Temporal profiling of the ultrashort laser pulses by dispersive acoustooptic methods

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1. BACKGROUND & METHOD

Temporal shaping of ultrashort laser pulses is one of the problems in modern laser physics [1, 2]. Efficient pulse shaping is required at different time scales: from few-cycle femtosecond pulses to nanosecond pulses in high-energy laser systems.

Acousto-optic (AO) devices are used in ultrafast optics as pulse pickers, Q-switches, frequency shifters, and dispersive delay lines [3–5]. Modulation bandwidth of AO devices is limited by the acoustic transit time $\tau_{\rm ac}$ defined as the time required for an acoustic wave front to travel through the region of interaction. For typical quasicollinear-type AO devices on the base of TeO_2 crystals (paratellurite) modulation bandwidth is of the order of 10 kHz.

Using special phase modulation of light and ultrasound and broadband phase matching one can obtain modulation of laser pulses in the GHz frequency range, i.e. $\sim 10^6$ times wider than by means of direct modulation. The RF waveform that is applied to the AO cell is chirped and modulated in time domain [6]. The passband of the Bragg cell $\delta\lambda$ is related to the bandwidth of phase matching δf is

$$\delta f = \frac{\delta\lambda}{\lambda} f \sim \frac{1}{\tau_{\rm ac}} \qquad (1)$$

For a chirped broadband laser pulse which is wavelength-by-wavelength phase-matched with the ultrasound in the AO crystal amplitude modulation of ultrasound results in amplitude modulation of both diffracted and zero-order transmitted light. If the optical pulse were chirped with the second-order dispersion D_2, the duration $\Delta\tau_{\rm opt}$ equals to

$$\Delta\tau_{\rm opt} \approx \frac{4\,|D_2|}{\tau_{\rm ftl}} \propto \Delta\lambda, \qquad (2)$$

where it is taken into consideration that the Fourier-transform limited pulse duration $\tau_{\rm ftl}$ is inversely proportional to the spectrum width $\Delta\lambda$.

Modulation rise/fall time in optical domain is expressed as:

Duration of the chirped laser pulse

$$\delta\tau_{\rm opt} = \frac{\delta\lambda}{\Delta\lambda}\Delta\tau_{\rm opt} \qquad (3)$$

That makes possible to calculate the modulation bandwidth:

Bandwidth of laser emission

$$\Delta\nu = \frac{1}{\delta\tau_{\rm opt}} = f\frac{\Delta\lambda}{\lambda}\frac{\tau_{\rm ac}}{\Delta\tau_{\rm opt}} \qquad (4)$$

RF signal bandwidth

Unlike Eq. (1), modulation bandwidth described by Eq. (4) is proportional to the acoustic wave travel time $\tau_{\rm ac}$ because greater length of AO interaction provides higher spectral resolution. Moreover, the lower the optical dispersion D_2 (i.e. the shorter the chirped laser pulse) the higher the modulation bandwidth while the condition $\Delta\tau_{\rm opt} \gg \tau_{\rm ftl}$ is satisfied.

Estimations of the bandwidth were made for the parameters corresponding to the experimental conditions described in Sec. 2 and 3, namely $\Delta\lambda = 4$ nm, $\lambda = 1053$ nm, $\tau_{\rm ac} = 51.2$ μs, $\Delta\tau_{\rm opt} = 1.6$ ns:

$$\Delta\nu = f\frac{\Delta\lambda}{\lambda}\frac{\tau_{\rm ac}}{\Delta\tau_{\rm opt}} = 75\text{ MHz} \times (1/250) \times 32000 \approx 9.6\text{ GHz} \qquad (5)$$

As follows form Eq. (4), the time-bandwidth product $\Delta\nu\Delta\tau_{\rm opt}$ does not depend on the dispersion D_2 of the stretcher. Higher temporal resolution of the modulator is obtained for wider spectrum of laser emission $\Delta\lambda$. Greater acoustic travel time $\tau_{\rm ac}$ (i.e. greater length of AO interaction) is required also.

