Interferometric correlation of infrared femtosecond pulses with two-photon conductivity in a silicon CCD

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We present an experimental setup capable of performing a single-shot interferometric correlation of femtosecond pulses using two-photon conductivity in a standard silicon CCD camera. The method is demonstrated with 100-fs pulses at 1.4 μm. © 2002 Optical Society of America

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1. Introduction

Interferometric correlation of ultrashort laser pulses is one of the first techniques introduced to extract information about the complex amplitude of an ultrafast optical waveform.[1,2] Owing to its experimental simplicity in comparison with other phase-sensitive techniques, the interferometric correlation method is one of the most commonly used techniques for the characterization of ultrashort laser pulses. Although a complete phase characterization of the ultrashort waveform requires a complex iterative processing of the measured interferometric correlation function,[2] a simple phase function such as a linear chirp can be inferred easily from the characteristic form of the correlation trace. The correlation function of an ultrashort laser pulse commonly is produced through sum-frequency generation in a nonlinear optical crystal.[1] However, this method becomes less effective for the characterization of broadband optical signals, because the efficiency of the wave-mixing process is affected by the nonuniformity of the phase matching across the spectral bandwidth of the measured signal. To overcome this, researchers have introduced methods based on two-photon absorption in semiconductor materials and photodetectors.[3–7] The characterization of femtosecond pulses employing two-photon absorption in semiconductor photodetectors has a number of advantages over the methods that are based on nonlinear wave mixing: (i) semiconductor materials exhibit a nonlinear response in a wide optical-frequency range below the bandgap, allowing the detection of extremely broadband optical signals without the limitations imposed by the phase-matching process[6]; (ii) free electrons that are generated in the process of nonlinear absorption in a semiconductor photodetector are converted to an electrical current directly, simplifying the detection process; and finally (iii) when semiconductor detector arrays are used, simple and reliable single-shot characterization systems can be constructed.

In recent years numerous photodetectors have been used to perform both interferometric and intensity correlations of ultrashort laser pulses (see review in Ref. 8). The most commonly used apparatus is based on a delay-line autocorrelator, which uses mechanical scanning in order to record a multishot correlation trace but is therefore incapable of making a single-shot measurement. Arrays of semiconductor photodetectors[3,5] have been used to perform single-shot intensity autocorrelation measurements, but to the best of our knowledge no single-shot interferometric correlator based on nonlinear absorption in photodetectors has been reported. In this paper we present an experimental setup capable of implementing a single-shot interferometric correlation of femtosecond pulses in the infrared region using two-photon conductivity in a standard silicon CCD. We demonstrate the operation of the apparatus using 100-fs pulses from the optical parametric amplifier (OPA) operating at 1.4 μm.

The interferometric correlation of an ultrashort la-

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ser pulse can be obtained through an introduction of the signal into a Michelson or Mach–Zehnder interferometer with a nonlinear detector (a combination of a nonlinear medium and an intensity detector) at the output.[1] The electric field at the output of the interferometer is a superposition of the two replicas of the input signal with a relative time delay τ:

$$E(t, \tau) = \mathscr{E}(t - \tau)\exp[i\omega(t - \tau)] + \mathscr{E}(t)\exp(i\omega t), \tag{1}$$

where $\mathscr{E}(t)\exp(i\omega t)$ is the complex amplitude of the input field at a carrier frequency ω. The nonlinear medium responds to the square of the optical field $E(t, \tau)^2$, which is integrated in time by an intensity detector, yielding the interferometric correlation

$$I(\tau) \sim \int_{-\infty}^{\infty} |\{\mathscr{E}(t - \tau)\exp[i\omega(t - \tau)] + \mathscr{E}(t)\exp(i\omega t)\}^2|^2 \, dt. \tag{2}$$

The background value of the interferometric correlation is obtained from Eq. (2), when it is evaluated at large time delays τ, yielding $I(\infty) = 2 \int |\mathscr{E}(t)|^4 \, dt$. The maximum value of $16 \int |\mathscr{E}(t)|^4 \, dt$ occurs at time delay $\tau = 0$, giving an 8:1 peak-to-background ratio in the correlation trace. This property is useful in the testing of the validity of the experimental implementation of the interferometric correlation.

