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Increasing the brightness of a femtosecond laser system via two-stage nonlinear conversion

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Received August 28, 2024
Revised October 9, 2024
Accepted October 9, 2024

The brightness of the femtosecond ytterbium laser system has been increased from $1.2 \cdot 10^{17}$ to $15.8 \cdot 10^{17}$ W/(cm$^2 \cdot$ sr) using nonlinear self-phase modulation and second harmonic generation processes.

Keywords: radiation brightness, femtosecond lasers, pulse compression.

DOI: 10.61011/TPL.2025.02.60630.20096

Brightness B of laser beams with a planar wave front is written as $B = 4I/(\pi\theta)^2$, where I is the radiation intensity and θ is the far-field divergence angle [1]. In the case of Gaussian light beams, this expression may be reduced to the form

$$B = \frac{P}{\lambda^2 M_x^2 M_y^2},$$

where P is the radiation power, λ is the wavelength, and M_x^2 and M_y^2 are the laser beam quality parameters characterizing the ratio between the beam divergence in two mutually perpendicular planes and the diffraction divergence of a Gaussian beam of the same diameter. This expression defines the maximum intensity value that may be achieved by focusing a laser beam. Accordingly, research focused on increasing the brightness of radiation is relevant to nonlinear optics, super-strong light fields, laser plasma, etc.

An increase in brightness may be achieved by raising the pulse power, reducing the wavelength, and making the laser beam quality parameters as close to unity as possible. The laser beam power may be increased by reducing the pulse duration. The method of reducing the pulse duration based on spectrum broadening with nonlinear self-phase modulation and subsequent time compression is used widely at present [2]. The wavelength may be reduced significantly in the process of generation of radiation harmonics in crystals. It was reported in [3] that second harmonic generation from a frequency chirped pulse allows for an additional two-fold reduction of the pulse spectrum width. The possibility of reducing the pulse duration via two-stage nonlinear conversion (self-phase modulation and second harmonic generation from a chirped pulse) was demonstrated in [4]. The aim of the present study is to optimize the parameters of such a two-stage nonlinear conversion system in order to achieve the maximum increase in brightness of laser radiation.

The diagram of the experiment is shown in Fig. 1. A femtosecond ytterbium oscillator−regenerative amplifier laser system (TETA, Avesta) was the radiation source. The central radiation wavelength was 1030 nm, the duration of the spectrally limited pulse was 240 fs, and the maximum pulse energy was 300 μJ at a pulse repetition rate up to 20 kHz. The values of M_x^2 and M_y^2 did not exceed 1.1 with a Gaussian distribution of the light beam intensity.

Laser radiation was focused at the inlet of a 70-cm-long quartz capillary with an internal hollow channel 250 μm in diameter positioned in a 125-cm-long stainless steel chamber. The chamber was filled with krypton. The capillary size and the gas type were chosen according to the following criteria: a spectrum broadening of more than 10 for a pulse with an energy of 300 μJ, an energy efficiency above 70%, and compact size (the capillary length should not exceed 1 m) [5]. The diameter of the radiation spot at the capillary inlet was 160 μm at the $1/e^2$ level. With this ratio of diameters of the radiation spot and the capillary channel, the distribution of laser radiation and the fundamental mode of the capillary are matched, ensuring that the transmittance of the capillary is maximized. The measured capillary transmittance was 77%, while the calculated transmittance of a capillary with similar parameters is 84%. The slight difference between the measured and calculated values may be attributed to inaccurate matching of spatial modes of the capillary and laser radiation and to inhomogeneities of the walls of the hollow channel.

As was demonstrated in [5], the maximum spectrum broadening at the capillary outlet is achieved for a laser pulse energy at which the pulse power is close to the critical self-focusing power. As the laser pulse power gets closer to the critical one, the capillary transmittance decreases and the spatial structure of output radiation becomes distorted due to the excitation of higher modes in the capillary. Since the critical self-focusing power is inversely proportional to the nonlinear refraction index, which, in turn, is proportional to the gas pressure, the optimum gas pressure was chosen by measuring the capillary transmittance and recording the spatial distribution of radiation at the capillary outlet under a varying gas pressure level. Under the conditions of the experiment with a pulse