2. INSTRUMENTATION

Quasicollinear type of AO diffraction in optically anisotropic media is based on collinear group velocities of light and ultrasound in birefringent crystals [7]. This type of diffraction is also used for controlling the spectral phase of optical pulses because birefringence of the crystal and AO coupling of the eigenwaves provide dispersive optical delay [3, 4]. The transmission function of quasicollinear AO devices is determined by the Fourier transform of the ultrasonic wave packets in the crystal [6, 8]. Schematic configuration of the AO cell used in the experiments is shown in Fig. 1. The output facet of the AO cell is tilted to provide the diffracted beam direction parallel to the incident. Angular chirp at the output of the AO cell is partially compensated.

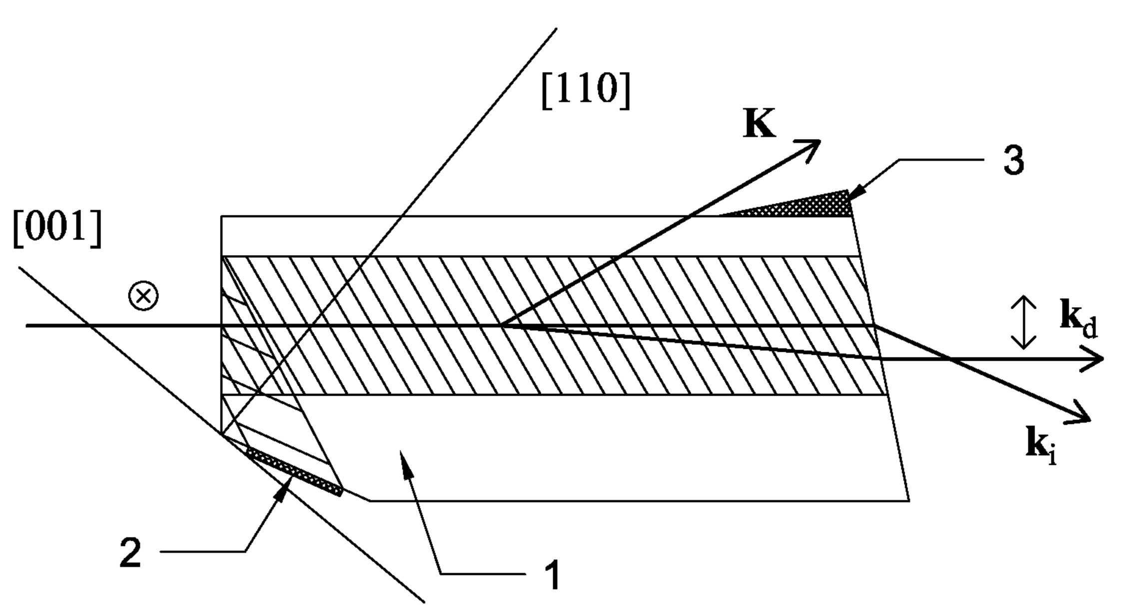

Figure 1. Schematic of the acousto-optic quasicollinear Bragg cell: 1 — paratellurite single crystal; 2 — piezotransducer; 3 — acoustic absorber.

