Single-shot autocorrelator based on a Babinet compensator

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A compact, single-shot, second-harmonic autocorrelator for ultrashort laser pulse measurements is presented. The autocorrelator uses a Babinet compensator to split the pulse to be measured into two replicas with a relative delay between them varying across the beam. It consists of a few optical elements only, requires no sensitive alignment, and offers a robust diagnostics tool for low repetition rate femtosecond laser amplifiers.
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Although methods for complete ultrashort laser pulse diagnostics, such as, for example, FROG[1] and SPIDER[2] are now available, the intensity autocorrelation measurement remains a valuable tool for diagnostics and maintenance of many femtosecond systems because of its simplicity and robustness. In multipass or regenerative femtosecond laser amplifiers with a repetition rate below 1 kHz, single-shot second-harmonic autocorrelators provide a convenient real-time diagnostics tool and are commonly used.

In a single-shot autocorrelator, two replicas of the pulse to be measured overlap in a nonlinear crystal in which the sum frequency (second harmonic) is generated. If the delay between the pulses varies with position along the axis perpendicular to the pulse propagation direction, the intensity autocorrelation function is mapped into the spatial intensity distribution of the sum frequency beam at the output face of the crystal. A classical optical system providing such an arrangement consists of a beam splitter and a set of mirrors that steer the two beams of pulses so that they cross at a small angle in a nonlinear crystal. However, in such a setup, there are three sensitive degrees of freedom, namely the beams spatial overlap and the relative delay between the pulse replicas. This deficiency of a single-shot autocorrelator can be overcome, for example, by use of a Fresnel biprism.[3]

Two pulse replicas necessary in any autocorrelator can be obtained in another way. In Ref. 4, an interferometric autocorrelator containing two birefringent plates was demonstrated. One of the plates was rotated (swung) to provide a time-varying delay between two pulse replicas with perpendicular polarizations formed in the other plate. In Ref. 5, a Wollaston prism was used to split the laser beam into two spatially separated parts with mutually perpendicular polarizations. The variable delay was achieved by scanning the prism in the direction perpendicular to the beams. Finally, the two pulses overlapped on the light-emitting diode surface that served as a nonlinear (quadratic) response detector. Both setups are suitable for high repetition rate sources such as Ti:Sapphire oscillators.

The use of polarization separation in a single-shot autocorrelation measurement was demonstrated in Ref. 6. In a rather complex experimental setup, the pulses were split by a Wollaston prism and after traveling separate paths they were overlapped in the nonlinear crystal for second-harmonic generation. The tilted pulse fronts provided an additional increase in the time range. In this design, a significant number of optical elements introduce a material dispersion that limits its use to pulses with a duration of the order of 100 fs. A Wollaston prism was also used for the separation of two polarization components of the laser beam in Ref. 7. The pulses subsequently generated second harmonic in a thick (i.e., with the thickness limiting the conversion bandwidth below the pulse spectral width) nonlinear crystal. From the recorded two-dimensional trace—a sonogram—the complete pulse electric field can be reconstructed in the generalized projections inversion algorithm.

In this article, we describe a simple single-shot autocorrelator with the minimum number of elements. With no sensitive degrees of alignment and a compact design, it provides a convenient real-time diagnostics of femtosecond laser pulses from low repetition rate amplifier systems.

A schematic of the autocorrelator is presented in Fig. 1. The beam of pulses passes through a pair of wedges made of a birefringent material forming a Babinet compensator. The optic axis of each wedge is perpendicular to the beam propagation direction and the axes of the two wedges are perpendicular to each other. As is well known from an elementary course in optics,[8] the Babinet compensator introduces a variable phase shift between two perpendicular polarizations. It is easy to show that it provides also a variable delay between two perpendicular polarizations in the beam. For the input beam, linearly polarized at 45° with respect to the optic axes of the wedges, each pulse is split into two replicas with equal intensities and perpendicular polarizations, and the delay τ between these two varies with position as

$$\tau = 2\left|\frac{1}{\nu_g^o} - \frac{1}{\nu_g^e}\right| x \tan\alpha,$$

where ν_g^o and ν_g^e denote group velocities of the pulses propagating as ordinary and extraordinary waves, respectively, x is the position measured from the symmetry plane, and α is the wedge angle.

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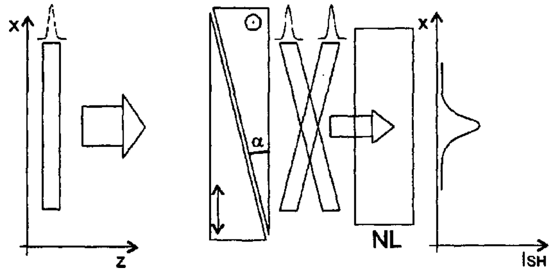

FIG. 1. A single shot autocorrelator based on a Babinet compensator. A set of two birefringent wedges with perpendicular optic axes (indicated by arrows) provides a delay between two pulse replicas that varies linearly with position x. Second-harmonic intensity I_{SH} distribution generated in type-II process in the nonlinear crystal is proportional to the intensity autocorrelation.

If the two pulses fall on a nonlinear crystal cut for type-II second-harmonic generation (and oriented in such a way that one pulse propagates as an ordinary and the other as an extraordinary wave), the resulting spatial distribution (along the x direction) of the sum frequency is proportional to the intensity autocorrelation.

