Direct measurement of a photoconductive receiver's temporal response by dithered-edge sampling

Jake Bromage, Ian A. Walmsley, and C. R. Stroud, Jr.

The Institute of Optics, University of Rochester, Rochester, New York 14627

Received June 14, 1999

We present the results of a direct measurement of the temporal response of a terahertz (THz) photoconductive receiver obtained by dithered-edge sampling. The receiver response has structure that accounts for the negative-going leading edge of the pulse shape that is often seen in measurements made with these receivers in a conventional sampling arrangement. We show that the THz pulse shape measured by conventional photoconductive sampling is indeed a cross correlation of the pulse with the measured receiver's response.

OCIS codes: 320.7080, 320.7100.

Many applications of terahertz (THz) radiation (e.g., time-domain spectroscopy,[1] imaging of optically opaque materials,[2] and impulse ranging[3]) rely on photoconductive antennas to detect THz pulses. The response function of such antennas has never been directly measured as far as we know, even though knowledge of the function is critical for determining the performance of THz spectrometers based on photoconductive sampling. In this Letter we present a technique for measuring directly the temporal response of a photoconductive receiver.

Typically, a THz receiver is a broadband antenna that has a gap in the antenna structure filled with a semiconductor material.[4] A THz pulse electric field can produce a current in the antenna only if the gap is made conducting by being illuminated with an ultrashort optical pulse tuned above the semiconductor bandgap. This pulse acts as a trigger to turn on the receiver. Semiconductors with subpicosecond carrier lifetimes lead to a receiver response that is a narrow temporal window. In photoconductive sampling (PCS), this window can be used to measure the shape of THz pulses in the following way: The current induced by the THz pulse is measured as a function of delay between the arrival of the THz and optical trigger pulses. For perfect sampling, the receiver response should be a delta function in time. In practice, however, the finite carrier lifetime of the semiconductor and the geometry of the antenna lengthen the temporal response to several hundred femtoseconds.[5]

We measure the receiver response by using the ultrawide-bandwidth dithered-edge sampling (DES) technique.[6] We show experimentally, for a range of receiver responses, that the signal measured by the receiver (operated in the conventional PCS mode) is indeed the cross correlation of the THz electric field (E) and the receiver's response (R). That is, the signal is given by

$$S(\tau) = \int_{-\infty}^{\infty} E(t)R(t-\tau)\mathrm{d}t\,, \tag{1}$$

where τ is the delay between the THz pulse and the pulse that triggers the receiver.

One way to determine R is to measure the response of the detector to an impulse. Equation (1) shows that, if $E(t)$ is much shorter than the response time of the receiver, $S(\tau)$ will equal $R(-\tau)$. Making a source of such THz pulses, however, may be difficult.

Another way to characterize a detector is to measure its response to an abrupt discontinuity, or edge. For example, in the spatial domain, one can use a knife-edge to determine the spatial resolution of an imaging system.[7] The analogous quantity for a THz receiver is the temporal edge formed by an electric field that drops abruptly from a constant value (E_0) to zero. If a receiver that measures this field is gated at a time τ relative to the edge, the signal $S(\tau)$ from Eq. (1) becomes

$$S(\tau) = E_0 \int_{-\infty}^{-\tau} R(t')\mathrm{d}t', \tag{2}$$

and thus

$$R(-\tau) \propto \frac{\mathrm{d}S}{\mathrm{d}\tau}(\tau)\,. \tag{3}$$

So, to determine R, one can measure S as a function of τ and calculate its derivative. The numerical derivative of data, however, is sensitive to high-frequency noise. To overcome this limitation we use the derivative dither technique to sample R directly. In this method the delay (τ) between the arrival of the THz pulse edge and the receiver's gate pulse is slowly modulated or dithered with amplitude $\delta\tau$. Then a lock-in amplifier measures the resultant variation of the current from the receiver at the dither frequency. For small dither amplitudes, this modulation is proportional to $\mathrm{d}S/\mathrm{d}\tau$. In this way, as shown by relation (3), we directly sample $R(-\tau_0)$, which is the receiver response that overlaps the average edge position τ_0. This combination of a fast temporal edge and derivative dither techniques forms the basis of the DES technique.

