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Generation and temporal compression of second harmonic pulses of spectrally broadened radiation of a femtosecond ytterbium laser

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It is shown that the use of a second harmonic generation scheme with two sequentially located KDP crystals allows achieving the conversion efficiency of the chirped pulse of ytterbium laser radiation of up to 50 %. The obtained second harmonic pulses with a spectrum corresponding to a transform-limited pulse with a duration of 7 fs are compressed to 9 fs.

Keywords: second harmonic, femtosecond lasers, pulse compression.

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A setup for converting an IR radiation pulse of an ytterbium laser with a duration of 230 fs and a wavelength of 1030 nm into a visible radiation pulse 11 fs in length with an energy conversion efficiency of more than 20 % has been proposed in our previous paper [1]. This setup implemented two stages of nonlinear conversion. At the first stage, the IR pulse spectrum was broadened in the process of nonlinear self-phase modulation as a pulse propagated within a gas-filled capillary. At the second stage, the phase-modulated (chirped) pulse was converted into second harmonic radiation with a wavelength of 515 nm in a birefringent crystal. This was associated with additional broadening of the spectrum. The chirped second harmonic pulse was then compressed in time in a prism compressor.

The process of broadening of the pulse spectrum during self-phase modulation in a gas-filled capillary has been studied in detail in [2,3] and is widely used in circuits with time compression of laser pulses. A quartz capillary filled with krypton was used in [1]. The spectrum at the capillary outlet corresponded to a transform-limited pulse with a duration of 13 fs. The setup with this capillary was found to be fairly stable and reliable in operation. The transmittance of the capillary filled with inert gas remained unchanged at the level of 75 % over several months of operation.

It was demonstrated in [4] that an efficient conversion of a chirped pulse into second harmonic radiation provides an opportunity to achieve twofold broadening of the spectrum of the harmonic pulse relative to the spectrum of the fundamental frequency pulse. KDP crystals, which have the widest frequency matching band in the region of 1000 nm [5], were chosen for second harmonic generation [1]. A twofold broadening of the pulse spectrum and the generation of pulses with a spectrum corresponding to a transform-limited pulse 7 fs in length were obtained for a KDP crystal with a thickness of 0.5 mm. The small crystal thickness and nonlinear effects arising at high radiation intensities [6] limited the conversion efficiency obtained in this crystal to 20 %. When the crystal thickness was raised to 1 mm, the efficiency of harmonic generation exceeded 40 %. However, owing to narrowing of the frequency matching band that is inversely proportional to the crystal thickness, the second harmonic spectrum became narrower and the transform-limited pulse duration increased to 10 fs. Thus, the setup did not achieve its full potential due to the difficulty of reaching a high conversion efficiency level coupled with twofold broadening of the harmonic spectrum and minimization of the pulse duration after time compression.

The aim of the present study was to investigate the possibility of second harmonic generation for a chirped radiation pulse of a femtosecond ytterbium laser with an efficiency up to 50 % with a view to obtain (following time compression) gigawatt sub-10 fs pulses of the visible range.

The optical diagram of the experimental setup is shown in Fig. 1, *a*. A TETA 6 (Avesta) femtosecond ytterbium laser system with a radiation wavelength of 1030 nm, which combines a fiber seed oscillator and a solid-state regenerative amplifier, was used as a laser source. The pulse duration was 230 fs. The spectrum width at half intensity was 7 nm. The maximum pulse energy was 400 μJ. Experiments were performed at a pulse repetition rate of 10 kHz. The pulse spectrum was broadened in the process of self-phase modulation in propagation of a laser pulse within a quartz capillary with an internal diameter of 250 μm and a length of 70 cm. The capillary was positioned in a 125-cm-long chamber filled with compressed krypton.

The pulse spectrum was recorded using an ASP-75m (Avesta) spectrometer. The pulse duration was measured by an ASF-5 (Avesta) single-shot autocorrelator based on non-collinear second harmonic generation. The autocorrelator used reflective optics with metal mirrors only. Non-collinear second harmonic generation was performed in a 10-μm-thick BBO crystal.

