

LETTERS

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Two-cascade acousto-optic dispersive delay line for ultrashort laser pulses

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***Abstract*. An optical dispersive delay line for controlling the spectral composition and phase of ultrashort laser pulses is considered. To control independently the spectral amplitude and spectral phase of pulses, it is proposed to use the cascade arrangement of two acousto-optic cells with different control signals.**

Keywords: *femtosecond laser systems, dispersive delay line, acousto-optic diffraction.*

Adaptive dispersive delay lines based on the acousto-optic (AO) effect are a universal and effective tool for controlling femtosecond laser pulses. Acousto-optic delay lines make it possible to compress ultrashort laser pulses and perform phase and amplitude correction of their spectrum [1 – 3]. Generally, a dispersive delay line is based on the effect of collinear or quasi-collinear AO diffraction [3]. In contrast to tunable AO filters, an ultrasonic wave in the AO crystal used in the delay line is both frequency- and amplitude-modulated. The frequency modulation range corresponds to the spectral width of the laser pulse. Different spectral components of the electromagnetic wave are diffracted at different points in the crystal, which gives rise to phase shifts between the spectral components. In the weak-field approximation the transmission function of an AO device is determined by the Fourier transform of the spatial distribution of the ultrasonic wave field in the interaction medium and has a complex character [1, 4]. This circumstance relates the amplitude of the transmission function and its phase, which is determined by the Kramers – Kronig relations [5]; as a result, the amplitude modulation of an ultrasonic wave generates higher order dispersions, which distort the pulse shape.

In the simplest case of linear frequency modulation of a control signal with a constant amplitude, the induced dispersion is quadratic. It can be shown that, if the ultrasonic signal envelope has a Gaussian shape with a width T_0, and the frequency changes in the range ΔF, the dispersion B_2 of the diffracted-beam group velocity is described by the expression

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$$B_2 = \frac{\pi^3 \Delta F T_0^3}{\varkappa^2 (1 + \pi^2 \Delta F^2 T_0^2)} \approx \frac{\pi T_0}{\varkappa^2 \Delta F}\,. \quad (1)$$

Here, $\varkappa$ is the ratio of the cyclic frequency of light to the ultrasonic wave frequency; this ratio is determined (in the single-frequency regime) by the acousto-optic interaction geometry. The approximate equality in (1) is valid at $\Delta F T_0 \gg 1$, the relation being valid for almost all operating regimes of the dispersive delay line.

The dispersion control in a delay line is based on changing the frequency modulation law. If the frequency modulation of an ultrasonic wave is accompanied by amplitude modulation, the delay line controls the spectral amplitude of electromagnetic radiation. Generally, the spectral amplitude must be corrected in optical pulse amplification systems. For example, the optimal solution for regenerative optical amplifiers [6] is the formation of an amplitude dip in the optical emission spectrum.

Simultaneous frequency and amplitude modulation of ultrasonic waves limits significantly the functionality of a conventional delay line. Due to the presence of second-order dispersion B_2, the optical pulse width increases, and an AO cell cannot be located in the multipass channel of optical amplifiers.

To improve the functionality of delay lines, we propose to assign the functions of controlling the spectral phase and the spectral light amplitude to two independent AO cascades. In contrast to the scheme of a double AO monochromator [7, 8], which makes it possible to increase the contrast and improve the shape of the transfer function, the two AO cascades in this system have different functions and are controlled by differently shaped signals.

The scheme of a two-cascade AO delay line with independent control is shown in Fig. 1. The first cascade is aimed at controlling the spectral phase of radiation and its design is similar to that of a conventional AO delay line, i.e., output radiation is in the first diffraction order. The second cascade, which is designed for controlling the spectral amplitude of radiation, is different: its output radiation is in zero diffraction order. In this configuration the second cascade of the AO delay line works as an optical adaptive notch filter, and the frequency-modulated control signal synthesises a specified transmission function in zero order. Electromagnetic waves do not undergo additional phase distortions in this cascade. The natural dispersion of the AO crystal can be compensated for using the first cascade or some external passive devices.