The phase sensitivity of the interferometric correlation technique can be best described by considering, for example, a linearly chirped pulse. Since the leading and trailing edges of the chirped pulse contain different frequency components, they will not interfere with each other, and the correlation trace $I(\tau)$ will not display the interference fringes for the large values of time delay τ when the leading edge of the pulse overlaps its trailing edge. Therefore the interferometric correlation of a linearly chirped pulse will be characterized by an interference pattern that is narrower than the width of the pulse-intensity autocorrelation. For linearly chirped Gaussian pulses, $I(\tau)$ can be calculated analytically, and the chirp value can be found by measuring the width of the fringe pattern.[1]

An efficient realization of a single-shot interferometric correlation measurement requires the matching of the size of the correlation function to the size of the CCD array and the spacing of the interference fringes to the resolution of the CCD. In our correlator we employ a technique of creating a pulse-front tilt that utilizes a dispersive element[9] such as a grating or a prism. The experimental setup is shown schematically in Fig. 1. We used a laser system consisting of a Ti:sapphire mode-locked oscillator producing 100-fs pulses at 800 nm, followed by a regenerative amplifier and OPA capable of producing ~100-fs pulses at 1 KHz tunable in the range from 1 to 2 microns. A cylindrical lens telescope expands the spatial mode in order to provide a uniform beam cross section in the direction of the time-delay axis.

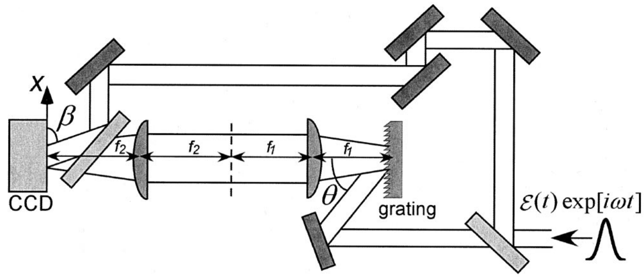

Fig. 1. Experimental setup. Diffraction grating in the lower arm of the interferometer is telecentrically imaged onto the surface of the CCD array using lenses f_1 and f_2, creating a pulse-front tilt. The value of the tilt determines the size of the correlation function, decoupling it from the interference fringe spacing, controlled by the incidence angle β of the pulse in the upper arm of the interferometer.

We used a 200 lines/mm diffraction grating to introduce the pulse-front tilt into the beam in one of the arms of the Mach–Zehnder interferometer. Two cylindrical lenses with focal lengths f_1 and f_2 are used to image telecentrically the grating onto the CCD, yielding the electric field on the surface of the camera:

$$\mathscr{E}_1 = \mathscr{E}[t + x \sin\theta/(Mc)]\exp(i\omega t), \tag{3}$$

where $\theta = 16°$ is the angle of incidence on the grating, c is the speed of light in vacuum, and $M = f_1/f_2 = 2$ is the magnification factor of the telescope (see Fig. 1). The resulting beam with the tilted pulse front described by Eq. (3), is interfered with the signal from the second arm of the interferometer, introduced at an angle β:

$$\mathscr{E}_2 = \mathscr{E}(t)\exp[i\omega t + ik\cos(\beta)x], \tag{4}$$

where k is the magnitude of the wave vector of the input field. Here we have omitted the effect of the angular tilt in the amplitude factor, as typically $\pi/2 - \beta$ is much smaller than θ (in our experiment $\pi/2 - \beta$ was less then 0.5°). A two-photon absorption process in the CCD with successive integration in time generates the interferometric correlation as described by Eq. (1):

$$I(\tau) \sim \int_{-\infty}^{\infty} |\{\mathscr{E}[t + x\sin\theta/(Mc)] + \mathscr{E}(t)\exp[ik\cos(\beta)x]\}^2|^2 \, dt. \tag{5}$$

This expression is characterized by two independent time delays across the spatial profile of the beam: $x \sin\theta/Mc$ and $x \cos\beta/c$ in amplitude and phase, respectively. Consequently, the width of the correlation function envelope is determined by the value of the pulse-front tilt, controlled by both the value of the grating dispersion angle θ and the magnification factor M. The fringe spacing is determined by the value of the angle β, which is set independently such that the interference fringes in the correlation function are resolved by the CCD camera. We performed the calibration of the time axis by introducing a known time delay in one of the signals with a mirror mounted on a translation stage and observing the signal shift on the CCD camera.[10] We used a standard silicon CCD camera (Pulnix TM7-EX) with 640 × 480 pixel array size, 10-μm pixel size, and a linear response in the spectral range of 0.4–1.0 μm. The CCD response as a function of the input optical power at 1.4 μm was measured, verifying the expected quadratic behavior due to the two-photon process. We would like to emphasize that although we have used a two-dimensional chip, the detected signals are one-dimensional, and we simply used a linear scan along the x axis of the CCD. Consequently, the CCD can be replaced by a one-dimensional photodetector array.