In our autocorrelator, the wedges were made of calcite with the angle $\alpha=7°$ which gives a 148 fs/mm delay at 800 nm measured at the output face of the nonlinear crystal. In order to increase the sensitivity of the device, a thin fused silica cylindrical lens of 100 mm focal length was placed in front of the wedges and focused the beams to a line along the x direction on a 100 μm thick type-II beta-barium borate (BBO) crystal placed just after the wedges. The second harmonic generated in the crystal was spectrally filtered with a color glass filter to remove the fundamental wave and the crystal output surface was imaged with a spherical lens ($f=100$ mm) on a charge coupled device (CCD) camera connected to an eight-bit frame grabber in a personal computer.

Time calibration of the autocorrelator can be easily deduced from the calculated delay versus the position at the output face of the crystal and the magnification of the imaging lens. We have chosen another direct method of calibration in which the knowledge of the magnification factor is not required. A crystalline quartz plane-parallel plate of a known thickness (1.4 mm in our case) was placed in the input beam. The plate had the optic axis parallel to its surface and the autocorrelation trace was recorded for two orientations of the optic axis: 45° and −45° relative to the laser beam polarization (i.e., parallel and perpendicular to the x direction). The two measurements differ by $\Delta\tau=2|L/\nu_g^o-L/\nu_g^e|$ in an additional delay introduced between the two pulses by the plate, where ν_g^o and ν_g^e are group velocities of ordinary and extraordinary waves in quartz and L is the plate thickness. This delay results in the shift of the autocorrelation trace by $\Delta\tau=83$ fs, as calculated for our plate, and this value was used for calibration.

To test the setup performance, we used our autocorrelator to measure 800 nm pulses from a commercial kilohertz regenerative amplifier (Alpha 1000, BMI, France) seeded with a home-built Ti:Sapphire oscillator. We also measured the same pulses with a scanning autocorrelator with a stepper motor driven translation stage and a 100 μm thick type-I BBO. The results of both measurements are presented in Fig. 2. The overall agreement of the measured autocorrelation shapes is good. The small discrepancy present in the low intensity wings may result from the spectral phase accumulated in different optical components (e.g., neutral density filters) used in the two measurements.

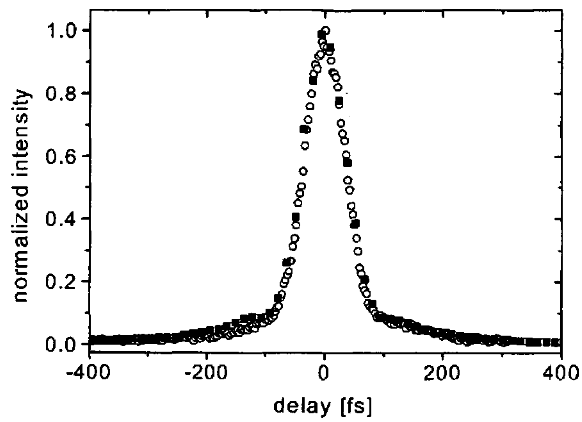

FIG. 2. Intensity autocorrelation of 55 fs laser pulses from a regenerative amplifier measured with the new single-shot autocorrelator (open circles) and with a standard scanning second-harmonic autocorrelator (filled squares).

For a given birefringent material, the time range of the autocorrelator is given by the wedge angle and the crystal size. With a fixed aperture of the nonlinear crystal, the maximum delay is proportional to the tangent of the wedge angle and thus to the total thickness of the wedges set. On the other hand, the time resolution is determined by diffraction effects in the nonlinear crystal and the resolution of the imaging part (the imaging lens and the camera), the latter being dominant in our setup.

We chose the wedge angle so as to obtain the delay range of about 800 fs with 5 mm BBO crystal aperture. One has to remember that the Babinet compensator itself introduces spectral phase leading to pulse distortion. We have estimated that in our setup, pulse lengthening is approximately 0.1% for transform limited Gaussian 55 fs full width at half maximum (FWHM) pulses and does not exceed 6% in the case of 20 fs pulses. For even shorter pulses, the smaller wedge angle may be chosen to maintain the pulse distortion at the desired level and still provide the necessary time range. We have derived a useful "rule of thumb" for Gaussian transform limited pulses and for calcite wedges. It reads that if 2% lengthening of the measured pulse is acceptable then the ratio (autocorrelator delay range)/(pulse duration FWHM) is equal to pulse duration (FWHM) given in fs.

It is worth stressing that our autocorrelator exhibits very little sensitivity both to the alignment of its components and to the input beam direction. If the incident beam of pulses is tilted, this will only affect the autocorrelator delay calibration. We calculated that for a tilt as large as 5° in any direction, the delay calibration changes less than 3%.

The idea of polarization separation can be applied to the construction of an even simpler autocorrelator in which two-photon absorption in a suitable material (e.g., dye) replaces second-harmonic generation in a nonlinear crystal as the method providing the necessary detection scheme with a quadratic response in the light intensity. A possible construction of such an autocorrelator would involve a dye layer (in a liquid or solid solvent) placed right after the wedges (e.g., as a direct coating on the wedge surface) and a filter absorbing the fundamental wavelength of the laser and transmitting the dye fluorescence light. In this case, there is no need for the imaging optics—the CCD chip of the camera can be placed in close proximity to the dye-filter sandwich. For such a setup, a 3:1 peak-to-background ratio in the autocorrelation would result instead of the background-free signal observed for type-II second-harmonic generation.

In conclusion, a simple autocorrelator for femtosecond laser pulses was designed and tested with pulses from a regenerative amplifier. To the best of our knowledge, the autocorrelator we constructed contains fewer components than any design presented so far. The components: A cylindrical lens, two calcite wedges, a nonlinear crystal, and a camera—of which only the first two may affect the measured pulse—have no sensitive degrees of freedom in alignment. This makes our apparatus a robust, useful, and reliable tool for low repetition rate laser systems.

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