Measurements of the phase shift and reshaping of terahertz pulses due to total internal reflection

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Using time-domain spectroscopic techniques with freely propagating electromagnetic beams of terahertz pulses, we have measured the phase shift and reshaping of subpicosecond pulses due to total internal reflection from a crystalline quartz prism. Our measured value of the phase shift is in excellent agreement with the theoretical prediction.

The reshaping of ultrashort electromagnetic pulses due to the phase change that occurs on total internal reflection (TIR) was first demonstrated by Cheung and Auston.[1] As their source of ultrashort far-infrared pulses, they generated an electromagnetic shock wave by driving the optical rectification effect in a nonlinear dielectric material with an ultrashort laser pulse.[2,3] In their experiments[1] they measured the reshaping of this shock wave after a TIR at the boundary of the nonlinear crystal.

A recent observation of electromagnetic shock waves emitted by surface-dipole distributions propagating on a dielectric surface[4] permitted the indirect measurement of the phase shift due to TIR. In that study the shock wave was the sum of a directly radiated term and a phase-shifted term from a TIR component. The good agreement between theory and experiment[4] confirmed the theoretical model that relied heavily on the pulse-reshaping effect due to the TIR phase shift.

In this Letter we report direct observations of the pulse reshaping due to TIR of freely propagating, low-divergence beams of subpicosecond terahertz pulses. In order to compare experiment and theory as precisely as possible, we used the new high-brightness terahertz beam source[5] together with a crystalline quartz prism in the TIR geometry. We observed strong reshaping of the propagating terahertz pulse compared with the incident pulse. With the technique of time-domain spectroscopy,[3,6] a comparison of the Fourier transforms of the incident and reflected pulses allows us to extract the TIR phase shift, which agrees with the theoretical prediction to within our experimental error of 2%.

The experiment is illustrated schematically in Fig. 1. The system is driven by the 70-fsec, 625-nm pulses from a compensated colliding-pulse mode-locked dye laser operating with a pulse repetition rate of 100 MHz and producing an average power of 5 mW in the driving beam. As previously described,[5] this beam is focused onto a micrometer-sized dipole antenna terminated by a coplanar transmission line fabricated on an ion-implanted silicon-on-sapphire (SOS) wafer. There is a bias voltage of 10 V across the line and also across the antenna gap. The driving laser pulses are focused on the gap and thereby short the antenna and produce a transient Hertzian dipole that radiates a terahertz pulse into the sapphire substrate.[5–7] The peak transient current in the antenna is approximately 0.01 A, corresponding to an average current of 0.5 μA. This radiation is then collimated to an approximately 5-mm beam diameter by a spherical sapphire lens in contact with the sapphire surface. The center of a truncated 9.5-mm-diameter sphere (lens) is 2.3 mm above the ultrafast dipolar antenna located at the focus of the lens. Because the output face of the lens is in the radiation zone for the frequency range of interest, the antenna pattern on the output face is the same for all frequencies. The effect of the lens is to collimate this pattern into a plane wave. From this point the beam can be considered as a superposition of waves diffracting from a 5-mm soft circular aperture. Although the 75-mm-aperture paraboloidal mirrors have a 12-cm focal length, a 17-cm distance was used between the sapphire lenses and the paraboloidal mirrors to compensate for the wavelength-dependent diffraction and to optimize the response of the system at the peak of the measured spectrum. It is important to note that because the incident beam diameter at the collimating mirror is proportional to the wavelength, a frequency-independent divergence is obtained after the collimation by the paraboloidal mirror.[5]

The experiment consists in measuring two reflec-

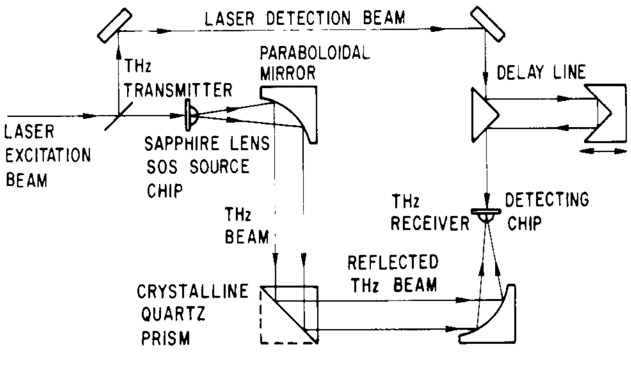

Fig. 1. Schematic diagram of experiment.

