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Acousto-optic programmable dispersive filter for adaptive compensation of group delay time dispersion in laser systems

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Abstract

It is demonstrated in this communication that using an acousto-optic interaction in an anisotropic birefringent medium it is possible to produce a chirped optical signal reproducing an original acoustic signal. This acoustic signal can then be used to generate a pre-distorted optical signal at the input of a laser chain to compensate for group delay time dispersions within the chain. The first experiments achieved with such a device are reported. © 1997 Elsevier Science B.V.

1. Introduction

Group delay time dispersion in laser cavities and laser systems, such as Chirp Pulse Amplification (CPA) systems, sets a lower bound on the shortest possible duration of femtosecond pulses. To compensate for this dispersion, it is customary to introduce in laser cavities prism-pairs, Gires-Tournois interferometers or dispersive mirrors. The resulting compensation, although efficient, is only partial (limited to the first orders), and is not programmable.

In CPA systems, even when the stretcher and the compressor are perfectly conjugated, i.e. when the sum of their delay times is a constant with respect to the frequency, the other elements in the system introduce group delay time dispersions that have to be compensated for in order for the system to reach its optimal performance.

In this paper, an acousto-optic programmable dispersive filter (AO-PDF) is presented, that can compensate for group delay time dispersions in laser cavities and CPA systems. This device makes use, in a birefringent uniaxial crystal, of the collinear and codirectional coupling by an acoustic wave of the ordinary (respectively extraordinary) and the extraordinary (respectively ordinary) optical waves.

The acoustic wave carries the programmable error signal that is transferred from the ordinary (respectively extraordinary) wave to the extraordinary (respectively ordinary) wave to compensate for the group delay time dispersion.

This AO-PDF device can be made from a number of crystals, such as $LiNbO_3$, $PbMoO_4$ or TeO_2, and can be operated in a bulk wave design or in a surface wave design.

2. Acousto-optic programmable dispersive filter

We consider a collinear acousto-optic interaction along the Ox axis, in an anisotropic photoelastic medium [1]. An incident optical wave, with frequency ω_1 and wavenumber β_1, is coupled to a diffracted optical wave, with frequency ω_2 and wavenumber β_2, through interaction with an acoustic wave, with frequency and wavenumber K. The nonlinear acousto-electric interaction is responsible for the product:

$$S_1(\omega_1)\exp[i(\omega_1 t-\beta_1 x)] \times S_{ac}(\Omega)\exp[i(\Omega t-Kx)] = S_2(\omega_2)\exp[i(\omega_2 t-\beta_2 x)], \qquad (1)$$

where $S_1(\omega_1)$, $S_{ac}(\Omega)$ and $S_2(\omega_2)$ stand respectively for the complex spectral amplitudes of the incident optical signal, the acoustic signal and the diffracted optical signal. The incident optical energy is transferred to the diffracted optical wave only in the vicinity of the following phase-matching conditions:

$$\omega_2=\omega_1+\Omega, \quad \beta_2=\beta_1+K. \qquad (2)$$

Under these conditions we have

$$S_2(\omega_2)=S_1(\omega_1)\times S_{ac}(\Omega), \qquad (3)$$

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or

$$s_2\left(t-\frac{n_2 x}{c}\right)=s_1\left(t-\frac{n_1 x}{c}\right)\otimes s_{ac}\left(t-\frac{x}{v}\right), \qquad (4)$$

where $s_1(t)$, $s_{ac}(t)$ and $s_2(t)$ are respectively the complex amplitudes of the incident optical signal, the acoustic signal and the diffracted optical signal. n_1 and n_2 are the optical indexes of the photoelastic material for the incident and diffracted wave, v is the velocity of the acoustic wave and c is the velocity of light in vacuum.

As a consequence, when the higher order terms of the nonlinear interaction are negligible in comparison to (1), the diffracted optical signal is the convolution of the incident optical signal with the acoustic signal. $s_2(t)$ can then be considered as the result of the filtering of $s_1(t)$ by a programmable filter with impulse response $s_{ac}(t)$.

As a special case, when the incident optical signal is a broad-band incoherent signal and the acoustic signal is a pure frequency signal, the diffracted optical signal is a pure frequency signal; this corresponds to the classical operation of an acousto-optic tunable filter (AOTF) [2,3].