In practice we do not have a THz pulse in the form of a step function, but we are able to impress a fast temporal edge in an otherwise slowly varying THz pulse by using an optically triggered attenuator. By

0146-9592/99/231771-03$15.00/0

dithering the location of the edge, we sample directly the receiver's response that coincides with the average edge position. Note that what is required is that the THz field be constant during the edge dither interval $\delta\tau$. The form of the field before or after the edge is immaterial.

A schematic of the experimental setup is shown in Fig. 1. The 130-fs, 810-nm optical pulses were provided by a Ti:sapphire regenerative amplifier at a 1-kHz repetition rate. The THz emitter was a standard large-aperture antenna, built from 1-cm^2 (100) semi-insulating GaAs.[8] When the antenna was biased with 3 kV/cm and uniformly illuminated with a 20-μJ optical pulse, the average THz power (measured with a helium-cooled bolometer) was 120 nW.

We cut a fast edge into the THz pulse by using a triggered attenuator. We made the attenuator from a 0.5-mm-thick wafer of semi-insulating GaAs. To trigger the attenuator we illuminated a 1-cm^2 area with an optical fluence of 30 $\mu J/cm^2$, creating a carrier density of $\sim 10^{18}$ cm^{-3}. This high density of carriers turns the semiconductor, which is normally transparent to THz radiation, into a quasi metal that reflects 80% of the incident THz power. Because of the long carrier lifetime of the semi-insulating GaAs, 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 that of the optical pulse that is used to trigger the attenuator.[9] It is the speed of this transition that provides the temporal resolution for the DES technique: A 130-fs trigger pulse provides a 3-dB sampling bandwidth of 3.4 THz.

The receiver that we used in this demonstration was a standard large-aperture photoconductive antenna.[8] 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. This 1.5-μm-thick layer was grown at 200 °C and annealed *in situ* at 600 °C to produce a short carrier lifetime of approximately 1–2 ps. The receiver was triggered by being illuminated uniformly with a 1-μJ optical pulse.

The DES scheme samples the shape of the receiver's response in the following way: First the THz pulse train passes through the attenuator. The attenuator is optically triggered to chop the THz pulses at their peak. Then the chopped pulses are incident upon the gated receiver under test. To map out the receiver's response, we vary the delay between the arrival of its optical gate pulse and a THz pulse.

To measure the receiver's response at the point coinciding with the edge, we dither the location of the edge relative to the receiver's response and measure the modulation of the receiver's photocurrent, using a lock-in amplifier. We dither the edge by changing the optical delay for the attenuator's trigger pulse, using a corner cube mounted upon a piezoelectric transducer. Typically, the dither amplitude, $\delta\tau$, is $\sim$100 fs, and the frequency, $\Omega/2\pi$, is $\sim$100 Hz. Note that a dither amplitude of this magnitude limits the bandwidth of the detection scheme to 7.1 THz (at the 3-dB point). Because the dither frequency is slow compared with the 1-kHz repetition rate of the laser pulses, the 1-kHz train of photocurrent pulses from the receiver is amplitude modulated at the dither frequency. This modulation is proportional to the receiver's response, $B(-\tau_0)$.

Figure 2 shows the measured response, $R(t)$; the inset shows the THz pulse that we measured by using a variant of the DES technique.[6] Note that the receiver response is much broader than the THz pulse, and so we expect significant distortion when this receiver is used in the conventional PCS mode to measure this THz pulse. Also note that the receiver's response has a negative trailing edge.

