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Theoretical analysis of third order interferometric autocorrelation signals for enhanced sensitivity towards pulse chirp and asymmetry

P.K. Sharma *, S.L. Pandey

Dept. of Physics, Bareilly College, M.J.P. Rohilkhand University, Bareilly, India

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ABSTRACT

In this paper, we report theoretical analysis of third order interferometric autocorrelation to achieve enhanced sensitivity towards pulse chirp and asymmetry. The analysis is based on interferometric correlative envelope (ICE) functions and ICE difference signals derived from interferometric autocorrelation signals. The third order ICE signals are compared with second order ICE signals obtained from a second order interferometric autocorrelation signals. It is shown that one out of six third order ICED signals may be used to obtain simultaneous detection and measurement of pulse chirp as well as pulse asymmetry of the chirped ultrashort laser pulse. This is in contrast to use of two out of three second order ICED signals for simultaneous detection of pulse chirp and asymmetry.

1. Introduction

Measurement of temporal pulse intensity and temporal phase, or pulse spectrum and spectral phase, and spatio- temporal or spatio-spectral distortions of ultrashort pulse laser beams are very important for any application involving ultrashort laser pulses [1,2]. In several experimental situations, one requires either temporally asymmetric or symmetric laser pulses. For instance, a temporal asymmetric laser pulse is desirable to enhance the nonlinear process [3]. In general, simple laser pulse diagnostics techniques are needed to characterize an ultrashort laser pulses and also even for generation of ultrashort duration laser pulses e.g. routine operation of a femtosecond laser oscillator. Several time and frequency domain techniques [4–9] have been developed to measure duration, shape, chirp of laser pulse and spatio-temporal distortions. Intensity and Interferometric autocorrelations (IAC) [4] signals and their several variants [10–12] are widely used in real time or quasi real time measurement of laser pulses and widely accepted techniques for routine characterization of laser pulses. In particular, the temporal asymmetry in ultrashort laser pulses is generally detected using third order intensity correlation [13] or intensity unbalanced second or third order IAC signals [9,14,15]. The maximum contrast ratio (ratio of maximum to background signal) of second order and third order IAC, obtained with equal intensity laser pulses, is 8:1 and 32:1 respectively. With increasing intensity unbalance factor (ratio of intensities of the two correlating pulses), the contrast ratio decreases from respective maximum values. Therefore third order IAC signals may be preferred, but require large laser pulse energy due to smaller efficiencies of third order nonlinear processes compared to second order nonlinear processes. However, former can be realized at wavelength regime using materials where second order processes cease to apply. These one-dimensional correlation signals can be obtained with great ease and in very compact setups [16,17]. Recently, it is demonstrated that interferometric correlation envelope (ICE) functions derived from unbalanced second order interferometric correlation signals are very sensitive and thus used for visual detection and measurement of pulse chirp and pulse asymmetry without direction of time ambiguity [11], even present in very small amount. Second order IAC signals consist of three envelope functions and thus three interferometric correlation envelope difference (ICED) signals are possible. Out of three, two ICED signals are essential to simultaneously detect the pulse chirp and pulse asymmetry.

In this paper, we apply ICE analysis on unbalanced third order IAC signal, derive interferometric correlation envelope functions and then compare them with those obtained from unbalanced second order IAC signal. Since third order IC signals contain four envelope functions, six different ICED signals are possible. It is shown that one out of six third order ICED signals may be used to provide simultaneous detection and measurement of pulse chirp as well as pulse asymmetry of the chirped ultrashort laser pulse.

2. Formulation

Consider a laser pulse with its amplitude E(t), expressed as $\sqrt{I(t)}\exp[i\omega_o t+\phi(t)]$, where I(t) is the laser pulse envelope, ω_o is the carrier frequency and ϕ (t) is the temporal phase. The n^{th} order

* Corresponding author. Tel.: +91 5812525300.
E-mail address: sharmapka@rediffmail.com (P.K. Sharma).

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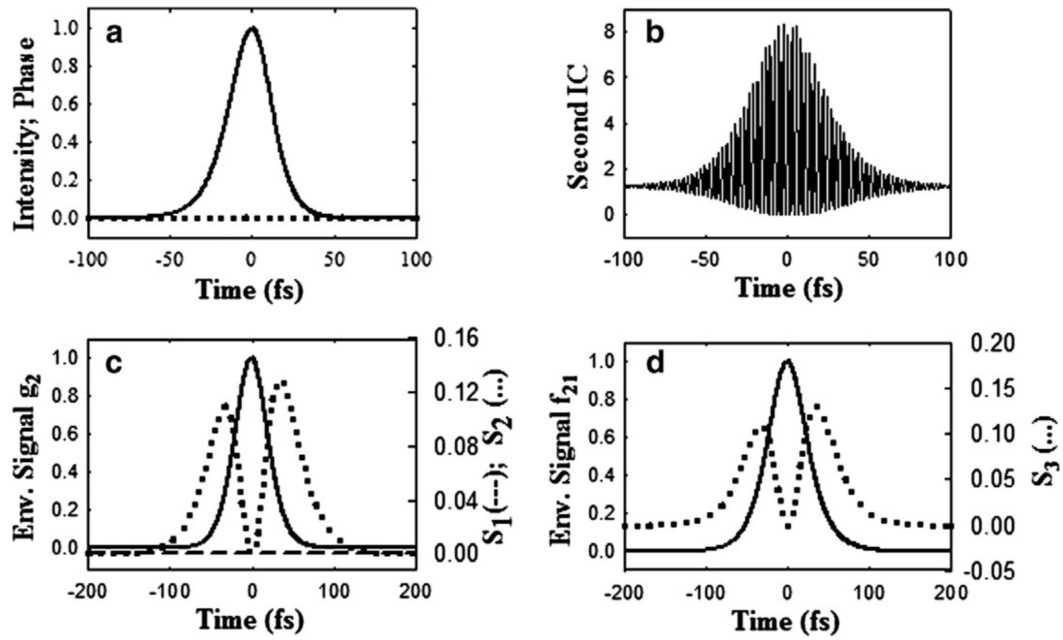