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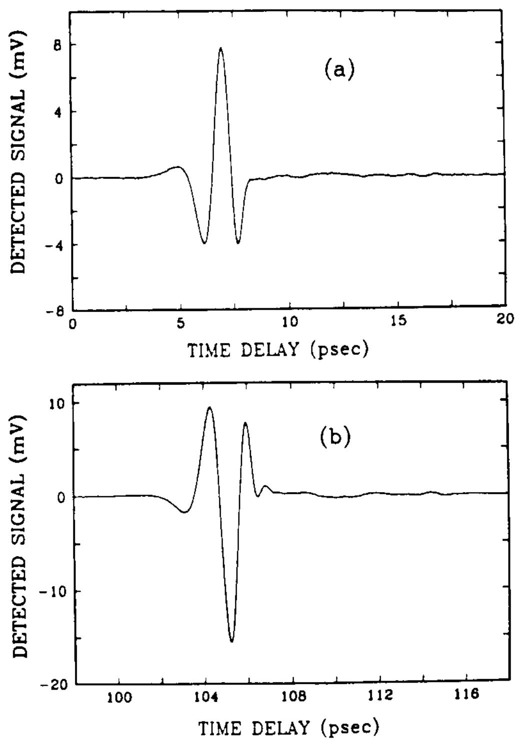

Fig. 2. (a) Reference pulse reflected from the front surface of the quartz prism at the position indicated by the dashed line in Fig. 1. (b) TIR pulse from the quartz prism oriented as shown by the solid line in Fig. 1.

tions from the crystalline quartz right-angle prism. The *C* axis of the crystal is perpendicular to the triangular plane, i.e., perpendicular to the plane of the diagram of Fig. 1. The transient Hertzian dipolar source is oriented so that the linear polarization of the terahertz beam is perpendicular to the *C* axis of the crystal and is in the plane of the diagram. The initial reference pulse is obtained with the prism oriented as shown by the dashed line in Fig. 1, so that the reflection from the dielectric interface is reflected to the second paraboloidal mirror, which focuses the reflected beam onto a second identical sapphire lens. This lens further focuses the terahertz beam onto the detector consisting of a second identical antenna assembly. At the detector the incident terahertz pulses bias the antenna gap. Consequently, an electric current can be obtained if the gap is shorted by means of an ultrashort light pulse in the presence of the terahertz pulse. The measurements consist of monitoring the collected current versus the relative time delay between the excitation and sampling light pulses. The totally internally reflected pulse is measured in a similar way by simply rotating the prism to the position shown by the solid line in Fig. 1.

The input (reference) pulse shown in Fig. 2(a) is the measured reflected terahertz pulse from the surface of the quartz prism oriented as shown by the dashed line in Fig. 1. Because the dispersion of the index of refraction of quartz is relatively small, this front surface reflection, to a good approximation, does not change the incident pulse shape. This measurement was made in a single 150-sec scan of the relative time delay between the excitation and detection pulses and has a signal-to-noise ratio of better than 250:1. The relatively large signal amplitude of 12 mV was calibrated by adjusting a dc bias voltage across the detector to obtain the same photocurrent. The ultrafast subpicosecond response of the system is evident from the observed pulse shape, where the pulse width (FWHM) of the main signal is approximately 0.8 psec.

When the position of the prism was oriented as shown by the solid line in Fig. 1, we observed the totally internally reflected pulse shown in Fig. 2(b). Because of the relatively low dispersion of the index of refraction of quartz, the normal-incidence reflections do not distort the transmitted propagating pulse. These reflections only attenuate the pulse and thereby do not affect the relative phase of the frequency com-

