Dithered-edge sampling of terahertz pulses

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We introduce a technique for ultrawideband measurement of terahertz pulses called dithered-edge sampling (DES). The technique makes use of a photoconductive receiver, but the detection bandwidth is much wider than that of the receiver alone. The key to increasing the bandwidth is the addition of an ultrafast optically triggered attenuator that chops the terahertz pulse before its detection. The bandwidth is limited only by the duration of the optical pulse used to trigger the attenuator. We use a combination of derivative dither and an integrating receiver to recover the terahertz field directly from the measured signal. When used alone, the slow receiver blurs the measured terahertz pulse width to 1.3 ps. However, the increased time resolution of the DES system (triggered attenuator plus receiver) allows one to measure source-limited terahertz pulse widths (400 fs in this case). © *1999 American Institute of Physics.* [S0003-6951(99)04541-6]

Terahertz (THz) pulses are now used in a wide variety of applications, including far-infrared[1] or time-domain spectroscopy,[2] study and control of Rydberg atoms,[3] and imaging of optically opaque materials.[4] Many applications depend on a coherent detection scheme that samples the electric field of the THz pulse with a bandwidth of several terahertz. The two most prevalent sampling techniques are photoconductive sampling (PCS),[5] which uses gated photoconductive receivers, and free-space electro-optic sampling (FSEOS).[6] In a recent comparison[7] it was shown that for low modulation frequencies and low optical peak power, PCS has a better signal-to-noise ratio and higher sensitivity than FSEOS. However, the temporal resolution of PCS is limited ultimately by the nonzero carrier lifetime of the receiver's photoconductive material.

In this letter, we introduce *dithered-edge sampling* (DES) as an alternate technique for measuring THz pulses. The detection scheme uses the best features of PCS; moreover, its bandwidth is not limited by the carrier lifetime of the photoconductive receiver material. Typically a THz pulse is sampled using a detector that is only sensitive to the pulse's electric field during a narrow measurement window. For example, in PCS techniques this window is determined by the time during which the receiver is conductive. In FSEOS, the window is determined by the overlap of the THz pulse with an ultrashort optical probe pulse in an electro-optic crystal. Ideally this window is much shorter than the time scales over which the THz pulse varies.

Scanning such a narrow window, however, is not the only way to sample a wave form. One can also use an abrupt discontinuity or *edge* to provide the required resolution. For example, in the spatial domain, a knife-edge and large detector can be used to characterize an optical beam profile with high precision.[8] Equivalently, in the time domain, the edge produced by a rapid change in the transmission of an attenuator can provide the required temporal resolution.

In our DES technique, the THz pulse is first passed through a ''triggered attenuator'' formed from a semiconductor wafer whose transmissivity undergoes a rapid decrease following the absorption of an ultrashort optical pulse. The decrease in transmission occurs in a time as short as the optical trigger pulse itself.[9] A relatively slow photoconductive receiver then measures the transmitted THz pulse. We use derivative dither techniques[10] to measure the THz field directly by rapidly varying (or ''dithering'') the time at which the attenuator is triggered relative to the THz pulse, and using lock-in detection to measure the receiver's photocurrent at the dither frequency. This combination of a fast transmission edge, a relatively slow photoconductive receiver, and dither techniques forms the basis of the dithered-edge sampling method.

If a THz pulse is incident on such an attenuator, the transmitted electric field is given by $E(t)G(t-\tau_G)$, where $E(t)$ is the electric field of the incident pulse, and $G(t-\tau_G)$ is the attenuator's time-dependent transmissivity or ''edge function,'' with the edge occurring at time τ_G. The transmitted THz pulse is then measured using a receiver with a temporal response $R(t-\tau_R)$, where τ_R is the delay between the time of arrival of the THz pulse and the receiver's optical gate pulse. The photocurrent signal is given by

$$S(\tau_G,\tau_R)=\int_{-\infty}^{\infty}E(t)G(t-\tau_G)R(t-\tau_R)dt. \tag{1}$$

