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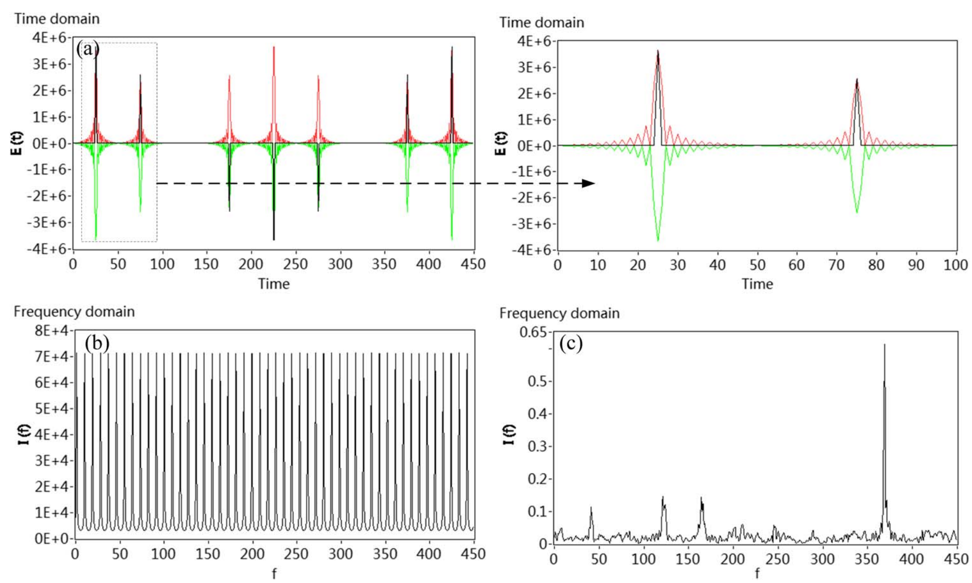

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Carrier-Envelope Phase Measurement With Linear Optical Sampling

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Abstract: In the few-cycle pulses, the temporal evolution of the electric field sensitively depends on the carrier-envelope phase (CEP). The ability to measure and stabilize the CEP therefore becomes a crucial issue for all applications. However, few studies are focused on the measurement of CEP with coherent linear optical sampling. We propose an efficient method to measure the CEP of the frequency comb pulses by employing a high-resolution linear optical sampling technique. It is shown that constant chirp and pulsewidth of frequency comb pulses have negligible effect on the CEP measurement.

Index Terms: Carrier-envelop phase measurement, optical sampling, Fourier optics and signal processing.

1. Introduction

Progress in femtosecond pulse generation has made it possible to generate optical pulses that are only a few cycles in duration (typically 5 fs for the Ti:sapphire laser) [1], [2], which ensure that optical frequency combs have the potential to revolutionize terabit communication [3]. However, the overall phase of the oscillating electric field does not affect the final measurement in optics, which is always of intensity [4]. To fully characterize such few-cycle pulses, the methods for charactering a multi-cycle pulse turn out to be not sufficient. The relative phase between the carrier waveform and the pulse envelope, i.e., carrier envelop phase (CEP), has to be introduced as a new quality [5]. The decisive influence of CEP in a few-cycle light-matter interaction which are relevant to the electric field of laser pulse rather than the intensity profile can be precisely controlled with the phase-stabilized few-cycle pulse. Therefore, the ability to measure and stabilize the CEP becomes a crucial issue for all applications.

