse at the capillary output and (b) autocorrelation function of the pulse compressed down to 17 fs.

A light beam of compressed radiation had a close-to-Gaussian spatial distribution with a diameter (at the e^{-2} level) of ~ 2 mm. Note that in focusing the compressed pulse by a lens with $F = 5$ cm, the focal spot diameter is ~ 30 μm, and the peak radiation intensity is 10^{14} W cm^{-2}. This circumstance, along with a sufficiently short pulse duration (approximately six light wave periods), opens possibilities of employing the ytterbium laser with a compressor in experiments on generation of high-order harmonics and attosecond pulses in gases.

The experiments on studying the influence of the PRR on output characteristics of the compressor have shown that at an energy of a single laser pulse fixed at a level of 50 μJ, the duration and power of the compressed pulse do not change in the range of PRR variations from 25 to 100 kHz. From this follows that the gas heating in a compression chamber related to the exit of laser radiation through capillary walls has no effect on compressor operation at an average laser power of up to 5 W.

4. Additional compression of the pulse in second harmonic generation in the crystal

A drawback of the pulse compression method based on spectrum broadening in the process of self-phase modulation is the principal existence of a low-intensity pedestal [7]. This circumstance is not critical in experiments with gas media. However, when a radiation pulse affects a solid body (for example, in generation of higher harmonics on a surface), the pedestal may become a critical factor. Thus, for obtaining femtosecond pulses with a higher contrast it is necessary to use additional methods of nonlinear conversion, in particular, second harmonic generation. In second harmonic generation in crystals, there is a possibility to perform additional time compression of a pulse [9]. Below we present experimental results on increasing the contrast and compression of a pulse during the second harmonic generation in the crystal.

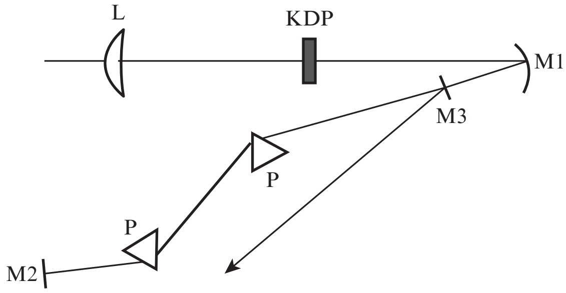

Figure 4. Optical scheme of the pulse compression based on the second harmonic generation in a KDP crystal: (L) lens with a focal distance of 3 cm; (M1, M2, M3) silver-coated mirrors (M1 is a spherical mirror with a focal length of 25 cm, M2 and M3 are plane mirrors); (P) prisms.

The optical scheme of the experiment is shown in Fig. 4. Laser radiation after a compressor on chirped mirrors was focused by a lens ($F = 30$ cm) into a 1-mm-thick KDP crystal. The oo-e type phase matching was used, which has a frequency band sufficient for generating pulses with durations shorter than 10 fs. The diameter of the focusing spot on the crystal was 200 μm, and the radiation intensity was about 1 TW cm^{-2}. Radiation of the second harmonic collimated by a concave silver-coated mirror was directed to a prism time compressor. The distance between quartz prisms of the compressor was 40 cm. The duration of the compressed second harmonic pulse was measured by an autocorrelator. The efficiency of the second harmonic conversion was 35%, and the average power of radiation at a wavelength of 0.515 nm was, respectively, 0.7 W.

A possibility of second harmonic pulse compression is related to the fact that in using a phase-modulated pulse of fundamental radiation one can obtain two-fold broadening in the spectrum of the second harmonic as compared to that of the fundamental radiation [9]. In our experiment, the pulse with a wavelength of 1.03 μm was chirped in passing through a 7-mm-thick focusing K8 glass lens. In this case, the pulse becomes approximately twice longer from 17 fs to 36 fs. Estimates show [9] that such chirping of the pulse should give two-fold broadening of the second harmonic spectrum.

Figure 5 shows a spectrum of second harmonic radiation and an autocorrelation pulse shape after the prism compressor. The spectrum corresponds to a transform-limited pulse with a duration of 9 fs. The shape of the second harmonic spectrum differs from the spectrum of radiation after the compressor on chirped mirrors (see Fig. 3a) because unshifted spectral components (near the frequency of the initial laser radiation) have a maximal intensity after self-phase modulation [7] and are converted to the second harmonic at the highest efficiency. The duration of the second harmonic pulse after the compressor was 11 fs in the Gaussian shape approximation. As one can see from the autocorrelation function (Fig. 5b), the fraction of energy comprised in the low-intensity pedestal was noticeably reduced (approximately from 40% to 5%) as compared to the pulse of fundamental radiation.

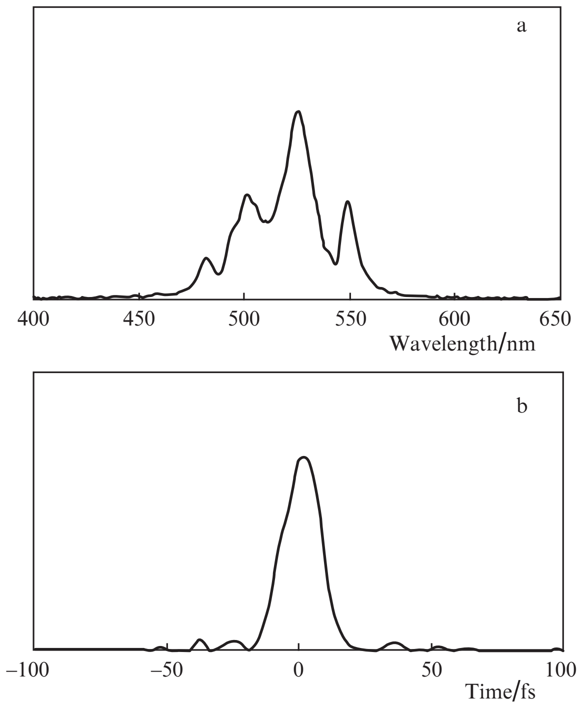

Figure 5. (a) Spectrum of the second harmonic pulse and (b) autocorrelation function of the pulse compressed down to 11 fs.

5. Conclusions

The following results have been obtained in the present work.

1. The conditions have been determined for obtaining a maximal degree of compression and increasing the power of a pulse compressed in the compressor based on nonlinear self-phase modulation in a gas-filled capillary.

2. Time compression of the radiation pulse of an ytterbium laser (260 fs, 50 μJ) has been realised at the pulse repetition rate of 100 kHz. The laser pulse was compressed down to 17 fs with an energy efficiency of 40%. A peak power of the compressed pulse was increased by a factor of 3.5 relative to the power of the initial laser pulse and reached 0.7 GW. The spatiotemporal characteristics of the light beam at the output from the compressor give a chance to employ the ‘ytterbium laser + capillary compressor’ system in experiments on generating higher harmonics in gases.

3. By using second harmonic generation in a KDP crystal, the laser pulse was additionally compressed. After the compressor, an 11-fs second harmonic pulse was obtained with an energy efficiency of 35% at the main pulse duration of 17 fs.

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