

High-temporal-resolution, single-shot characterization of terahertz pulses

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A technique for noncollinear cross correlation of electro-optic modulated optical pulses is presented for the single-shot characterization of terahertz waveforms and is compared to established electro-optic terahertz characterization methods. This technique is free from the limitations on time resolution and faithful reproduction of previously demonstrated single-shot amplitude modulation spectral encoding. © 2003 Optical Society of America

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Single-shot, time resolved measurement of subpicosecond terahertz (THz) radiation by amplitude modulation of a chirped optical pulse and subsequent spectral measurements of the optical pulse was previously demonstrated.^{1,2} Such single-shot techniques are essential for measurements of systems that are noisy or that possess large jitter. Recent measurements have demonstrated the single-shot characterization of relativistic electron bunches with durations of 1.7 ps, through the sampling of the copropagating Coulomb field.³ There is now a demand for techniques capable of diagnosing much shorter electron bunches, as short as 10 fs, which will be needed for future x-ray free-electron lasers and in injected laser wakefield acceleration schemes. However, the spectral encoding technique has a fundamental time-resolution limit that makes it inapplicable for such short-pulse diagnostics.^{4,5}

In this Letter we present a new method of single-shot characterization of THz pulses based on noncollinear cross correlation of an amplitude modulated chirped pulse that overcomes the time-resolution limits of previously demonstrated techniques. In contrast to spectral encoding, our cross-correlation technique is shown to faithfully measure a THz pulse with the same temporal resolution as obtainable with scanning delay line sampling.

As discussed by Sun *et al.*,⁴ electro-optic sampling of a THz pulse $E_{\text{THz}}(t)$ by a chirped optical pulse $E_{\text{opt}}(t)$ provides time-varying amplitude modulation of the form $E_M(t) = E_{\text{opt}}(t)[1 + \beta E_{\text{THz}}(t)]$. Through knowledge of the initial time-frequency mapping of

the optical pulse it is possible to recover information on the time-varying amplitude modulation by measurement of the spectra. However, this technique of spectral encoding is subject to time-resolution limitations by the intrinsic coupling between amplitude modulations and the optical carrier spectrum. This coupling introduces additional spectral modifications that cannot by themselves be distinguished from the desired spectral modulation.

In contrast to spectral measurement of the amplitude modulated carrier wave, a time-domain cross correlation of the modulated chirped pulse $E_M(t)$ with a short probe pulse (~ 50 fs) will directly return envelope information on the chirped pulse. Together with a reference envelope measurement, this is sufficient information to permit THz modulation to be determined without the limitations imposed by spectral measurement. Additionally, no specific frequency dependence of the chirp, or knowledge of the chirp, is required.

We have demonstrated such a cross-correlation measurement of a THz-modulated chirped optical pulse, using the single-shot technique of noncollinear second-harmonic generation (SHG) with expanded beam profiles.⁶ The experimental arrangement is shown schematically in Fig. 1. A 1-kHz amplified Ti:sapphire laser provided 2-mJ, 60-fs, 25-nm-bandwidth pulses that were split into a THz-generation beam, a cross-correlation 60-fs beam, and a THz sampling beam. For the cross-correlation THz diagnostic the sampling beam was chirped to ~ 30 ps FWHM. The amplitude modulation was provided by THz-induced

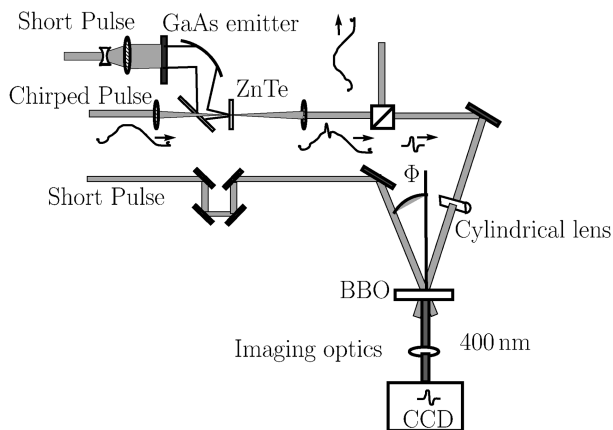


Fig. 1. Schematic of the experimental arrangement for chirped-pulse cross-correlation characterization of THz waveforms.

electro-optic rotation of the optical polarization in a 1-mm-thick $\langle 110 \rangle$ ZnTe crystal, followed by polarization selection by a cube polarizer, in the same manner as described in Ref. 2. The THz pulse was generated with a large-area biased GaAs emitter.