We recover $E(t)$ from this signal in the following way. The time at which the edge occurs, τ_G, is modulated at frequency Ω with amplitude $\delta\tau$, so $\tau_G=\tau_0-\delta\tau\cos(\Omega t)$. Also, the receiver trigger time, τ_R, is set so that the maximum of the receiver's response, R, is coincident with the rapid decrease in G, (i.e., $\tau_R=\tau_0+\Delta\tau$). In addition, we use a lock-in amplifier to measure the component of S that is modulated at the dither frequency, Ω. One can obtain an expression for this component if one replaces G with a Taylor expansion in $\delta\tau\cos(\Omega t)$ about $t-\tau_0$, and keeps terms modulated at the dither frequency. For small dither amplitudes this signal is

$$S_\Omega(\tau_0)=\delta\tau\int_{-\infty}^{\infty}E(t)G'(t-\tau_0)R(t-\tau_0+\Delta\tau)dt, \tag{2}$$

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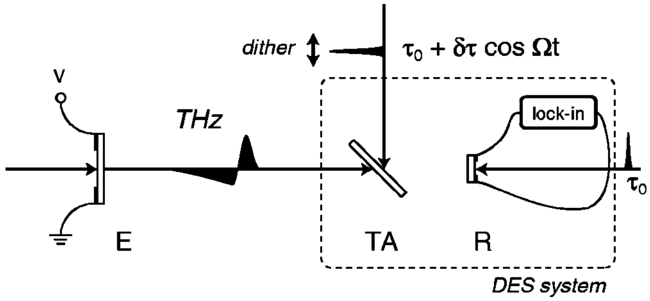

FIG. 1. Schematic of the DES system showing the THz emitter (E), the triggered attenuator (TA) and the photoconductive receiver (R). The lock-in amplifier was locked at the frequency of the delay dither.

where $G'(t)$ is the derivative of $G(t)$ with respect to time. We can see that if the drop in the edge function occurs sufficiently quickly, its derivative is a narrow sampling window centered on the time τ_0. In the limit of an extremely rapid edge, G' becomes a delta function and $R(t-\tau_0+\Delta\tau)$ can be replaced by its peak value, R_0. Then $S_\Omega(\tau_0)$ is proportional to $E(\tau_0)$, and by slowly varying τ_0 we map out the THz pulse electric field. In this way, the speed of the attenuator combined with the high sensitivity of the gated photoconductive receiver allows one to sample THz pulses with a much finer temporal resolution than is provided by the receiver alone.

A schematic of the experimental setup is shown in Fig. 1. The optical pulses used to trigger the emitter, attenuator, and receiver were produced by a Ti:sapphire regenerative amplifier running at a 1 kHz repetition rate. The 130 fs pulses were centered at 810 nm. Both the THz emitter and receiver were standard large-aperture photoconducting antennas.[11] We made the emitter from 1 cm^2 ⟨100⟩ semi-insulating GaAs biased with a field of 3 kV/cm via parallel Au-Ge-Ni electrodes. We fabricated the detector by depositing parallel Au-Ge-Ni electrodes, spaced 2 mm apart, upon an epilayer of low-temperature molecular-beam-epitaxy-grown GaAs (LT-GaAs). The 1.5-μm-thick LT-GaAs layer was grown at 200 °C and annealed *in situ* at 600 °C to produce a short carrier lifetime of ~1 ps. The emitter and receiver were triggered by illuminating them uniformly with an optical pulse energy of 20 and 1 μJ, respectively. The 120 nW average power of the THz beam from the emitter was measured with a helium-cooled bolometer (Infrared Laboratories), and corresponds to a peak electric field of ~350 V/cm.

