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. © 2004 American Institute of Physics.

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Although methods for complete ultrashort laser pulse diagnostics, such as, for example, FROG and SPIDER 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.

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, 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 (between these two varies with position as

\[ \tau = 2 \frac{1}{\nu_g} \frac{1}{\nu_e} x \tan \alpha, \]

where \( \nu_g \) and \( \nu_e \) denote group velocities of the pulses propagating as ordinary and extraordinary waves, respectively, \( x \) is the position measured from the symmetry plane, and \( \alpha \) is the wedge angle.
The results of both measurements are presented in color glass filter to remove the fundamental wave and the monic generated in the crystal was spectrally filtered with a 5 mm aperture. The delay calibration changes less than 3%. For a given birefringent material, 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 construc-
tion 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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8 See, for example, E. Hecht, Optics, 2nd ed. (Addison–Wesley, Reading, MA, 1987).