Single-shot SHG techniques commonly used for auto-correlation of ultrafast optical pulses⁶ are based on the temporal-to-spatial conversion that occurs through the spatial overlap of noncollinear beams in a SHG crystal. Using cross correlation of the chirped-pulse envelope with the transform-limited optical pulse rather than autocorrelation both provides a direct measure of the envelope and reduces the intensity required in the chirped pulse for second-harmonic (SH) generation. To increase the intensity available for SHG, a cylindrical lens gave a line focus of the chirped beam at a β -barium borate (BBO) crystal. The short pulse was collimated with a diameter of ~ 5 mm. The chirped-pulse and short-pulse energies at the BBO crystal were ~ 5 and ~ 100 μJ , respectively. With a beam diameter $D = 5$ mm and angle of incidence $\Phi = 15^\circ$, our measurements have a temporal window of⁶ $\tau = 2D \sin\Phi/c \sim 8$ ps. In many THz applications there is a requirement for both high temporal resolution and a several-picosecond measurement window, which in principle one can obtain simply by using larger beam size. For our measurements the beam size, and hence the temporal window, was limited only by the dimensions of the BBO crystal.

For the crystal axis and beam geometry shown schematically in Fig. 2, type I SHG phase matching of the 800- and 400-nm beams leads to the following relationship between angle of incidence Φ and crystal angle Θ :

$$\cos^2 \Theta = \left(\frac{n_{E,400}^2 n_{O,400}^2}{n_{O,800}^2 - \sin^2 \Phi} - n_{O,400}^2 \right) \frac{1}{n_{E,400}^2 - n_{O,400}^2}. \quad (1)$$

The BBO crystal was 300 μm thick, with the crystal axis $\Theta = 45^\circ$ from the normal. We effectively tuned the BBO axis to the correct phase-matching angle by tilting the crystal while maintaining the symmetry of the incident beams with respect to the crystal axis.

For our geometry, the 800-nm polarization should strictly be rotated to an angle $\gamma \sim 11^\circ$ from the horizontal (cf. Fig. 2) to be in the ordinary polarization. However, in practice the beams were actually used with p polarization.

The generated 400-nm SH radiation was imaged onto a linear CCD array by a single $f = 100$ mm lens, with the BBO crystal lying in the image plane and with an image magnification of $1.7\times$. This imaging arrangement compensates for a frequency dependent SH \mathbf{k} vector and is required for maintaining the time resolution of the diagnostic. Figure 3 shows the measured transverse profile of the SH, with the SH obtained with a quarter-wave plate before the polarizing cube shown in the upper profile. The signals that are due to imperfect polarization extinction and to THz-induced modulation are shown in the two profiles at the bottom of Fig. 3.

For comparison we measured the THz pulse by using the traditional (multishot) scanning delay line technique and also by chirped-pulsed spectral encoding. For measurement of the scanning delay line, a balanced detection arrangement was used, with a quarter-wave plate before the polarizing cube and the chirped pulse replaced with a 60-fs transform-limited pulse. For the spectral encoding measurement the THz-modulated chirped pulse shown in Fig. 1 was

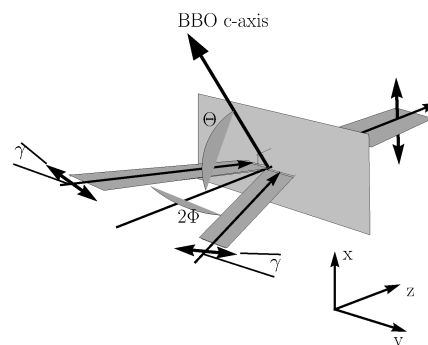


Fig. 2. Crystal and beam geometry of noncollinear SHG used for the THz cross-correlation measurement. The vertical (x) dimension of the optical beams is not shown.

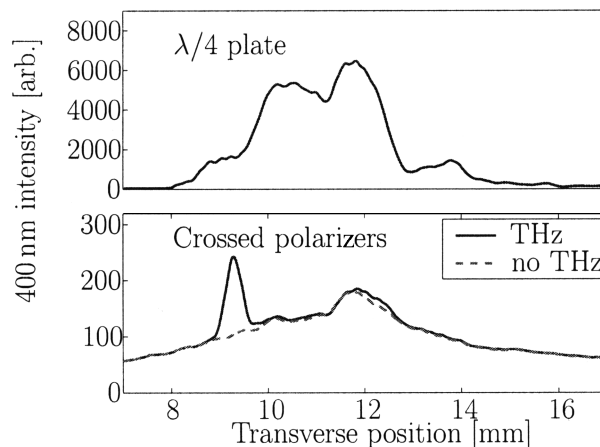


Fig. 3. Measured image of the SH generated in the cross-correlator BBO crystal. Top, with a quarter-wave plate before the polarizer; bottom, without the quarter-wave plate and with and without the THz signal.

