A HIGH RESOLUTION SINGLE-SHOT LONGITUDINAL PROFILE DIAGNOSTIC USING ELECTRO-OPTIC TRANSPOSITION*

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Abstract

Electro-Optic Transposition (EOT) is the basis for an improved longitudinal bunch profile diagnostic we are developing in ASTeC as part of the CLIC UK research program. The scheme consists of transposing the Coulomb field profile of an electron bunch into the intensity envelope of an optical pulse via the mixing processes that occur between a CW laser probe and Coulomb field in an electro-optic material. This transposed optical pulse can then be amplified and characterised using robust laser techniques – in this case chirped pulse optical parametric amplification and frequency resolved optical gating, allowing the Coulomb field to be recovered. EOT is an improvement over existing techniques in terms of the achievable resolution which is limited by the EO material response itself, reduced complexity of the laser system required since nanosecond rather than femtosecond lasers are used, and insensitivity of the system to bunch-laser arrival time jitter due to using a nanosecond long probe. We present results showing the retrieval of a THz pulse (Coulomb field stand-in) which confirms the principle behind the EOT system.

INTRODUCTION

The use of electro-optic (EO) techniques for the measurement of longitudinal bunch profiles has for many years held the potential to provide high temporal resolution, non-destructive measurements, and single shot aquisition. The core principle behind all EO techniques is that for suitably relativistic energies the Coulomb field of each electron flattens out, becoming more disc like, resulting in the overall Coulomb field of the bunch becoming an accurate representation of the charge distribution. When this Coulomb field propagates through an EO material the most common, but not always appropriate, approximation is that the refractive index is then modulated through the Pockels effect. A laser pulse is then used to probe this E-field induced change using techniques borrowed or developed from the fields of generation and detection of ultrashort THz pulses, which have very similar properties.

A number of schemes have been developed but there are often trade-offs in system performance or practicality. Spectral decoding [1] whilst simple to implement has a practically limited resolution of a few hundred fs, has a limited (few ps) sampling window, and requires a potentially complex ultrashort pulse laser. However, demonstrations using fibre lasers have been made alleviating this last drawback. Spatial encoding [2] and temporal encoding [3, 4] have higher temporal resolutions, but also have finite sampling windows, and due to the necessary cascaded nonlinear processes require high pulse energy regeneratively amplified laser systems which are very complex and sensitive. There are also methods that improve upon the resolution of Spectral Decoding via the implementation of standard optical pulse diagnostics such as Temporal E-field Cross-correlation (TEX) [5]. This is based on Spectral Interferometry and inherits both the associated resolution enhancement (tens of fs is possible), but also the significant alignment sensitivity associated with interferometric measurements. It has also been suggested that FROG methods could be used to analyse the spectral decoding signals for enhanced resolution (PG-FROG, BMX-FROG [6, 7]), but again this has a limited sampling window along with the requirement of high energy ultrashort pulse lasers to drive the required cascaded nonlinear optical processes.

EOT [8-10] is significantly different to the previously mentioned techniques in that the probe laser field is not necessarily derived from an ultrashort laser pulse. Instead of a compressed or chirped femtosecond pulse, the Coulomb field is probed with a single frequency laser. By applying a more fundamental description of the EO effect as one of nonlinear frequency mixing it can readily be shown, and has been demonstrated [11], that this maps the spectrum of the Coulomb field onto optical sidebands of the probe laser. As nonlinear optical mixing preserves the relative phase information of the spectral components of the Coulomb field this process also transfers information of its temporal profile into the electric field of the new optical waves, as

$$E^{out}(t) \propto \left(\frac{d}{dt}E^{in}(t)\right) \cdot E^{bunch}_{eff}(t), \tag{1}$$

where $E^{out}(t)$ is the newly generated EOT pulse, $E^{in}(t)$ is the input probe, and $E^{bunch}_{eff}(t)$ is the Coulomb field temporal profile accounting for spectral variations in the material response. What this indicates is that the amplitude of the Coulomb field is now mapped into the *envelope* of the new optical wave, with sign changes effectively becoming π phase jumps in the optical carrier wave.

This process now allows the use of Frequency Resolved Optical Gating (FROG) [12] – a standard and robust optical pulse diagnostic – to recover the Coulomb field profile from this new wave. Traditional FROG methods cannot be applied directly to the THz frequency range to recover the field directly as this would necessarily require recov-

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ering the absolute phase information (i.e. the carrier envelope phase), whilst FROG methods only reveal relative spectral phase. This difficulty has been overcome by the recent development of “ReD-FROG” [13], but this technique still requires the use of an ultrashort laser probe pulse for cross-correlation as nonlinear materials suitable for a self-referenced FROG scheme do not exist at THz frequencies.