When the incident optical signal is a very short pulse and the acoustic signal is a long pulse with duration T_{ac} chirped inside a bandwidth B_{ac}, the diffracted optical signal is a long pulse with duration T_{opt} chirped inside a bandwidth B_{opt} and is the optical temporal image of the acoustic pulse. This new regime can be named an acousto-optic programmable dispersive filter (AO-PDF). Because of the conservation of information between acoustic and optical signals, $B_{ac}/\Omega=B_{opt}/\omega_1$ and $B_{ac}T_{ac}=B_{opt}T_{opt}$. Furthermore, taking Eq. (2) into account as

$$n_2\frac{\omega_2}{c}=n_2\frac{\omega_1+\Omega}{c}=n_1\frac{\omega_1}{c}+\frac{\Omega}{v}, \qquad (5)$$

the optical and acoustic frequencies, bandwidths and pulse durations of an AO-PDF are given by

$$\frac{\Omega}{\omega_1}=\frac{B_{ac}}{B_{opt}}=\frac{T_{opt}}{T_{ac}}=\frac{|n_2-n_1|v}{c(1-n_2 v/c)}\approx|n_2-n_1|\frac{v}{c}. \qquad (6)$$

The modulation slope of the acoustic signal is then related to the modulation slope of the optical signal by

$$\frac{B_{ac}}{T_{ac}}=\left(|n_2-n_1|\frac{v}{c}\right)^2\frac{B_{opt}}{T_{opt}}. \qquad (7)$$

An AO-PDF achieving this convolution operation can be made with lithium niobate ($LiNbO_3$) or lead molybdate ($PbMoO_4$) as depicted in Fig. 1. When inserted in a laser chain designed for amplification of long chirped pulses, this device will allow for the correction of temporal dispersions of the chain. A CPA laser chain [4] includes (Fig. 2) an oscillator generating ultra short pulses, a stretcher for pulse stretching, amplifiers and a compressor for recompressing the high energy pulse back to its original duration. However, even when the stretcher and the compressor are perfectly matched, i.e. when the sum of their group delay time dispersions is a constant, the amplifiers in the chain disperse the signals, and the compressed signal is not identical to the original signal.

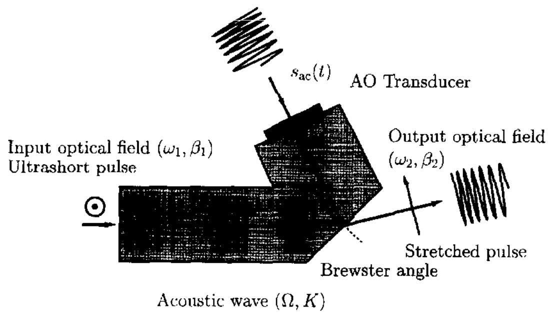

Fig. 1. Collinear acousto-optic programmable dispersive filter (AO-PDF) device configuration.

Defining $s(t)$ as the optical signal at the output of the laser chain, when the input optical signal coming from the oscillator is ultra short, $s(t)$ is the impulse response of the chain. Assuming that all chain elements including amplifiers are linear, if an acoustic signal $s_{ac}(-t)$ is applied to an OA-PDF placed between the oscillator and the stretcher (Fig. 2), the optical signal at the output of the device will be $s_2(-t)$, the time reversed image of the impulse response of the chain. This pre-distorted signal while propagating inside the chain will correct all parasitic dispersions in the chain and the output signal will be identical to the input signal.

If the amplifiers are not operating in a linear regime, the pre-distorted signal to be applied to the AO-PDF is not any more the time reversed image of $s(t)$, but can be obtained in closed-loop by a constrained optimization algorithm from the real-time measurement by an optical correlator of the pulse width at the output of the laser chain.

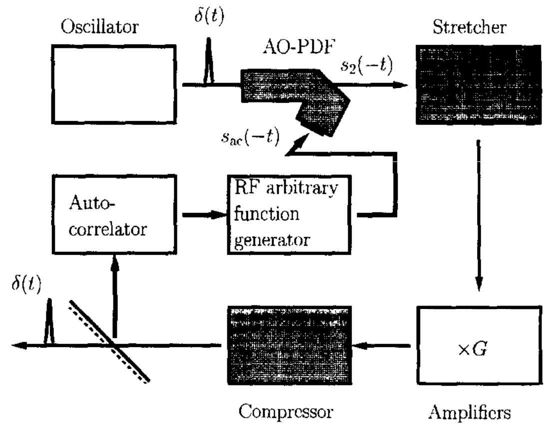

Fig. 2. New CPA laser architecture including the AO-PDF device.