Experimental results on the measurement of the interferometric correlation are shown in Fig. 2. We first investigated the pulse derived from the output of the OPA. The shape of the correlation function [see Fig. 2(a)] shows characteristic features of a pulse that is close to transform limited (the fringe pattern extends over the full range of the correlation peak all the way to the background level). The FWHM of the intensity autocorrelation function for the signal in Fig. 2(a) extracted by filtering out the zero-frequency component of the interferometric correlation[2] is about 150 fs. This result is in good agreement with the value of 125 fs obtained from the measured power spectrum width if a transform-limited Gaussian pulse is assumed. The filtered intensity autocorrelation contained ~5% background noise owing to insufficient separation of the low- and high-frequency components. The CCD pixel size in this case is a limiting factor to the maximum fringe frequency that can be detected. The effect of the insufficient frequency-component separation can be eliminated by using either a larger CCD chip and scaling up the size of the correlation function envelope or by using a CCD with a smaller pixel size and increasing the fringe frequency. The latter is preferable, as increasing the envelope size requires careful control of the spatial mode. Cameras with pixel sizes up to 2 times smaller than the one used in our experiments are currently available and should improve significantly the accuracy of the measurements.[11]

To investigate the performance of our method further, we used a pair of gratings to introduce a linear chirp to the input signal. The resulting correlation trace is shown in Fig. 2(b). The envelope of the correlation function becomes wider owing to the stretching of the input pulse in time, while the interference pattern fills only the central part of the envelope, indicating the presence of the linear chirp in the waveform.[1] The peak-to-background ratio in our measurements matched the theoretically predicted value of 8:1.

We have also compared the performance of our single-shot device with a conventional scanning delay-type correlator that is based on a silicon photodiode.[3] An attractive feature of this approach, when applied to high repetition rate (~100MHz) laser systems is real-time (although multishot) operation as fast delay line scanning can be used.[12] However, the 1-KHz repetition rate of our system requires a slower scanning speed, thereby restricting real-time operation. Another problem that we encountered while implementing a multishot system is output power fluctuation in our OPA. This instability made it practically impossible for us to conduct multishot correlation measurements without a reference channel tracking the power changes. Preliminary results obtained on a multishot correlation system with a reference channel showed good agreement with our single-shot correlation measurements.

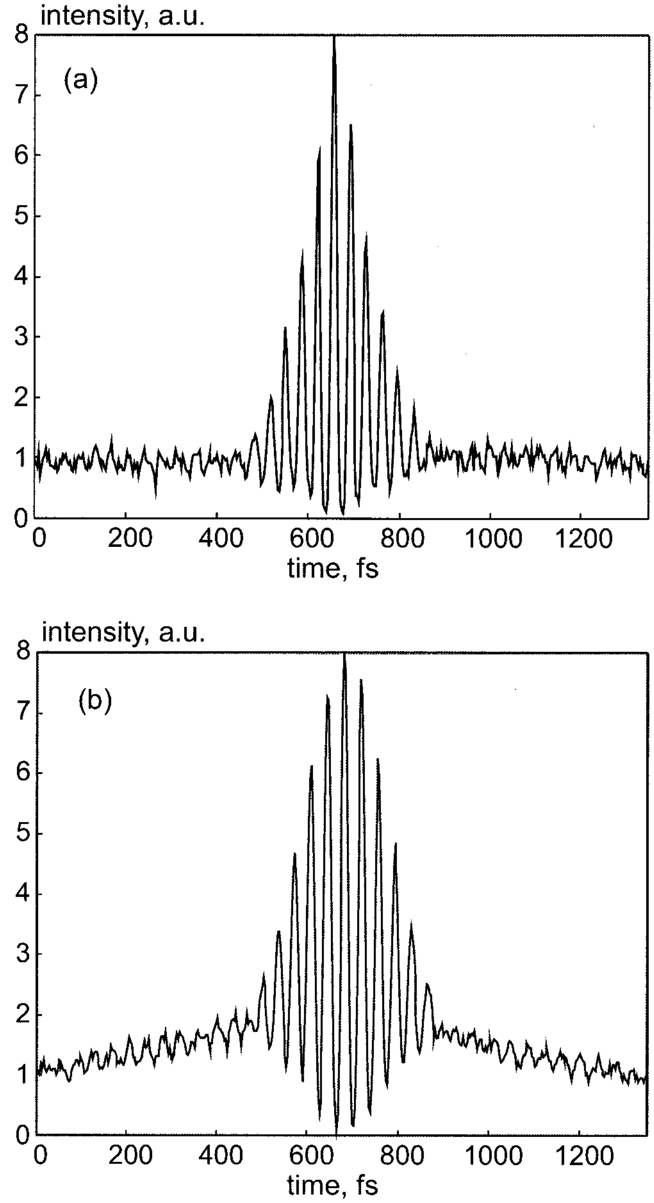

Fig. 2. Experimental results. Interferometric correlation for (a) the pulse from the output of the OPA and (b) the pulse stretched by a grating pair. The narrow interference pattern for the stretched pulse indicates the presence of the linear chirp.

