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Study of the frequency domain interference method for chirp measurement

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ABSTRACT

Frequency domain interference between a transform-limited pulse and a chirped pulse (FDITPCP) for measuring the chirp characteristics of linearly chirped pulse is studied, especially its applicability and stability. It is theoretically demonstrated that the FDITPCP method is applicable to pulses of complex waveforms. And this method is more accurate when measuring large chirps. Furthermore, if a chirp is introduced into the transform-limited pulse, the effects on the measurement results are analytically known, which is confirmed by simulation, and can be ignored when the introduced chirp is much smaller than that of the chirped pulse.

1. Introduction

In high time-resolution measurements, linearly chirped pulses are now widely used as probe light for single-shot measurement, because the instantaneous frequency of the chirped pulse changes with time and the ultrafast information in time domain is therefore mapped to frequency domain linearly by the chirped probe pulse, then a spectrometer which disperses and records the pulse spectrum can be used to achieve a high time-resolution measurement without fast response detectors [1–5]. So far, linearly chirped pulses have been employed in terahertz detection [6–9], laser driven shock waves [10–13], laser-induced plasmas [14–18], etc.

When making use of a linearly chirped pulse, one needs to know its chirp characteristics. There are several methods available for this, such as a streak camera coupled to a spectrometer [17], cross correlation method [19], optical Kerr gate technique (OKG) [20,21], two-photon absorption [22], and cross phase modulation (XPM) [23]. However, the time resolution of streak camera is unsatisfactory for measuring short pulses. Employing the other methods, nonlinear optical materials with large nonlinearities and fast response time, and relatively high intensity laser pulses are essential. To overcome these problems, we proposed a FDITPCP method for measuring the chirp characteristics of linearly chirped pulses, the corresponding theory was developed for Gaussian pulses [24]. This method belongs to the linear optical technique, and it works without intensity restrictions and nonlinear optical materials. For the spectral interference fringes of a transform-limited pulse and a chirped pulse in this technique, the widest fringe position is determined by the spectral phase of the chirped pulse [24–26]. However, when the pulse has a complex shape, the spectral phase could not be obtained analytically and the applicability of FDITPCP method is unknown in the case.

In this paper, we studied the FDITPCP method from another aspect, and the applicability to complex waveform pulses is confirmed from theory and simulation. In cases that the chirp to be measured is small and the transform-limited pulse is affected by a chirp, which are the quite practical issues in real experiments, the stability of FDITPCP technique is discussed in details.

2. Principle

Consider a femtosecond pulse which is transform-limited and whose electric field is

$$E_0(t) = f_0(t)\,\exp(\mathrm{i}\omega_0 t), \tag{1}$$

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where $f_0(t)$ is the envelope function, and ω_0 is the center frequency. Spectral interference of two such pulses with a time delay τ between gives an intensity distribution of

$$I_0(\omega) = \left|\Im\left\{E_0(t) + E_0(t-\tau)\right\}\right|^2 = 2\left|\tilde{E}_0(\omega-\omega_0)\right|^2\left[1+\cos(\omega\tau)\right], \tag{2}$$

where $\Im$ stands for Fourier transform and $\Im\left\{f_0(t)\right\} = \tilde{E}_0(\omega)$. It is obvious that the interference pattern $I_0(\omega)$ is a function of frequency ω and the fringe period is $2\pi/|\tau|$ inversely proportional to the time delay.

A linearly chirped pulse could be obtained by traveling a femtosecond pulse through a linear dispersive element [27], and the electric field of the chirped pulse is

$$E(t) = f(t)\exp\left[\mathrm{i}(\omega_0 + bt)t\right], \tag{3}$$

where $f(t)$ is the envelope function of the chirped pulse, and b is half the chirp rate. When above femtosecond pulse interferes with the chirped pulse in the frequency domain, the interference intensity can be expressed by

$$I(\omega) = \left|\Im\left\{E_0(t) + E(t-T)\right\}\right|^2, \tag{4}$$

where T is the time delay between the two pulses, and Fig. 1 shows the temporal relationship of the pulses. It is clear that the femtosecond pulse corresponds to a transient moment of the chirped one, which could be satisfied as long as the chirp is large enough. For the chirped pulse, its frequency

$$\omega(t) = \frac{\partial}{\partial t}\{[\omega_0 + b(t-T)](t-T)\} = \omega_0 + 2b(t-T) \tag{5}$$

is a linear function of time, and the frequency at the moment $S\,(t=0)$ where locates the femtosecond pulse is

$$\omega_s = \omega_0 - 2bT. \tag{6}$$

According to Eq. (6), the chirp rate $2b$ of the chirped pulse could be determined by measuring ω_s at different time delays T. And if T is given, ω_s could be acquired as follows. From Eqs. (5) and (6), we

