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Generation of picosecond UV pulses by an Nd^{3+} : YAG laser for amplification in an ArF amplifier*

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Abstract. **The scheme generating UV pulses with a duration 15 ps and output energy up to 11.5 mJ is implemented in the system consisting of a picosecond Nd^{3+} : YAG laser with multistage nonlinear-optical conversion of fundamental frequency radiation into radiation with a wavelength 193 nm followed by an excimer ArF amplifier. The temporal characteristics and the contrast of the amplified pulses are measured.**

Keywords: *picosecond laser pulse, travelling-wave parametric oscillator, excimer ArF amplifier.*

1. Introduction

Picosecond light sources in the UV range with a high output power are of great interest for a variety of applications, including laser purification of substances [1], ablation [2], photochemistry [3] and investigation of nonlinear effects in atoms [4]. They also seem to be a promising light source for surface physics [5]. Radiation from such sources can be used in superluminal generators based on UV photocathodes producing high-power directed electromagnetic pulses of submillimetre range [6].

Excimer lasers allow high energy of radiation, but their application is limited by the large pulse duration (greater than 15 ns without using additional techniques), significant divergence and large spectral width of radiation in the free oscillation regime. The main method for obtaining ultrashort pulses in the UV range is based on combining a picosecond generator of UV radiation with an excimer amplifier [7]. The first paper on the amplification of picosecond pulses from the master dye laser using an excimer XeCl laser was published in 1980 [8]. 'Oscillator – amplifier' systems possess a variety of characteristics and parameters that can be grouped with respect to the operating wavelengths, the possibility of radiation tuning, the methods of producing seed radiation, the amplification schemes, the temporal characteristics of the master and amplified radiation. The seed UV radiation that fits the peak gain of excimer amplifiers can be obtained using the generation of harmonics [8 – 11] and sum frequency [12 – 19], as well as the multiwave interaction [20, 21]. In many of the mentioned papers UV radiation was generated by the systems based on a dye laser and the systems incorporating a titanium sapphire laser with a tunable wavelength and harmonic generation unit [22 – 26].

Only in a few papers the results of measuring the radiation contrast with respect to the energy and intensity in the UV systems with a master laser, generating ultrashort pulses, and the excimer amplifier are presented. Thus, in Ref. [27] the high-power UV radiation was obtained, the energy contrast amounted to 10^6 and the intensity contrast, as declared by the authors, was equal to 10^{10}. In Ref. [28] a laser system is reported with the seed pulses generated at a wavelength 248 nm. The radiation energy contrast was from 43 to 0.3, depending on the preamplifier pump energy.

The main goal of the present paper is to obtain an UV pulse of picosecond duration by using an all-solid-state system, consisting of a picosecond Nd^{3+} : YAG laser, a multistage nonlinear-optical converter of fundamental frequency radiation into that with a wavelength 193 nm, and an excimer ArF amplifier, as well as to measure the temporal characteristics and contrast of the amplified pulse.

2. Experiment

Among the possible schemes of generating radiation at a wavelength $\lambda = 193$ nm we have chosen the scheme proposed in Refs [9, 12], in which the generation of sum frequency is implemented by mixing radiation of the fourth harmonic of the Nd^{3+} : YAG laser (266 nm) with signal wave radiation of the parametric oscillator (708 nm). The generation of the parametric signal wave is implemented using the scheme with pumping by the second harmonic (532 nm) of fundamental radiation of the Nd : YAG laser (1064 nm).

A schematic diagram of the experimental setup is presented in Fig. 1. The master oscillator was a 1064-nm passively mode-locked solid-state Nd : YAG crystal laser. A single pulse output from the master oscillator was amplified by three sequential amplifiers (not shown in the figure). After the amplification the pulse energy approached 30 mJ with a repetition rate 2 Hz, and the radiation polarisation was vertical. The pulse duration was measured using a PS-1/S1 streak camera [29, 30], developed and fabricated at the General Physics