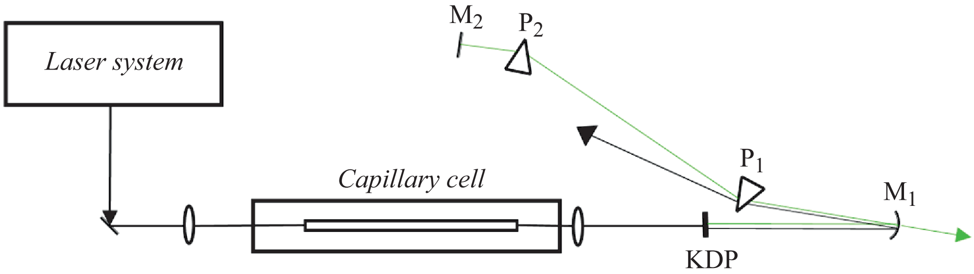

Figure 1. Diagram of the experimental setup. KDP — KH_2PO_4 crystal, M_1 and M_2 — mirrors with a silver coating (M_1 — concave mirror with a 50 cm focus), and P_1 and P_2 — fused quartz prisms with an apex angle of 22°. The light beam is output above mirror M_1 in the plane perpendicular to the image plane.

energy of 300 μJ, the krypton pressure corresponding to the maximum spectrum broadening was 4 atm. In this case, the capillary transmittance decreased to 75% without distortion of the spatial profile of the beam at the capillary outlet. This pressure level is consistent with estimates based on the value of nonlinear refraction index n for krypton, which is $n \approx 3 \cdot 10^{-19} p \cdot \mathrm{cm}^2/\mathrm{W}$, where p is pressure in atmospheres [6]. Accordingly, the critical self-focusing power at a pressure of 4 atm is ~ 1.5 GW, exceeding slightly the maximum laser pulse power under the experimental conditions, which is 1.25 GW (300 μJ, 240 fs).

The spectral width at half intensity of the spectrally broadened pulse was as large as 120 nm. The spectrum filled the region from 850 to 1150 nm. It had a jagged shape characteristic of the self-phase modulation process [1]. The spectral broadening of the pulse was assessed quantitatively by calculating the duration of the spectrally limited pulse for the spectrum of each pulse at the capillary outlet. The phases of spectral components were assumed to be equal in these calculations. Figure 2, *a* shows the dependence of the calculated duration of the spectrally limited pulse on energy of the input laser pulse. The minimum duration was 13 fs within the 270−300 μJ energy range. At lower input pulse energies, the spectrally limited pulse duration increases due to spectrum narrowing. At higher energies, the pulse spectrum also becomes narrower, and the pulse duration increases due to a reduction in transmittance of the capillary. It should be noted that the performed calculations of the spectrally limited pulse duration provide a fairly accurate prediction of the pulse duration after time compression with the use of optical elements with negative second-order dispersion. Specifically, a spectrally broadened pulse with a calculated duration of the corresponding spectrally limited pulse of 13 fs was compressed to 15 fs with the use of chirped mirrors in this arrangement.

Second harmonic conversion was carried out in crystals of potassium dihydrogen phosphate (KH_2PO_4, KDP) via the *oo-e* mechanism. Crystals with a thickness of 0.5 and 1 mm were used. A lens with a 15 cm focus mounted beyond the output window of the chamber with the capillary was used to focus radiation into the KDP crystal. Optical elements without antireflective coatings (with the exception of the input window of the chamber with the capillary) were used in the experiment. The distances between the lens and the output end of the capillary and between the lens and the crystal were chosen so that the diameter of the focal waist at the crystal was 320 μm at the $1/e^2$ level and exceeded the diameter of the spot at the capillary outlet by a factor of 2.

It was demonstrated in [3] that spectrum width $\Delta\nu_{2\omega}$ of a second harmonic pulse in conversion of a chirped pulse in the saturation mode is related to spectrum width $\Delta\nu_{\omega}$ of a fundamental frequency pulse in the following way:

$$\frac{\Delta\nu_{2\omega}}{\Delta\nu_{\omega}} = \left[4 - 3\left(\frac{\tau}{\tau_{ch}}\right)^2\right]^{0.5},$$

where τ_{ch} is the chirped pulse duration and τ is the duration of the spectrally limited pulse with a spectrum corresponding to the spectrum of the chirped pulse. In the discussed experiment, τ_{ch} was 240 fs, while τ did not exceed 17 fs. Therefore, the second harmonic spectrum should be 2 times wider than the spectrum of the pulse at the capillary outlet, and the duration of the calculated spectrally limited pulse should be 2 times shorter. The experimental results for a crystal with a thickness of 0.5 mm are in agreement with the calculations. It can be seen from Fig. 2, *a* that the minimum duration of the calculated spectrally limited pulse at the second harmonic frequency for a KDP crystal with a thickness of 0.5 mm reaches 7 fs with a duration of the corresponding fundamental frequency pulse of 13 fs.