With the development of the optical fiber communication, phase-shift keying (PSK) modulation have gain renewed attention to improve the spectral efficiency [6] and meeting the never-ending increasing demand for bandwidth in optical transmission systems [7]. Therefore, for these PSK signals, a temporal diagnostic capable of measuring samples of optical phase would be useful. Linear optical sampling [8] can offer the capability of measuring not only the intensity but the phase of electric field of an optical waveform using its interference with a train of sampling

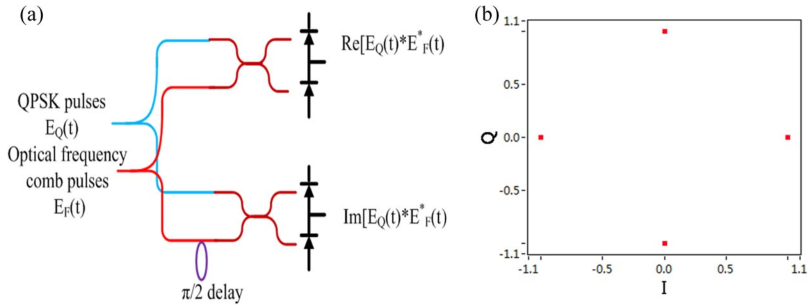

Fig. 1. (a) Schematic diagram of the linear optical sampling. QPSK signal and optical sampling frequency comb pulses have the same polarization. (b) Constellation diagram of QPSK signal.

pulses as well. It is nature to think that it is possible to measure the carrier-envelop phase of the frequency comb pulses by using the coherent linear optical sampling.

Furthermore, the CEP will become significant on the laser matter interaction for few cycle pulses. It is obviously that CEP plays an important role in physical processes, especially in attosecond pulse generation, such as interaction between inert gases and the few-cycle intense pulses [17], [18], therefore, precisely measuring the CEP is very necessary. Many methods have been proposed for CEP measurement based on the photoionization [9], [10], ultraviolet (UV) and terahertz emissions [11], [12]. Linear optical sampling technique has been used for characterizing various phase-related parameters, such as laser phase noise [13], [14], Polarization-Mode dispersion [15], Phase-shift keying signal constellation diagram [3], [6], high signal-to-noise ratio measurements of the transmitted optical electric fields [16]. However, in most of optical linear sampling, the carrier-envelop phase of frequency comb pulses is usually removed by digital signal processing in order to precisely retrieve the constellation diagram of phase-shifting keying signals. In this paper, differential quadrature phase-shift keying (QPSK) is used to realize coherent demodulation, and then measures the carrier-envelope phase of the frequency comb pulses in the linear optical sampling process. By exploiting the high resolution of linear optical sampling with different digital signal processing, we precisely test the carrier-envelope phase of optical sampling frequency combs pulses.

2. Carrier-Envelope Phase Measurement With Linear Optical Sampling

The schematic diagram of linear optical sampling is shown in Fig. 1(a). The phase and intensity of QPSK pulses, $E_Q(t)$, can be measured by observing its interference with two orthogonal quadratures of optical sampling frequency comb pulses $E_F(t)$. The corresponding constellation diagram of QPSK signal is displayed in the Fig. 1(b). In the upper branch, the balanced detectors is used to measure the interference of the QPSK signal and optical sampling frequency comb pulses $Re[E_Q(t) \cdot E_F^*(t)]$. The optical frequency comb pulses are delayed in phase by $\pi/2$ before interfering with the QPSK signal in the lower branch. Therefore, the balanced detectors in the lower branch test the interference signal $Im[E_Q(t) \cdot E_F^*(t)]$. Furthermore, the quadrature interference signals in the two branches together determine the complex quantity $E_Q(t) \cdot E_F^*(t)$ completely. High temporal resolution can be implemented even with low speed detectors by using a short sampling pulse, which functions essentially as a sampling gate in linear sampling. The complex filed of QPSK signal can be represented by

$$E_Q(t) = e_Q(t) * \exp[i\omega_Q t + i\varphi_Q(t)] \tag{1}$$

where e_Q, ω_Q, φ_Q is the amplitude, the carrier frequency, and modulation phase of QPSK signal, respectively, and $\varphi_Q(t) = (0, \pi/2, \pi, \pi 3/2)$. The electric field of the optical frequency comb pulses for sampling source $E_F(t)$ can be expressed as