In the EOT diagnostic schema this new optical pulse is characterised using a variation of FROG known as GRENOUILLE [13]. A GRENOUILLE measurement is essentially a single-shot spectrally resolved autocorrelation from which a spectrogram is obtained. This is followed by the application of robust and experimentally proven algorithms to recover the temporal profile / spectral amplitude & phase. The self-referencing nature of autocorrelation is central to this diagnostic as it obviates the need for an ultrashort pulse probe, and the combination of this method with the now potentially several nanoseconds long probe pulse makes the EOT diagnostic highly tolerant to electron bunch timing jitter. GRENOUILLE is the most sensitive self-referenced FROG, but it still requires higher pulse energies than is expected from the EOT process with practical laser pulse energies and Coulomb field strengths. Because of this a temporal profile preserving broad bandwidth optical amplifier based on non-collinear optical parametric amplification, which is pumped by the same nanosecond laser from which the probe is derived, is integrated into our design. The >60 THz bandwidth design of this amplifier, with a gain capable of exceeding 1000x, has been reported elsewhere [8, 9].

EO methods are still not commonly implemented accelerator diagnostics, which may be due to the complexity and reliability of the amplified ultrashort pulse laser systems needed for high resolution systems. As all the optical pulses needed for the EOT diagnostic are on the nanosecond scale, they can all be derived from a Q-switched laser. This type of laser is commercially available as ‘turn-key’ systems having industrial levels of reliability.

PROOF OF PRINCIPLE

As part of system development and design it was necessary to verify the transposition principle central to the EOT diagnostic. As access to a suitable accelerator was not available a laser laboratory based experiment was devised around a laser driven large area photoconductive antenna (PCA) THz source, which operated as a stand in for the Coulomb field. The <3 THz bandwidth of this source was insufficient for testing the temporal resolution of the system, which in our design is limited by the material response itself (sub ~50 fs rms if GaP is used), however, the moderate THz field strength of >100 kV/m and consistent pulse parameters allowed a multi-shot autocorrelation based FROG measurement to be performed.

A schematic of the experimental system is shown in Fig. 1. The primary laser system was a 1.5 mJ, 50 fs, 500 Hz amplified Ti:Sapphire laser, which was split into 2 beams: 90% of the energy was used to pump the 75 mm diameter PCA, and the remaining 10% was used to generate the probe pulses. To accomplish this it was propagated through a scanning delay line and a 4-f spectral filter. The filter is convenient device that allows the spectral content of the ultrashort pulse to be filtered, without introducing dispersion, by adjusting the width of a slit aperture placed at its centre. In this way access to either a scanning 50 fs probe for THz Time Domain Spectroscopy (THz-TDS), or a narrow linewidth (~45 GHz) 10ps long probe, was accessible, for first measuring a true reference temporal profile and then performing the EOT evaluation respectively. The PCA bias voltage was triggered at half the rep rate of the laser (250 Hz) to facilitate lock-in detection. The THz and optical beams were then combined coaxially on an ITO coated glass substrate, after which they propagated to the EO crystal (4 mm ZnTe) where the nonlinear mixing took place. In order to make the THz-TDS reference measurement the following quarter wave plate was used to circularise the transmitted waves prior to entering a balanced detection scheme. The outputs of the balanced diodes were fed into a lock-in amplifier (SRS530) that triggered with the same 250 Hz as the PCA.

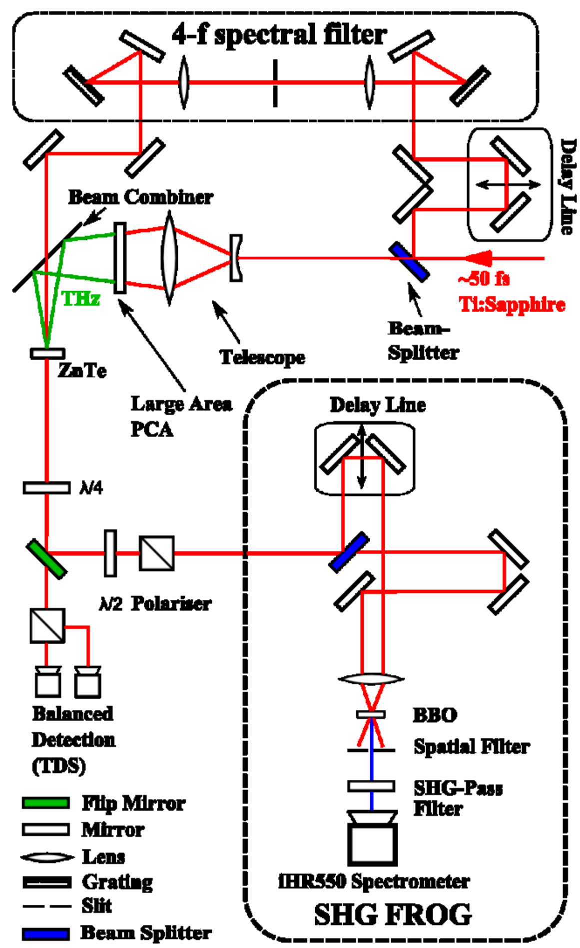

Figure 1: Schematic of the EOT verification system.

