# Single-iteration compression of femtosecond laser pulses

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We demonstrate a technique for correcting arbitrary spectral-phase aberrations in a single iteration with no reference pulse. By utilizing spectral-phase interferometry for direct electric field reconstruction and a programmable liquid-crystal spatial light modulator, we have achieved compression of complex pulse shapes from nearly picosecond extent down to 70 fs. © 2004 Optical Society of America

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Ultrafast lasers have seen tremendous growth in the past decade and are now found in laboratories throughout the world.[1] In parallel with the advances in laser systems, pulse-shaping devices have demonstrated their importance to the ultrafast community, particularly in the area of quantum control.[2,3] The broad spectrum of femtosecond pulses allows pulse-shaping techniques based on manipulating spectrally dispersed components. The use of a liquid-crystal spatial light modulator[4] (LC-SLM) in the Fourier plane of a "zero-dispersion pulse compressor" is a popular technique and is the one we employ here. Researchers have used such pulse shapers to iteratively search for optimum pulse shapes using feedback signals such as second-harmonic generation.[5,6] An alternative is to measure the complete electric field and then adjust the pulse accordingly. Such measurement techniques that characterize the amplitude *and* the phase of ultrashort pulses have also advanced rapidly. One technique, frequency-resolved optical gating[7] (FROG), uses an iterative method to return a time–frequency spectrogram of the optical pulse. FROG has been used in conjunction with deformable-mirror pulse shapers to correct for dispersion.[8] A variant of FROG, called temporal analysis by dispersing a pair of light e-fields,[9] uses a reference pulse to noniteratively recover the amplitude and phase and has been used to generate arbitrary pulse shapes in one or two iterations.[10] In a handsome demonstration recently by Garduño-Majía and coworkers, designer femtosecond pulses were achieved by combining a deformable-mirror membrane with FROG in a feedback loop to zero in on specified target spectral phases.[11] Their results indicate that combining pulse shaping and pulse measurement is possible in near real time to high accuracy.

A different technique that lends itself to directly recovering the spectral phase is spectral interferometry, whereby a modified ultrashort pulse is mixed with a reference pulse in a spectrometer. This technique has been used with a light-valve pulse shaper to obtain desired pulse shapes and to correct for dispersion.[12] A more recent technique for pulse characterization is spectral interferometry for direct electric field reconstruction[13] (SPIDER), which has the advantages of requiring no reference pulse and using a noniterative algorithm to retrieve the optical pulse.

In this paper, we report a method for correcting spectral-phase aberrations in a single iteration with no reference pulse. The technique uses a SPIDER apparatus to measure the spectral phase of an arbitrary ultrashort pulse and to send a corrective signal to a liquid-crystal spatial light modulator. Since both techniques operate on the spectral phase, they are ideally suited for one another. Two results are presented, one for correcting quadratic chirp, the second for correcting a complex phase profile.

Our apparatus is shown in Fig. 1. For this experiment, we are using a Ti:sapphire oscillator operating at 80 MHz with a center wavelength of 800 nm, a pulse duration of 70 fs, and an average power of 20 mW. The pulse travels first to the pulse shaper[14] shown in the upper portion of Fig. 1. It consists of a $4f$ zero-dispersion pulse compressor and a LC-SLM. The gratings used to disperse the spectral components have 1200 lines/mm, and the lenses have 10-cm focal lengths. The LC-SLM is placed at the Fourier plane of the $4f$ system and consists of two parallel polarizers and two 128-pixel liquid-crystal arrays, which are aligned pixel to pixel by the manufacturer (Cambridge Research SLM-256). This system provides for full amplitude and phase control over each spectral element, although in this experiment we are only shaping the spectral phase. (Note: With this system, it would be possible to adjust the spectral phase *and* the spectral amplitude in a single iteration, either by adding a second spectrometer to record the fundamental spectrum or by utilizing Dorrer's trick of measuring simultaneous interferograms.[15] In our experiment, we were power limited; thus we performed shaping on the spectral phase only, in which case a single LC would suffice.) The LC-SLM applies retardation to each spectral element without affecting the spectral intensity or the alignment. A second 10-cm lens and grating recombine the spectral components into the output beam.