Figure 3 shows a comparison of two THz pulse shapes. One was measured by the receiver operated in the PCS mode. The other is the pulse shape predicted by Eq. (1), which we calculated by using the THz pulse and receiver response shown in Fig. 2. The agreement shows that Eq. (1) is indeed an accurate method for the distortion of the shape of a THz pulse by the nonideal response of a receiver. In principle, depending on the signal-to-noise ratio of the measurements and the specifics of the spectrum of $R(t)$, one may be able to deconvolve the measured receiver response from a PCS measurement of the THz pulse.

To test this model further, we intentionally broadened the receiver's response by using the receiver at an oblique angle of incidence to the copropagating THz and optical beams [as shown schematically in Fig. 4(a)]. For each angle of incidence, we made two measurements. First we used the DES technique to measure

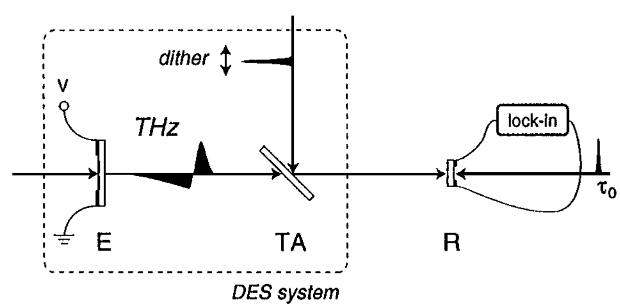

Fig. 1. Schematic of the experimental setup, showing the THz emitter (E), the triggered attenuator (TA), and the receiver under test (R). The lock-in amplifier was locked at the frequency of the delay dither.

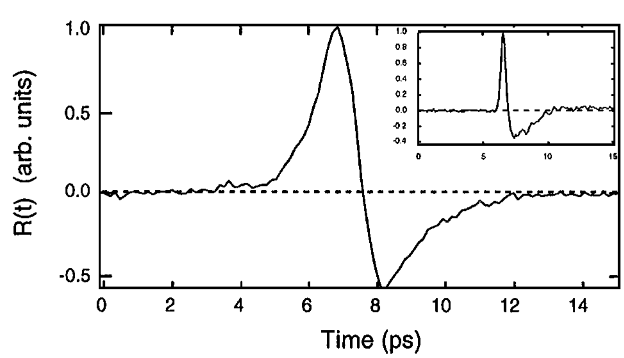

Fig. 2. Temporal response of the receiver. Inset, the electric field of the THz pulse from the large-aperture emitter, measured with a variant of DES.

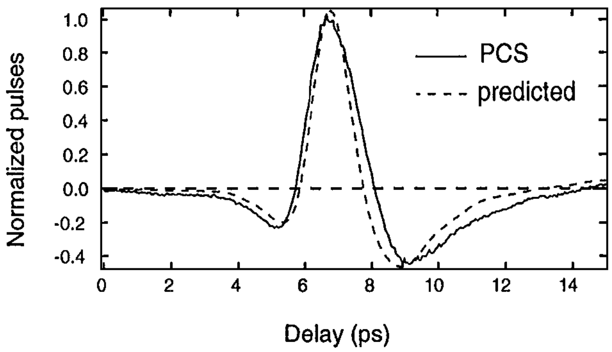

Fig. 3. Comparison of the PCS measurement of the THz pulse shape with the prediction calculated by use of the measured receiver response.

