SINGLE-SHOT ELECTRO-OPTIC DETECTION OF BUNCH SHAPES AND THZ PULSES: FUNDAMENTAL TEMPORAL RESOLUTION LIMITATIONS AND CURES USING THE DEOS STRATEGY*

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Abstract

We review a recent work aiming at improving the resolution of single-shot longitudinal diagnostics, that are based on electro-optic (EO) detection using a chirped laser pulse. This classical technique has indeed been known to present severe limitations in time resolution (and usable bandwidth), especially when long recording windows and/or short bunches are considered. We review recent results on a strategy designed for overcoming this limit, the DEOS technique (Diversity Electro-Optic Sampling). A special experimental design enables to reconstruct numerically the input electric signal with unprecedented temporal resolution. As a result, 200 fs temporal resolution over more than 10 ps recording length could be obtained at European XFEL - a performance that could not be realized using classical spectrally-decoded electro-optic detection. Although DEOS uses a radically novel conceptual approach, its implementation requires few hardware modifications of currently operating chirped pulse electro-optic detection systems.

INTRODUCTION: LIMITATION OF CLASSICAL CHIRPED PULSE ELECTRO-OPTIC DETECTION

Recording electric field evolutions in single-shot and with sub-picosecond resolution is required in electron bunch diagnostics, and THz applications. A popular strategy consists of transferring the unknown electric field onto a chirped laser pulse, which is eventually analyzed [1, 2] (see Fig. 1). The technique has been investigated and/or been used as routine diagnostics at FELIX, DESY, PSI, Eu-XFEL, KARA, SOLEIL, etc. However fundamental time-resolution limitations have been strongly limiting the potential of these methods. This limitation has been generally expressed as the shortest bunch duration τ_R (or THz pulse duration) that can be recorded without deformation [3]:

$$\tau_R = \sqrt{\tau_w \times \tau_L}, \tag{1}$$

where τ_L is the compressed laser pulse duration, and τ_w is the stretched pulse duration, i.e., the duration of the recording window.

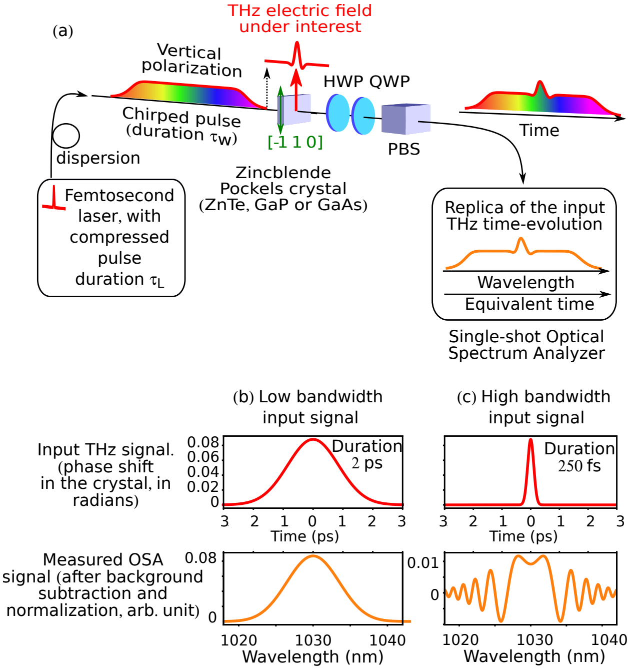

Figure 1: (a) Typical setup and limitations of classical single-output chirped pulse EO detection systems. The THz-bandwidth electric field is typically the Coulomb field created by an electron bunch, or a coherent THz pulse generated by coherent synchrotron radiation, coherent transition radiation, etc. The electric field modulates the intensity of a chirped laser pulse. The readout is performed (also in single-shot) using an optical spectrum analyser, usually composed of a grating and a camera. QWP and HWP: Quarter- and half-wave plates, PBS: Polarizing Beam-Splitter. As a main idea, one can expect the temporal laser modulation to be approximately replicated in the optical spectrum. Actually this works only for relatively low bandwidth THz pulses (b). For short (i.e., large bandwidth) THz pulses, strong deformations are observed (c). The DEOS technique presented here aims at solving this time resolution issue.

TRANSFER FUNCTION APPROACH

A main point of the DEOS approach consists of using the information contained at the two outputs of spectrally decoded EO systems. This involves two steps (see also Fig. 2):