The pulse then travels to our SPIDER apparatus (based on a design by Christophe Dorrer[16]) shown in the lower portion of Fig. 1. It operates by receiving an input

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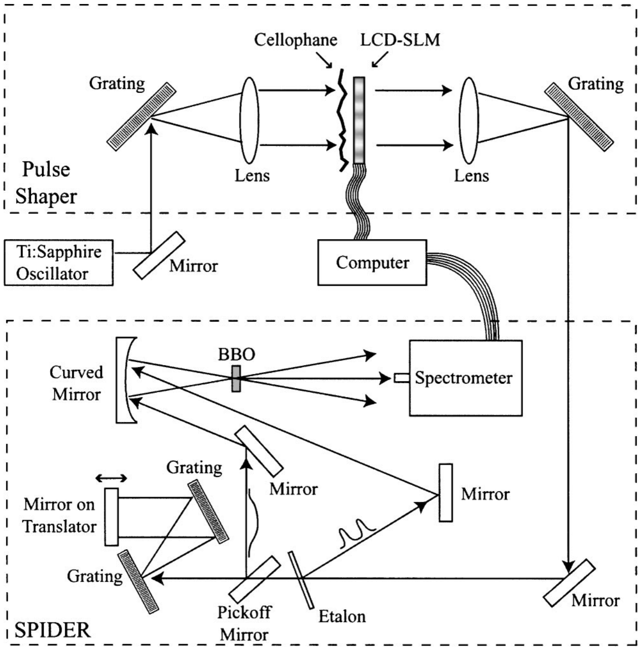

Fig. 1. Schematic of our apparatus with pulse shaper (top) and SPIDER (bottom).

pulse and immediately generating three pulses from the input. The input beam first passes through a thin etalon (microscope coverslip) to generate two reflections, one from each surface of the etalon, separated by 1.7 ps. The remainder of the input beam travels through the etalon to a grating-pair stretcher (actually a “compressor” in the typical ultrafast jargon, but equivalent to a stretcher with opposite sign of chirp). The beam diffracts from two gratings (1200 lines/mm, 7.5-cm separation) and reflects from a mirror mounted on a translation stage. This translation stage allows for temporal overlap of the pulses, but is not moved during the operation of SPIDER. The mirror is tilted down slightly so that a pick-off mirror can separate the return beam. The two beams (pulse pair and chirped pulse) travel parallel to one another to a spherical mirror ($R = 20\,\mathrm{cm}$) and are focused into a type I beta-barium borate nonlinear crystal (BBO), where upconversion takes place. The noncollinear geometry allows for easy separation of the upconverted beam, which now consists of two blue pulses (400 nm) separated in time and center frequency (because they are generated from different spectral components of the chirped pulse). This beam is then sent into our spectrometer (Ocean Optics USB 2000), where it produces a spectral interferogram, or “Spidergram.” This Spidergram contains the spectral-phase information, and through a series of numerical Fourier transforms and filters, the spectral-phase information is recovered. Details of this inversion can be found in Iaconis and Walmsley.[17] This process is direct and noniterative, and requires no knowledge of the input pulse. Together with the spectrum of the pulse, the complete pulse information is therefore known, and the pulse can be represented in either the frequency or the time domain. Once the computer has recovered the spectral phase, it instructs the LC-SLM to add the inverse of this to the pulse, thereby flattening the overall spectral phase.

For optimum performance from this system, there are two key elements that must be addressed: (1) SPIDER must accurately record the spectral phase, and (2) the LC-SLM must accurately apply the inverse of this phase. With SPIDER, it is critical to do a proper calibration by measuring an accurate reference phase, which corresponds to knowing the pulse-pair temporal separation and the stretched pulse chirp. However, once this reference phase has been measured, no further calibrations are needed. To verify the accuracy of our calibrated SPIDER, we measured several pulses with varying chirps and compared SPIDER’s measurements to an independent autocorrelation measurement (Del Mar Ventures AA-10D). The temporal profiles agreed to roughly 3%. SPIDER is also quite sensitive to spatial chirp on the input pulse, and therefore the $4f$ system must be carefully aligned to minimize spatial chirp on its output pulse. An excellent recipe is given by Weiner.[14]

The LC-SLM has two key calibrations. First, for each LC element, we need to calibrate the retardance as a function of applied voltage. This was performed in a previous step. The second calibration involves identifying which wavelength components are passing through each LC element. This calibration must be done with any change to the alignment of the pulse shaper. To address this issue, Dorrer and Salin[18] used phase jumps to calibrate the spectral positioning of their pulse shaper. Since in our device we have both phase and amplitude control, we are able to use spectral-amplitude notches to achieve proper calibration.