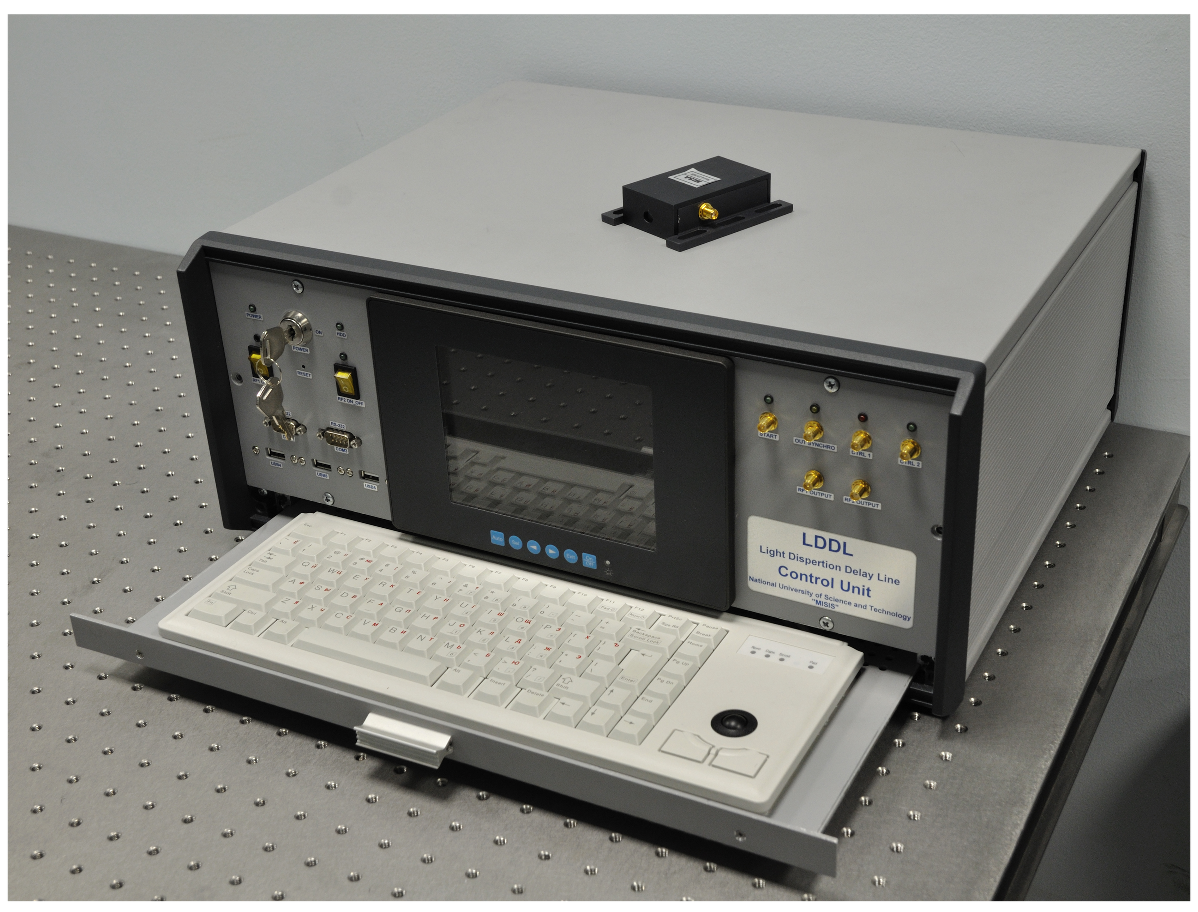

Figure 2. Acousto-optic Bragg cell with the electronic control unit.

Quasi-collinear AO Bragg cell with spectral resolution of the order 10^4 based on the TeO_2 single crystal was designed and fabricated. The length of the crystal was 67 mm that provided the maximum acoustic wave travel time approximately 100 μs. Diffraction efficiency in the experiments was higher than 85% in the spectral window 12 nm with the peak RF driving power 10 W.

The electronic control unit was generating RF waveforms with amplitude and phase modulation. The waveforms were synchronized with the laser system (see Sec. 3).

