Interaction between femtosecond radiation and sound in a light dispersive delay lines using effect of strong elastic anisotropy

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Abstract. Femtosecond optical amplifiers typically have high nonlinear spectral dispersion breaking relationships of the spectral phases of femtosecond pulse. It is necessary to use some additional dispersive device for controlling of spectral amplitude and phases of amplified laser pulses. We discuss the investigation of light dispersive delay lines based on the light-sound interaction in crystals. The light dispersive delay lines geometry uses the effect of strong elastic, photoelastic and optic anisotropy in the TeO$_2$ single crystal. Different experimental delay lines were designed and tested. The problem of femtosecond laser beam angular chirp compensation was solved also. The experiments were performed at the OPCPA femtosecond laser system.

1. Introduction

The creation of superpowerful femtosecond laser systems has been one of the most striking breakthroughs of physics at the turn of the 20th-21st century. The most recent decade is characterized by the conquest of new frontiers in energetic and temporal characteristics of femtosecond laser radiation. Previously reached record power, and impulse duration values have been exceeded by several orders of magnitude.

Today, peak laser impulse power achieved in just several of the world’s labs amounts to 1 petawatt, a hundred times higher than the sum total of all energy sources on our planet. In the nearest future, such laser sources will provide the opportunity to conduct fundamental research in absolutely new areas. For instance, it will be possible to study the properties of vacuum in the presence of superstrong fields, to model in laboratory conditions the processes at the core of stars and planets, or to perform quantum control of intramolecular and interatomic processes. The newest line of research is the creation of laser-powered charged-particle accelerators based on the impact of petawatt optical impulses on gas and solid state targets, creating new possibilities for low-dose x-ray phase contrast tomography, hadron therapy for cancer, protonography, etc.

In most applications, the quality of compressed pulses (pulse duration, lack of prepulses, and high contrast ratio) are critical. The pulse quality is determined by a noncompensated high-order dispersions and spectral deformation in the amplifiers. An adaptive device that compensates for the induced high-order dispersion and spectrum distortion in the system by modifying the spectral amplitude and phase of the seed femtosecond pulse can be used to decrease the duration of the compressed pulse and suppress the prepulses. This conceptual solution helps increase femtosecond radiation power not by increasing the energy of the laser system, but by decreasing the duration of the pulse due to the correctly arranged spectral phase. Independent control of the spectral amplitude helps produce pulses of required shape, oriented at optimal conditions for amplifying the subsequent cascades.

Currently, three principal methods for controlling the spectral phase are known: chirped mirrors, a line of liquid crystal-based phase-modulated transparencies, and wave-electronics devices: adaptive time-delay
lines based on the acoustooptical effect. The experience of working with powerful laser systems shows that the third method has a number of incontestable advantages, such as linear geometry that doesn’t require to be rigidly coordinated with stretcher geometry; continuous phase control; the possibility of independently controlling not only spectral phase, but also amplitude; high-speed adaptation facilities.

Thanks to these advantages, acoustooptical time-delay lines have proven themselves to be the best among such devices.

2. Light spectra processing by acoustooptical light dispersive delay lines
A collinear acoustooptic filter for compression of ultrashort laser pulses was first proposed in 1986 by Pustovoit and Pozhar [1, 2]. According to their concept the anisotropic acoustooptical interaction converts the fast (slow) input spectral component into a slow (fast) diffracted component. The amplitude and the phase of each spectral component is determined by the sound spectral amplitudes and the frequencies. The control of sound waves provides laser pulse shaping both in the spectral phase delay and the amplitude; a concept that proved to be practical. Tournois [3, 4] proposed in 1997 the same technical solution for femtosecond pulse shaping termed an acoustooptic programmable dispersive filter (AOPDF). Now this system, the Dazzler, manufactured by Fastlite, France, is widely used in femtosecond laser equipment.

Acoustooptical light dispersive delay lines (LDDL) remain a virtually unstudied new generation of photonics devices. Consumer feedback shows that the Dazzler has a number of typical weaknesses: low diffraction efficiency, low spectral resolution, limited optical delay and low adaptive ability [5, 6]. The aim of this paper is the further development of LDDL based on TeO2 crystal for optimal performance.

We would like to point attention on the features of LDDL. Acoustooptic interaction always performs consequent spectrum analysis. LDDL is the only type among all other acoustooptical devices providing parallel but not consistent light spectrum processing. For example, acoustooptical modulators and deflectors control monochromatic laser radiation by multifrequency sound. Acoustooptical filter provides consistent light spectrum analysis by tunable monochromatic sound. Factually, LDDL can be considered as tunable acoustooptical filter, having adaptive spectral transmission function (spectral window) synthesized by multifrequency sound injected into the crystal according to the given rules [7, 8].

3. Theoretical consideration
The analysis has been carried out for plane (1-10) of paratellurite crystal according [9]. The well-known formalism of wave-vector diagrams for the uniaxial crystal was used. This formalism defines the relationship between the frequency of Bragg synchronism and the angles of propagation of light and sound relative to crystallographic axes with the understanding that waves are considered to be plane. The efficiency of interaction of light with sound is determined by the effective photoelastic constant. From the definition of the quasicollinear acoustooptical interaction follows that wave vector \( k_i \) of incident light propagating at angle \( \phi \) should be collinear to acoustic group velocity \( V_{g1} \) defined in the same coordinate system (figure 1).