$$E_F(\mathrm{t}) = \sum_N e_F(t - NT_F) * \exp\left[i\omega_F(t - NT_F) + iN\Delta\varphi_{\mathrm{cep}} + i\varphi_{F0}\right] \tag{2}$$

where e_F is the analytic signal of each sampling pulse, T_F is the period of the optical sampling frequency comb pulses source, ω_F is the carrier frequency of the sampling source, and $N\Delta\varphi_{\mathrm{ceo}} + \varphi_{F0}$ describes the relative phase between the analytic signal (its slowly varying component) and the carrier for pulse N (its quickly varying components, with a period around the optical cycle of the source). The variations in the phase arise for example due to the difference between the group and phase velocities in the laser cavity of the mode-locked laser. In general, for a steady state system, the relative phase between successive pulses is an unknown constant [1]. Since QPSK signal is generated by using the modulator, therefore, the output electrical field of the QPSK signal has not carrier-envelope phase offset. Linear optical sampling operates by splitting QPSK signal and the optical frequency comb pulses and recombining them into two pairs of fields on which balanced detection is performed. Assuming that the bandwidth of photodetectors is much larger than the repetition rate of the sampling comb and much smaller than that of the carrier fields, the two balanced detectors yield separate sampling events and enable us to monitor, simultaneously, the intensity and phase (frequency) modulation of the QPSK signal

$$S_{A,N} = real\left[\exp\left[i\left((\omega_Q - \omega_F)t + \omega_F NT_F - N\Delta\varphi_{\mathrm{cep}} + \varphi_A + \varphi_Q(t) - \varphi_{Q0}\right)\right] \cdot \int_{-\infty}^{+\infty} e_Q(t) \cdot e_F^*(t - NT_S)dt\right] \tag{3}$$

$$S_{B,N} = imag\left[\exp\left[i\left((\omega_Q - \omega_F)t + \omega_F NT_F - N\Delta\varphi_{\mathrm{cep}} + \varphi_A + \varphi_Q(t) - \varphi_{Q0}\right)\right] \cdot \int_{-\infty}^{+\infty} e_Q(t) \cdot e_F^*(t - NT_S)dt\right] \tag{4}$$

where the constant phase φ_A describes a relative phase between the two fields, depending on the optical path differences between the splitters and combiners. These samples can be combined to give

$$S_N = \exp\left[i\left((\omega_Q - \omega_F)t + \omega_F NT_F - N\Delta\varphi_{\mathrm{cep}} + \varphi_A + \varphi_Q(t) - \varphi_{Q0}\right)\right] \cdot \int_{-\infty}^{+\infty} e_Q(t) \cdot e_F^*(t - NT_S)dt. \tag{5}$$

Therefore, a sampling event achieves a complex sample proportional to the correlation of the field of QPSK signal with field of the corresponding optical sampling frequency comb pulses $\int_{-\infty}^{+\infty} e_Q(t) \cdot e_F^*(t - NT_S)dt$. The quantity $\int_{-\infty}^{+\infty} e_Q(t) \cdot e_F^*(t - NT_S)dt$ can be written using the frequency representation $\tilde{e}_Q$ and $\tilde{e}_F$ of the fields e_Q and e_F

$$\int_{-\infty}^{+\infty} e_Q(t) \cdot e_F^*(t - NT_S)dt = \int_{-\infty}^{+\infty} \tilde{e}_Q(\omega) \cdot \tilde{e}_F^*(\omega) \cdot \exp(iN\omega T)d\omega. \tag{6}$$

It is assumed in this paper that the optical sampling frequency comb is chosen to provide high temporal resolution. For optical sampling frequency comb pulses with constant spectral density and phase over the spectral support of QPSK signal (i.e., the range of optical frequencies where QPSK signal has significant spectral density). In practice, this is done by using a local oscillator a few times shorter than the inverse of the bandwidth of the QPSK signal source.