3. EXPERIMENT

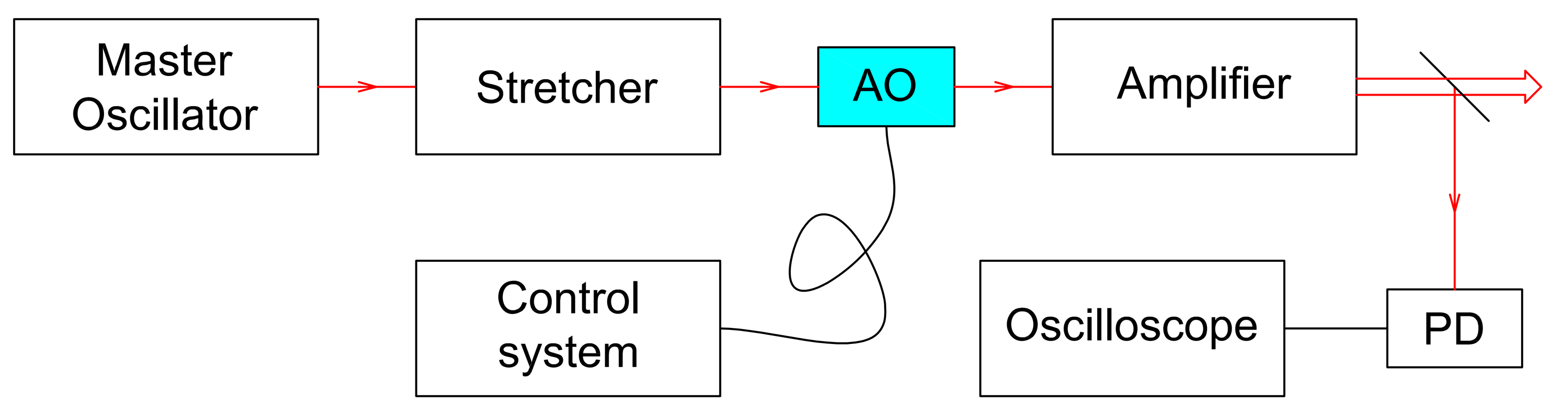

Figure 3. Schematic of the experimental setup.

The experiments were performed with a sub-picosecond terawatt laser system (Fig. 3). At the output of the stretcher the pulses had the spectrum $\Delta\lambda \approx 4$ nm ($\lambda = 1054$ nm) and were stretched to the duration of $\Delta\tau_{\rm opt} = 1.6$ ns. The AO cell described in Sec. 2 was located between the stretcher and the laser amplifier. Intensity of the undiffracted beam (the zeroth order) was recorded after the single pass through the Nd-glass amplifier. The pulse picker (not shown in the scheme) was synchronized with the amplifier pump and the AO control unit

Temporal response of the AO pulse modulator was controlled by means of the in house designed software of the control unit (.NET Framework hardware drivers and MATLAB user interface). In the following experiment (Fig. 4) it was determined as:

$$H(t) = \mathrm{rect}\left(\frac{t}{\tau_{\rm w}}\right)\left[1 - \exp\left(-\frac{t^2}{\tau_{\rm mod}^2}\right)\right] \qquad (6)$$

where $\tau_{\rm w} = \Delta\tau_{\rm opt} = 1.6$ ns, $\tau_{\rm mod} = \varkappa\delta\lambda$, $\varkappa = 0.4$ ns/nm. The Gaussian modulation was centered relatively the RF waveform. Optical pulses at the output of the AO cell are shown in Fig. 4 where various widths of the Gaussian modulation pattern were applied. The spectral dips with the width $\Delta\lambda < 0.7$ nm corresponded to the temporal modulation with the frequency > 6 GHz were not resolved by the detection system.