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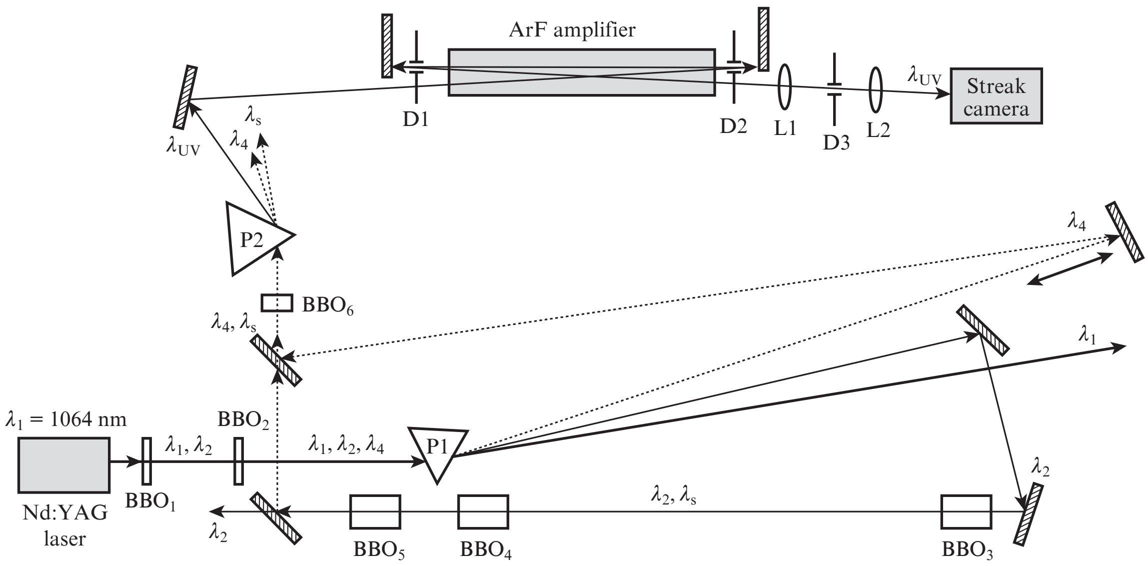

Figure 1. Schematic diagram of the experimental setup:
(λ_1), (λ_2) and (λ_4) wavelengths of fundamental radiation (1064 nm), second (522 nm) and fouth (266 nm) harmonics; (λ_s) wavelength of signal radiation (708 nm) of the parametric oscillator; (λ_{UV}) wavelength of the UV radiation (193 nm); (BBO$_1$, BBO$_2$) crystals for generating second and fourth harmonics; (BBO$_{3,4,5}$) crystals of the parametric oscillator; (BBO$_6$) crystal for generating the sum frequency; (P1, P2) silica prisms; (D1), (D2) and (D3) aperture diaphragms; (L1) and (L2) lenses.

Institute, Russian Academy of Sciences. In the streak camera the electro-optical converter (EOC) with a silver–oxygen–caesium photocathode was used. To provide the spectral sensitivity of the photocathode in the UV range, the EOC input window was made of uviol glass with a transmission lower boundary 185 nm. The EOC operated in the linear sweep regime with the rate 92 ps cm^{-1}. The images obtained at the camera screen were recorded and processed by the readout system with a C8484 CCD matrix (Hamamatsu). The time dependence of the intensity recorded using the streak camera was approximated by the Gaussian function (Fig. 2). The fundamental harmonic pulse duration at the half-maximum intensity level amounted to 33–35 ps (Fig. 2a). To measure the pulse power and energy we used Ophir 3A-P-QUAD and Coherent J-10MB-LE meters, respectively. The radiation spectra were determined using an Ocean Optics fibre-optical spectrometer USB2000+UV-VIS.

Amplified radiation of the Nd^{3+}:YAG laser was converted into radiation of the second harmonic (532 nm), the energy of which approached 7.5 mJ, then into the fourth harmonic (266 nm) with the energy up to 1.5 mJ. To generate these harmonics we used BBO crystals with the first type of phase matching. The energy instability of radiation was ±5%. Further conversion of the obtained radiation into the one with the wavelength λ = 193.4 nm was implemented in the two-stage scheme.

