A FEMTOSECOND RESOLUTION ELECTRO-OPTIC DIAGNOSTIC USING A NANOSECOND-PULSE LASER

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Abstract

Electro-optic longitudinal profile diagnostic systems with intrinsically improved reliability and a time resolution of 20 fs rms are being developed for the CLIC Project at CERN. Exploiting the electro-optic effect, the bunch electric field 'pulse carves' an optical replica from a narrow bandwidth nanosecond-duration laser probe. All-optical characterisation of the optical replica is via spectrally resolved auto-correlation, providing a sub-20fs resolution capability. An optical parametric amplification stage following the pulse carving, driven by same nanosecond laser that provides the probe, enables sufficient intensity for single-shot measurement. By basing the optical system on nanosecond Q-switched lasers, bypassing complex femtosecond laser systems, the potential for robust instrumentation development is enhanced. Experiments on the optical subsystems, using laser-produced THz as an electron bunch mimic, are presented. We also describe the observation and interpretation of an unexpected effect of small beam misalignments on the electro-optic signal, which has implications for EO diagnostics in general.

INTRODUCTION

Electro-optic (EO) techniques have for some time held the promise of high time resolution non-destructive bunch longitudinal profile diagnostics. A range of EO diagnostic systems has been developed and demonstrated, such as Spectral Decoding [1], Spatial Encoding [2], Temporal Decoding [3], and Spectral Upconversion [4]. Despite the large number of demonstrations of EO diagnostic concepts, there are only a very limited number of examples of EO diagnostics being integrated into operational accelerator diagnostic systems [5-7], which can partially be attributed to the complexity and limited reliability of the ultrafast laser systems that have until now been necessary.

ELECTRO-OPTIC TRANSPOSITION

We present a variant of electro-optical temporal characterisation, which we label Electro-Optic Transposition (EOT) [8], which eliminates the need for ultrafast femtosecond lasers, and also provides a higher optical time resolution capability than previous approaches. As in other electro-optic schemes, the technique is based on the $\chi^{(2)}$ nonlinear encoding processes, although a variant based on a $\chi^{(3)}$ process is also being developed to address electro-optic material bandwidth limitations. In the $\chi^{(2)}$ scheme presented here, the interaction between particle beam and optical laser probe can be described as frequency mixing between the Coulomb field and the (general) optical probe field,

$$\begin{aligned}\hat{E}_x^{out}(\omega) &= \hat{E}_x^{in}(\omega) + i\alpha_x \int \hat{E}_x^{in}(\omega-\Omega)\hat{E}^{bunch}(\Omega)d\Omega \\ \hat{E}_y^{out}(\omega) &= \hat{E}_y^{in}(\omega) - i\alpha_y \int \hat{E}_y^{in}(\omega-\Omega)\hat{E}^{bunch}(\Omega)d\Omega\end{aligned} \quad (1)$$

where the subscript refers to orthogonal polarisation components in the interaction principal axis frame, $\hat{E}^{out}(\omega)$, $\hat{E}^{in}(\omega)$ refer to the optical probe input and signal output, while $\hat{E}^{bunch}(\omega)$ is the Coulomb field spectrum. For ultrafast pulses, with a broadband transform limited optical probe then $\hat{E}^{in}(\omega-\Omega) \approx \hat{E}^{in}(\omega)$ and the effect of the interaction can be reduced to the phase change $\hat{E}_x^{out}(\omega) \approx \hat{E}^{in}(\omega)e^{i\alpha E^{bunch}(\tau)}$, as expected for consistency with the commonly employed picture of a Coulomb field-induced refractive index change. We instead choose to probe with a narrow band quasi-CW laser $\hat{E}(\omega) = \hat{E}(\omega_0)\delta(\omega-\omega_0)$, so that Eq. 1 simplifies to

$$\begin{aligned}\hat{E}_x^{out}(\omega) &= \hat{E}_x^{in}(\omega_0)\delta(\omega-\omega_0) \\ &\quad + i\alpha_x \hat{E}_x^{in}(\omega_0)\hat{E}^{bunch}(\omega-\omega_0)\end{aligned} \quad (2)$$

This describes the creation of additional spectral components in the optical probe, an amplitude rather than a phase change. The measurement of this spectral content constitutes the "EO Spectral Upconversion" (EOSU) technique, which has been described and demonstrated elsewhere [4]. Here we instead target a direct temporal measurement of the upconverted signal, which has an intensity envelope of

$$E^{out}(t) \approx \left(\frac{d}{dt}E^{in}(t)\right) \cdot E^{bunch}(t) \quad (3)$$

From equations 2 and 3 the same process can be viewed as a spectral upconversion in the frequency domain, or the creation of an optical replica if viewed in the time domain. It is this combination that gives rise to the labelling as EO Transposition [8]. While the $\chi^{(2)}$ encoding interaction is identical to that of EOSU the temporal measurement is free from the ambiguity associated with loss of phase information in the spectral measurement.