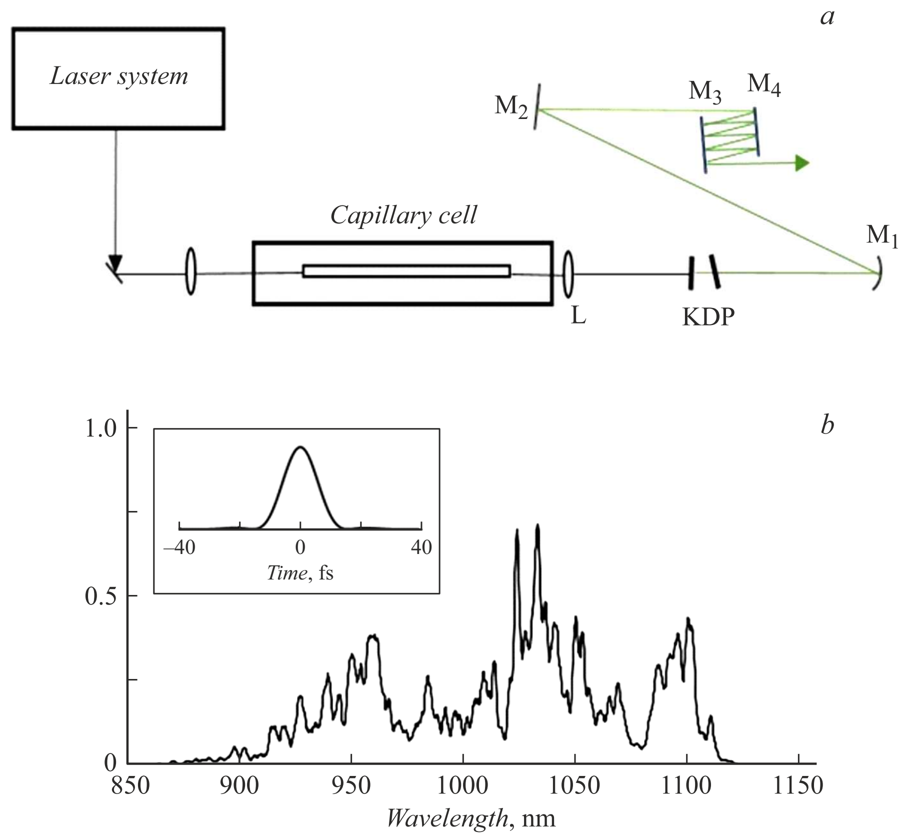

Figure 1. *a* — Optical diagram of the experimental setup; KDP — KH_2PO_4 crystals, L — lens with a focal distance of 150 mm, M_1 and M_2 — mirrors with a silver coating, and M_3 and M_4 — chirped mirrors. *b* — Spectrum of a pulse at the capillary outlet at an ytterbium laser pulse energy of 170 μJ and a krypton pressure of 8 atm. The inset shows the shape of the calculated transform-limited pulse with a duration of 13 fs at half intensity.

In the course of experiments, the laser pulse energy was varied simultaneously with the krypton pressure in order to maintain the maximum pulse spectrum width at the capillary outlet, which is reached when the pulse power approaches the critical self-focusing power [3]. A reduction in capillary transmittance marked the onset of self-focusing. It was found that the pulse spectrum width at the capillary outlet remains unchanged with the following relation between pulse energy E at the capillary outlet and krypton pressure p: $E\,[\mu\text{J}] = 900/p\,[\text{atm}]$. The capillary transmittance was maintained at 75 % (with the calculated value being 82 %) under varying pressure and pulse energy levels. Figure 1, *b* presents the measured shape of the pulse spectrum at the capillary outlet and the shape of the transform-limited pulse with a duration of 13 fs calculated for this spectrum.

A setup with two birefringent crystals [4,7] was used to increase the efficiency of second harmonic generation for a broadband chirped pulse. Crystals in this setup have a thickness of T at which the frequency matching band of the crystal is approximately 2 times narrower than the chirped pulse spectrum. In addition, these crystals are oriented at such an angle to the direction of light beam propagation that a half of the spectrum and, accordingly, a part of the chirped pulse energy is converted into harmonic radiation in each crystal. In this case, the frequency matching band of two crystals with thickness T is equivalent to the matching band of a crystal with thickness $T/2$, while the efficiency of harmonic conversion corresponds to a crystal with thickness T. Since the second harmonic radiation intensity increases quadratically with crystal thickness [8], the harmonic conversion efficiency of the setup with a dual-crystal design may be improved compared to a standard single-crystal design.

