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Direct amplification of picosecond pulses in F_2^- : LiF crystals

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***Abstract*. An amplifier of picosecond pulses with an output power up to 10^{10} W and an energy up to 30 mJ at 1180 nm is developed on the basis of F_2^- : LiF colour-center crystals. A 3 – 5-ps, 0.03-mJ probe pulse at 1.18 μm was obtained upon intracavity SRS conversion in a passively mode-locked Nd^{3+} : $KGd(WO_4)_2$ laser. The F_2^- : LiF crystals were pumped by 1053-nm nanosecond pulses from a Nd : YLF laser, amplified in a GLS-22 phosphate glass to an energy of 5 J. The probe SRS pulses were amplified in a four-crystal two-cascade amplifier based on F_2^- : LiF crystals with the total length of the active medium of 360 mm, by using counterpropagating pump beams. The dependences of the output radiation energy on the pump and input signal energies are measured.**

Keywords: *picosecond pulses, SRS oscillator, colour-centre amplifier, mode locking.*

In recent years, much attention has been paid to the development of picosecond and femtosecond lasers with terawatt output powers [1 – 3]. This is caused by extending applications of such lasers for generating X-ray pulses used in material processing, photochemistry, photobiology, and medicine.

The variety of such devices is restricted mainly by a limited choice of efficient amplifying of materials with large (100 – 1000 cm^2) exit apertures and a high radiation resistance, like, for example, laser glasses doped with Nd and Yb ions, Ti : sapphire crystals, and KDP nonlinear crystals [1].

A year ago, lithium fluoride crystals with F_2^- colour centres were proposed as such a wide-aperture amplifying medium [4]. These crystals have been efficiently used for the last two decades in various regimes, from cw lasing to generation of femtosecond pulses [5, 6]. A record high power (10^9 W) of tunable nanosecond pulses was obtained using wide-aperture (20 cm × 4 cm) F_2^- : LiF crystals [7]. The single-frequency and superbroadband (with $\Delta\lambda \geqslant$ 100 nm) lasing regimes were demonstrated in [6, 8]. A high efficiency (20 % – 40 %) of lasing and amplification in the spectral range from 1090 to 1290 nm under pumping by neodymium lasers was achieved in [9].

All this allowed us to use wide-aperture F_2^- : LiF crystals for the development of a high-power multi-terawatt laser system with direct amplification of picosecond and femtosecond pulses from nano- and microjoules to joules. A specific feature of this project is that our system generates radiation in new wavelength regions: the fundamental radiation at 1100 – 1260 nm and its harmonics at 550 – 630 nm, 366 – 420, and 275 – 315 nm.

The efficient amplification of nanosecond pulses in LiF crystals with F_2^+ and F_2^-colour centres was demonstrated in [6]. Recently, picosecond pulses were amplified with a relatively high (above 30 dB) gain for the first time in F_2^- : LiF crystals synchronously pumped by pico- and nanosecond laser pulses [4].

The advantages of the LiF crystal as an active medium are the wide range of optical transparency, high thermal conductivity (even higher than that of a Nd : YAG crystal), the minimum values of the linear and nonlinear refractive indices n and n_2 compared to oxide crystals and other solids, and the minimum dispersion in the region of generated wavelengths.

The absorption and amplification bands of the F_2^- : LiF crystal extend approximately from 850 to 1150 nm and from 1000 to 1300 nm, respectively. Such broad bands are promising for amplification of ultrashort pulses with a duration as short as several femtoseconds. The spectral positions of the absorption and luminescence bands dictate the choice of sources for amplification and pumping of active F_2^- : LiF crystals [4].

In this work, we study a scheme for amplification of picosecond pulses in F_2^- : LiF crystals pumped by counterpropagating nanosecond beams. The scheme includes a Nd^{3+} : $KGd(WO_4)_2$ (Nd : KGW) laser generating in the passive mode locking regime 3 – 5-ps pulses at the fundamental wavelength 1067 nm and SRS pulses at 1180 nm [10]. These probe SRS radiation is amplified in three cascades of F_2^- : LiF amplifiers, first upon collinear copropagating picosecond pumping at 1067 nm and then using counterpropagating nanosecond pump pulses at 1053 nm. The nanosecond pumping is provided by a single-frequency Nd : YLF laser with amplifiers based on neodymium phosphate glass. The gain of the three-cascade F_2^- : LiF system exceeds 33 dB. As a result, we obtained picosecond pulses with an energy of 25 – 30 mJ and a peak power up to 10^{10} W.

The experimental setup (Fig. 1) consisted of two synchronised master oscillators based on Nd : KGW (*1*)

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and Nd : YLF (*2*) crystals, preamplifier (*7*), two subsequent cascades amplifying ultrashort pulses (USPs) (*8*, *9*), and two corresponding cascades for amplification of nanosecond pump radiation (*4*, *6*). The beams of nanosecond pumping at 1053 nm and probe USP radiation at 1180 nm propagated collinearly in opposite directions and their optical paths were equalized so that the population inversion in the F_2^- : LiF crystal, in which the excited-state lifetime is 55 ns, was produced in a proper time.

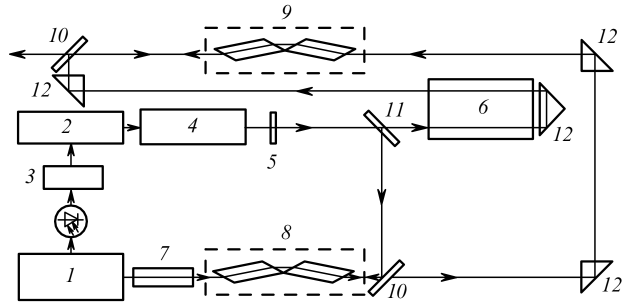

Figure 1. Scheme of the laser setup: (*1*) passively mode-locked picosecond Nd : KGW oscillator with intracavity SRS conversion, (*2*) single-mode nanosecond Nd : YLF master oscillator, (*3*) control unit for triggering the pump laser, (*4*) intermediate three-pass phosphate glass (∅8 mm × 120 mm) amplifier, (*5*) half-wave plate, (*6*) two-pass phosphate glass amplifier with the aperture of 45 mm, (*7*) F_2^- : LiF preamplifier with synchronous picosecond pumping, (*8*, *9*) F_2^- : LiF amplifying cascades (8 mm × 17 mm × 90 mm and 17 mm × 17 mm × 90 mm) with nanosecond pumping, (*10*) dichroic mirror, (*11*) beamsplitter, (*12*) prisms.

USPs were generated in a cavity of length 120 cm with a Nd : KGW active element (∅5 mm × 70 mm) and a passive *Q* switch based on a dye-doped polymer matrix. The output mirror reflectivity was 35 %. The passive *Q* switch was mounted on a wedge highly reflecting mirror. An aperture placed in the cavity selected the TEM_{00} mode. The high-power intracavity picosecond pulses of the fundamental radiation at 1067 nm generated in the KGW matrix SRS radiation at the wavelength 1180 nm of the first Stokes component with a frequency shift of 901 cm^{-1}. The number of USPs in the fundamental radiation train was 10 – 12 and the number of SRS pulses at 1180 nm was usually 2 – 3 (Fig. 2). The total energy of the USP train at the fundamental wavelength was 1.5 – 2 mJ, while the energy of the Stokes component was 0.07 – 0.1 mJ. The SRS and fundamental beams coming from the cavity propagated through F_2^- : LiF preamplifier (*7*) (Fig. 1), where SRS pulses were amplified upon synchronous pumping by copropagating picosecond beams at the fundamental wavelength [4].

A part of the picosecond Nd : KGW laser radiation at the fundamental wavelength was directed to an avalanche photodiode to control the *Q* switch of the nanosecond master oscillator – a Pockels *Q*-switched single-frequency Nd : YLF laser [11]. The Nd : YLF crystal was cut and the cavity was adjusted so that this laser generated 1053-nm pulses, which can be then amplified in neodymium phosphate glass. The duration of pulses was 10 – 12 ns and the output energy was very stable and achieved 5 mJ. The synchronisation of the two lasers is illustrated in Fig. 2. The triggering level of the scheme was chosen so that, with allowance for the lasing delay, the Nd : YLF pulse coincided

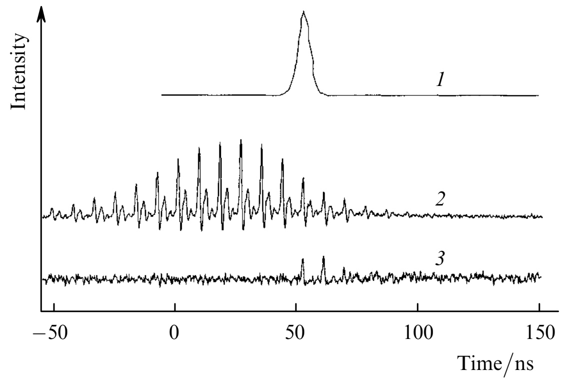

Figure 2. Oscillograms of (*1*) the nanosecond pulse of the Nd : YLF laser, (*2*) the radiation of the picosecond Nd : KGW laser at the fundamental wavelength, and (*3*) the first Stokes component of the SRS radiation.

with the first SRS pulse. In the case of reproducible trains of the Nd : KGW laser pulses, the instability of triggering of the Nd : YLF oscillator did not exceed half of the axial round-trip time (8 ns).

Then, the radiation of the Nd : YLF laser was directed to three-pass preamplifier (*4*) (Fig. 1) based on a GLS-22 glass rod ∅8 mm × 120 mm in size, at the output of which the energy achieved 150 mJ at a pulse repetition rate up to 1 Hz. About 60 % of this energy was used for pumping first nanosecond amplifying cascade (*8*) based on two F_2^- : LiF crystals cut at the Brewster angle (8 mm × 17 mm × 90 mm). Half-wave plate (*5*), which rotated the polarisation, was used to minimise the reflection losses from the faces of the F_2^- : LiF amplifiers.