We made the attenuator from a 0.5-mm-thick wafer of semi-insulating GaAs. To trigger the attenuator, a 1 cm^2 area was illuminated with a fluence of 30 $\mu J/cm^2$, creating a carrier density of $\sim 10^{18}\,cm^{-3}$. This high density of carriers turn the semiconductor, which is normally transparent to THz radiation, into a quasimetal, which reflects 80% of the incident THz power. Because semi-insulating GaAs has a long carrier lifetime, the reduced transmission persists for nanoseconds. When the pump photon energy (1.55 eV) is just above the band edge (1.42 eV), the transition from transparent to opaque can occur in a time as short as the optical pulse that is used to trigger the attenuator.[9]

The DES scheme samples the shape of THz pulses in the following way. First the THz pulse train passes through the attenuator. The attenuator's edge is optically triggered to chop the THz pulses at the point to be sampled. Then chopped pulses are incident on the gated receiver. We set the delay of the receiver's gate pulses so that the maximum of the receiver's response coincides with the chopped part of the THz pulses. To sample the THz pulse shape, we scan the mean delay τ_0 for both the attenuator and the receiver using a single delay stage.

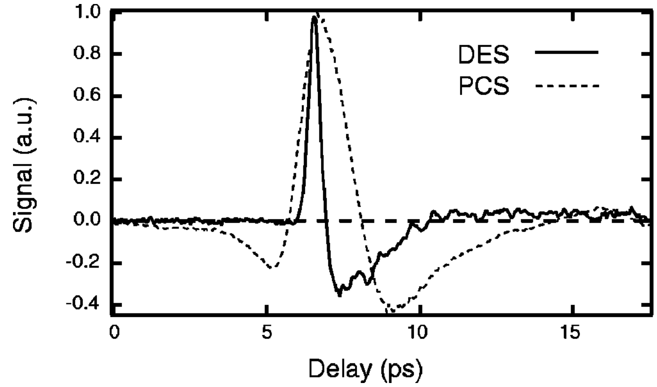

FIG. 2. Comparison of the THz pulses measured using the dithered-edge sampling (DES) and the photoconductive sampling (PCS) techniques. The source was a large-aperture emitter (1 cm^2) with 3 kV bias. Note that the same large-aperture receiver was used in both measurements.

To measure the THz pulse at the point coinciding with the attenuator's edge we dither the location of the edge relative to the THz pulse and measure the modulation of the receiver's photocurrent using a lock-in. The edge is dithered by changing the optical delay for the trigger pulse about the mean τ_0 using a corner cube mounted on a piezoelectric transducer. Typically, the dither amplitude, $\delta\tau$, is ~100 fs, and the frequency, $\Omega/2\pi$, is ~100 Hz. First, note that the dither amplitude is less than the 130 fs Ti:sapphire pulse width, and so the dither does not affect the temporal resolution of the detection scheme. Second, note that the dither frequency is slow compared to the 1 kHz repetition rate of the laser pulses, and thus the 1 kHz train of photocurrent pulses from the receiver is amplitude modulated at the dither frequency. This modulation is proportional to the electric field of the THz pulse at time τ_0.

The measured THz pulse shapes are shown in Fig. 2; their spectral amplitudes are shown in Fig. 3. The solid lines represent the DES measurement, and the dashed lines are the PCS measurement made with our large-aperture receiver in the standard way. There are three things to notice; first, the bandwidth of the DES measurement of the pulse is roughly three-times larger than the bandwidth of the PCS measurement. In addition, the DES measurement agrees with independent interferometric measurements of the spectrum from this type of large-aperture source.[12] Second, the pulse shape measured by the DES technique does not have the negative leading edge which is typically found in PCS measurements. Indeed, the abrupt rise in the electric field seen in the DES measurement agrees with the ''current-surge model'' of the THz pulse from a photoconductive source.[13] Finally, oscillations due to water vapor absorption[14] are faithfully reproduced in the DES measurement. These absorption lines[15] are shown in the plot of the spectral amplitude in Fig. 3.