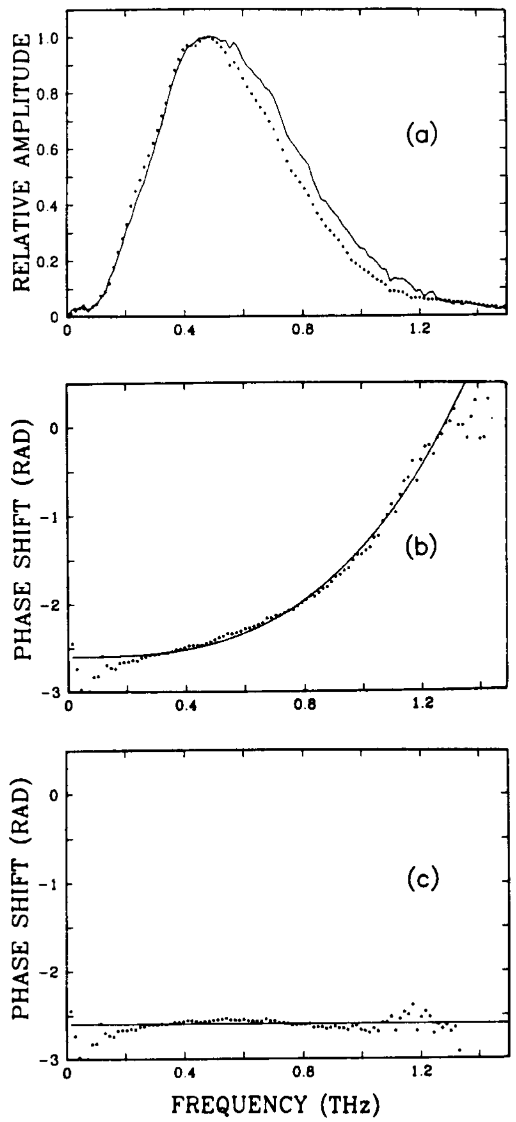

Fig. 3. (a) Normalized amplitude spectra of Figs. 2(a) (solid curve) and 2(b) (dotted curve). (b) The relative phase in radians of the spectral components of the (TIR) pulse of Fig. 2(b) with respect to the reference pulse of Fig. 2(a); the solid curve describes the constant TIR phase shift plus the effect of a quadratic frequency dependence of the index of refraction of crystalline quartz. (c) The relative phase in radians of Fig. 2(b) with respect to Fig. 2(a) compensated for the dispersion of crystalline quartz.

ponents of the transmitted pulse. In addition to the comparative increase in signal strength due to the total reflection, the pulse shape changes significantly. The polarity is reversed, the lobes on either side of the main pulse no longer have the same strength, and structure appears on the trailing edge. These changes are due to the frequency-independent TIR phase shift that occurs on the reflection at the internal surface of the prism and to the frequency-dependent absorption and dispersion of crystalline quartz.

The normalized amplitude spectra of the two pulses of Fig. 2 are shown in Fig. 3(a) and extend from low frequencies to beyond 1 THz. A slight absorption of the higher-frequency components is evident for the TIR pulses that traversed the 25-mm-long path within the quartz prism. For the entire bandwidth the measured amplitude absorption coefficient is less than 0.2 cm^{-1}.

The relative phase of the spectral components of the TIR pulse with respect to those of the reference pulse is shown by the dotted curve in Fig. 3(b). To obtain these results, the pulses were first numerically overlapped in time to eliminate the linear phase shift due to $n_o(0)$ and then the complex Fourier transforms were made. The relative phase is considered to be accurate in the frequency range from 0.2 to 1.2 THz. Outside this range the amplitudes of the spectral components are too low and the relative phase shows considerable scatter as it drops into the noise level of the measurement. In addition to the TIR phase shift, the strong frequency-dependent phase shift is due to the frequency-dependent index of refraction of crystalline quartz. Incidentally, Fig. 3(b) presents what is to our knowledge the most precise measurement to date of the dispersion of quartz in this frequency range. The calculated solid curve corresponds to a constant TIR phase shift plus a quadratic frequency dependence of the index of quartz. The index of quartz has been assumed[8] to be of the form $n_o(f) = n_o(0) + Af^2$, where f is the frequency in terahertz and A describes the strength of the dispersion. As shown in the figure, our experimental data are well fitted by the value $A = 0.0024/(\text{THz})^2$, in agreement with that obtained at higher frequencies.[8]

Subtracting the quadratic dependence, we obtain the TIR phase shift shown in Fig. 3(c). In accordance with the reality of the measured field, i.e., no imaginary component, the phase shift changes sign for negative frequencies. Here, in the frequency range from 0.2 to 1.2 THz, the resulting measured phase is independent of frequency and agrees well with the predicted value[9] of −2.55 rad shown by the horizontal line for an incident angle of 45°. Most of the data are contained within the band centered on the predicted value of 2.55 ± 0.05 rad, indicating the accuracy of our measurement. Experimentally, the incident angle was set accurately (to within 0.1°), because the TIR phase shift is strongly dependent on the incident angle and deviations of a few degrees show phase-shift changes of several tenths of a radian.[9] We have measured this sharp angular dependence, and our results agree with the theoretical predictions.

In summary, by using the powerful combination of time-domain spectroscopic techniques with high-brightness terahertz beams, we have performed what is to our knowledge the most accurate measurement to date of the frequency-independent TIR phase shift.

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