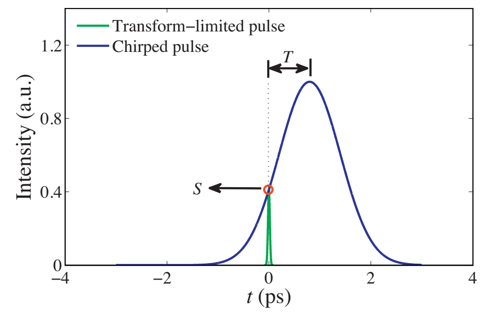

Fig. 1. A transform-limited pulse and the corresponding chirped pulse.

know that the time delay τ between the same frequency ω of the femtosecond pulse and the chirped pulse is

$$\tau(\omega) = t(\omega) = \frac{\omega - \omega_0}{2b} + T. \tag{7}$$

Since the fringe period is inversely proportional to the time delay $|\tau(\omega)|$ in the spectral interference pattern $I(\omega)$, there is a maximum at ω_s where $t(\omega)=0$, and the fringe period symmetrically decreases with $|t(\omega)|$ increasing. Consequently, ω_s is acquired as the central position of the widest fringe in the spectral interference pattern. In the deduction above, we did not fix any specific shape of the pulse envelopes, including that of the femtosecond one and the chirped one. Actually, the pulse envelopes could be Gaussian-shape [24], or other complex shapes which are common in practical cases.

To confirm the theory, spectral interference between a transform-limited femtosecond pulse and linearly chirped pulses is simulated. In this simulation, the femtosecond pulse has the duration and center wavelength of 30 fs, 800 nm. The chirped pulses have different envelope shapes but the same chirp rate of $2b = 2.76\times10^{-6}$ rad fs^{-2}. Fig. 2(a)–(c) shows the chirped pulse envelope shapes considered, including Gaussian-shape, rectangular-shape and an irregular shape, among which the Gaussian case acts as a reference. The corresponding spectral interference patterns, the time delay between the interference pulses is $T = 5$ ps, are shown in Fig. 2(d)–(f). It is clear that there is a very wide fringe in each pattern, and the centers of the widest fringes locate at the same position of $\omega_s = 2.342$ rad fs^{-1}, as predicted independent

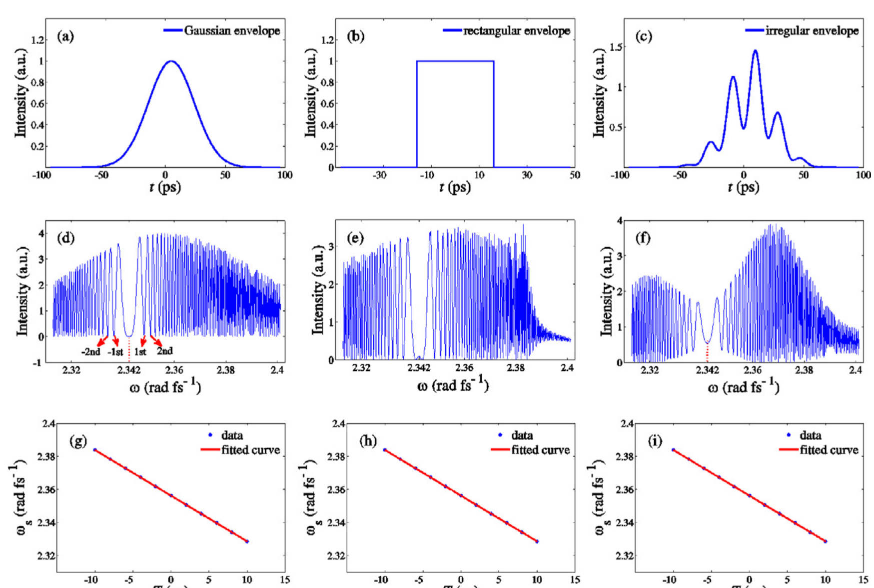

Fig. 2. Spectral interference between a transform-limited pulse and different chirped pulses. (a)–(c) Envelope shapes of the linearly chirped pulses, (d)–(f) the corresponding spectral interference fringes, (g)–(i) the widest fringe central position versus time delay.