When a 1-mm-thick KDP crystal was used, the second harmonic spectrum became narrower (Fig. 3, *a*), and the duration of the spectrally limited pulse increased. As estimates show, this is attributable to narrowing of the crystal's spectral synchronism band, which is inversely proportional to its thickness. The minimum duration of the spectrally limited second harmonic pulse increased to 9 fs as a result (Fig. 2, *a*). However, an increase in crystal thickness resulted in a significant increase in efficiency of the second harmonic generation process. The efficiency rose from 20% for a 0.5-mm-thick crystal to 47% for a 1-mm-thick one (Fig. 2, *b*). Attempts to increase the efficiency for a 0.5-mm-thick crystal via tighter focusing of radiation into the crystal failed due to the influence of nonlinear phase detuning [7]. In view of this, further experiments were performed with a

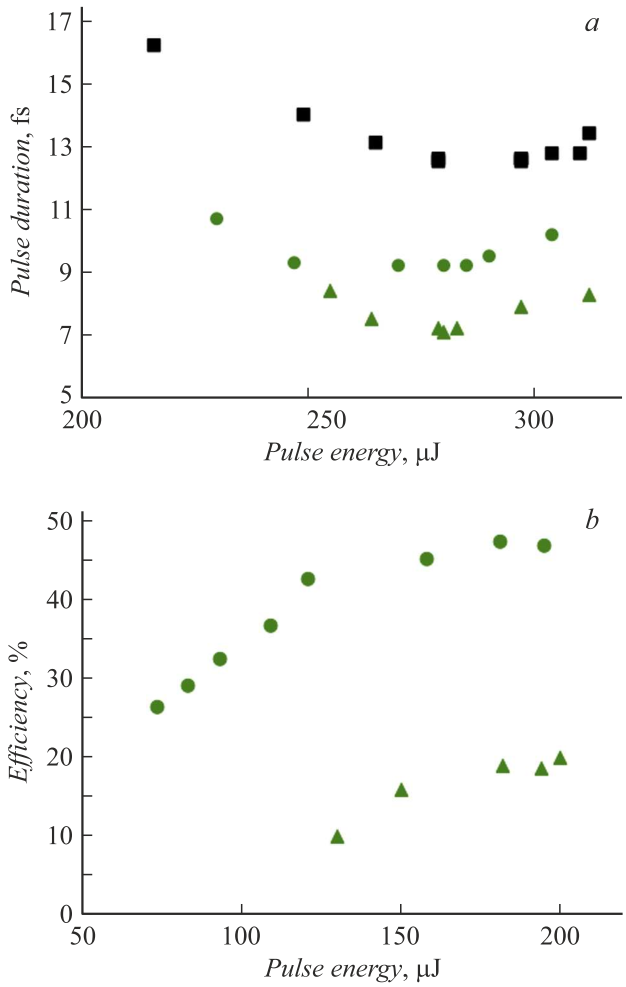

Figure 2. *a* — Dependences of the calculated spectrally limited pulse duration on the laser pulse energy at the capillary inlet; *b* — dependences of the second harmonic generation efficiency in the KDP crystal on the energy of a chirped pulse entering the KDP crystal. Squares — radiation with a wavelength of 1.03 μm, circles — radiation with a wavelength of 0.51 μm and a KDP crystal 1 mm in thickness, and triangles — radiation with a wavelength of 0.51 μm and a crystal 0.5 mm in thickness.

1-mm-thick crystal, which made it possible to obtain higher-power second harmonic pulses.

A prism compressor was used for temporal compression of the chirped second harmonic pulse. Fused quartz prisms with an apex angle of 22° were used. This apex angle choice was driven by the need to shorten the optical path in the first prism in order to suppress the influence of third-order dispersion [8]. The compressor transmittance (with the uncoated faces of prisms and reflection from two silver-coated mirrors taken into account) was 80%. At a distance of 140 cm between the prisms, the duration of a sech^2 compressed pulse measured by an autocorrelator (ASF-5, Avesta) was 10.7 fs (Fig. 3, *b*). The central peak of the pulse contains 75% of its energy. The resulting second harmonic pulse power was 5 GW at an energy of 70 μJ.