Fig. 1. (a) Chirp-free asymmetric laser pulse intensity (solid line) and phase (dotted line); (b) second order IAC signal $S_{SIC}(\tau)$; (c) ICE signals $g_2(\tau)$ (solid line), $S_1(\tau)$ (dashed line), $S_2(\tau)$ (dotted line); and (d) ICE signals $f_{21}(\tau)$ (solid line), $S_3(\tau)$ (dotted line).

interferometric (auto/cross) correlation (IC) signal $S_n^{IC}(\tau)$ can be expressed [4,5,14,15]

$$S_n^{IC}(\tau) \propto \int\left(\left|E_1(t) + E_2(t-\tau)\right|^2\right)^n dt = \int I^n(t,\tau)dt \quad (1)$$

where $E_1(t)$ and $E_2(t)$ are the laser pulse field in the two arm of the auto-correlator. While first order IAC signal (n = 1) or field autocorrelation is used to retrieve the pulse spectrum, the second (n = 2) and third order signals (n = 3) are used to characterize the ultrashort laser pulses. The electric field E(t) is related to power spectrum $S(\omega)$ and spectral phase $\varphi(\omega)$ as $E(t) = FT^{-1}[\sqrt{S(\omega)}\exp\{i\,\varphi(\omega)\}]$; where FT^{-1} is the inverse Fourier transform. The spectral phase $\varphi(\omega)$ equals to $\sum\varphi_n\,(\omega\text{-}\omega_o)^n$, where φ_n is linear, quadratic, cubic, quartic and quintic spectral phase for n = 1, 2, 3, 4, and 5 respectively. For an intensity unbalance ratio (k) of the two interfering beam, second (S_{2SIC}) and third order (S_{3IAC}) IAC signal can be given as

$$S_{SIC}(\tau) = 1 + k^2 + 4G_2(\tau) + 8F_{21}(\tau)\cos\omega_o\tau + 2F_{22}(\tau)\cos 2\,\omega_o\tau \quad (2)$$

$$S_{TIC}(\tau) = 1 + k^3 + 18G_3(\tau) + 30F_{31}(\tau)\cos\omega_o\tau + 12F_{22}(\tau)\cos 2\omega_o\tau + 2F_{33}(\tau)\cos 3\omega_o\tau \quad (3)$$

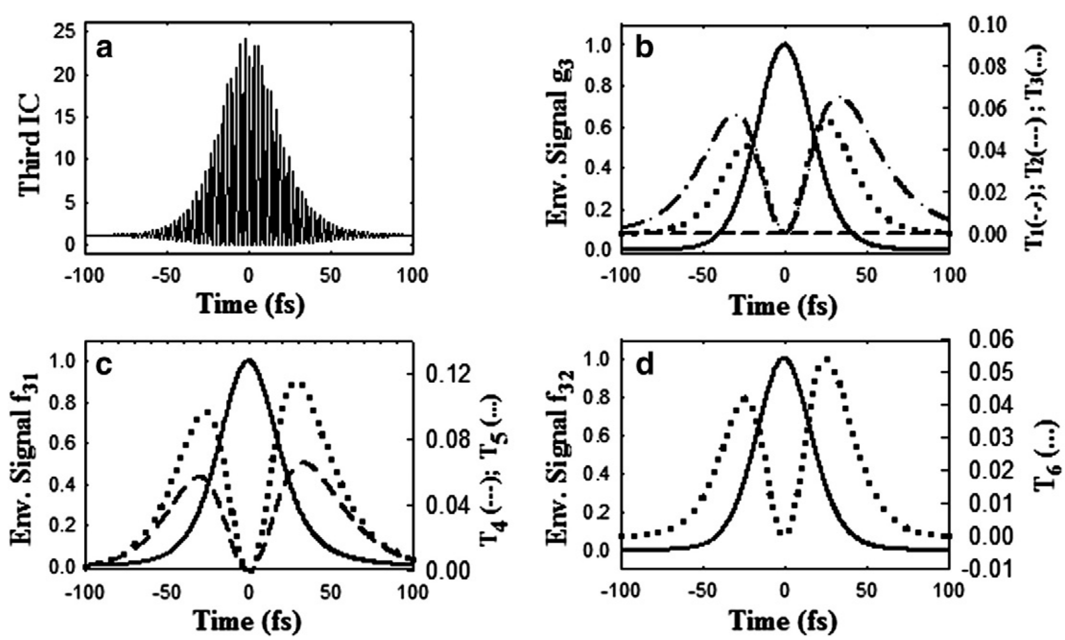

Fig. 2. Various third order signals: (a) Third order IAC signal; (b) ICE signals $g_3(\tau)$ (solid line), $T_1(\tau)$ (dash-dotted line), $T_2(\tau)$ (dotted line), $T_3(\tau)$ (dashed line); (c) ICE signal $f_{31}(\tau)$ (solid line), and ICED signals $T_4(\tau)$ (dashed line), $T_5(\tau)$ (dotted line); (d) ICE signal $f_{32}(\tau)$ (solid line), and ICED signal $T_6(\tau)$ (dotted line).