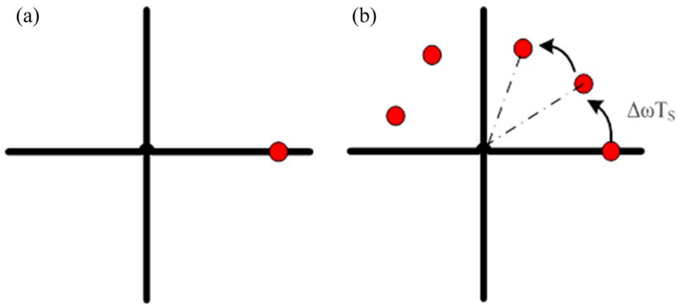

Fig. 2. Constellation diagram when the data phase is constant. (a) $\Delta\omega = 0$ and (b) $\Delta\omega \neq 0$.

That is why the optical frequency comb pulses are suitable for optical sampling source. Equation (6) can be rewritten as

$$S_N = \exp\left[i\left((\omega_Q - \omega_F)t + \omega_F NT_F - N\Delta\varphi_{\text{cep}} + \varphi_A + \varphi_Q(t) - \varphi_{F0}\right)\right] \cdot \widetilde{e}_Q(NT_S)\widetilde{e}_F^*(0). \tag{7}$$

Equation (7) is the main results of the analysis of linear optical sampling process. There are several important conclusions that can be derived from (7). Firstly, Linear optical sampling can provide the temporal filed of the waveform under test (QPSK signal) $e_Q(NT_s)$ at the times with infinite time resolution for signals with limited spectral support. This can be achieved by having a flat spectral density and phase over the spectral support of the optical sampling frequency comb pulses. Secondly, the CEP does not play any role in the measurement of the complex envelope of the QPSK signal. This is because linear optical sampling is proportional to the amplitude of the electric field of the QPSK signal at the times NT_S. Finally, following (7), the measured samples are also sensitive to the carrier-envelop phase of the optical sampling comb pulses. However, additional phase terms in (7) must be taken into account. φ_A is a geometrical constant phase that is uniform for all the samples if optical paths in the linear sampling are stable over the measurement time. Consider the special case when the QPSK signal are uniform and the optical sampling frequency comb pulses period is an integer multiple of the period of the QPSK pulses. When the carrier frequency offset is zero, $\Delta\omega = \omega_Q - \omega_F = 0$, the measurement will yield an identical results for every sampling pulse as it is shown in Fig. 2(a). However, when $\Delta\omega \neq 0$, the measurement will yield a different result for every sampling pulse which is rotated by phase angle of $\Delta\omega T_S$ between successive sampling pulses, as it is shown in Fig. 2(b). The constellation diagram can be obtained without this deterministic rotation of phase by locking one of the modes of the optical frequency comb pulses to the optical carrier of the QPSK signal. This rotation of the measured phase can potentially be corrected using a proper software correction scheme [19]. The constant phase terms correspond to a global rotation of the measured samples in the complex plane. It is usually not important for carrier-envelop phase measurement, and its effect can be removed simple by discriminating the phase between successive sampling pulses, that is $\varphi = \arg(S_N) - \arg(S_{N-1}) = \omega_F T_F - \Delta\varphi_{\text{cep}} + \varphi_{Q(t)}$. In order to cancel the effect of the differential quadrature phase-shift keying signal, the phase samples $\varphi_Q(t)$ need be done by the Viterbi–Viterbi algorithm [20]. Furthermore, as in the optimal case, the angular frequency of the signal laser under test (QPSK signal) and the repetition frequency of the sampling frequency comb are constant. Therefore, $\Delta\varphi_{\text{cep}} = \omega_F T_F - \varphi$.

