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SPATIO-TEMPORAL MEASUREMENTS OF THz PULSES*

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Abstract

Electro-optic sampling is a powerful technique in the characterization of terahertz radiation and electron bunches. Using a CCD, an extended form of electro-optic sampling is demonstrated, allowing for simultaneous THz field measurements at each CCD pixel. Together, the measurements at each pixel comprise a 2-transverse + 1-temporal dimensional representation of the measured THz radiation. The equations that relate phase retardation to CCD signal are derived and a proof-of-concept measurement of subcycle terahertz radiation is presented.

INTRODUCTION

As the accessible fields of optically generated terahertz (THz) pulses continue to increase, their application to particle accelerator technology becomes more promising [1–4]. These applications may involve the interaction of particles in engineered structures or in free space, and in either case, an accurate measure of the pulse spectral content and transverse profile are essential. THz spectra are often extracted from electro-optic sampling (EOS). EOS is a time-domain electric field measurement utilizing an ultrashort optical probe which can resolve subpicosecond oscillations. It has been applied as a measure of THz pulses [5], electron bunches [6, 7], and the quantum vacuum [8]. Most EOS measurments rely on a balanced photodetector to analyze changes in probe polarization, but in some of these methods, a CCD was implemented to either capture spatial [9] or a combination of spatial and temporal information [7]. However, these methods did not produce balanced measurements, which would allow direct reconstruction of the electric field.

While a complementary measure of the THz transverse profile may be made with a microbolometer, this along with conventional EOS are not sufficient to capture spatio-spectral correlations like spatial chirp. As a consequence of this, the overall energy spectrum of a THz pulse may be misrepresented. For example, it was shown that the spectrum of a THz pulse as measured by EOS shifted in frequency upon linear propagation through the focal region [10]. Since changes in the overall frequency content of the system are not possible under linear propagation, this was explained as the redistribution of various spectral components throughout the focal volume. Since a measure of the full 2-transverse + 1-temporal THz profile would contain all of the spectral content of the pulse, it would allow direct observation of such behavior.

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EXPERIMENTAL SETUP

In this letter, a balanced method of measuring the spatio-temporal profile of transient electric fields is described and demonstrated. THz pulses were generated by optical rectification of a 1450 nm pump in DSTMS. The pump was generated by optical parametric amplification in a LightConversion TOPAS pumped by a Coherent Astrella 30 fs 1 kHz Ti:Sapphire laser system. The collimated pump profile is shown in Fig. 1 with a 3 mm pupil indicating the clear aperture of the DSTMS crystal. A slice through the center of the profile is compared to a super-Gaussian of order 1.5 with very good agreement.

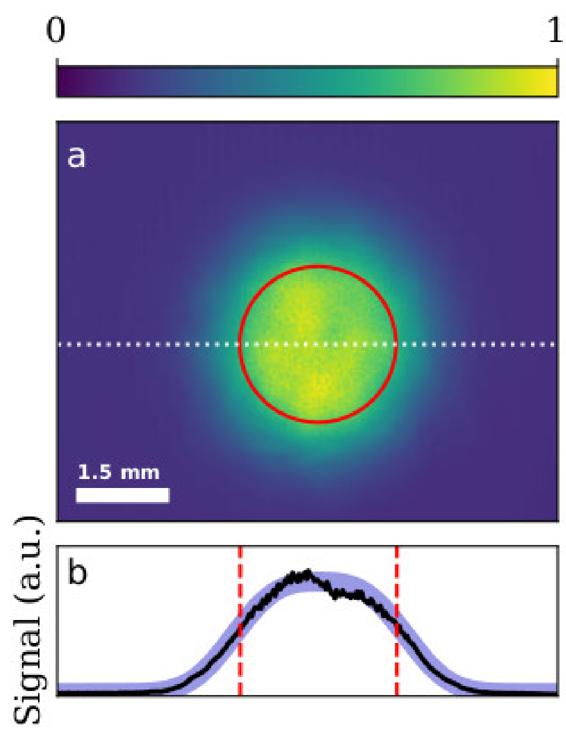

Figure 1: Pump profile. (a) The 1450 nm pump profile measured with an InGaAs SWIR camera. A 3 mm diameter red pupil indicates the clear aperture of the DSTMS crystal. (b) The radial profile in black overlaid on a super-Gaussian profile of order 1.5 (blue) showing good agreement.

