Ultracompact autocorrelator for femtosecond laser pulses

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We present a novel optical and mechanical design of an autocorrelator which allows unmatched compactness. The device, capable of measuring laser pulses in the femtosecond regime, consists of the minimum number of elements, resulting in little distortion in pulse shape. A Mach–Zehnder interferometer provides operation for a wide range of input beam directions, making this autocorrelator a reliable tool for femtosecond lasers diagnostics. [DOI: 10.1063/1.1351833]

In the last decade Ti:sapphire Kerr lens mode-locked lasers have become the most popular source of femtosecond pulses in many laboratories all over the world. Although commercially available diode-pumped systems provide excellent long-term stability, there is still a need for fast and reliable laser pulse diagnostics. Two methods, now commonly used, capable of complete electric field characterization (FROG[1] and SPIDER[2]) require complex setups and mathematical retrieving procedures. Although interferometric autocorrelation measurement cannot provide complete information on the electric field amplitude and phase, it still allows pulse duration estimation. The chirp magnitude can also be qualitatively deduced.[3]

Each autocorrelator consists of two parts: an optical arrangement forming two pulse replicas with adjustable delay between them and a detector with a nonlinear response to the incident light intensity. Here we limit ourselves to detectors with a quadratic dependence (i.e., those for which the signal is proportional to the intensity squared). If the detector signal is recorded as a function of the delay between two replicas, we get the so-called second order interferometric autocorrelation function $S(\tau)$:

$$S(\tau)=\int_{-\infty}^{+\infty}\left|[E(t)+E(t+\tau)]^2\right|^2 dt, \tag{1}$$

where τ is the time delay between the two pulse replicas and $E(t)$ is the pulse electric field. The time integration appears due to slow detector response.

Since the laser pulse duration reached the femtosecond region, far below the resolution of any purely electronic devices, many designs have been proposed for autocorrelators.[4–7] While addressing the new one, described in detail below, the following aspects were taken into account:

(1) the device should be as compact as possible to be easily set in any part of the experimental setup where space is often tight;
(2) preferably with no precise alignment required, either internal (of the components) or external (of the input beam position and direction);
(3) the distortion in the measured pulse phase should be reduced to the minimum;
(4) no computer control–autocorrelation function to be displayed on an oscilloscope;
(5) ''real time'' readout (at least a 10 Hz refresh rate for comfortable operation).

As for the time range, it should cover the typical pulse duration from Ti:sapphire lasers, i.e., between around 10 and 100 fs.

A schematic of our autocorrelator optical arrangement based on the Mach–Zehnder interferometer is presented in Fig. 1. Such a setup has several advantages over the commonly used Michelson interferometer. The same number of reflections in both arms means that the output beams are parallel for any direction and position of the input beam. The retroreflected beam disturbing laser operation, a serious problem in Michelson-based designs, is eliminated. A reduced number of optical elements results in low losses on the mirrors and little pulse distortion due to dispersion. As both arms are identical, there is no need for any additional compensating elements.

In a previously proposed autocorrelator[8] the variable delay was realized by a rotating glass plate. In such a design, also used in many commercially available devices, the plate itself limits the resolution of the autocorrelation measurement by introducing additional phase distortions. In the present setup, the delay between pulses traveling in two interferometer arms is varied by rotating the bar with one of the beamsplitters and the mirror attached to it. The bar does not need to rotate the full circle. Instead, it is mounted on a flat spring and it oscillates with its own mechanical resonance frequency. The oscillations are driven by a small electromagnet supplied with alternate current. Using the oscillatory motion allows us to make the autocorrelator much smaller than was possible with the rotating bar.

The output beams are focused on the junction of a red light-emitting diode (LED) that serves as a nonlinear detector. Properties of light emitting diodes for autocorrelation measurement have been studied extensively.[9,10] The diode is much smaller and cheaper than the ''nonlinear crystal + photomultiplier tube'' (PMT) setup commonly used in autocorrelators. It is also insensitive to the input beam polarization and provides a large bandwidth. A red (660 nm peak

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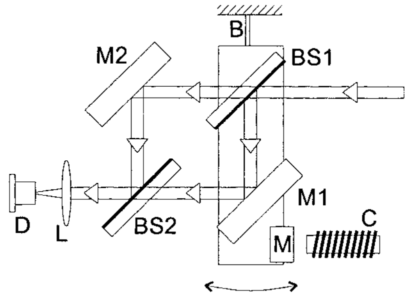

FIG. 1. Schematic of the autocorrelator design. Mirrors M1 and M2 together with beamsplitters BS1 and BS2 form a Mach–Zehnder interferometer. The path length difference between pulses traveling in two arms is varied by oscillating the bar on which BS1 and M1 are mounted. By changing the spring B, the desired resonance frequency can be set. Oscillations are driven by alternating current supplied to coil C interacting with magnet M. The beams are focused with lens L on a light-emitting diode D.

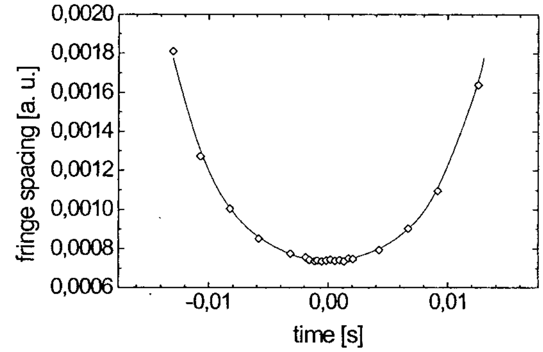

FIG. 2. Measured (points) and calculated (line) fringe spacing vs time. Time zero was chosen at the equilibrium position of the oscillating bar. The fringe spacing is constant to within 2% for times between −1.8 and 1.8 ms corresponding to a delay range of 140 fs. For nonlinearity of 4%, the delay range is 180 fs.

emission) AlGaAs LED turned out to be suitable for 800 nm pulses from a Ti:sapphire laser. By changing the diode type one can easily switch between different spectral regions. The diode junction dimensions are important for autocorrelator performance. Large junction area results in a wider usable angle range of the input beam, thus making the alignment of the whole setup easier. On the other hand, the capacitance of the diode junction should be as low as possible to minimize the RC constant in the current measurement. The diode current is displayed on the oscilloscope without amplification.