When passing the spectral phase from SPIDER to the LC-SLM, there are two adjustments that must be made. The first is to reindex the phase versus wavelength array from SPIDER to the pixel versus wavelength calibration of the LC-SLM, since each has a different spacing for the discrete wavelengths. The second adjustment involves correcting for linear phase terms in SPIDER. Since SPIDER is insensitive to linear phase (a linear phase amounts to a temporal shift of the pulse), the recovered spectral phase can have arbitrary linear phase terms. These are computationally removed to prevent the LC-SLM from reaching the limit of its phase retardation range (at 800 nm, this amounts to roughly $8\pi$).

Once the system was operational and calibrated, we tested its performance by deliberately adding a small amount of positive or negative quadratic phase. To achieve this, we misaligned the zero-dispersion compressor by moving the second grating closer or farther from the optimum $4f$ position. The resultant pulses were temporally chirped, and SPIDER’s results agreed very well with the independent autocorrelation. An example of correcting for positive chirp is shown in Fig. 2. Figure 2(a) shows the phase and the spectrum of the pulse with the misaligned grating. The inset shows the temporal profile with a FWHM pulse duration of 176 fs. This spectral phase was recovered by the computer’s SPIDER algorithm, which then instructed the LC-SLM to apply the inverse of this phase to the optical pulse, i.e., a negative quadratic phase. (The grating was not touched.) After correction, we again measured the pulse with SPIDER and obtained the flat spectral phase shown in Fig. 2(b). The temporal profile has been compressed to 70 fs. We should note that the spectral window for this correction was 785 nm to 815 nm, which is clearly evident in Fig. 2(b). We performed a second experiment with the grating translated in the opposite direction to generate a negative quadratic chirp, and the results were nearly identical. All temporal profiles agreed very well with the independent autocorrelation measurements.

To test this procedure on a more complicated phase profile, we inserted a phase plate just before the SLM. In this case, our phase plate consisted of a wrinkled piece of cellophane, shown in Fig. 1. The cellophane did little to disturb the spectrum of the pulse but had a strong effect on the spectral phase, shown in Fig. 3(a).[19] The inset of Fig. 3(a) shows the temporal intensity, which has multiple peaks over a time window of nearly one picosecond. This pulse also had reasonable agreement with the independent autocorrelation trace. The same procedure for correction was applied. The corrected pulse, shown in Fig. 3(b), has considerably flatter spectral phase over the spectral window, and the temporal profile is again restored to a fairly clean 70-fs pulse. This single iteration took roughly 30 s owing to a number of technical inefficiencies (we were using two computers because of a hardware incompatibility between the spectrometer and the SLM), but there is nothing to prevent this from operating in real time.