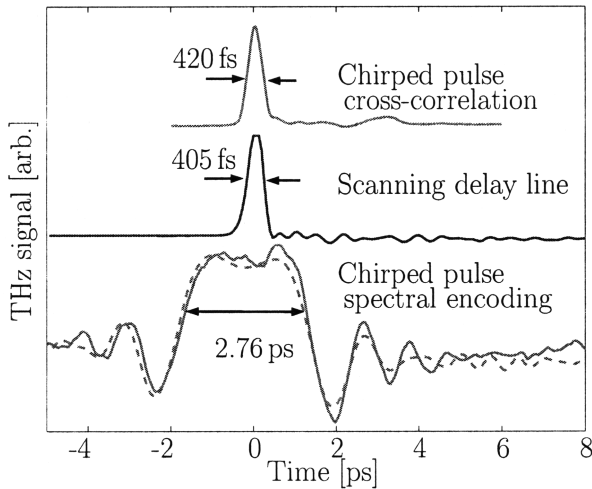


Fig. 4. THz pulses measured by electro-optic sampling with chirped-pulse cross correlation, a scanning delay line, and spectral encoding. Dashed curve, calculation of the expected THz spectral encoding signal.

redirected to a 0.75-m scanning spectrometer; a balanced detection arrangement was again used, with the spectra of both polarizations recorded simultaneously but over many laser shots. The THz signals measured by all three techniques are shown in Fig. 4.

The cross-correlation technique retrieves a THz waveform that has only a slightly increased FWHM (420 fs) compared with that obtained with the scanning delay line measurement (405 fs). In marked contrast, the spectral encoding technique displays a FWHM of 2.76 ps, together with artifacts that are intrinsic to the technique, as described below.

The use of a 1-mm-thick ZnTe crystal for the electro-optic modulation will limit the time resolution of the measurement to approximately⁷ 350 fs. The time duration of the THz pulse is also consistent with that expected from large-area GaAs emitters such as that used here. However, we conclude from the measured FWHM of the THz pulse that the time resolution of the cross-correlation measurement is better than 420 fs.

The time-resolution limitations of the cross-correlation technique are similar to those encountered in single-shot autocorrelators, i.e., dispersion of the chirped-pulse envelope as it is transported to the SHG crystal, velocity mismatch of the chirped and transform-limited pulse within the SHG crystal, and phase mismatch between the fundamental and the SH beams.⁶ The time-resolution limitation that is due to the ZnTe THz optical velocity mismatch discussed above is considered the dominant influence in these experiments, and additional efforts to minimize the cross-correlator dispersion and velocity mismatch were not required.

We note that our technique is logically similar to the single-shot THz measurements of Shan *et al.*,⁸ in which THz and optical probe beams were noncollinearly propagated through an electro-optic crystal. However, such a technique requires knowledge of the THz beam profile to characterize the temporal-to-spatial

conversion that occurs in the electro-optic crystal, which may limit its practical application.

The THz signal obtained by the technique of spectral encoding requires further explanation. The modulated electric field $E_M(t)$ has a complex spectrum, given by $\tilde{E}_M(\omega) = \tilde{E}_{\text{opt}}(\omega) + \beta \tilde{E}_{\text{opt}}(\omega) * \tilde{E}_{\text{THz}}(\omega)$, and the measured spectral difference caused by the THz modulation will be $S(\omega) = |\tilde{E}_M(\omega)|^2 - |\tilde{E}_{\text{opt}}(\omega)|^2$. Assuming a Gaussian spectrum linearly chirped optical pulse centered at time t_0 , such that $\tilde{E}_{\text{opt}}(\omega) = \tilde{E}_0 \exp[-(\omega - \omega_0)^2/\Gamma^2] \exp[i\alpha(\omega - \omega_0)^2 + i(\omega - \omega_0)t_0]$, the spectral difference for an arbitrary THz pulse $E_{\text{THz}}(t)$ will be

$$S(\omega) \approx 2\beta |\tilde{E}_{\text{opt}}(\omega)|^2 \times E_{\text{THz}}(t - \tau_0) * \Re[G(\tau)] \quad (2)$$

where

$$G(t) \equiv \text{FT} \left[\exp \left(i\alpha - \frac{1}{\Gamma^2} \right) \Omega^2 \right] \\ = \left(\frac{\pi}{-i\alpha + \frac{1}{\Gamma^2}} \right)^{1/2} \exp \left[\frac{t^2}{4 \left(i\alpha - \frac{1}{\Gamma^2} \right)} \right] \quad (3)$$

and $\tau = 2\alpha(\omega - \omega_0)$. In the limit of an infinite-bandwidth optical pulse, $\Gamma^2 \rightarrow \infty$, or, equivalently, assuming a constant spectral amplitude of the chirped pulse over the THz bandwidth, we obtain a measured spectral difference $S(\omega) = \sqrt{\pi/\alpha} 2\beta |\tilde{E}_0(\omega)|^2 \times E_{\text{THz}}(t - \tau_0) * \cos(t^2/4\alpha - \pi/4)$, in substantive agreement with the result of Fletcher for a specific THz waveform.⁵ The expected spectral modulation signal has been calculated from Eq. (2), with the THz pulse obtained from the scanning delay line measurement taken as $E_{\text{THz}}(t)$. This calculation is shown in Fig. 4 with parameters $\alpha = 3.06 \text{ ps}^2$, $\Gamma = 4.2 \text{ ps}^{-1}$, and a spectrometer resolution of 0.5 nm, and displays good agreement with the measured spectral signal.

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