Amplitude and phase control of ultrashort pulses by use of an acousto-optic programmable dispersive filter: pulse compression and shaping

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We demonstrate experimentally that an arbitrary phase and amplitude profile can be applied to an ultrashort pulse by use of an acousto-optic programmable dispersive filter (AOPDF). Our filter has a large group-delay range that extends over 3 ps and a 30% diffraction efficiency over 150 THz. Experiments were conducted on a kilohertz chirped-pulse amplification laser chain capable of generating 30-fs pulses without additional pulse shaping. Compensating for gain narrowing and residual phase errors with an AOPDF in place of the stretcher results in 17-fs transform-limited pulses. Arbitrary shaping of these 17-fs pulses is also demonstrated in both the temporal and the spectral domains.

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Femtosecond oscillators can routinely deliver nearly transform-limited sub-10-fs laser pulses. However, subsequent amplification in a chirped-pulse amplification (CPA) chain will result in a sometimes substantial lengthening of the output pulses owing to gain narrowing and uncompensated phase errors. Maintaining the short pulse duration after amplification calls for a programmable device that is capable of compensating for large amounts of dispersion over large spectral bandwidths while at the same time providing amplitude shaping with high contrast. Existing devices are generally employed in the Fourier plane of a zero-dispersion line. Spatial light modulators have been extensively studied[1,2] and were shown to provide useful pulse compression and shaping. Deformable mirrors[3] and acousto-optic deflectors have also been employed.[4] All these apparatuses require high-quality optical elements and are rather bulky.

The acousto-optic programmable dispersive filter (AOPDF) proposed by Tournois[5] can provide for large dispersion-compensation ranges. The AOPDF is based on a collinear acousto-optic interaction that maximizes the interaction length. The acoustic frequency is a variable function of time and provides control over the group delay of the diffracted optical pulse. Simultaneously, the spectral amplitude of the diffracted optical pulse is driven by the acoustic signal's intensity. A unique feature of the AOPDF is that it does not have to be positioned in the Fourier plane of a dispersion line. As we show below, the device is compact, and its implementation in an existing CPA laser chain requires only minor changes.

A schematic of the AOPDF is shown in Fig. 1. An acoustic wave is launched by a transducer excited by a temporal signal. The acoustic wave propagates with a velocity V along the z axis and hence reproduces spatially the temporal shape of the rf signal. It is well known[6] that two optical modes can be coupled efficiently by acousto-optic interaction only in the case of phase matching. If there is locally only one spatial frequency in the acoustic grating, then only one optical frequency can be diffracted at a position z. The incident optical short pulse is initially in mode 1. Every frequency ω travels a certain distance before it encounters a phase-matched spatial frequency in the acoustic grating. At this position $z(\omega)$, part of the energy is diffracted into mode 2. The pulse leaving the device at mode 2 will be made of all the spectral components that have been diffracted at various positions. If the velocities of the two modes are different, each frequency will see a different time delay. The amplitude of the output pulse, or diffraction efficiency, is controlled by the acoustic power at position $z(\omega)$. The optical output $E_{\mathrm{out}}(t)$ of the AOPDF is a function of the optical input $E_{\mathrm{in}}(t)$ and of the electric signal $S(t)$. More precisely, it has been shown[5] to be proportional to the convolution of the optical input and of the scaled electric signal:

$$E_{\mathrm{out}}(t) \propto E_{\mathrm{in}}(t) \otimes S(t/\alpha)\,, \tag{1}$$

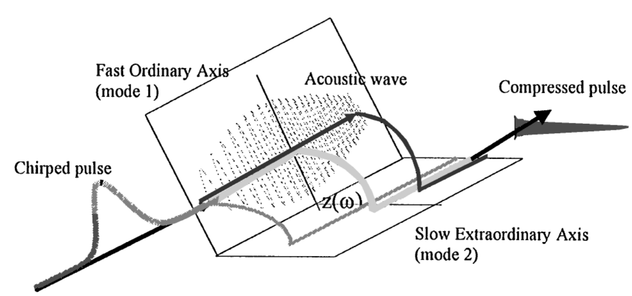

Fig. 1. Schematic of the AOPDF.

where the scaling factor

$$\alpha = \Delta n (V/c) \qquad (2)$$

is the ratio of the speed of sound to the speed of light times the index difference between the ordinary and the extraordinary waves. α is the ratio of the acoustic frequency to the optical frequency, and relation (1) can be written in the frequency domain as

$$E_{\mathrm{out}}(\omega) \propto E_{\mathrm{in}}(\omega) S(\alpha \omega)\,. \qquad (3)$$