The THz radiation is relayed to a 100 µm thick GaP crystal along with a co-propagating 800 nm femtosecond probe (see Fig. 2). The relative timing between the THz and the probe is scanned by a variable delay in the probe beam line. This is in common with conventional EOS methods like that used in [5]. The temporal resolution of this technique is limited by the mismatch of the probe group velocity to the THz phase velocity to about 0.1 ps [6, 11], Limiting the spectral bandwidth to about 10 THz.

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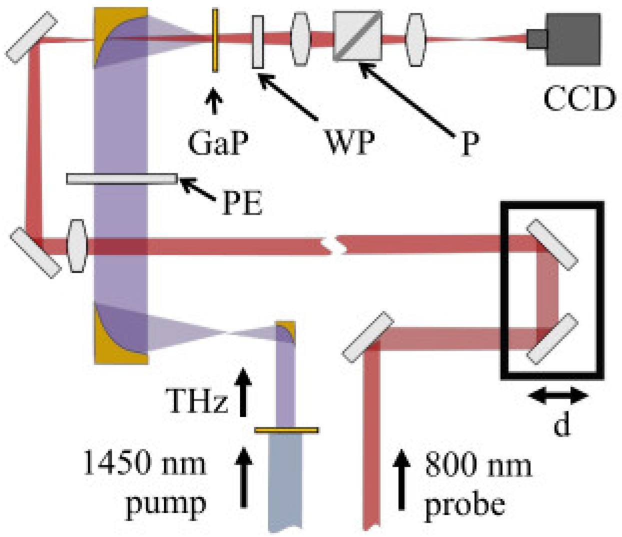

Figure 2: Experimental Setup. An ultrashort 1450 nm pump generates a THz pulse in DSTMS. This THz is relayed to a GaP electro-optic crystal, where it co-propagates with a 30 fs 800 nm probe. The probe is transversely wider than the THz spot at the GaP and its timing with respect to the THz pulse is scanned with a delay line. The probe is imaged through a quarter wave plate (WP) and a polerizer (P) to a CCD.

In contrast to conventional EOS, at the GaP, the probe is transversely larger than the THz profile while still temporally shorter than the THz period. The *local* THz electric field induces a *local* polarization transformation in the probe. Then, upon exiting the crystal, the probe is imaged through a quarter-wave plate and polarizer to a CCD. The polarizer causes changes in probe polarization to manifest as changes in fluence on the CCD which are analyzed to recover the THz electric field strength. A series of these measurements at a range of probe delays constitutes a 2-transverse + 1-temporal dimensional measurement of the THz electric field.

DERIVATION

Under the influence of the THz electric field (which can be taken as quasistatic in GaP), birefringence is induced by Pockels effect and the accumulated phase difference that results between fast and slow components of the probe is the retardation Γ. We relate the local phase retardation $\Gamma(x, y)$ to the fluence on a CCD $V(x, y)$ using Jones calculus. The polarization state of the probe is represented by a vector with two complex elements which represent magnitude and phase of x- and y-linear polarization states. Transformations of this polarization state by optical elements are represented by Jones matrices, and the Jones matrices for a retarder with axes oriented at 45 degrees to x and y and a polarizer transmitting only the x component are,

$$T(\Gamma) = \begin{bmatrix} \cos\Gamma/2 & -i\sin\Gamma/2 \\ -i\sin\Gamma/2 & \cos\Gamma/2 \end{bmatrix} \tag{1}$$

$$P = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}. \tag{2}$$

Thus for an initially vertically polarized probe E_i, the signal on the CCD can be calculated,

$$E_i = \begin{bmatrix} 0 \\ E_0 \end{bmatrix} \tag{3}$$

$$V(\Gamma) \propto |PQT(\Gamma)E_i|^2 = E_0^2\,(1 + \sin\Gamma/2\cos\Gamma/2)\,. \tag{4}$$

Here, $Q = T(\pi/4)$ is the Jones matrix for a quarter-wave plate oriented at 45°. Without knowing the constant of proportionality, we can use a reference image V_0, for which the THz is blocked to recover the retardation from the CCD signal,

$$\sin\Gamma\cos\Gamma = 2(V(\Gamma)/V_0 - 1) \approx \Gamma, \tag{5}$$

where the approximate equality represents the small angle approximation.