A more detailed analysis[16] of the origin of the DES signal reveals two further points. The first point is that the sig-

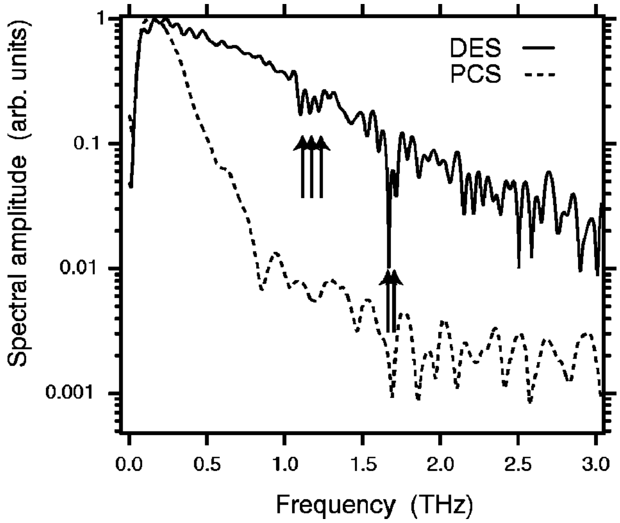

FIG. 3. Spectral amplitudes of the THz pulses shown in Fig. 2. Arrows show the location of water vapor resonances.

nal is also carried on sidebands due to the mixing of the dither frequency with the laser's repetition rate. Thus, rather than lock to the low dither frequency, one can reduce baseband noise by locking to these higher sidebands. The second point that the analysis shows is that the bandwidth of the system depends on the product of two quantities. The first is the bandwidth of the derivative of the edge function—the faster the edge, the faster the detection system. The second quantity depends solely on the dither amplitude, $\delta\tau$. Thus, to increase the signal, one can increase the dither amplitude until the detection bandwidth becomes compromised and the measurement is distorted. As increasing the amplitude of the dither is much easier than modifying components (such as the dimensions of photoconducting antenna structures or electro-optic crystals), this adds to the flexibility of the technique.

As the slow photoconductive receiver is not responsible for the time resolution of the detection technique, its sensitivity can be optimized without a bandwidth constraint. Although our demonstration used a low-repetition-rate, high-pulse-energy laser system, the technique can be scaled down to high-repetition-rate, low-pulse-energy systems. This is done reducing the size of the attenuator to ~ 0.5 mm in diameter and placing it at the waist of the focused THz beam (the typical placement position for a dipole receiver in PCS, and the EO crystal in FSEOS).

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[1] D. Grischkowsky, S. Keiding, M. van Exter, and Ch. Fattinger, J. Opt. Soc. Am. B **7**, 2006 (1990).
[2] S. R. Keiding, Comments At. Mol. Phys. **30**, 37 (1994).
[3] R. R. Jones, Phys. Rev. Lett. **76**, 3927 (1996).
[4] B. Hu and M. Nuss, Opt. Lett. **20**, 1716 (1995).
[5] D. H. Auston, K. P. Cheung, and P. R. Smith, Appl. Phys. Lett. **45**, 284 (1984).
[6] Q. Wu and X.-C. Zhang, Appl. Phys. Lett. **68**, 1604 (1996).
[7] Y. Cai, I. Brener, J. Lopata, J. Wynn, L. Pfeiffer, J. B. Stark, Q. Wu, X. C. Zhang, and J. F. Federici, Appl. Phys. Lett. **73**, 444 (1998).
[8] Y. Suzaki and A. Tachibana, Appl. Opt. **14**, 2809 (1975).
[9] P. N. Saeta, J. F. Federici, B. I. Greene, and D. R. Dykaar, Appl. Phys. Lett. **60**, 1477 (1992).
[10] See, for example, *Modulation Spectroscopy*, Supplement 11 of *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic, New York, 1969).
[11] J. T. Darrow, D. H. Auston, and J. D. Morse, Proc. SPIE **1861**, 186 (1993).
[12] D. You, R. R. Jones, P. H. Bucksbaum, and D. R. Dykaar, Opt. Lett. **18**, 290 (1993).
[13] A. J. Taylor, P. K. Benicewicz, and S. M. Young, Opt. Lett. **18**, 1340 (1993).
[14] M. van Exter, Ch. Fattinger, and D. Grischkowsky, Opt. Lett. **14**, 1128 (1989).
[15] R. T. Hall, D. Vrabec, and J. M. Dowling, Appl. Opt. **5**, 1147 (1966).
[16] One calculates the spectrum of the signal from the cross-correlation of the THz pulse train with the receiver's temporal response and the dithered-edge function.