The whole device is contained in a $8\times5\times2\ cm^3$ box. In principle these dimensions could be reduced even further with the only limit imposed by the laser beam diameter.

The first step during the calibration of the autocorrelator was to measure the properties of the variable delay. The frequency of the square wave driving the electromagnet coil was chosen so as to tune to the mechanical resonance (14 Hz). The amplitude of the oscillations measured at mirror M1 was around 2 mm. The LED was replaced with a silicone photodiode and a Ti:sapphire laser was run in the continuous wave (cw) regime. The photodiode output corresponding to the whole period of oscillations was recorded on a digitizing oscilloscope. From such a record, two things can be found: whether the oscillating mirror provides parallel beams at the interferometer output (which is a necessary condition for interferometric autocorrelation measurement) and what is the nonlinearity (deviation from linear delay versus time dependence). By measuring the fringe visibility throughout the whole period, one can get information on the angle between two beams (for parallel beams the visibility equals one). The fringe spacing measured as a function of the mirror's distance from the equilibrium position (where one expects to have a linear delay versus time dependence) allows one to estimate the nonlinearity. The results are presented in Fig. 2 together with theoretical calculation assuming single-frequency oscillations at 14 Hz.

If nonlinearity of 2% is acceptable, the time range is 140 fs and for 4% it increases to 180 fs. The measured fringe visibility was above 0.9 for the whole period.

The time range can be increased in two ways: the amplitude of the oscillations could be increased or the nonlinearity (which can be accurately measured) can be corrected for. For higher amplitudes, we observed undesired modes of oscillations (such as twisting) to arise. The other solution would require computer data processing or dedicated electronics.

If the small size of the autocorrelator is not so important, one can also use a rotating bar instead of the oscillating one. This extends the delay range significantly,[11] preserving all the advantages of the Mach–Zehnder arrangement mentioned above.

A typical autocorrelation measured for pulses from a home-built Ti:sapphire laser is shown in Fig. 3. Fringes are clearly resolved and the peak-to-background ratio is 8:1, in agreement with formula (1).

Concluding, we have presented an ultracompact autocorrelator that consists of the minimum number of elements while still satisfies the condition of parallel output beams and equal path lengths (thus constant delay) independent of input beam direction and position. The Mach–Zehnder arrangement is especially suitable for really short pulses (of below 10 fs duration) where any dispersive element, such as a rotating glass plate, may lead to severe phase distortions. The new design presented here will not replace the traditional scanning Michelson-based autocorrelators with their long

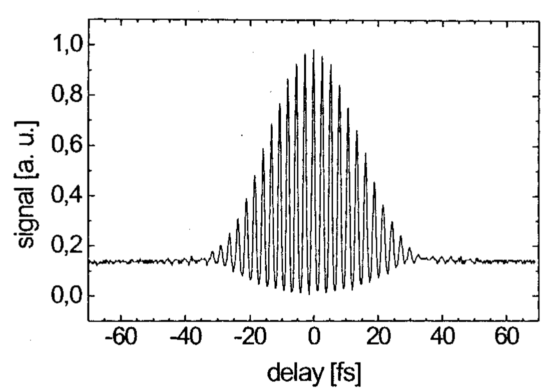

FIG. 3. Autocorrelation function recorded for 800 nm centered pulses from a Kerr lens mode-locked Ti:sapphire laser. The pulse duration full width at half maximum (FWHM) is 22 fs assuming a $sech^2$ shape.

time range (up to picoseconds) and linearity better than 0.001 easily achieved. Still, it has proved to be a useful tool in everyday femtosecond laser maintenance and operation as well as during setting up different experiments where one needs to the minimize pulse duration after propagation through dispersive elements (lenses, windows).

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[1] R. Trebino and D. J. Kane, J. Opt. Soc. Am. A **10**, 1101 (1993).
[2] C. Iaconis and I. A. Walmsley, Opt. Lett. **23**, 792 (1998).
[3] J.-C. M. Diels, J. J. Fontaine, I. C. McMichael, and F. Simoni, Appl. Opt. **24**, 1270 (1985).
[4] Z. A. Yasa and N. M. Amer, Opt. Commun. **36**, 406 (1981).
[5] P. Myslinski, Rev. Sci. Instrum. **58**, 711 (1987).
[6] G. Xinan, M. Lambsdorff, J. Kuhl, and W. Biachang, Rev. Sci. Instrum. **59**, 2088 (1988).
[7] J. A. I. Oksanen, V. M. Helenius, and J. E. I. Korppi-Tommola, Rev. Sci. Instrum. **64**, 2706 (1993).
[8] P. Wasylczyk, Optica Applicata **30**, 121 (2000).
[9] J. K. Ranka, A. Gaeta, A. Baltuska, M. S. Pshenichnikov, and D. A. Wiersma, Opt. Lett. **22**, 1344 (1997).
[10] D. T. Reid, M. Padgett, C. McGowan, W. E. Sleat, and W. Sibbett, Opt. Lett. **22**, 233 (1997).
[11] D. M. Riffe and A. J. Sabbah, Rev. Sci. Instrum. **69**, 3099 (1998).