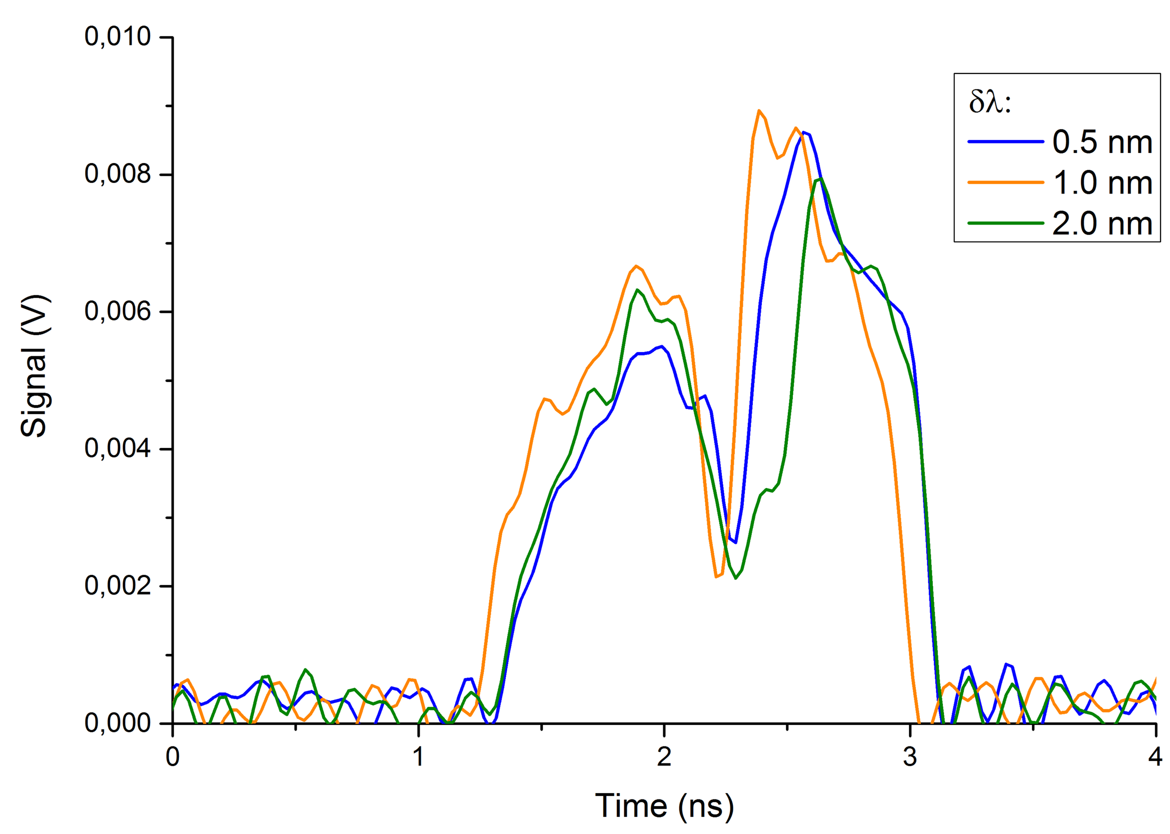

Figure 4. Experimental temporal profiles of modulated chirped laser pulses with different width of the Gaussian modulation pattern.

We obtained minimum temporal valley in the laser pulse $\delta\tau_{\rm opt} = 170$ ps (limited by the 6 GHz bandwidth of the photodetector and the oscilloscope).

4. SUMMARY

This work is a development of instrumentation for ultra-high intensity laser facilities. It is operating at the front end of high-power laser systems, and the experiments performed were made in the front end (namely in the first-stage amplifier) of a TW laser facility. Being an adaptive front-end device, our instrumentation can be used both in ultra-high intensity lasers for temporal shaping of output emission.

The response time of ordinary collinear AO devices is limited by the acoustic transit time defined as the time required for an acoustic wave front to travel along the AO crystal. The AO dispersive method of controlling chirped laser pulses allows to overcome the fundamental limitation caused by AO apparatus response time. The performed research demonstrated clearly that dispersive AO methods seem to be efficient for temporal pulse profiling up to 10 GHz.

References

1. A.M. Weiner, ***Review of Scientific Instruments***, v. 71, № 5, p. 1929, 2000.
2. A.M. Weiner, ***Optics Communications***, v. 284, № 15, p. 3669, 2011.
3. P. Tournois, ***Optics Communications***, v. 140, № 4-6, p. 245, 1997.
4. V.Ya. Molchanov, S.I. Chizhikov et al., ***Applied Optics***, v. 48, № 7, p. C118, 2009.
5. S.I. Chizhikov, S.G. Garanin et al., ***Laser Physics Letters***, v. 10, № 1, p. 015301, 2013.
6. V.Ya. Molchanov, K.B. Yushkov, ***Optics Express***, v. 22, № 13, p. 15668, 2014.
7. V.Ya. Molchanov, V.B. Voloshinov, O.Yu. Makarov, ***Quantum Electronics***, v. 39, № 4, p. 353, 2009.
8. K.B. Yushkov, V.Ya. Molchanov, ***Optics Communications***, v. 355, p. 177, 2015.