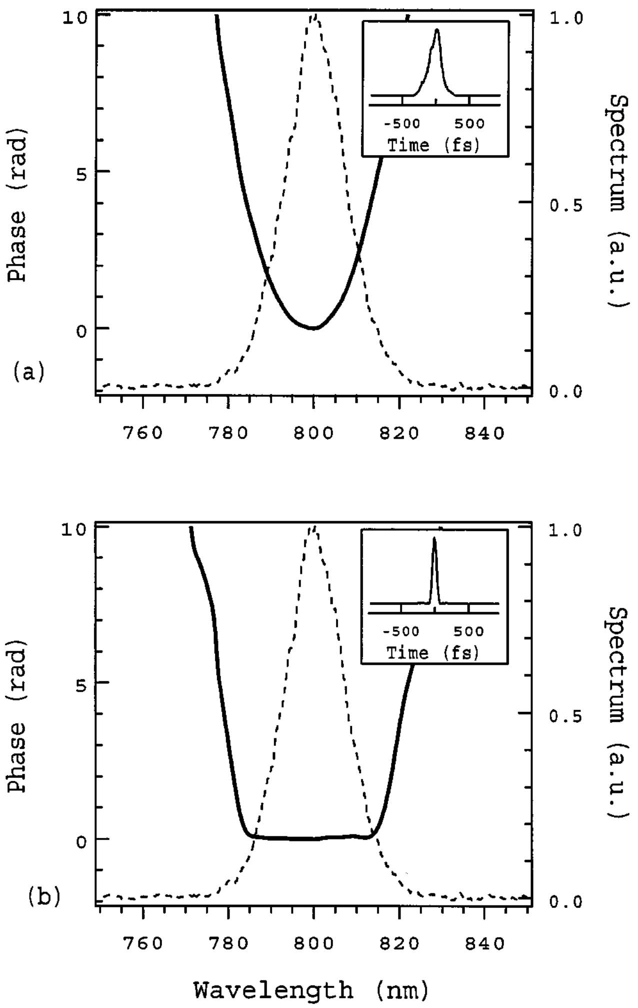

Fig. 2. Spectral phase (solid curve) and spectrum (dashed curve) of our laser pulse with a misaligned stretcher (a) before correction and (b) after correction. The inset shows the corresponding temporal intensity calculated from SPIDER.

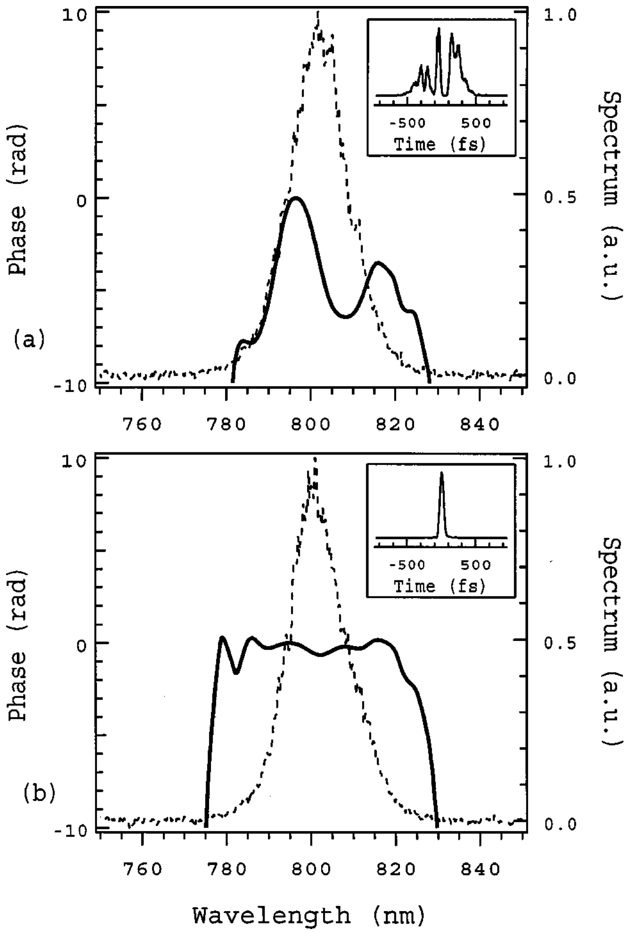

Fig. 3. Spectral phase (solid curve) and spectrum (dashed curve) of our laser pulse passing through cellophane (a) before correction and (b) after correction. The inset shows the corresponding temporal intensity calculated from SPIDER.

A number of demonstrations of adaptive pulse optimization have been presented in the literature. These have the benefit of not requiring an accurate calibration, since the pulse shaper will adjust itself automatically to maximize the feedback signal. With nonadaptive optimization such as demonstrated here, calibration of spectral components is critical to achieving the desired pulse shape. However, once calibrated, the system performs consistently well. In summary, we have demonstrated a technique for correcting spectral-phase aberrations of femtosecond pulses with a single iteration and no reference pulse using SPIDER and a LC-SLM. Single-iteration correction is ideal for a number of applications, particularly for extremely high-energy lasers where the repetition rates can approach one shot per hour or slower. We also note that our experiment was performed with an oscillator operating at 80 MHz; thus the SPIDER measurement averaged over many pulses. In principle, however, there is nothing keeping this procedure from being single shot, since SPIDER can operate on a single-shot basis.[20] The first shot of the laser would indicate the unwanted spectral phase, the computer would adjust the SLM, and the second shot of the laser would be corrected. Thanks to SPIDER's having no moving parts, it is capable of working at speeds up to 1 kHz,[21] and the LC pixels in the SLM-256 have a quoted capability of changing retardance in less than 1 ms (although the interface from computer to SLM was much slower than this in our apparatus). Another class of pulse shapers, based on acoustooptic modulators,[22] is capable of even faster update rates. Thus there is no reason to think that single-iteration correction at kilohertz rates is not attainable in the near future.

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