Spatiotemporal focusing of single-cycle light pulses

S. Hunsche
Bell Laboratories, Lucent Technologies, 101 Crawfords Corner Road, Holmdel, New Jersey 07733

S. Feng and H. G. Winful
Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122

A. Leitenstorfer† and M. C. Nuss
Bell Laboratories, Lucent Technologies, 101 Crawfords Corner Road, Holmdel, New Jersey 07733

E. P. Ippen
Department of Electrical Engineering and Computer Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received March 8, 1999; accepted April 1, 1999

We investigate experimentally and numerically the properties of single-cycle terahertz pulses propagating through a focus. The experimental data clearly show changes in pulse shape resulting from the Gouy phase shift and apparent superluminal pulse propagation. The pulses are also considerably distorted by diffraction effects. A solution of the time-domain diffraction integral is necessary to explain the details of the data and leads to an excellent agreement between experiment and theory. © 1999 Optical Society of America

OCIS codes: 320.5540, 320.0230, 350.5500.

The optics of extremely short light pulses with duration of few optical cycles has been a topic of intense research for several years. While single-cycle pulses of terahertz (THz) radiation excited by moderately short femtosecond laser pulses have already found a broad range of applications,1 the development of femtosecond laser sources is also continuously moving toward few-cycle optical pulses.2 These pulses will open a new regime of nonlinear optics, where the light–matter interaction depends critically on the absolute phase of the pulses, not only on their average intensity and pulse duration.2–4 Understanding changes in pulse shape and phase induced by focusing and diffraction, as discussed in several recent papers,5–8 will clearly be one key issue in this regime. One of the most striking phenomena associated with focusing of light is the Gouy phase shift. It is well known from Gaussian-beam theory that the optical phase of a laser beam experiences a shift by $\pi$ when propagating through a focus.9 For single-cycle pulses this will be associated with significant changes in pulse shape. Recent analytical calculations for Gaussian pulses predict that the pulse will evolve from symmetric to antisymmetric (or the reverse) and back and change sign upon focusing.5,6 In this paper we present an experimental study and new numerical simulations of single-cycle pulses near a focal point. The measured data show clear signs of the predicted phase changes, including a phase velocity larger than the vacuum speed of light, but they are also strongly influenced by diffraction effects. A numerical solution of the time-domain diffraction integral leads to an excellent agreement between experiment and theory.

In the experiment, THz pulses are created in a GaAs emitter biased by a gold stripline and optically excited by laser pulses of a Ti:sapphire oscillator with duration of approximately 100 fs. The THz radiation is coupled into free space by an aplanatic hyperhemispherical silicon substrate lens1 collimated by an off-axis paraboloid mirror and focused by a second paraboloid with a focal length of 7.5 cm. The beam profile in the collimated region is approximately Gaussian with frequency-independent beam diameter.10 The THz detector consists of a conventional photoconductive dipole antenna with 50-μm dipole length fabricated on ion-implanted silicon-on-sapphire. Since the dipole size is much smaller than the wavelength of the radiation, it can be assumed to act as a simple point probe of the THz field.11 The antenna faces the incoming THz pulse and is gated by a time-delayed femtosecond pulse that is focused through the transparent substrate to avoid any distortion of the THz pulse by propagation through the substrate material. The detector setup is moved through the focal region along the optical axis z with a stepper motor, while the time delay is varied with a fast-scanning optical delay line. A second stepper motor-driven delay line compensates the time-delay offset.
field is measured as a function of the local time of the propagating pulse, \( \Delta t = t - \frac{z}{c} \).

Figure 1 shows (a) measured THz waveforms and (b) simulations obtained with the model described below for several positions along the optical axis, where \( z = 0 \) is the focal point. The direction of \( z \) corresponds to the propagation direction of the THz pulse; i.e., positive values indicate positions behind the focal plane. Besides an overall decrease in amplitude, the pulses show significant broadening and distortions of the waveforms outside the focal point. The corresponding amplitude spectra shown in Fig. 2 clearly indicate a loss of high-frequency components and an overall red shift for \( z \neq 0 \). Waveforms at similar positive and negative \( z \) appear to be very similar if one assumes reverse direction of the time axis, and there is an overall change in pulse shape from an antisymmetric to a symmetric pulse and back, as predicted by theory. However, the experiment does not show a complete sign reversal of the pulse, and the distortions are not completely symmetric with respect to \( z = 0 \), so that the pulse at \( +15 \text{ mm} \) most closely resembles the one at \(-10 \text{ mm} \). Quite remarkably, the pulses seem to propagate forward in local time while going from negative to positive \( z \); i.e., they seem to propagate faster than the speed of light.