The acoustic power to be applied to an AO-PDF can be evaluated when the device operates as a linear dispersive filter. Within a long acoustic pulse with duration T_{ac}, linearly chirped inside a bandwidth B_{ac}, a given frequency inside the bandwidth spreads over a duration T_f given by [5]

$$T_f = \frac{T_{ac}}{\sqrt{B_{ac}T_{ac}}} = \sqrt{\frac{T_{ac}}{B_{ac}}} . \tag{8}$$

The coupling length L_c, relative to phase-matching for a single frequency, is given as a function of the acoustic power I_{ac}, of the acousto-optic figure of merit M_2 of the material in the direction of propagation and of the optical wavelength in vacuum, by [6]

$$L_c = \frac{\lambda}{\sqrt{2M_2 I_{ac}}} . \tag{9}$$

For the conversion of the incident wave to the diffracted wave to be complete, L_c has to equal the length filled inside the crystal by a given acoustic frequency of the bandwidth B_{ac}, or

$$L_c = \frac{\lambda}{\sqrt{2M_2 I_{ac}}} = v\sqrt{\frac{T_{ac}}{B_{ac}}} , \tag{10}$$

or equivalently:

$$I_{ac} = \frac{\lambda^2}{2M_2 v^2}\left(\frac{B_{ac}}{T_{ac}}\right) = \frac{\lambda^2(n_2-n_1)^2}{2M_2c^2}\left(\frac{B_{opt}}{T_{opt}}\right). \tag{11}$$

It is preferable to select a crystal and a direction of propagation maximizing the figure of merit M_2. For example, Table 1 lists the values of the relevant parameters for lithium niobate when the propagation of light is along the Y axis (respectively, the X axis) of the crystal and a transverse acoustic wave polarized along the X axis (respectively, a longitudinal acoustic wave) is used, and for lead molybdate when the propagation of light is along the C axis of the crystal and a longitudinal acoustic wave is used.

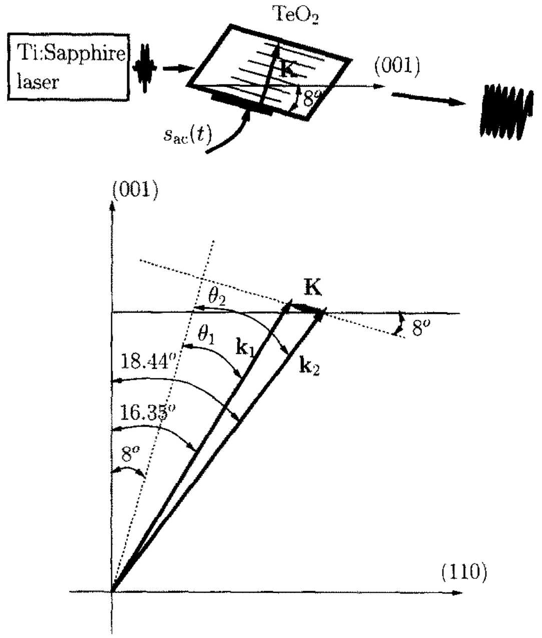

Fig. 3. Experimental set-up with a non-collinear TeO_2 acousto-optic programmable dispersive filter.

3. First experiment

A first experiment designed for demonstrating the operation of an AO-PDF was performed using a TeO_2 crystal using a very slow transverse acoustic wave ($v = 680$ m/s) since the figure of merit M_2 is very large in that case:

Table 1
Materials for the AO-PDF device. $\lambda = 0.8$ μm

	v (10^3 m/s)	$(n_2\sin\theta_2 - n_1\sin\theta_1)v/c$ ($\times 10^{-5}$)	f_{ac} (MHz)	M_2 ($\times 10^{-5}$ s^3/kg)	$\lambda^2/2M_2v^2$ ($\times 10^{-16}$ kg/s)	Attenuation (dB/μs ·GHz^2)
Collinear $LiNbO_3$ (C axis on Z)						
Shear acoustic wave,						
Y propagation, X polar	4	0.120	450	9.82	2.04	1
Long. acoustic wave,						
X propagation	6.57	0.197	739	7	1.06	1
Collinear $PbMoO_4$						
Long. acoustic wave,						
C-axis propagation	3.75	0.156	585	36	0.632	6.3
Non-collinear TeO_2						
Shear acoustic wave						
(see Fig. 3)	0.68	0.0187	70	790	0.876	18

$M_2 = 790 \times 10^{-15}\ \mathrm{s^3/kg}$. Unfortunately, collinear interaction cannot be achieved in TeO_2. We have then chosen a configuration (Fig. 3) for which the incident optical wave, whose polarization is orthogonal to the plane of incidence, and the diffracted optical wave, whose polarization is in the plane of incidence, are quasi-collinear, in order to minimize the angular dispersion of the diffracted wave with respect to the optical frequency or wavelength.