In this formulation, $S(t/\alpha)$ appears as the impulse response of a filter applied to the input optical pulse. By generating a proper function $S(t)$ one can achieve any arbitrary convolution with a temporal resolution given by the inverse of the available filter bandwidth. We numerically compute the $S(t)$ function by defining its phase and amplitude and send it to the crystal. The acoustic wave is generated in the crystal by a piezoelectric transducer. The practical generation of acoustic signals was described in Ref. 7. The TeO_2 crystal is 2.5 cm long, the speed of sound V in the z direction is 1000 m/s, the index difference is $\Delta n = 0.04$, and the maximum achievable group delay is ~3 ps. The acoustic frequency that corresponds to diffraction at the 800-nm wavelength is 52.5 MHz, corresponding to approximately $\alpha = 10^{-7}$. The acoustic power is limited to 4 W, which results in a maximum diffraction efficiency of 30%. The transducer has a bandwidth larger than 20 MHz near 52.5 MHz, which translates into an optical bandwidth of 150 THz near 375 THz; the associated temporal resolution is then 6.7 fs, or 450 resolution points in the 3-ps group-delay range.

In CPA laser chains there are three major applications of a programmable filter such as the AOPDF. First, the filter permits precompensation for gain narrowing, through amplitude shaping before amplification. Second, it allows phase errors that arise from imperfect matching of the dispersions of the pulse-lengthening elements and the compressor to be corrected. As shown by the convolution formula [relation (1)], amplitude and phase can be controlled simultaneously and independently and will therefore permit the generation of shorter and Fourier transform-limited pulses. Third, the AOPDF can be used for rather arbitrary pulse shaping; e.g., multiple pulses can be generated that are well defined in both the spectral and the temporal domains, owing to perfect phase and amplitude control. The experiments presented in this Letter demonstrate the ability of the AOPDF as a pulse shaper to perform the tasks described above.

The experiments were conducted on a commercially available amplified femtosecond chain (Omega 1000; FemtoLasers GmbH). A mirror-dispersion-controlled Ti:sapphire oscillator (FemtoSource Pro; FemtoLasers GmbH) pumped by a diode-pumped frequency-doubled $Nd:YVO_4$ laser (Millenia; Spectra-Physics, Inc.) delivers sub-10-fs pulses at a 75-MHz repetition rate. Because of the broad bandwidth of the seed pulses (~120 nm FWHM) the material dispersion of a 10-cm-long SF57 glass block and a Faraday isolator is sufficient to stretch the pulses to more than 20 ps.[8] The excessive negative cubic phase introduced by a prism compressor is precompensated by 36 reflections onto specially designed chirped mirrors. The stretched pulse train is then injected into a nine-pass amplifier. A detailed description of the amplifier can be found in Ref. 8. Pumping the amplifier with 12 mJ of power from a lamp-pumped frequency-doubled Nd:YLF laser (620D-2 from Thomson-CSF laser/BMI) results in a pulse energy of slightly more than 1 mJ. The amplified pulses are compressed with a prism compressor consisting of two pairs of Brewster-angled fused-silica prisms separated by 5 m. The output pulses have an energy of 1 mJ, a pulse duration of 30 fs, and a spectral width of 35 nm (FWHM) and are delivered in a beam with 25-mm diameter.

To demonstrate the capabilities of the filter, we had to modify the amplifier slightly. The heavy flint glass block and the chirped mirrors were replaced by the AOPDF, and the prism separation in the compressor was reduced to 4 m. The material dispersion of the 2.5-cm-long TeO_2 crystal in the AOPDF ($12,500\ fs^2$) is comparable with the dispersion introduced by the heavy flint glass stretcher ($22,000\ fs^2$). High-order dispersion compensation is obtained with the AOPDF. Owing to the in-line geometry of the acousto-optic interaction, the output beam is roughly collinear to the input beam; therefore no major changes in the beam steering were required.

In a first step, amplitude control was demonstrated to overcome gain narrowing. To obtain a wider spectrum at the output, we convolved the seed pulse with a filter whose transfer function was a combination of a linear chirp ($1000\ fs^2$) and an amplitude mask that has a 200-nm-wide Gaussian shape and a transmission minimum at 800 nm. The linear chirp was added to help to stretch the pulses further. The resultant filter allowed us to compensate partly for gain narrowing, resulting in broadening of the amplified spectrum from 35 nm FWHM to 75 nm FWHM at the output at the CPA laser chain, as shown in Fig. 2. The transmission through the AOPDF was only 10% because the acoustic power was kept below its maximum value to prevent any heating of the filter. However, this reduced seed energy was sufficient for the same output characteristics to be achieved as with the higher seed energy for the standard setup. The achieved output pulses had an energy of ~1 mJ and showed no sign of any degradation as a result of nonlinear effects in the amplifier. This was possible even though the dispersion of the AOPDF was smaller than that of the heavy flint glass stretcher because the amplified bandwidth had been substantially increased. In a second step the output pulses were fully characterized by the frequency-resolved optical gating (FROG) technique. A fourth-order polynomial was fitted to the measured spectral phase. It was used to calculate the new transfer function for the filter, also permitting a correction for the residual phase error to be made. A comparison between the output of the uncorrected and of the corrected lasers is shown for amplitude and phase in Fig. 2. The final pulse has less than 2-rad