![Figure 1. Orientation of optical facet 1 of LDDL is defined from wave vector diagram and slowness curve.](image)

Further we assume that the acoustic wave reflects from the input facet of crystal. Here: \( k_d \) and \( K \) – wave vectors of diffracted light and sound, \( n_o \) and \( n_e \) – ordinary and extraordinary indexes of refraction; \( \psi_1 \) - walk-off angle between phase and group velocities of sound. We introduce the main parameter of filter \( \alpha_1 \)

![Figure 2. Transducer facet 2 of LDDL is defined from the rule of equal projections of \( V_{p1} \) and \( V_{p2} \).](image)
as an angle between phase velocity $V_{p1}$ of the acoustic wave reflected from the input facet of the crystal and the axis of the crystal [110]. We also define: $\alpha_2$ as an angle between phase velocity $V_{p2}$ of the acoustic wave generated by piezotransducer, and [110] axis, $\psi_2$ as a walk-off angle between phase $V_{p2}$ and group $V_{g1}$ velocities of the acoustic wave (figure 2).

The orientation of the input optical facet is defined by angle $\pi/2-(\alpha_1+\psi_1)$ between the facet plane and axis [110] of the crystal (figure 1). The orientation of the transducer facet is defined by angle $\pi/2-\alpha_2$ between the facet plane and axis [110] of the crystal (figure 2). The value of angle $\alpha_2$ is determined as a function of $\alpha_1$ [6, 9]. When $\alpha_1=1.78^0$ and $\alpha_1=13.31^0$ the optical and acoustical facets are orthogonal. Acoustic wave vectors of incident and reflected sound columns have to satisfy the requirement of equal projection in the crystal.

Different LDDL were designed using the mathematical approach described above. Operating points of LDDL are represented by the surface shown of figure 3. When $\alpha_1=1.78^0$ the operating point is point $A$.

Figure 3. Operating point of LDDL at $\lambda = 1550$ nm. Point $A$ corresponds to $\alpha_1 = 1.78^0, f = 52.2$ MHz, $\phi = 160.1$ deg.

4. Features of adaptive optical delay line
Optical scheme of LDDL is presented in figure 4. The input facet (5) of the crystal (4) is orthogonal to the wave vector (1) of the incoming laser radiation. Polarization of laser radiation is shown schematically in figure 4. The acoustic wave generating by transducer (7) reflects from the input facet (5) of crystal. The quasi-collinear interaction takes place within the sound column reflected from the input optical facet (5) of the LDDL. The sound column is dissipated by acoustic absorber (8). Experimental devices were fabricated by bonding method of our own utilizing the vacuum interdiffusion of atoms in In-Au nanostructures.

Figure 4. Optical scheme of LDDL ($1.78^0<\alpha_1<13.31^0$). 1. incoming beam; 2. diffracted beam; 3. non-diffracted beam; 4. TeO2 crystal; 5. input optical facet; 6. output facet; 7. transducer; 8. acoustic absorber.

The angular dispersion in LDDL leading to an angular chirp of femtosecond laser beam originates from the angular spectral dependence of Bragg synchronism. The reduction of angular chirp (figure 5a) can be done by adding a compensating prism with inverse dispersion to the output facet (6) of the crystal as it is shown in figure 4. In practice it is convenient to employ LDDL when the diffracted beam (2) propagates
collinear to the input beam (1). In this case the angular chirp compensation will be not so perfect (figure 5b). The angular chirp will be nevertheless less than a typical divergence of femtosecond laser beam.

The spectral transmission function bandwidth of one of LDDL utilizing the angle $\alpha_1=1.78^\circ$ measured in a single frequency regime by optical spectrum analyzer at -3 dB level is about 0.24 nm at 1550 nm. The crystal length is 67 mm, the optical aperture is 4x4 mm. Other specifications are as follows: central laser wavelength – 800 nm, maximum optical delay exceeds 20 psec. The frequency of Bragg synchronism at 800 nm is 105 MHz. Owing to our origin transducer's bonding technology the driving RF power in a single frequency regime was extremely low (60 mW at 90% efficiency) that permitted to control the whole femtosecond spectrum up to the 200 nm. The general view of experimental device is presented in figure 6.

The experiments with another LDDL ($\alpha_1=3.8^\circ$) has been carried out at subpetawatt OPCPA laser system created by the Institute of Applied Physics of the Russian Academy of Sciences [6, 10]. An LDDL was placed between a femtosecond oscillator and a stretcher. The femtosecond master oscillator was a Cr:forsterite laser generates 40 fs pulses at a central wavelength of 1250 nm. The measured efficiency of LDDL over the whole femtosecond pulse spectrum bandwidth 120nm was 70%. The spectrum bandwidth of the signal radiation in the OPA was approximately 12 nm. Shaping of the sound amplitude distribution that provides a Gaussian valley in transforming function produced corresponding modifications in the signal spectrum (figure 7).

5. Conclusion

Femtosecond light delay lines are the only class among all other types of acoustooptical device because they provide parallel but not consistent optical spectral processing. The designed LDDL systems have revealed high efficiency, high spectral resolution, flexibility of pulse control and simplicity in operation.

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