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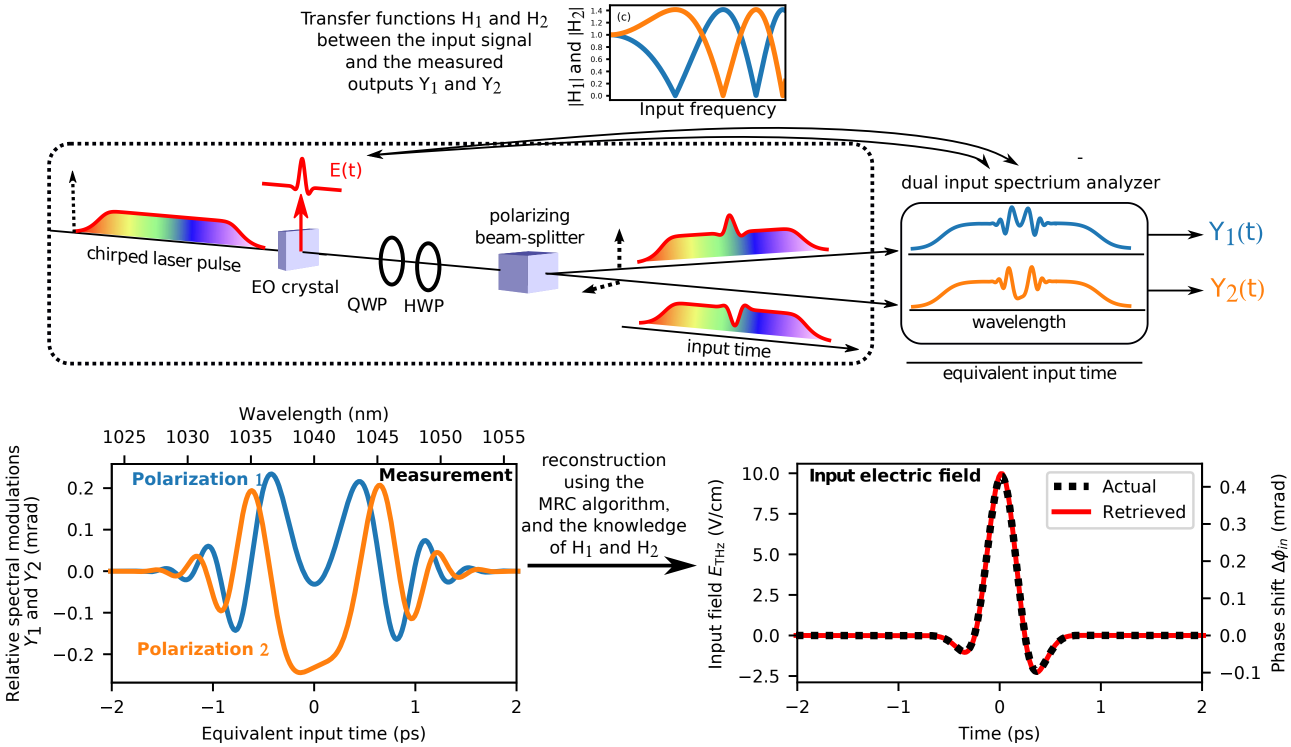

Figure 2: Principle of Diversity Electro-Optic Sampling (DEOS). Top: experimental setup. The key point consists of recording simultaneously the two output spectra exiting the polarizing beam-splitter, and choosing adequate waveplate orientations (see [4]). Bottom: reconstruction of the input field evolution, using the two recorded EO optical spectra (numerical simulation used for testing the strategy at the start of the project). Adapted from [4].

1. Finding the general relationship between the EO input and the measurements, using a Fourier-space approach.
2. Using this knowledge for "inverting the problem", i.e., retrieving the electric field to be measured, from the measurements. We will see that this will be possible (i.e., mathematically well-posed) by using the information contained in the **two outputs** of spectrally encoded EO systems.

Although this requires a non-trivial analytical work (see [4] for details), it can be shown that the input field is related to the output, through relatively simple transfer functions. If we note $\Delta\phi_{in}(t)$ the electric field-induced phase shift in the EO crystal, and $Y_1(t)$, $Y_2(t)$ the optical spectra at the two polarizing beam-splitter outputs, after background subtraction and normalization:

$$\tilde{Y}_1(\Omega) = H_1(\Omega)\Delta\tilde{\phi}_{in}(\Omega) \tag{2}$$

$$\tilde{Y}_2(\Omega) = H_2(\Omega)\Delta\tilde{\phi}_{in}(\Omega), \tag{3}$$

where the tildes denote the Fourier transform. The forms of the transfer functions $H_1(\Omega)$ and $H_2(\Omega)$ depend on the precise orientations of the laser polarization, EO crystal, and waveplates.

Classical Waveplate and Crystal Orientations

Before focusing on the new DEOS strategy, it is worth examining the transfer functions corresponding to the classical spectral decoding method. With the classical arrangement (see, e.g., [5, 6]), it can be shown that [4]:

$$H_1(\Omega) = \cos\left(\frac{\Omega^2}{2C}\right) \tag{4}$$

$$H_2(\Omega) = -\cos\left(\frac{\Omega^2}{2C}\right), \tag{5}$$

where C is the chirp rate of the laser pulse ($C = d\omega/dt$, where ω is the laser optical frequency). Two conclusions may be drawn from this first study:

- Each transfer function vanishes at specific frequencies, the first zero being at $\Omega = \sqrt{C\pi}$. This implies that it is impossible to retrieve the input from the output, without prior knowledge, when the bandwidth exceeds $\sqrt{C\pi}$. For instance, the inversion formula:

$$\Delta\tilde{\phi}_{in}(\Omega) = \tilde{Y}_1(\Omega)/H_1(\Omega) \tag{6}$$

  is obviously mathematically ill-posed.
- The zeros of the two transfer functions occur at the same frequencies.