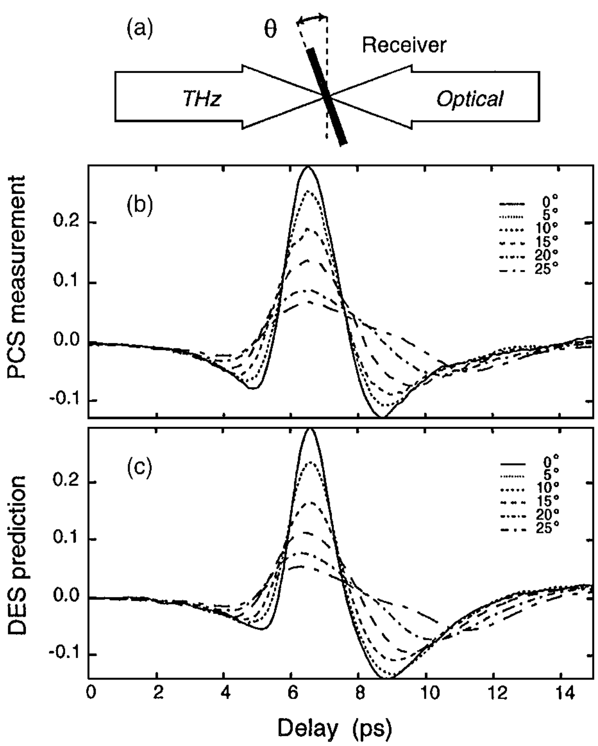

Fig. 4. (a) Schematic of the angle-broadening experiment. The THz pulse is polarized along the axis of rotation. (b) THz pulse shapes measured by the receiver in PCS mode. (c) THz pulse shapes predicted from DES measurement of receiver's response.

the receiver's response. Then we blocked the attenuator's trigger beam and measured the THz pulse, using the receiver in the PCS mode. Figure 4(b) shows the PCS measurements, which decreased in amplitude and became broader as we increased the incidence angle. Figure 4(c) shows the predictions calculated from the DES measurement of the receiver's response for each incidence angle. A comparison of the figures shows that the DES measurement of the receiver response predicts the general shape and relative amplitudes of the PCS measurements for the entire range of incidence angles.

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. One does this by reducing the size of the attenuator to ~0.5 mm in diameter and placing the attenuator at the waist of the focused THz beam (the typical placement position for a dipole receiver in PCS and the electro-optic crystal in free-space electro-optic sampling[10]).

In this Letter we have shown how to measure directly the temporal response of a photoconductive receiver by using dithered-edge sampling. Such measurements allow one to optimize the antenna geometry and choice of materials to increase the receiver's sensitivity and bandwidth. Because our measurement technique relies on the optical response of a triggered attenuator rather than on an electronic response, the response function of the antenna can be measured directly. This suggests the possibility of sampling the response of any THz detection system with a bandwidth ultimately limited by the bandwidth of the attenuator trigger pulse.

We thank G. Wicks for providing the low-temperature molecular-beam-epitaxy-grown GaAs samples and acknowledge helpful discussions with C. Iaconis, L. J. Waxer, and M. Currie. This research was supported by the U.S. Army Research Office, the National Science Foundation, and the TRW Foundation. J. Bromage acknowledges the support of a Horton Fellowship through the Laboratory for Laser Energetics of the University of Rochester. I. A. Walmsley's e-mail address is walmsley@optics.rochester.edu.

References

1. D. Grischkowsky, S. Keiding, M. van Exter, and Ch. Fattinger, J. Opt. Soc. Am. B **7,** 2006 (1990).
2. B. Hu and M. Nuss, Opt. Lett. **20,** 1716 (1995).
3. R. A. Cheville and D. Grischkowsky, Appl. Phys. Lett. **67,** 1960 (1995).
4. D. H. Auston, K. P. Cheung, and P. R. Smith, Appl. Phys. Lett. **45,** 284 (1984).
5. P. Uhd Jepsen, R. H. Jacobsen, and S. R. Keiding, J. Opt. Soc. Am. B **13,** 2424 (1996).
6. J. Bromage, I. A. Walmsley, and C. R. Stroud, Jr., Appl. Phys. Lett. **75,** 2181 (1999).
7. R. A. Jones, Appl. Opt. **7,** 133 (1968).
8. J. T. Darrow, D. H. Auston, and J. D. Morse, Proc. SPIE **1861,** 186 (1993).
9. P. N. Saeta, J. F. Federici, B. I. Greene, and D. R. Dykaar, Appl. Phys. Lett. **60,** 1477 (1992).
10. Q. Wu and X.-C. Zhang, Appl. Phys. Lett. **68,** 1604 (1996).