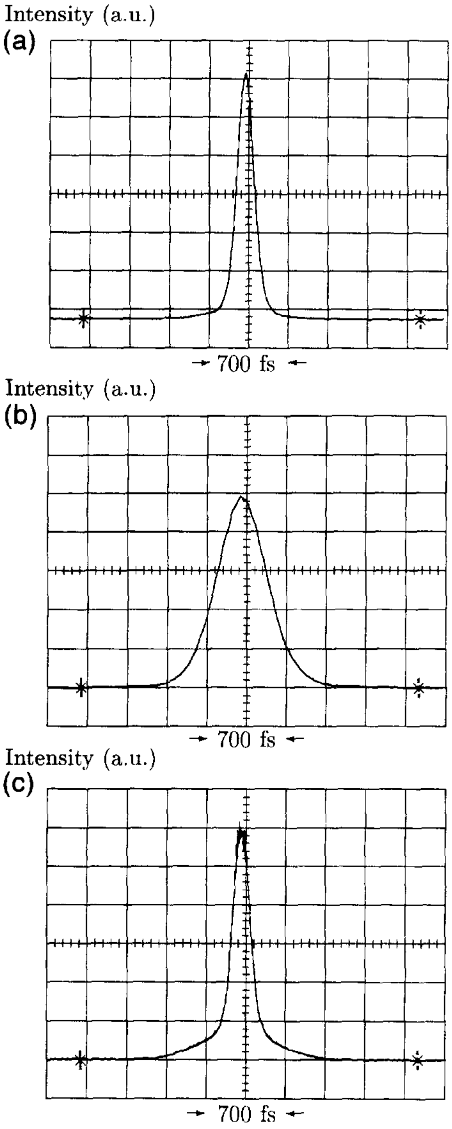

Fig. 4. Experimental results for a time dispersion of 330 fs in a 3.9 THz bandwidth. (a) Experimental autocorrelation of the pulse (FWHM 112 fs assuming a sech^2 fit) at the output of the oscillator. (b) Experimental autocorrelation of the pulse (FWHM 330 fs assuming a sech^2 fit) at the output of the OA-PDF without acoustic signal applied. (c) Experimental autocorrelation of the pulse (FWHM 116 fs assuming a sech^2 fit) at the output of the OA-PDF with acoustic signal applied.

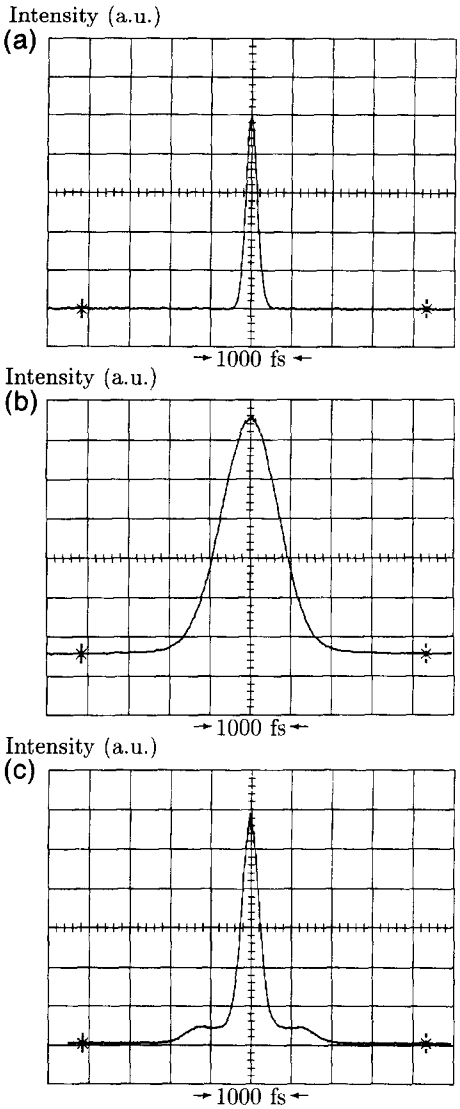

Fig. 5. Experimental results for a time dispersion of 508 fs in a 6.3 THz bandwidth. (a) Experimental autocorrelation of the pulse (FWHM 108 fs assuming a sech^2 fit) at the output of the oscillator. (b) Experimental autocorrelation of the pulse (FWHM 508 fs assuming a sech^2 fit) at the output of the OA-PDF without acoustic signal applied. (c) Experimental autocorrelation of the pulse (FWHM 150 fs assuming a sech^2 fit) at the output of the OA-PDF with acoustic signal applied.