Once the reference trace was recorded (blue line, Fig. 3b), the quarter wave plate was set to cancel residual birefringence in the ZnTe so that a maximum extinction of the “THz-off” narrow-linewidth probe could be

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achieved on the following Glan-Laser polariser. This separated the newly generated EOT pulse from the remaining, much higher energy, single frequency probe. The EOT pulse was then coupled into a home-made scanning autocorrelation FROG based on second harmonic generation in a 0.3 mm thick BBO crystal, an iHR550 imaging spectrometer, and a DiCAM Pro intensified camera.

The EOT pulse energy was measured to be just 0.5 nJ, leading to the need for 7680 single shot spectra to be averaged at each of the 128 time delays (62.5 fs steps) of the FROG spectrogram to reduce the noise to usable levels. Recording of the full spectrogram took several hours. This spectrogram was then analysed using commercially available and verified FROG deconvolution software, including pre-processing to remove excess noise and background signal. The processed spectrogram is shown Fig. 2 alongside the FROG recovered version.

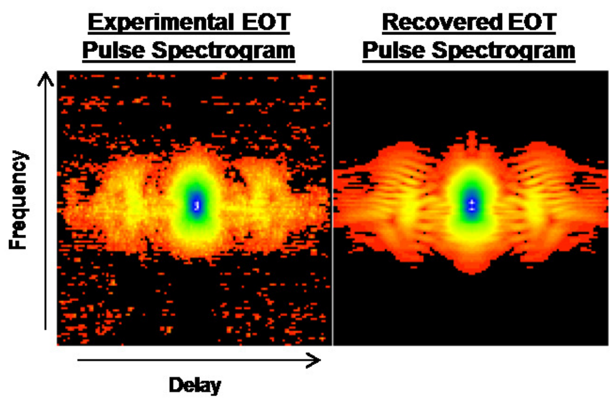

Figure 2: Filtered experimental and FROG recovered spectrograms shown in false colour to enhance visibility. The similarity in the traces can be seen.

The good agreement between the experimental and recovered spectrograms is clear, and is a good indicator that the FROG deconvolution was successful, despite the remaining noise. The FROG error was 0.007 – which is typical for a 128x128 spectrogram.

The temporal profiles are compared in Fig. 3. The FROG code returns intensity and phase, and THz-TDS returns the E-field, but it is straight forward to calculate the equivalent profiles as has been done here. There is a good match in the traces, including the electric field sign change at ~0.5 ps. However, in this particular measurement a well-known phase ambiguity of $\pm n\pi$ for well-separated pulses in SHG FROG necessitated the manual addition of π phase for the oscillations at ~2 ps in order for the profiles to match. It is envisaged that an improved signal-to-noise ratio, along with measuring a Coulomb field which should be monopolar, will mitigate this.

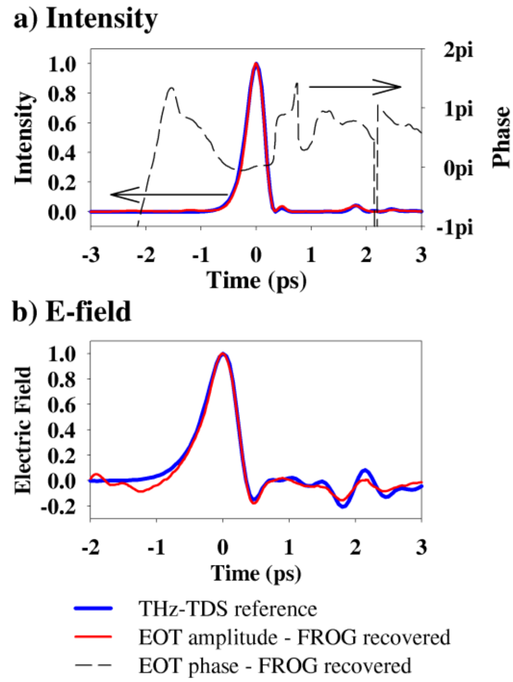

Figure 3: A comparison of the temporal profiles of the THz pulse measured via THz-TDS and EOT / FROG.

SUMMARY

We have demonstrated that the EOT process faithfully maps the THz temporal electric field profile into the temporal envelope of an optical pulse, which was then recovered using an autocorrelation based FROG technique. This verifies the core principles behind the proposed EOT electron bunch diagnostic, allowing us to proceed with developing this jitter insensitive diagnostic whose resolution is now only limited to the EO material response. The practical issue of having sufficient pulse energy will be addressed by implementing a non-collinear optical parametric amplifier in the EOT pulse path before the GRENOUILLE measurement is made. The main components of this EOT system are now tested, and a complete system is in the final stages of construction. It is anticipated that a complete end to end test (on a laser based THz pulse), using commercial nanosecond lasers (a Continuum Surelite and Sirah Cobra), will be performed soon.

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