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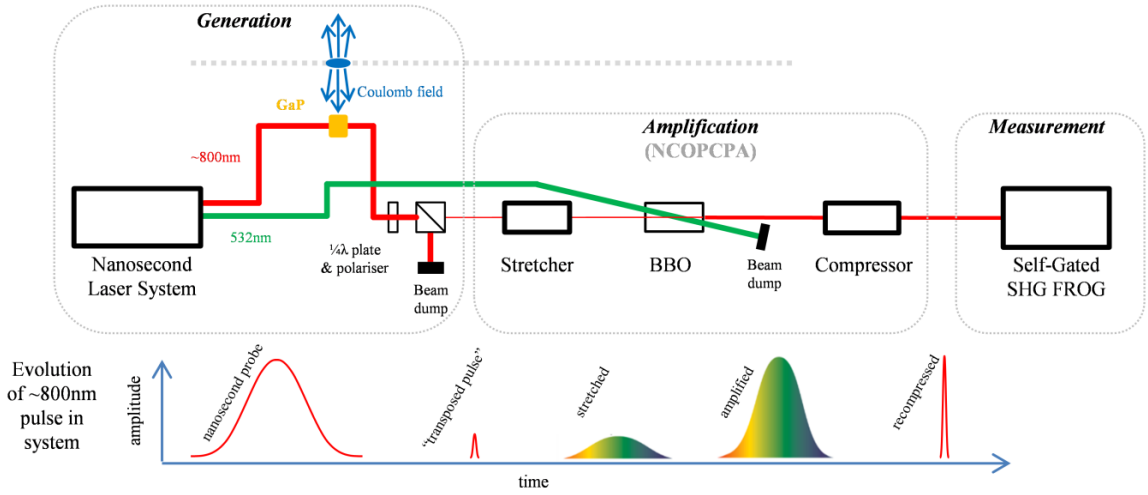

Figure 1: Schematic of the electro-optic transposition system. The system can be considered as 3 separate stages: generation of the optical probe and subsequent up-converted signal pulse; amplification of the signal pulse to a level that can be characterised, and finally measurement of the signal to reveal its temporal structure.

To measure the optical envelope time profile, the EOT scheme uses Frequency Resolved Optical Gating (FROG), an established laser technique which allows unambiguous retrieval of the optical pulse envelope with resolution better than 10 fs [9, 10]. As the FROG measurement will be a self-referenced spectrally resolved autocorrelation, it requires no additional ultrafast lasers and is inherently insensitive to timing jitter. This enables the technique to be used for characterising very weak, high repetition rate pulses (bunches) having a significant timing jitter that prevents their measurement in another way. For single-shot diagnostics however, a signal pulse energy of significantly greater than 10 nJ is required. Such optical signal pulse energies are generally not realistically achievable directly from the EO process. To overcome this problem, our scheme includes an integrated Non-Collinear Optical Parametric Chirped Pulse Amplification (NCOPCPA) stage for the signal; the amplification stage is driven by the same nanosecond laser system that produces the input probe, maintaining the overall laser system robustness and expected system reliability.

A prototype system with a resolution approaching 50 fs FWHM (20fs rms) is shown in Fig. 1. The system is centred around a robust Q-switched Nd:YAG with frequency-doubled 532 nm output of 10 ns duration and >10 mJ energy. The 532 nm output pumps an Optical Parametric Oscillator (OPO) to generate the optical probe. The integrated optical parametric oscillator produces a narrow line-width (~0.1 cm^{-1}) pulse at ~830 nm with an energy of around 1 mJ. The 532 nm output will also pump optical parametric amplification of the probe signal following the electro-optic interaction with the bunch, raising the signal levels to that necessary for single-shot FROG.

In order to verify the performance of the system design, a test bed has been built around a regeneratively amplified femtosecond Ti:Sapphire laser- driven terahertz source. In this system near-unipolar terahertz pulses were emitted from a large area photoconductive antenna (PCA) [11] excited by the ultrafast Ti:Sapphire pulses, providing a pulsed field as a mimic of the bunch Coulomb field. A synchronised narrow bandwidth optical probe was obtained by spectrally filtering a picked-off fraction of the 50 fs, 800 nm pulses that were exciting the PCA. The spectral filter was tunable in both bandwidth and wavelength, and was free from angular, spatial and temporal chirp. Transform limited 10 ps pulses were used for the narrow band probe results described here, with the pulse duration verified via autocorrelation.