We used KDP crystals with thickness $T = 1$ mm. Second harmonic conversion was carried out by type I phase matching. The crystals were positioned in the region of the focal waist formed by lens L (Fig. 1, *a*). The diameter of the fundamental radiation beam with a near-Gaussian intensity distribution on the crystal surface was 300 μm at the $1/e^2$ level. The distance between the crystals was 20 mm [4].

The widest possible frequency matching band for type I KDP crystals is established at a fundamental radiation wavelength of 1034 nm and a phase matching angle of 41.169° [5]. With detuning from the matching angle (crystal rotation), the matching band splits into two narrower frequency regions that diverge toward the short-wave and long-wave sides of the spectrum as the detuning

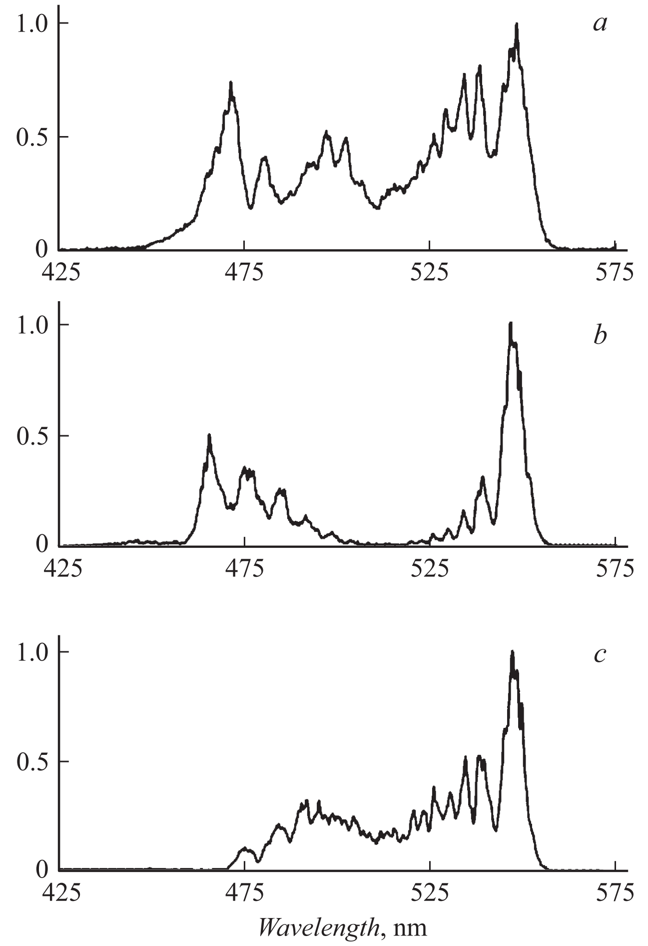

Figure 2. Spectra of second harmonic pulses: *a* — spectrum for two KDP crystals; *b* — spectrum after the first (in the direction of light beam propagation) crystal; *c* — spectrum after the second crystal (with the first one removed).

angle increases. This is attributable to the non-monotonic wavelength dependence of the ordinary refraction index of a KDP crystal within the region of 1000 nm [5].

Figure 2, *a* shows the second harmonic spectrum recorded in the setup with two crystals. The angles of both crystals were adjusted to maximize the second harmonic spectrum width and conversion efficiency. A spectrum with a duration of the corresponding transform-limited pulse of 7.1 fs was obtained in the optimum regime. Figures 2, *b* and *c* present the second harmonic spectra recorded in experiments where one of the crystals was removed following the procedure of their alignment aimed at maximizing the spectrum width. Figure 2, *b* shows the second harmonic spectrum at the output of the first (with respect to the introduction of fundamental radiation into the crystals) crystal. It is evident that the crystal is positioned so as to ensure the most efficient conversion to the short-wavelength (blue) region of the spectrum. Two spectral regions of phase matching are seen clearly. Figure 2, *c* shows the second harmonic spectrum at the output of the second crystal recorded with the first crystal removed from the optical circuit. It can be seen that this crystal was aligned so as to convert predominantly the long-wave wing of the spectrum of fundamental radiation.