At the first stage the second harmonic radiation was converted in the travelling-wave parametric oscillator with three sequentially placed BBO crystals with the aperture 6×7 mm and the length 15 mm each, cut at the angle close to that of collinear phase matching θ = 21.2° (conversion of the first phase-matching type). The signal radiation of the parametric oscillator was tuned to the wavelength λ_s = 708 nm. The use of three crystals in the parametric oscillator allowed one, in particular, to partially compensate for the relatively large spatial walk-off of the beam (0.8 mm at the length 15 mm) that limits the conversion efficiency, and to provide the amplification of the signal wave. The parametric superluminescence excited in the first crystal was broad-band (greater than 20 nm). To reduce the spectral linewidth we used spatio-frequency filtration at the expense of increasing the separation between the third and the second crystals (100 cm) with compensation of aperture effects. In the experiment radiation at a wavelength 708 nm (with the possibility of continuous tuning from 665 to 850 nm) with the width at the half-maximum signal level 3.6 nm and the energy up to 1.5 mJ was obtained. The efficiency of converting the energy of the second harmonic radiation into the signal wave amounted to 20%.

At the second stage radiation with the wavelength 193.4 nm to be further amplified in the ArF excimer amplifier was generated at the sum frequency as a result of nonlinear-optical mixing of the parametric oscillator signal wave (708 nm) with radiation of the fourth laser harmonic (266 nm) in the BBO crystal (aperture 5×7 mm, length 5 mm, cut at the angle, close to that of synchronism 75.8°). The measured transmission coefficient of the BBO crystal at the wavelength 193 nm was found to be only 15% (the corresponding absorption coefficient is 3.8 cm^{-1}, while in Ref. [22] it was found to be 1.39 cm^{-1}, and in Ref. [18] – 1.15 cm^{-1}). The temporal overlapping of the fourth harmonic radiation pulses and the pulses from the parametric oscillator in the BBO$_5$ crystal was implemented using the optical delay line. By mixing radiation with a wavelength 708 nm and energy 0.7 mJ (beam diameter 2.2 mm) with radiation at λ = 266 nm and energy 0.9 mJ (beam diameter 1.7 mm) the UV pulses (193 nm) were obtained with an energy up to 7 μJ. The measured duration of the UV pulse amounted to 14–16 ps (Fig. 2b).

Picosecond UV pulses with the energy 0.3 μJ (beam diameter 6 mm) entered the CL7000 excimer ArF amplifier (OOO 'Optosistemy'). The parameters of the amplifier were as follows: the discharge gap volume ~7×2×100 cm, the pressure 2.6 atm., the discharge voltage 25 kV, the discharge duration 45 ns, and the unit starting time ~1 μs with the instability ±2 ns. The windows of the ArF amplifier were made of CaF_2 plates, turned by the angle sufficient to suppress the parasitic oscillation due to Fresnel reflection. The synchroni-