3. Results and Discussion

In this section, we describe the effects of the finite pulse-width and linear chirp of the sampling comb on the measurement of carrier-envelop by retaining perturbation terms up to $(\Delta t/\Delta t_S)^2$,

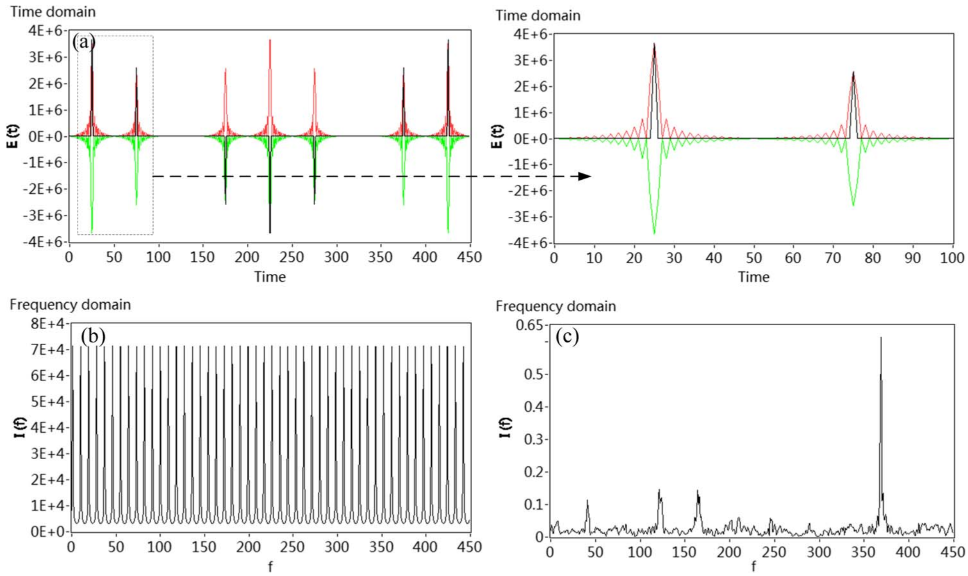

Fig. 3. (a) Time domain representation of a train of with $\Delta\varphi_{\text{cep}} = \pi/4$ and the corresponding open area. (b) Fourier transform of the optical sampling frequency comb pulses. (c) Fourier transform of QPSK signal.

which were ignored in (7). As an example, we consider the case of Gaussian pulses for optical sampling frequency comb pulses. The slowly varying envelop of Gaussian sampling pulse is

$$e_F(t) = e_{F0}\frac{e^{-(1+iC)\left(\frac{2ln2t^2}{\Delta t_S^2}\right)}}{\sqrt{\frac{\sqrt{\pi}\Delta t_S}{2\sqrt{ln2}}}} \tag{8}$$

where C is the chirp parameter of the sampling pulse, and the energy of a pulse is $|e_{F0}|^2$. The corresponding Fourier transform of the sampling comb envelop is

$$\tilde{e}_F(\omega) = e_{F0}\sqrt{\frac{\sqrt{\pi}\Delta t_F}{\sqrt{ln2}(1+iC)}}e^{-\frac{\omega^2\Delta t_F^2}{8ln2(1+iC)}}. \tag{9}$$

Let us assume that one of the modes of the optical sampling frequency comb is locked to the optical carrier of the data signal under test (QPSK signal) so that $\Delta\omega = \omega_Q - \omega_F = 0$. Then, (7) becomes

$$S_N = \exp\left[i\left(\omega_F NT_F - N\Delta\varphi_{\text{cep}} + \varphi_A + \varphi_Q(t)\right)\right]\cdot\tilde{e}_Q(NT_S)\tilde{e}_{F0}(0)\sqrt{\frac{\sqrt{\pi}\Delta t_S}{\sqrt{ln2}(1+iC)}}. \tag{10}$$

Numerical simulation was performed to confirm the analytic results presented above. The pulse-width of the optical sampling frequency comb pulses was set to be 70 fs [21]. The central wavelength of the optical sampling frequency comb pulses and the differential quadrature phase-shift keying signal are at 1550 nm. The repetition frequency of sampling comb is 50 MHz. The amplitudes of the samples were normalized to unit value to measure the phase. The optical sampling frequency comb pulses does not have any chirp and the carrier-envelop phase was constant (in this example, $\Delta\varphi_{\text{cep}} = \pi/4$). Fig. 3 is the corresponding numerical simulation diagram. The test result φ is 6.07629E+22. The corresponding carrier-envelope phase is $\pi/4$. We can investigate the effects of chirp and finite pulse-width of the sampling comb on the carrier-envelop phase