The dependence of the second harmonic generation efficiency on the fundamental radiation pulse energy is shown in Fig. 3, *a*. Compared to a single-crystal arrangement, the use of two crystals allowed us to expand (toward lower energies) the range of energies of fundamental radiation pulses within which the conversion efficiency is higher than 45 % [1]. With the fundamental radiation pulse energy varying from 70 to 180 μJ (at a Kr pressure from 13 to 5 atm), the conversion efficiency remained within the range of 45–50 %. The duration of a transform-limited pulse calculated based on the harmonic spectrum did not exceed 8 fs (Fig. 3, *a*).

Chirped mirrors, which allowed for more accurate compensation of a positive frequency chirp of a compressed pulse (compared to a prism compressor), were used to compress a chirped second harmonic pulse. Second harmonic radiation was collimated at the output of the crystals by silver-coated mirror M_1 (Fig. 1, *a*) and planar silver mirror M_2 and directed to a compressor made of chirped mirrors M_3 and M_4. The distance between the chirped mirrors was 100 mm. The energy efficiency of the

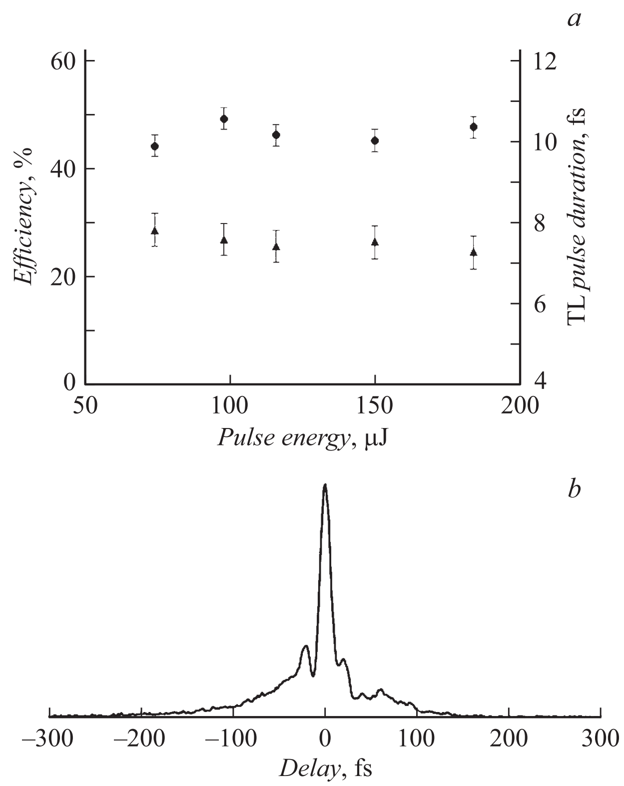

Figure 3. *a* — Variation of the second harmonic conversion efficiency (circles) and the duration of the calculated transform-limited pulse with energy of the fundamental frequency pulse at the input of crystals (triangles); *b* — autocorrelation function of the second harmonic pulse after time compression with a duration of 9 fs at half intensity under the assumption of a sech^2 pulse shape.

compressor was 80 % (radiation input losses at the silver mirrors included). Figure 3, *b* shows the autocorrelation function of a compressed second harmonic pulse. With a sech^2 shape assumed, the pulse duration was 9 fs. This pulse was obtained with a negative group delay dispersion of $-600\,\mathrm{fs}^2$ introduced by the chirped mirrors. This value is consistent with the calculated dispersion required to compress a 200-fs-long pulse to 7.5 fs. In our view, the measured pulse duration exceeds the calculated one due to an incomplete compensation of the pulse chirp by mirrors with negative dispersion.

It should also be noted that the divergence of the second harmonic light beam was close to the diffraction limit. The M^2 value did not exceed 1.2.

Thus, the use of a setup with two KDP crystals provides an opportunity to achieve a high efficiency of conversion of a broadband chirped pulse (45–50 %) and to obtain, following time compression, pulses shorter than 10 fs within a wide range of ytterbium laser pulse energies.

Conflict of interest

The authors declare that they have no conflict of interest.

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