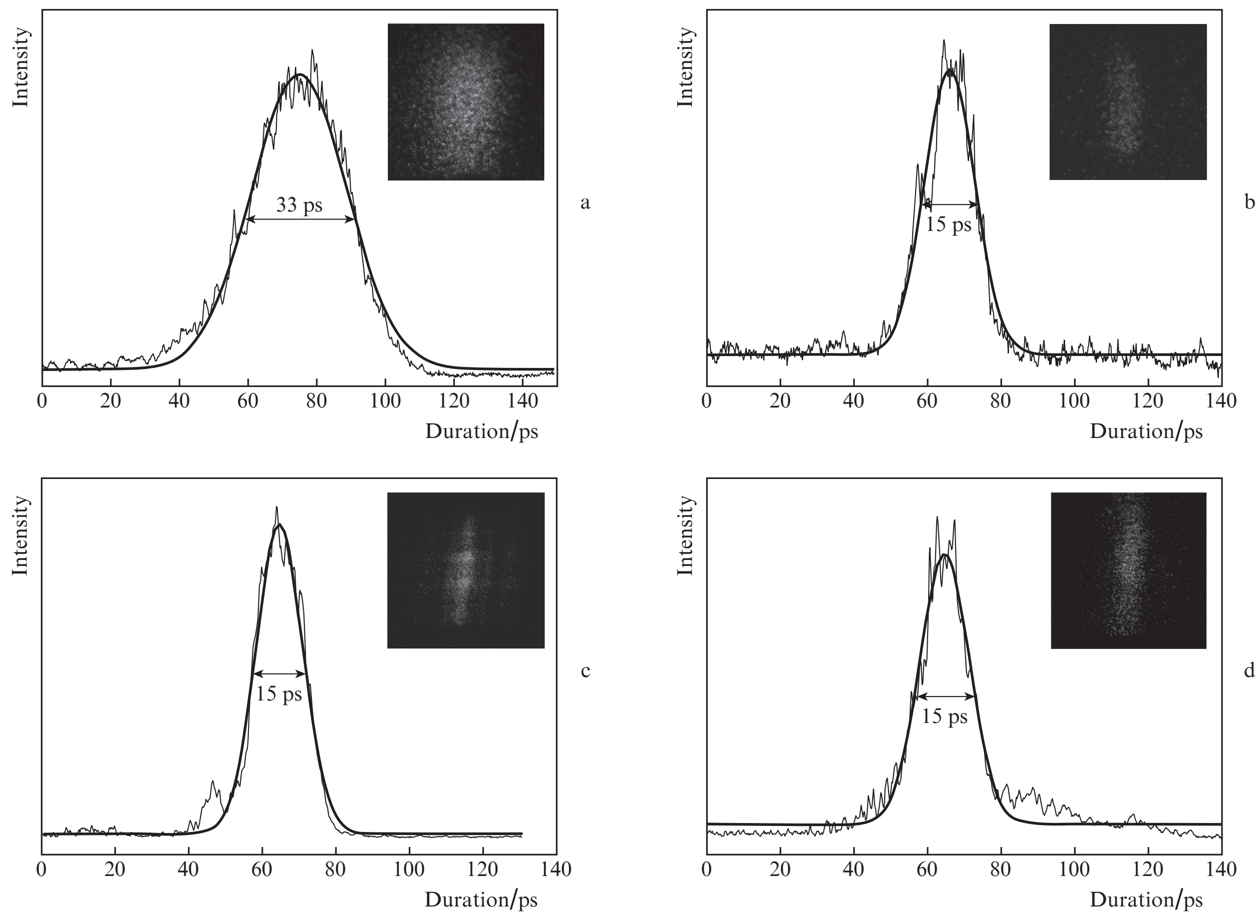

Figure 2. Pulses of radiation recorded with the streak camera for the master oscillator (a); at the input of the amplifier (193 nm) (b), at the amplifier output (193 nm) in the single-pass (c) and three-pass scheme (d).

sation of the master oscillator was performed using a DG535 four-channel digital pulse generator (Stanford Research Systems).

In the single-pass operating regime the gain of 10^3 was obtained with the energy density in the spot ~0.4 mJ cm^{-2} (which agrees with the results of Ref. [18]) and the output pulse duration 14–16 ps (Fig. 2c).

In the three-pass amplifier scheme the discrimination of the parasitic background radiation in the tracts of the second and the third pass was provided by aperture diaphragms. The output radiation [the pulse energy up to 1.5 mJ, the duration 14–16 ps (Fig. 2d)] was 'cleaned' by means of the spatial filter, consisting of a telescope and a diaphragm. The use of the three-pass amplification scheme allowed the reduction of the superluminescence energy contribution into the total pulse energy to the acceptable value (not exceeding 10%). The intensity contrast measured using the streak camera amounted to 70–150. The spread is due to the instability of synchronising the weak input signal with the pump pulse of the excimer amplifier (the intensity of the amplified picosecond pulse, the superluminescence, and the background was measured).

3. Results

To summarise, let us formulate the advantages of the developed system. The seed pulse (λ = 193 nm) is generated using a single solid-state Nd^{3+} : YAG laser. The picosecond UV pulses are synchronised with high-power picosecond visible and IR pulses. No additional elements for rotating the polarisation in the nonlinear-optical conversion are necessary. At the output of the ArF amplifier the UV pulses with the duration 15 ps, the energy up to 1.5 mJ and the repetition rate 2 Hz are obtained. The contribution of superluminescence to the total energy of the pulse does not exceed 10%. The measured intensity contrast amounts to 70–150. The efficiency of energy conversion from the fundamental mode (1064 nm) into the seed pulse radiation (193 nm) is 0.03%.

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