The essential part of our correlator design is the telecentric lens system imaging the surface of the grating onto the surface of the CCD. For 100-fs

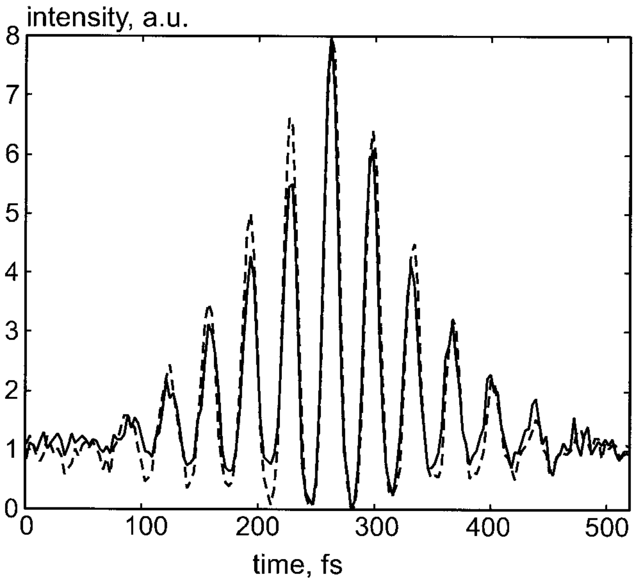

Fig. 3. Correlation signals obtained in a single-shot regime (solid curve) and with averaging over 16 laser pulses (dotted curve).

pulses we can neglect chromatic aberrations in lenses; however, this effect needs to be taken into account for the detection of signals with a broader spectral bandwidth. We anticipate that a broadband signal pulse on the surface of the CCD will appear chirped, introducing error into the measurement. We believe that a correlator design using only reflective components (i.e., cylindrical or spherical mirrors) is feasible and should be considered if one is dealing with a bandwidth of several hundred nanometers.[13]

The results presented in Fig. 2 were obtained with a CCD exposure time of 16 ms, generating a correlation function, which is effectively averaged over approximately 16 laser pulses. We also tested our setup (see Fig. 1) in a single-shot mode of operation by setting the CCD exposure time to 1 ms. By observing the result (see Fig. 3) we conclude that the single-shot correlation does not differ significantly from that obtained with averaging.

Next we discuss the lower bound on the input-pulse power that is required for the operation of the technique. The average current, $\bar{J}$, generated in a semiconductor photodetector by use of two-photon absorption of pulse train from a mode-locked laser source can be approximately expressed by

$$\bar{J} \propto (E_p^2/\tau)\Delta t/T, \qquad (6)$$

where E_p is the energy per pulse, T is the laser pulse repetition period, Δt is the CCD exposure time, and τ is the laser pulsewidth. Equation (6) is a phenomenological estimate obtained under the assumption that the number of generated photoelectrons is proportional to the number of pulses $\Delta t/T$, averaged by the CCD during the exposure time and the squared intensity of the input field $(E_p/\tau)^2$ integrated over the pulsewidth. A typical low-power femtosecond mode-locked oscillator operates with ~100-fs pulsewidth, several nanojoules of energy per pulse, and an approximately 100-MHz pulse repetition rate, whereas the high-power amplified system that we use produces 100-fs pulses with approximately 1 μJ of energy per pulse and a 1-KHz repetition rate. Examining Eq. (6), we conclude that with the CCD exposure time Δt set to approximately the repetition period of a high-power oscillator (i.e., 1 ms), we obtain comparable (within one order of magnitude) photoinduced current densities for both high-power and low-power systems. This estimate suggests that it is possible to apply our system for the detection of pulses from low-energy ultrashort laser systems. Indeed, in our setup the minimum detectable pulse-energy values for the CCD integration periods of 1 and 16 ms were ~1 μJ and $\sim 2 \times 10^2$ nJ respectively, approximately following Eq. (6). It should be noted that under these conditions, the generated correlation function will be averaged over a large number (10^5) of pulses for a low-power system; however, real-time detection should be possible owing to the high repetition rate.

In conclusion, we presented a technique for generating single-shot interferometric correlation for ultrashort pulses in the infrared range, utilizing nonlinear conductivity in a silicon CCD imaging array. We applied the method for characterization of 100-fs OPA pulses with the energy per pulse E_p in the range of 1 μJ. Preliminary investigations show that this technique has the potential for real-time detection and the characterization of low-energy pulses.

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