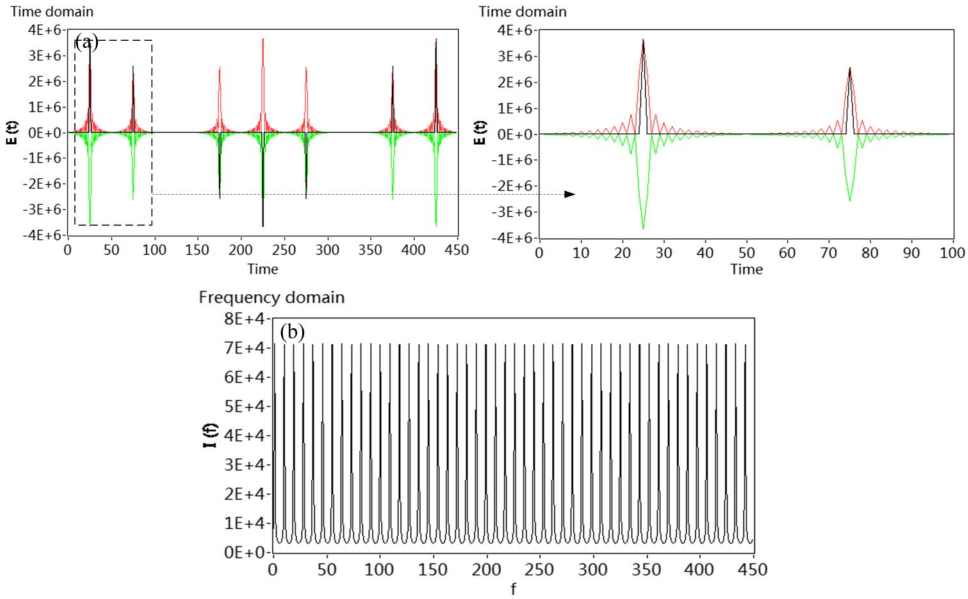

Fig. 4. (a) Time domain representation of a train of with $\Delta\varphi_{cep} = \pi/4$ and the corresponding open area with C = 1.5 when other parameters are the same as Fig. 1. (b) Fourier transform of the optical sampling frequency comb pulses when C = 1.5.

measurement using (10) and the corresponding simulation results are displayed in Fig. 4 when the chirp parameter is set to 1.5. It is found that the carrier frequency (black line) of the sampling comb due to the chirp in Fig. 4(a) is changed by comparing with Fig. 3(a). Although the phase of samples is affected by the chirp of the sampling comb, which result into the spectral relative movement of the sampling comb, the corresponding results can be obtained by comparing Fig. 3(b) with Fig. 4(b), the phase difference (that is $\varphi = \arg(S_N) - \arg(S_{N-1}) = \omega_S T_S - \Delta\varphi_{ceo}$) between successive samples are not affected when the chirp is constant. The chirp of the sampling comb only affects the amplitude of the samples. Pulse-width of the sampling comb does not affect the measurement of carrier-envelop of sampling comb if the sampling pulse-width is much smaller than that of the data signal under test. The obtained results are consistent with those in [8].

4. Conclusion

In conclusion, we have analyzed how to achieve the carrier-envelope phase measurement of the optical frequency comb by employing the coherent linear optical sampling process. It is found that the measured intensity is proportional to the spectral power density of the sampling pulse at the carrier frequency of the data signal and the pulse-width of the sampling comb. From the analytical and simulation results, it is found that the constant chirp, pulse-width of the sampling comb pulses can affect the carrier phase and amplitude of the samples, respectively. However, they cannot affect the carrier-envelope phase final measurement.

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