The optical probe was mixed with the terahertz pulse in a 4 mm thick ZnTe crystal; the higher bandwidth response achievable with alternative EO materials was not necessary because of the ~3 THz bandwidth of the PCA emission. The electro-optically transposed pulses were then separated from the input probe through polarisation selection, and coupled into a spectrometer for analysis. In this system the spectral filter could be fully opened to allow the 50 fs pulses through, allowing a conventional terahertz time domain spectroscopy (THz-TDS) measurement of the pulse temporal profile, and hence spectrum, to be taken as a reference.

The electro-optically transposed spectrum obtained with a narrow bandwidth probe is shown in Fig. 2(a), both with and without the THz pulse Coulomb field mimic. The terahertz spectrum is closely replicated in the optical domain as sidebands on the probe, with the fundamental probe attenuated through polarisation rejection.

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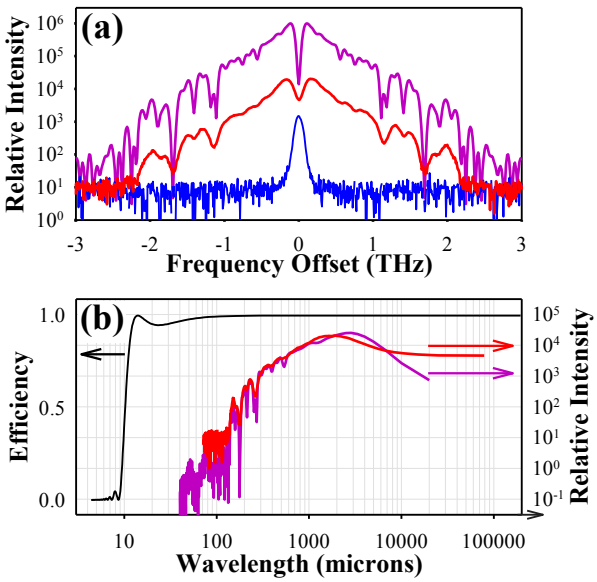

Figure 2: (a) Sideband spectra as measured by EO upconversion, and as measured via THz-TDS. The TDS spectrum has been offset to enable a clear comparison with the upconverted spectrum. (b) The sum-frequency components of the sideband spectra presented on a wavelength scale, along with the phasematching efficiency of the NCOPCPA scheme.

The lower resolution of the upconverted spectra shown in Fig. 2 is due to a combination of the resolution of the spectrometer used, and the convolution of the ~35GHz linewidth of the probe used (currently limited by the spectral filter). The spectra are also presented in Fig. 2(b) against the equivalent wavelength components of the bunch Coulomb field, along with a plot of half of (as sum and difference frequencies are to be amplified) the calculated phasematching efficiency of the NCOPCPA system. The measurement of spectral components down to DC (infinite wavelength) is possible as they are now carried at the narrow-band probe's frequency. The measurements in Fig. 2(b) are shown truncated to the resolution of the spectrometer, but could indeed also have a DC component, i.e. at the 0 THz offset in Fig. 2(a).

Measurements of the energy conversion efficiency in the electro-optically transposed pulse, combined with the properties of the rest of the system, have allowed us to estimate that for CLIC bunch parameters a transposed pulse energy of ~15 nJ should be produced for an input probe intensity of 100 kW (or 1 mJ in 10 nS).

Amplification

The electro-optically transposed pulse energy obtained directly from the EO interaction is insufficient for the implementation of a single-shot FROG [9]. Our system will use NCOPCPA to overcome this problem. NCOPCPA is a commonly used technique for the amplification of ultrashort pulses and is regularly used to amplify Fourier-transform-limited pulses by 6 or 7 orders of magnitude with minimal distortion.

In chirped pulse parametric amplification, efficient amplification of a sub-picosecond pulse by the few-nanosecond duration parametric amplifier pump is achieved by stretching the seed pulse in time to improve pulse overlap. With a subsequent compensating pulse-compressor, the original input pulse duration can be regained post-amplification. Such temporal manipulation is readily achieved through the spectral dispersion induced by a pair of diffraction gratings. This non-collinear amplification geometry has an additional benefit of a broad bandwidth gain, allowing for amplification of the spectral content associated with sub 10 fs duration pulses. An even broader bandwidth could be arranged at the expense of a greater phase distortion, but is unnecessary in this case.