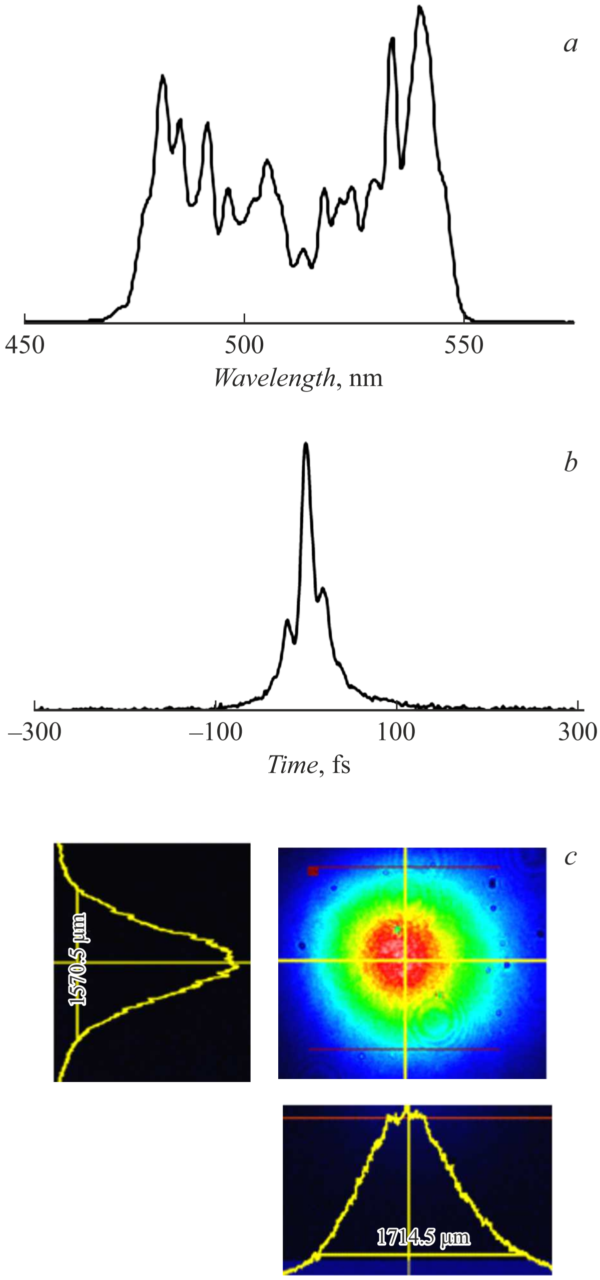

Figure 3. *a* — Second harmonic radiation spectrum for a KDP crystal 1 mm in thickness at a laser pulse energy of 300 μJ; *b* — pulse autocorrelation function after time compression; *c* — spatial distribution of second harmonic radiation at the output of the prism compressor.

The measured diameter of the second harmonic radiation spot on the KDP crystal was 320 μm (at the $1/e^2$ level) at a conversion efficiency close to 50%, matching the diameter of the fundamental radiation spot. At the compressor outlet, the diameters of the harmonic radiation spot were $d_x \approx 1.71$ mm and $d_y \approx 1.57$ mm (Fig. 3, *c*). The beam quality parameters calculated based on the measured spatial beam distribution characteristics were $M_x^2 = 1.16$ and $M_y^2 = 1.03$.

Thus, the measured brightness of converted radiation with a central wavelength of $0.51\,\mu$m was $15.8 \cdot 10^{17}$ W/(cm$^2 \cdot$ sr) at a brightness of $1.2 \cdot 10^{17}$ W/(cm$^2 \cdot$ sr) of original laser radiation with a wavelength of $1.03\,\mu$m. It should also be noted that the use of optical elements with antireflective coatings at the capillary outlet and in the prism compressor should provide a 1.3-fold increase in output power and help achieve a brightness of $\sim 2 \cdot 10^{18}$ W/(cm$^2 \cdot$ sr).

Radiation intensity I at the target surface for a beam with diameter d focused by a lens with focal length F is written as $I \approx (d/F)^2 B$. For example, a lens with ratio $d/F \sim 1/3$ installed in this laser system may provide a radiation intensity at the target surface in excess of 10^{17} W/cm^2. In our view, the use of such a laser system holds promise for construction of micrometer-sized X-ray sources [9] and generation of attosecond pulses [10].

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin