LETTER

Acousto-optical adaptive correction of a chirped laser pulse spectral profile in a Nd-phosphate glass regenerative amplifier

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Abstract

We present results of experimental research carried out with the help of an acousto-optical light dispersive delay line (LDDL) on spectral correction of chirped laser pulses in a Nd-doped phosphate glass regenerative amplifier (RA) characterized by high gain ($G \approx 4 \times 10^7$). The spectral resolution of the LDDL was equal to 1.1 cm$^{-1}$ at a diffraction efficiency greater than 80%. The use of the LDDL made it possible to implement operating conditions of the RA under which the duration of the output chirped pulse did not shorten in comparison with the duration of the input one, which meant that the width of the spectral emission could be preserved.

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser systems using Nd-doped phosphate glass occupy a special place among devices with ultrashort (circa 1 ps) emission pulses. This is related to the fact that lasers of this type are technologically the most developed ones, especially the ones aimed at achieving ignition in large-scale systems for laser inertial fusion [1–3]. For instance, at present, there are about 10 lasers operating in the world with power more than 100 TW in which Nd-doped glass is used as an active medium to amplify the chirped pulse [4]. Several projects on multipetawatt laser systems on the basis of Nd-doped glass are also under development [4–9]. With respect to the possibility of obtaining a laser pulse of short duration (0.2–0.4 ps), this active medium has a substantial drawback, namely the relatively small width of the gain spectrum (20–30 nm). This prevents such a short pulse duration from being obtained after amplification and compression, even in the case of using combined silicate and phosphate Nd-doped glasses [10]. In connection with this, more broadband lasing media on the basis of Ti:sapphire [11] are now being intensively developed. Another trend is to use fundamentally different methods of broadband optical amplification, e.g. on the basis of parametric light amplifiers [12].

As applied to amplifiers on Nd-doped glass, a method of efficient spectral broadening of chirped pulses by the use of self-phase modulation of laser pulses in a bulk nonlinear medium and by limiting the breakup integral through the use of spatial filters was recently investigated [10]. Another promising method of broadening the efficient gain bandwidth is spectral control of the chirped laser pulses in the amplifying system. If one modifies the laser pulse spectrum so that the...
intensity of the central spectrum components are reduced, it is possible to expect preservation of the spectral width and chirp linearity of the amplified chirped pulse. As a consequence, a short duration of the compressed pulse comparable with the initial one is expected. An acousto-optical light dispersive delay line (LDDL) is a convenient instrument for the desired modification of the spectrum of the chirped pulse [13–16].

Acousto-optical devices (spectral filters and equalizers) are widely used in laser instrumentation for transforming spectra of laser emission in WDM telecommunication systems [17], intracavity laser tuning [18], laser spectrometry [19], etc. Recently, LDDL devices have been used in high-power laser systems for pulse shaping. They are capable of controlling spectral amplitudes and phases in order to form the optimal spectral composition of the emission and compensate for higher-order dispersions [14–16]. The principle of collinear acousto-optical interaction of the electromagnetic wave in a crystal with frequency- and amplitude-modulated ultrasound underlies the operation of devices of this class [13]. A recent survey [20] covers modern aspects of ultrashort pulse control and compares LDDLs with other pulse shaping methods. Usually, the LDDL is placed at the output of the master oscillator and thereafter the amplification of the chirped pulse takes place [16, 21, 22]. Thus, the device forms predistortions of the optical pulse, which means that optimal conditions must be ensured for pulse compression after it has passed through the amplifier chain. Spectral broadening of the amplified chirped laser pulse with the help of an LDDL was experimentally demonstrated in [23, 24] for ultrabroadband optical regenerative amplifiers (RAs). In that work, a programmable acousto-optical filter was placed inside the cavity of a Ti:sapphire RA. Application of the LDDL made it possible to broaden the spectrum of the 1 mJ amplified chirped laser pulse almost four times, from $\Delta \lambda \approx 32$ nm up to $\Delta \lambda \approx 130$ nm.

The problem of application of LDDLs in laser systems with relatively narrow spectra consists in the rather high requirements for spectral resolution of the acousto-optics. It should be mentioned that not all special features of acousto-optical interaction in crystals are now used by the developers of LDDLs in full measure. Although quasicollinear acousto-optical interaction makes it possible to obtain an essentially higher spectral resolution than in the orthogonal geometry of diffraction, it is usually insufficient for shaping of pulses whose spectral width does not exceed 10 nm. Thus, in order to realize all potentialities of the LDDL for control of sub-picosecond ultrashort pulses, further efforts should be exercised in the search for new solutions in the acousto-optical engineering.

The present research has experimentally demonstrated the possibility of spectral control of chirped pulses in a laser system with Nd-doped glass amplifiers. For that purpose, we developed an LDDL with a configuration of acousto-optical interaction that ensured the required spectral resolution. The LDDL was placed inside the cavity of a ring RA. It performed the spectral gain correction in every pass through the amplifier cavity. The study made it apparent that the conservation of the spectral width of pulses in the RA is possible due to correction of the emission spectrum with the help of the LDDL.

2. Experiments

2.1. Laser setup and experimental procedures

The experiments were performed on a sub-picosecond terawatt laser system that was in operation at the RFNC–VNIIEF [25]. The laser was built on the principle of generating Fourier-transform-limited ultrashort pulses of $\tau_{t_1} \approx 200$ fs duration ($\lambda_0 \approx 1054$ nm, $\Delta \lambda \approx 8$ nm), which were stretched to a duration of $\tau_{\text{fwhm}} \approx 1.6$ ns ($\Delta \lambda \approx 4$ nm), followed by amplification of the chirped pulse in the RA, double pass, and single-pass power amplifiers, and further compression of the amplified pulse. The amplifier chain of the laser system was built on the basis of Nd-doped phosphate glass. A bandwidth narrowing down to $\Delta \lambda \approx 2$ nm takes place because of an insufficient gain bandwidth of the active medium in amplifiers. For that reason, after compression the pulse duration noticeably exceeds the initial one and amounts to up to $\tau_1 \approx 800$ fs. The schematic diagram of the laser system with the experimental configuration is shown in figure 1. The power amplifiers and the compressor were not involved in the present experiments.

On account of losses in the optical elements of the stretcher and the transport system, the pulse energy at the input of the RA amounts to approximately 0.05 nJ. The RA operates in the mode of small signal gain with a great number of round trips ($N = 20$). Unsaturated gain with practically equal magnitude $K_0$ from pass to pass takes place due to the weak inversion depletion. The chirped pulse is amplified to an energy level of about 1–10 mJ (amplification factor $K_{\text{amp}} = (K_0T)^N \sim 10^8$ with respect to the transmission of cavity elements $T \approx 0.3$; overall small signal gain $G = K_0^N \sim 10^{18}$). An intracavity diaphragm with a diameter of $D = 1.5$ mm provided the diffraction-limited beam quality and the breakup integral below the critical value.

Since measurement of the emission spectrum in every single pass through the cavity of the RA requires the use of unique high-sensitivity spectral equipment with temporal resolution, our measurements were based on recording the temporal shape of the chirped pulse, amplified in every pass, by means of a fast-response photodiode and broadband oscilloscope. Considering that the pulse on the stretcher output possesses a linear chirp, the suggested method of
The acousto-optical interaction in the paratellurite crystal of Molchanov et al. over the spectral resolution in accordance with the work of acousto-optical diffraction in the paratellurite was optimized. Merlin, namely characterized by a relatively low acousto-optical figure of merit, namely $M = 120 \times 10^{-18} \text{s}^3 \text{g}^{-1}$, which is practically four times less than the maximum possible value for the quasicollinear diffraction geometry in paratellurite [17]. The technology of vacuum interdiffusion of atoms in chemically active nanolayers was applied for fabrication of the acousto-optical cell. That ensured a low level of driving radio-frequency (RF) power of the order of several dozens of milliwatts in monochromatic mode. A high diffraction efficiency was obtained in the experiments owing to a relatively small spectral width of emission. Under a constant amplitude and duration of the ultrasonic wave packet, the spectral power density is inversely related to the width of the RF spectrum. It follows from this that the diffraction efficiency is higher for narrowband electromagnetic emission compared with broadband emission. As a result, the developed LDDL provides a diffraction efficiency higher than 80% in the spectral window $\Delta \lambda = 12$ nm with a peak RF driving power of $P_{\text{max}} = 10$ W.

The important parameter of the LDDL is the value of the intrinsic dispersions of the acousto-optical crystal, which is defined by the spectral dependence of the refractive indices. Specific values of the dispersions in paratellurite are accurately determined by the Sellmeier equations [27]. The dispersion coefficients of an ordinary wave from the second to the fourth orders are, respectively, equal to $b_2 \approx 340 \text{fs}^2 \text{mm}^{-1}$, $b_3 \approx 250 \text{fs}^3 \text{mm}^{-1}$, and $b_4 \approx 110 \text{fs}^4 \text{mm}^{-1}$ at a wavelength of $\lambda_0 = 1054$ nm. If the output beam of the LDDL is of the first diffraction order then the intrinsic dispersion of the crystal adds up to the dispersion induced by ultrasound, the latter being defined by the frequency profile of the RF signal. On the other hand, with the use of the zeroth order as the output one, the LDDL loses the function of controlling the spectral phase of the emission, and the phase distortions depend only on the optical properties of the crystal [28]. For correction of the amplification coefficient inside the RA cavity it is advisable to use the output beam of the zeroth order of the LDDL, as diffraction losses and beam distortions turn out to be minimal. Such a configuration of the RA in which the undiffracted beam goes back to the cavity was used in the experiments (see figure 1). In this case the beam of the first diffraction order emerged from the cavity and it could be used to control the diffraction parameters. The input and output facets of the LDDL were fabricated with multilayer antireflection coating providing less than 0.1% of scattering from each surface.

To perform the experiments, an electronic control system was developed for the LDDL, and appropriate software was created. The electronic control system made it possible to synthesize the spectral transmission function of the LDDL with arbitrary amplitude modulation and phase profiles [29]. The profiles of the driving RF signal were defined as the sequence of frequency and amplitude values of the ultrasonic wave packet sampled at 50 ns rate. The LDDL spectral transmission function was assigned in the MATLAB computing language. This provided the necessary adaptiveness of the spectral shape control, regardless of which of the LDDL diffraction orders, the zeroth or the first, was used.

![Figure 2. Experimental measurement of the chirped pulse narrowing in the RA.](image-url)
2.3. Spectral resolution of the LDDL

The spectral resolution of the LDDL is the key factor defining the possibilities for its application in sub-picosecond laser systems with narrow spectra of emission. In this research, the width of the LDDL transmission function was equal to $\delta \lambda \approx 0.12 \text{ nm}$ in monochromatic mode at a central wavelength of $\lambda_0 = 1054 \text{ nm}$. This value is determined by the configuration of the acousto-optical interaction and can be achieved only when several conditions are satisfied: on the one hand, the measurements are carried out in a stationary mode with the light diffraction by a single-frequency ultrasonic wave; on the other hand, the diffraction-limited divergency of laser beam should not exceed the angular aperture of the delay line. The diameters of the light beam and acoustic beam in the crystal also have to be in agreement with one another. The pulsed mode, under which the duration of ultrasonic wave packages is less than the time of running of the acoustic wave through the crystal, is typical of LDDL operation and leads to a reduction in the spectral resolution relative to the diffraction limit [30].

For measurement of the LDDL spectral resolution in the broadband mode, the shape of the chirped laser pulse with narrow modulation was obtained experimentally. The frequency and amplitude modulation of the ultrasonic signal provided the diffraction in the spectral bandwidth of $\Delta \lambda = 0.5$ nm centered at $\lambda_0 = 1054$ nm. Thus, a narrowband rejection of the pulse spectrum took place. The shape of the chirped optical pulses was measured on the undiffracted beam at the output of the LDDL. Amplitude modulation of the chirped pulse was also used as a marker for frequency calibration of the RF signal generator of the electronic control system.

In figure 3, the envelope of the unchanged pulse (a) is compared to a pulse in which a narrow dip was formed by the LDDL (b). The measured width of the dip (by the FWHM criterion) was $175 \pm 25 \text{ ps}$, which corresponds to its spectral width of $0.7 \text{ nm}$. In this case, narrower dips in the spectrum were observed on the recorded traces but their width could not be measured correctly since the dip width in the temporal shape of the pulses became less than the width of the pulse response of the measurement system (photodiode and oscilloscope), which was not less than $100 \text{ ps}$. The measurements were conducted with the RA switched off and the cavity loop opened.

3. Results and discussion

The main purpose of the experiments set forth in this letter was to correct the spectral shape of the chirped pulse in such a way as to secure conservation of its duration (and consequently conservation of its spectral width) in the process of regenerative amplification. In the experiments performed the RA was adjusted for seven round trips since at this number of passes the foremost narrowing of the spectrum takes place (see figure 2).

Typical traces of the chirped pulse envelope are presented in figure 4. The delay between the pulses equals the round-trip time of the cavity. The pulse shape without correction (a) is compared with the pulse shape corrected with the help of the LDDL (b), both at the same small signal gain $K_0 \approx 12$. The overall gain amounted to as much as $G \approx 4 \times 10^7$. To make a correction to the pulse shape with the help of the LDDL, the transmission function had a symmetrical dip with a width of $\Delta \lambda = 3.5$ nm centered at $\lambda_0 = 1054$ nm. The maximum diffraction efficiency amounted to approximately 30%, as there was no need for stronger suppression of the spectral components of the emission.

The results of the analysis performed on the chirped pulse duration inside the cavity are shown in figure 5. In the regular mode of operation of the RA (without the LDDL), a steady reduction of the chirped pulse duration is observed.
Figure 4. The evolution of the pulse shape in the RA for seven round trips: (a) without correction; (b) with correction by use of the LDDL. The gain of the RA is $G = 4 \times 10^7$.

Figure 5. The chirped pulse duration in the amplifier cavity: 1—without correction; 2—after correction with the LDDL. The solid curves represent approximation of the experimental data.

Figure 6. The experimental spectral amplification factor: 1—without correction; 2—after correction with the LDDL. The solid curves represent approximation of the experimental data.

amplification curve allows us to conclude that retention of the pulse duration and correspondingly the width of the signal spectrum will be observed in the case of increasing the number of round trips through the cavity to $N = 20$, which corresponds to the regular operating mode of the RA. In addition, an insignificant suppression of the central spectral components of the emission at the output of the RA will make it possible to obtain a more uniform pulse spectrum at the output of a power amplifier.

4. Summary

In the results given in this letter, the possibility of using an LDDL for spectral equalization of amplification is experimentally demonstrated. For the first time, such results were obtained for a narrowband amplification system on Nd-doped phosphate glass. For this purpose an LDDL with an outstanding spectral resolution was created, as well as an original control system and software for synthesis of the transmission function. Owing to this, it became possible to establish an operation mode of the RA where the duration of the output chirped pulse did not diminish in comparison with the duration of the input chirped pulse. This meant that the width of the emission spectrum remained unchanged. Such an architecture of an RA with intracavity spectral gain correction makes the control over the parameters of the output pulses much easier in comparison with the method of pulse predistortion at the input of the amplifier. The adaptivity of the LDDL offers a way to change the characteristics of the gain curve, thus making it possible to obtain optimal operational modes of the RA, as well as to control the shape of the output pulses.

One of the purposes of this letter is to bring to professional notice the potential of the LDDL possibilities. The ultimately achieved results contribute noticeably to the development of acousto-optical methods of control over sub-picosecond pulses, generate new possibilities for adaptive control in laser systems of this class, and speed up practical applications. The optimization of the operational mode of
the RA is aimed at increasing the output power through broadening of the output emission spectrum, that is, without building up the power amplifier stages. The dissemination of information on the LDDL might be useful in the advancement of other designs of ultrashort pulse lasers, for instance, fiber femtosecond lasers which have to use intracavity spectral filters.

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References