The experimental dependence of the output energy of first nanosecond F_2^- : LiF amplifier (*8*) on the incident USP energy at a fixed pump energy of 130 mJ is shown in Fig. 3. The energy was measured with a Molectron J3-05 pyroelectric detector with a sensitivity of 2.6 V mJ^{-1} and recorded with a Tectronix oscilloscope. The dependence of the output energy of this amplifier on the nanosecond pump energy at a fixed input USP energy of 0.05 mJ is shown in Fig. 4. The pump energy was varied using neutral filters. One can see that the amplifier efficiency achieves 5 % for the gain of the cascade below or equal to 20 dB.

A considerable scatter in the data is related to the stochastic nature of the passive mode-locking and SRS

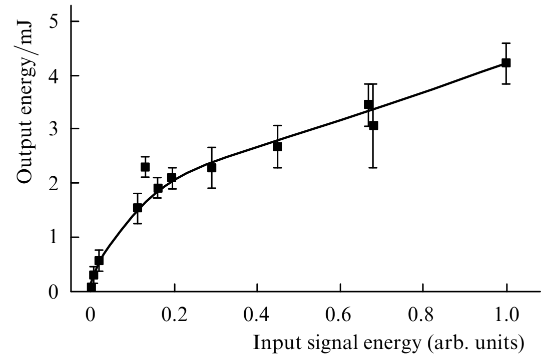

Figure 3. Dependence of the output energy of the first F_2^- : LiF nanosecond amplifier on the input USP energy for the pump energy of 130 mJ.

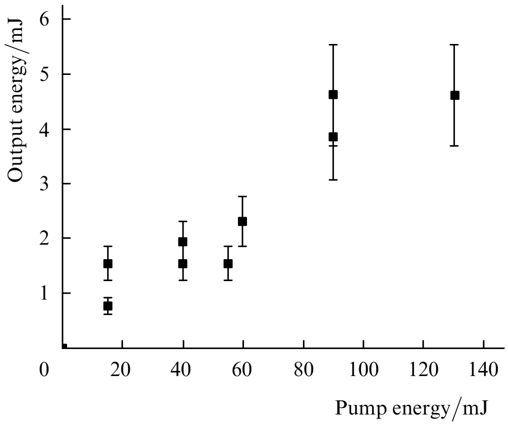

Figure 4. Dependence of the output energy of the first F_2^- : LiF nanosecond amplifier on the pump energy for the input USP energy of 0.05 mJ.

in the nonlinear medium of the master oscillator and to the fluctuations in the arrival time of the nanosecond pump pulse and the amplified picosecond SRS pulse. Note that, while the energy incident on picosecond preamplifier (*7*) was distributed over two-three pulses, its output energy was concentrated in one amplified picosecond pulse.

The USPs were further amplified in second nanosecond amplifying cascade (*9*) (Fig. 1) consisting of two F_2^- : LiF crystals of size 17 mm × 17 mm × 90 mm oriented at the Brewster angle to the incident beam. These crystals were pumped by radiation of high-power two-pass nanosecond amplifier (*6*) based on a GLS-22 phosphate glass rod (∅45 mm × 680 mm), which amplified 60 mJ of the 1053-nm pump radiation to the output radiation of 5 J. The use of the wide-aperture glass rod restricted the pulse repetition rate to one pulse per minute. The gain measured in this two-crystal amplifier (*9*) is shown in Fig. 5. One can see that the gain saturates at the pump energy density of 0.3 – 0.4 J cm^{-2} and the further increase in this density to 1.5 J cm^{-2} does not increase the output energy.

The measurement of the USP duration with an Imacon-500 streak camera showed that the duration of the USP generator pulses at the fundamental frequency was 8 – 15 ps and the duration of SRS pulses was 3 – 5 ps. The output power of the picosecond pulses at 1180 nm after the second amplifier achieved 10^{10} W.

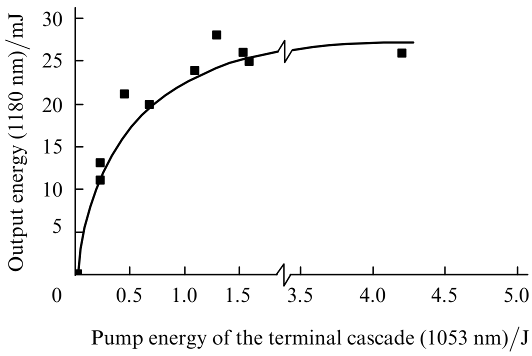

Figure 5. Dependence of the output energy of the F_2^- : LiF amplifying system on the pump energy of the terminal cascade.

Note in conclusion that the systems for amplification of picosecond pulses in F_2^- : LiF crystals can be further developed using the crystals with more than 100 times larger apertures, which allows one to expect a hundredfold increase in the gain and output energy of ultrashort pulses.

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