Under these conditions, relations (6) and (7) become:

$$\frac{\Omega}{\omega_1} = \frac{B_{ac}}{B_{opt}} = \frac{T_{opt}}{T_{ac}} \approx (n_2 \sin\theta_2 - n_1 \sin\theta_1)\frac{v}{c},$$

$$\frac{B_{ac}}{T_{ac}} = \left((n_2 \sin\theta_2 - n_1 \sin\theta_1)\frac{v}{c}\right)^2 \frac{B_{opt}}{T_{opt}}. \tag{12}$$

θ_1 and θ_2 are respectively $\pi/2 - \theta_1'$ and $\pi/2 - \theta_2'$, where θ_1' and θ_2' are respectively the angles between vectors $\boldsymbol{K}$ and $\boldsymbol{k}_1$, and $\boldsymbol{K}$ and $\boldsymbol{k}_2$. For the configuration we have chosen, $\theta_1 = 8.35°$, $\theta_2 = 10.44°$, $n_1 = 2.2245$, $n_2 = 2.2380$ and $v = 680$ m/s, yielding for $\lambda = 0.8$ μm, $(n_2 \sin\theta_2 - n_1 \sin\theta_1)v/c = 0.0187 \times 10^{-5}$, or $f_{ac} = \Omega/2\pi = 70$ MHz and $B_{ac}/T_{ac} = 3.497 \times 10^{-14}\ B_{opt}/T_{opt}$.

As TeO_2 is dispersive as a function of frequency, when a ultra short pulse is injected in the device with no acoustic wave applied, the output pulse is a long chirped pulse. The pulse length depends on the length of the crystal L, equaling 2.4 cm in our experiment, and on the variation of the refractive indexes n_1 and n_2 with the optical frequency in the bandwidth of the ultra short pulse.

To the first order, the dispersion is linear and we have obtained in our experiment a long pulse of duration $T_{opt} = 330$ fs (Fig. 4b) chirped inside a bandwidth $B_{opt} = 3.9$ THz ($\Delta\lambda = 8.3$ nm), i.e. $B_{opt}/T_{opt} = 11.8$ THz/ps, for a 112 fs incident pulse (Fig. 4a).

This long pulse must be recompressed by applying to the AO-PDF an acoustic pulse linearly chirped in a bandwidth $B_{ac} = 1.87 \times 10^{-7} B_{opt} = 0.73$ MHz, with a slope $B_{ac}/T_{ac} = 3.5 \times 10^{-14} B_{opt}/T_{opt} = 0.4$ MHz/μs, and with an acoustic intensity of approximately 0.35 W/mm^2. The experimental result is shown in Fig. 4c. It can be seen that the 330 fs pulse is almost compressed back to its original duration for a 0.35 MHz/μs acoustic slope, in good agreement with the theoretical prediction.

For a 70 fs pulse inside the oscillator, stretched to 108 fs at the output of the oscillator (Fig. 5a) by the dispersion of its mirrors and whose bandwidth is larger ($B_{opt} = 6.3$ THz, or $\Delta\lambda = 13.4$ nm), a 508 fs long pulse is obtained (Fig. 5b) that can only be recompressed to 160 fs using a linear acoustic ramp (Fig. 5c). In that case, the recompression cannot be complete since the larger bandwidth introduces orders of dispersion higher than the linear order, that cannot be compensated for by an acoustic linear chirp signal. To compensate for the higher orders, it is necessary to use acoustic nonlinear chirp signals. It is also the reason why the compressed signal (Fig. 5c) shows low pre- and post-pulses.

4. Conclusion

We have demonstrated the principle of group delay time dispersion compensation in laser systems using an acousto-optic programmable dispersive filter (AO-PDF) coupling two collinear and codirectional optical waves through an acoustic wave. An OA-PDF device utilizing a perfectly collinear interaction for the optical and acoustic wave vectors in lithium niobate or lead molybdate will allow for a larger group delay time dispersion compensation (compared to the TeO_2 device we have used in our experiment) in CPA laser chains and will lead to new laser system architectures delivering Fourier transformed femtosecond pulses.

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