RESULTS

Measurements by this method provide a 2-transverse + 1-temporal dimensional representation of the pulsed beam. x-t and y-t oriented slices of this domain through the center of the pulse are shown in Fig. 3. The wavefronts of the pulse are seen to be concave-forward at the head of the pulse and concave-rearward at the tail. Similarly, the pulse on-axis is shorter than it is off-axis, requiring spatio-spectral correlations within the pulse.

Possible origins of spatio-spectral correlation could be dispersive media, diffractive optics, nonlinearities, and systematic error in the measurement. Since the relay imaging of the THz is carried out with metallic mirrors, the only dispersive media in the beam path are the DSTMS crystal, a polyethylene filter, and the GaP electro-optic medium. Each of these are aligned at normal incidence to the THz at locations where it is collimated (the GaP being at the THz focus), so refraction as a source of spatial chirp is unlikely. All optics are laser quality would not be diffractive at THz frequencies. While these THz fields are quite high, they are lower than what has already been reported in [5], wherein similar THz pulses were generated and no nonlinearity was reported.

Sources of systematic error considered should have radial symmetry. Approximations with such symmetry are the paraxial approximation applied to the THz, and the approximation that the probe is effectively flat in the electro-optic medium. For the former, we can calculate the numerical aperture of the THz with an initial beam diameter of 3 mm, the clear aperture of the DSTMS. This magnifies 6× to a diameter $D = 18$ mm after the first two parabolas, and is then focused with a final focal length of $f = 2"$. We can use this to compare the $f/\#$, $N = f/D$ to the numerical aperture, $NA = \sin(\arctan D/2f)$ to get $N(2NA) = 0.98$ which in

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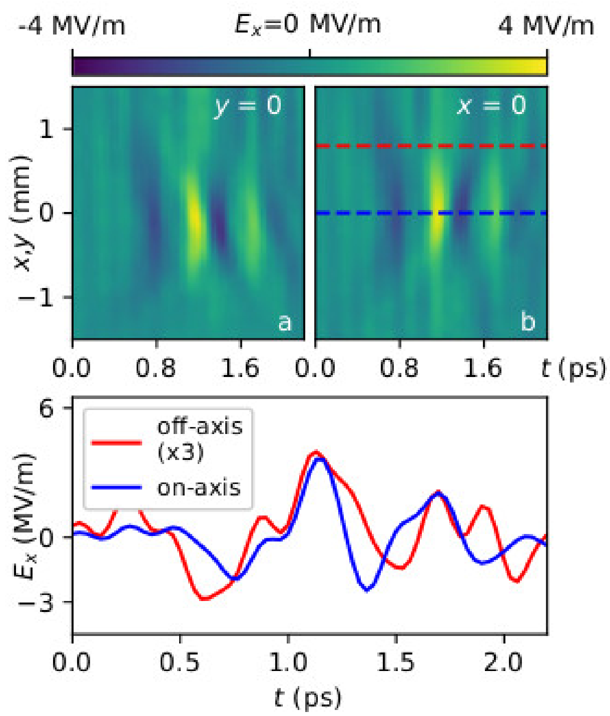

Figure 3: Spatio-temporal profile of a THz pulsed beam. Curved wavefronts and position-dependent pulse length indicate spatio-spectral correlations. On-axis, the pulse period and pulse length are shorter than that off-axis, indicating stronger localization of higher frequencies.

the paraxial approximation is taken as unity. Therefore, the paraxial approximation holds in this case. Finally, assuming a Gaussian probe profile, the curvature of the pump at the GaP can be calculated. The probe is focused with $f/17$ so accounting for divergence, the probe at a radius 3 mm (the approximate field of view of the CCD) lags the center by $\delta l = 0.04$ mm. This is much less than the THz wavelength which means the probe is effectively flat over the field of view.

Ruling these out, this spatial chirp can be explained as a natural phenomenon following from the ultrabroadband nature of the THz pulse. An initially uncorrelated beam (temporally consistent across the transverse profile) will develop correlations at the focus as the higher frequency components focus more tightly than the lower frequency components. This is consistent with an explanation of longitudinal spatio-spectral evolution in [10], and constitutes an alternative representation of the same effect.

CONCLUSION

The application of a CCD for spatio-temporal electro-optic sampling of picosecond electric fields has been demonstrated. The implementation and analysis is comparable in simplicity to conventional electro-optic sampling techniques while attaining substantially more information. Spatio-temporal correlations were observed in a THz pulse generated by optical rectification in DSTMS, and this technique may also be applicable to other electro-optic sampling measurements like temporal characterization of relativistic electron bunches.

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