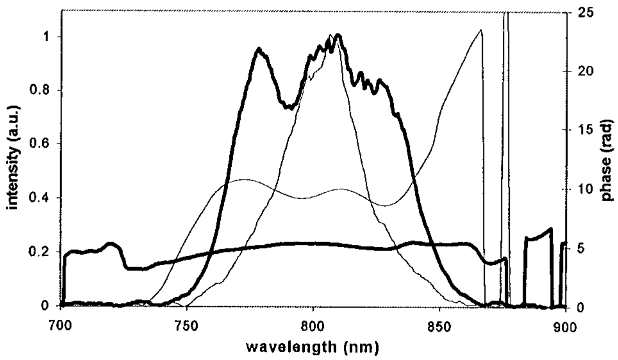

Fig. 2. FROG measurement of the output pulse before (thin curves) and after (thick curves) application of the filter.

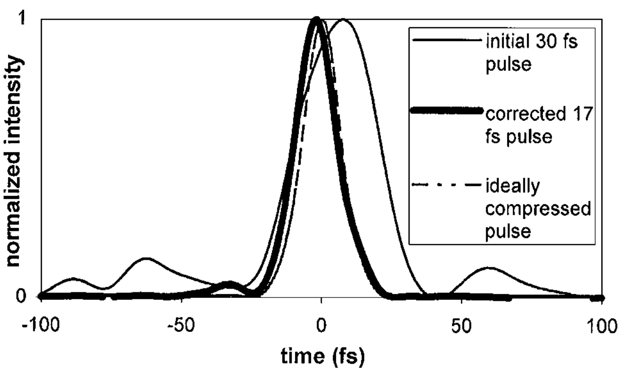

Fig. 3. Computed temporal intensity profiles.

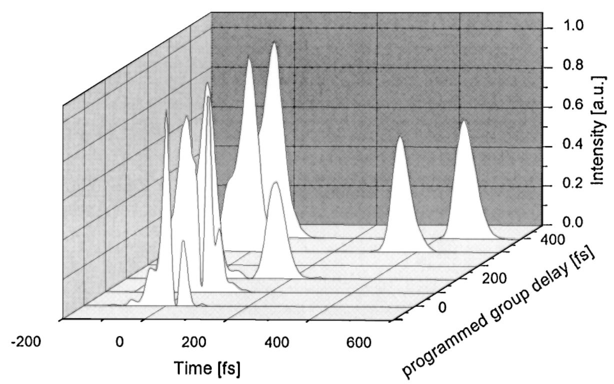

Fig. 4. FROG measurement of the generation of two pulses separated by a programmable delay.

phase distortion over 150 nm. The intensity profiles as computed from the FROG measurements are shown in Fig. 3. The estimated 17-fs FWHM duration of the corrected output pulse is close to the transform-limited pulse duration of 15.6 fs FWHM. An interferometric autocorrelation measurement (not shown here) also resulted in an estimated 17-fs FWHM duration.

In a final step, to illustrate the versatility of the AOPDF we performed pulse-shaping experiments. The filtering operation described by relation (1) or (3) gives some freedom for shaping the pulses in the time and frequency domains. For instance, the incoming pulse can be split into several pulses that are separated in both the spectral and the temporal domains. The separation in time is achieved by application of different group delays to different spectral components, and the spectral separation is obtained by amplitude shaping. Figure 4 shows such pulse-shaping results when a programmable delay has been introduced between two pulses. Note that the different additional group delays for the different frequency ranges and the additional amplitude shaping were added to the filter transfer function. In Fig. 4 it is clearly shown that the measured pulse separation is in good agreement with the desired separation. From this measurement it can be concluded that the realized filter behaves much as predicted by the theory and is linear over a broad group-delay range.

We have reported what is to our knowledge the first experimental implementation of an AOPDF in a CPA laser chain. Owing to independent and simultaneous control of amplitude and phase, we have been able to compensate for gain narrowing in the amplifier and for phase distortions of the whole laser chain. The resultant 17-fs FWHM amplified pulses are compressed to their transform limit. We further demonstrated the versatility of the AOPDF by performing pulse-shaping experiments. We believe that the large dynamic range, in the in-line geometry, the compactness, and the general convolution operation achieved by the AOPDF are unmatched by other pulse-control technologies available today.

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