When using two cascades, the complex transmission function $T(\omega)$ of the AO delay line can be presented as the

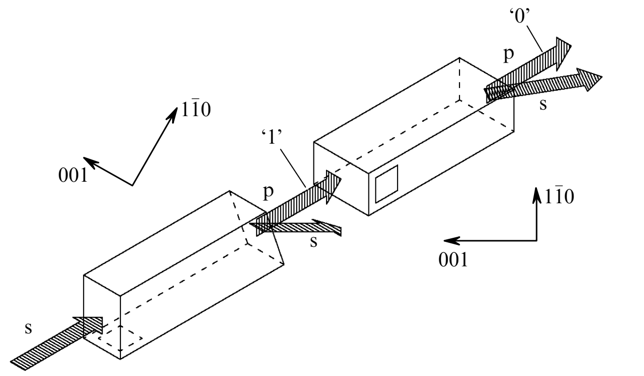

Figure 1. Schematic diagram of beam paths in a two-cascade AO delay line: s and p indicate, respectively, the horizontal and vertical polarisations and '1' and '0' are the first and zero diffraction orders. The diffraction planes in the cascades are orthogonal.

product of the transmission functions of the cascades: $T(\omega) = T_1(\omega)T_2(\omega)$. Here, the transmission function of the first cascade can be written as $T_1(\omega) = \arg T(\omega) = \exp[i\Psi(\omega)]$, where the real function $\Psi(\omega)$ is the spectral phase. The transmission function of the second cascade has the form $T_2(\omega) = |T(\omega)|$. Thus, the control signal for the first cascade must provide a constant spectral amplitude of the transmission function $T_1(\omega)$ in the entire emission band, $\Delta\omega$, and the law of change in the phase $\Psi(\omega)$ specified in this range, while the control signal of the second cascade must form the real zero-order transmission function $T_2(\omega)$. Since the second cascade of the AO delay line does not induce an additional dispersion when controlling amplitude, it can be used as an efficient tool for equalising the amplitude characteristic in multipass regenerative amplifiers (in contrast to the conventional single-cascade delay line [2]).

In accordance with the results of [9], we designed and fabricated an experimental two-cascade AO delay line based on paratellurite with the following parameters: each crystal 60 mm long, the experimental spectral resolution in the single-frequency regime no worse than 6 cm^{-1}, the driving power less than 60 mW, and the central frequency 76 MHz. The radiation source in the experiment was a femtosecond laser with a central wavelength of 790 nm and a spectral width of 80 nm. Figure 2 shows as an example the emission spectrum at the output of one of the cascades of the AO delay line in the regime of formation of a narrow spectral dip by the corresponding modulation of the ultrasonic pulse. The range of variation in the ultrasonic frequency, ΔF, over the time $T_0 = 50$ μs amounted to 15.9 MHz. A calculation from formula (1) shows that, with these parameters of the paratellurite crystal, the maximum (in magnitude) value of the second-order dispersion, which is introduced as a result of the AO interaction, is 43000 fs^2, while the passive intrinsic second-order dispersion of the crystal is 30000 fs^2. The passive second-order dispersion in both cascades can be compensated for by tuning the stretcher and the compressor, whereas the first cascade of the AO delay line makes it possible to perform fine tuning of dispersion, including the higher order one.

The above analysis showed that the proposed method of separate independent AO control of both the spectral phase and spectral amplitude of ultrashort pulses is characterised by a higher flexibility and accuracy of processing optical spectra in comparison with the known method [1–3]. A

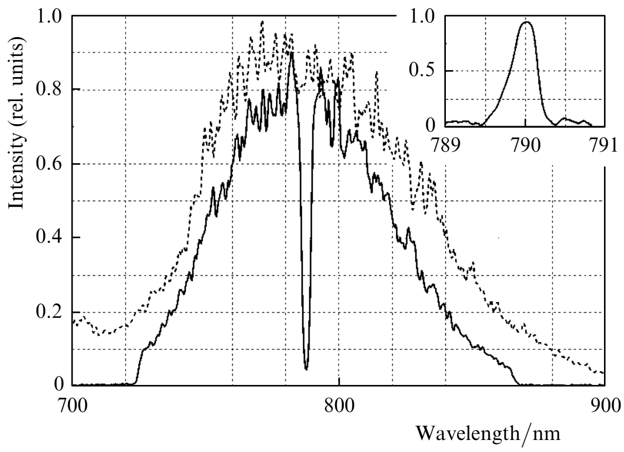

Figure 2. Emission spectrum at the output of the AO dispersive delay line (solid line) and the input radiation spectrum (dotted line). The inset shows the transmission function of the delay line in the single-frequency regime; the width at a level of −3 dB is 0.35 nm.

device based on this method can be used in femtosecond laser systems of different architecture, in particular, as a correcting element, installed in the multipass optical regenerative amplifier.

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