DEOS Waveplate and Crystal Orientations

As a main idea of DEOS, it is possible to adjust the optics (i.e., the laser polarization, and waveplate orientations) so that the zeros of the two transfer functions H_1 and H_2 are interleaved. Many laser polarization and waveplate arrangements are possible. We consider here the situation considered in [4]:

$$H_1(\Omega) = -\frac{1}{\sqrt{2}} \cos\left(\frac{\Omega^2}{2C} - \frac{\pi}{4}\right) \tag{7}$$

$$H_2(\Omega) = \frac{1}{\sqrt{2}} \cos\left(\frac{\Omega^2}{2C} + \frac{\pi}{4}\right). \tag{8}$$

The zeros of the two transfer functions occur at different frequencies. Therefore, the inversion problem (i.e., retrieving $\Delta\phi_{in}(t)$ from $Y_1(t)$ and $Y_2(t)$) is now mathematically well-posed. Several techniques are possible, and a classical one is the so-called Maximum Ratio Combining (MRC), that has been developed in the fifties for wireless communications [7], and for the photonic time-stretch ADC [8]. The input phase shift can be expressed as a function of the two measured outputs Y_1 and Y_2 as:

$$\Delta\tilde{\phi}_{in}^{retr}(\Omega) = \frac{H_1(\Omega)\tilde{Y}_1(\Omega) + H_2(\Omega)\tilde{Y}_2(\Omega)}{H_1^2(\Omega) + H_2^2(\Omega)}. \tag{9}$$

Then, the input signal $\Delta\phi_{in}^{retr}(t)$ is obtained from an inverse Fourier Transform of $\Delta\tilde{\phi}_{in}^{retr}(t)$.

Note on the Theoretical Limitation DEOS

In contrast to classical spectral decoding, the reconstruction formula Eq. (9) does not present the $\sqrt{\tau_L \tau_w}$ time resolution limitation. Hence the achievable time resolution is expected to be limited by the compressed laser pulse duration τ_L or the crystal bandwidth, whichever dominates. This is confirmed by numerical simulations [4].

EXPERIMENTAL RESULTS

Experimental Measurements at Eu-XFEL

After performing a series of tests using a table-top source [4], we realized a test at DESY, using a modification of the recently developed EO measurement setup [6] placed at the second bunch compressor. The bunch energy and RMS duration are of the order of 700 MeV and 200 fs respectively. A Gallium Phosphide (GaP) crystal is placed near the electron bunch, so that the bunch Coulomb field is along the [001] axis (note that DEOS crystal orientation differs from the classical EO case by 90 degrees). The setup and typical results are displayed in Fig. 3. As in the above numerical study, and table-top test, the raw spectrally decoded EO data present the typical oscillations, that are due to the non-flat nature of the transfer functions (see Fig. 3b). The DEOS reconstruction (see Fig. 3c) of the electric field presents a main peak, that corresponds to the electron bunch Coulomb field, and a small trailing component with opposite sign, that may be attributed to a reflection or wakefield in the vacuum chamber.

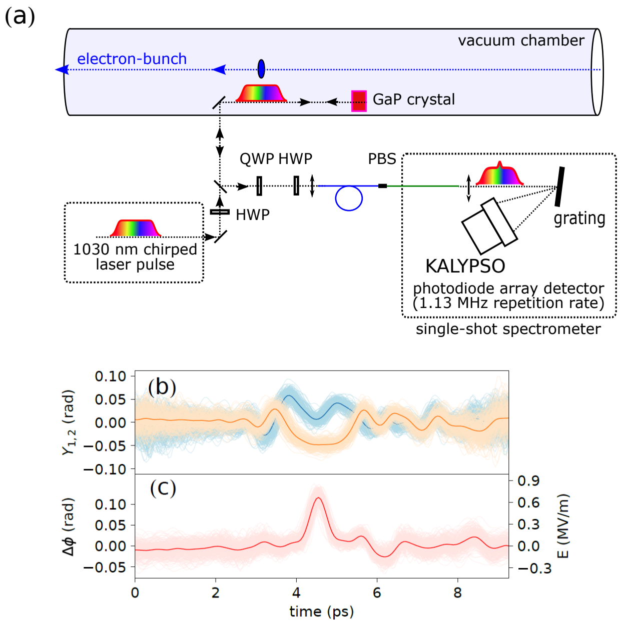

Figure 3: Typical longitudinal electron bunch shape measurements using DEOS at European XFEL. (a): experimental setup. (b): raw EO measurement on the two polarizations outputs. (c): retrieved Coulomb field of the electron bunch (From [4]).

CONCLUSION

We proposed a novel approach allowing electric field evolutions to be recorded in singe-shot. As a main advantage over previous spectrally encoded techniques, the time resolution is no more limited by the well-known limit $\tau_R = \sqrt{\tau_L \tau_w}$. The new recording bandwidth is found to be now limited by the compressed laser pulse duration τ_L or electro-optic crystal bandwidth, whichever come first. Theory and experimental tests are detailed in [4].

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