For the EOT diagnostic, an NCOPCPA system based around a type 1 phasematched BBO crystal has been designed with an expected single-pass gain of an input pulse greater than a factor of 1000. The gain and bandwidth of the amplification stage has been tested through its ability to amplify 50 fs FWHM pulses obtained directly from an amplified Ti:Sapphire laser system. This provided a bandwidth comparable to that generated from transposing the Coulomb field of a 50fs FWHM bunch, which the PCA was unable to deliver. For the concept tests, the amplifier was pumped by a custom-modified Continuum Leopard Nd:YAG laser delivering 532 nm pulses of 50 ps duration and up to 30 mJ energy, which were attenuated to provide the same irradiance as a the pump pulse described in the previous paragraph. The predicted 10^3 gain and preservation of the pulse bandwidth was verified by attenuation and subsequent amplification of the 50 fs pulse back to its original energy.

The impact on the spectral phase of the amplified pulse must also be considered. In the typical case where NCOPCPA is used to generate very high energy pulses, systems are often operated such that the energy of the amplified pulse becomes large enough to cause a significant depletion of the pump pulse. In the system we have designed the pulse will be amplified to ~1 μJ, which is sufficiently small when compared to the pump pulse energy of 10 mJ for the depletion-induced phase distortion to be negligible. For this condition, the spectral phase change can be calculated using the equations derived in [12, 13], and does not exceed $\pm\pi/4$ across the phasematched bandwidth.

ANGULAR AND ALIGNEMENT EFFECTS IN EO DIAGNOSTICS

During the experiments with the laser produced THz test-bed it was found that the measured sideband spectra were unexpectedly sensitive to the alignment of the THz beam. According to Eq. 2, and as described in [4], for few-THz bandwidth pulses the probe beam is expected to develop equal positive and negative frequency sidebands, corresponding to the sum and difference frequency mixing of the THz (Coulomb) field spectrum. It has however been found that the sum and difference mixing

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spectra are often asymmetric, and that the asymmetry is dependent on the alignment of the probe and THz beams, together with details of the probe collimation and optical collection system. This sensitivity to parameters that are usually considered of secondary importance has implications for the EOT scheme, and indeed for all EO measurements. In the particular case of EOT, the symmetric nature of the upconverted spectrum of Eq. 2 is implicit in obtaining a time-domain optical envelope proportional to the square of the bunch temporal profile. In other EO techniques, for example sampling measurements, the symmetry of sum and difference frequency mixed components is implicit in the expectation of a phase change in the optical field.

It has been determined that the asymmetry is due to the up-converted spectra being angularly dispersed under the conditions of non-collinear phase matching, a condition present with small off-axis misalignments of the THz (or probe) beam, combined with a limited spatial/angular acceptance into the optical fibre. In this case one would expect to see the higher frequency components (those further from the probe wavelength) being generated at an angle higher than those at lower frequencies due to the relative scaling of the k-vectors. To verify this experimentally the THz pulse was deliberately misaligned with respect to the probe beam by an angle of 10 degrees, keeping the probe and ZnTe fixed, and a slit translated across the front of a large aperture fibre coupler to observe the spatially dispersed spectra. The slit was set to 150 microns, and measurements made at 300 micron intervals. The results are presented in Fig. 3.

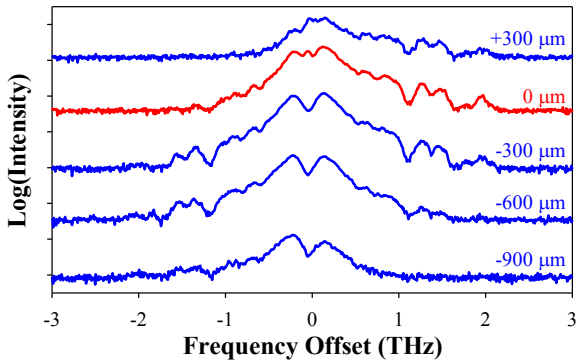

Figure 3: Measured upconversion spectra for a 10 degree incident THz pulse at a number of sampling angles. Traces are offset for clarity.

The red trace in Fig. 3 indicates the measurement made along the axis of the probe beam, where the system would typically be optimised. The potential for producing erroneous measurements is clear. However, with an understanding and inclusion of these alignment effects in the optical design a robust and consistent diagnostic can be achieved. A communication that includes a more complete model of this phasematching, and reports on experiments analysing the potentially wide-reaching implications, is currently being prepared for publication.

CONCLUSIONS

We have described the underlying principles and layout of an electro-optic detection system that will be capable of measuring relativistic bunch longitudinal profiles in a non-destructive manner without the need for femtosecond laser systems. Experiments have been performed and reported that verify design parameters. A dependency of the EO signal on optical and Coulomb-field alignment has been found that has significant implications for EO diagnostic systems, and more generally also for many THz-TDS set-ups. A complete prototype based on an industrial, reliable, nanosecond Nd:YAG laser is currently in the final stages of development.

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