Whereas the exact analytic model in Ref. 5 describes a beam with frequency-independent Rayleigh length, in the experiment the Rayleigh length is approximately proportional to the wavelength, owing to the constant collimated beam diameter. This is illustrated in Fig. 3, showing the signal amplitude versus \( z \) for several frequencies within the bandwidth of the THz pulses. Therefore the analytic solution cannot be used to simulate the experimental data. The numerical simulations presented here were obtained by (1) assuming a radially Gaussian beam profile, (2) fitting the experimental spectrum at the focus, (3) fitting the wavelength-dependent Rayleigh range, and (4) solving the time-domain Kirchhoff diffraction integral for an incoming spherical wave front. The last point is absolutely crucial for reproducing the pulse distortions found in the experiment. The spectrum of the simulated THz signal is derived from the analytic expression in Ref. 5, but a frequency dependent Rayleigh length is allowed for. The spectrum has a generic spectral dependence \( f^n \exp(-\alpha f) \), where the parameters \( n \) and \( \alpha \) can be determined from fitting the experimental spectrum at the focus. Assuming a Rayleigh length proportional to the wavelength, \( z_R = (q_2 f)^{1/2} \), the on-axis spectrum is given by

\[
S(f) = \exp(-\alpha f) f^n \]
with

\[ q_1 = \frac{nc}{2\pi f_p}, \quad n = \frac{\ln 2}{b - \ln b - 1}, \]

where \( f_p = 0.5 \text{ THz} \) and \( b = 1.2 \text{ THz} f_p \) correspond to the peak frequency and the full width at half-maximum of the experimental spectrum at \( z = 0 \) and \( q_2 \) is chosen to reproduce the experimentally determined Rayleigh length of 4.91 mm at 0.5 THz.

Figure 3(b) shows the \( z \) dependence of the signal amplitude calculated by Eq. (1). The corresponding pulse forms are obtained by inverse Fourier transform of the spectra and are shown for several \( z \) positions in Fig. 4. These pulses are very similar to the ones calculated by the exact analytical model in Ref. 5 and make it possible to explain qualitatively the basic features of the experimental data. The calculated pulses at comparable positive and negative displacement appear to be identical—however, with a reversed time axis—very similar to the experimental results. Also, the calculations show that in the \( z \) range covered by the experiments, a complete polarity reversal of the pulse cannot be expected, because the maximum displacement of the detector is still on the order of the Rayleigh length. However, the simulations in Fig. 4 do not reproduce the strong pulse distortions seen in Fig. 1. Furthermore, the changes in pulse shape calculated by Eq. (1) are completely symmetric with respect to the focus, in contrast with the experimental results.

These features can be reproduced in the calculations only by explicitly taking into account diffraction effects by solving the time-domain Kirchhoff diffraction integral\textsuperscript{12} for an incoming spherical wave at the position of the focusing mirror:

\[ u(P_0, t) = \int \frac{\cos (\mathbf{n}, \mathbf{r}_0)}{2\pi c r_0} \frac{d}{dt} u(P_1, t - \frac{r_0}{c}) ds, \]
which gives the field component \( u \) at the position of the detector, \( P_0 \), as a function of time \( t \) for a given incoming wave at points \( P_1 \) within the diffracting screen \( \Sigma \). The incoming pulse shape is calculated from Eq. (1), the diffracting screen taken as circular with a radius of 21 mm—slightly smaller than the actual radius of the focusing mirror—and spherical, matching the incoming wavefront that converges at the focal point. Figure 1(b) shows the calculated waveforms for different detector positions \( z \), and the corresponding amplitude spectra are plotted in Fig. 2(b). Obviously, the agreement between the simulation and the experimental data is excellent.\(^{13} \)

The above model gives an immediate intuitive explanation for the observed pulse broadening. All secondary pulses coming from the diffraction add up exactly in phase only when the detector is at the focal point but overlap with finite time delays if the detector is moved to any other position. Moving the detector on the optical axis by a distance \( d \) leads to a path difference between on-axis signal contributions and secondary pulses coming from the edge of the diffracting screen. Denoting the center of the incoming spherical wavefront at the diffracting screen as \( C \), an off-axis point as \( A \), and the position of the detector as \( B \), the path difference \( (AB-BC) \) is positive for \( z < 0 \) and negative for \( z > 0 \) so that all off-axis signal contributions arrive later than the on-axis pulse for \( z < 0 \) and earlier for \( z > 0 \). Furthermore, the absolute value of the path difference is smaller within second order of \( \delta \) for a displacement in positive than in negative \( z \)-direction. The latter fact explains the asymmetry of the pulse distortions with respect to \( z = 0 \), and the first argument explains qualitatively why the pulse seems to propagate forward in time. This effect simply corresponds to the fact that the Gouy phase shift is indeed associated with a phase velocity greater than the speed of light. As can be seen from the curves in Fig. 4, this effect leads to a shift of the amplitude maximum of the pulse to an earlier position within the pulse envelope that is fixed at \( t = -z/c = 0 \).

In conclusion, we present an experimental and numerical study illustrating the pulse distortions of focused single-cycle pulses. The basic changes in pulse shape from antisymmetric to symmetric and back can be understood in terms of the Gouy phase shift, while major pulse distortions arise from diffraction effects that can be precisely modeled by numerical solution of the time-domain diffraction integral. Although our present experimental data are limited to the on-axis case, the numerical model can be easily extended to predict the pulse behavior at every point in space.

ACKNOWLEDGMENT

S. Hunsche acknowledges support by the Alexander von Humboldt foundation.

Address correspondence to S. Hunsche at the address below or by phone, 973-386-3813; fax, 973-386-3127; e-mail, shunsche@lucent.com

*Present address, Physik-Department E11, TU Munchen, D-85748 Garching, Germany.

†Present address, Lucent Technologies, 67 Whippany Road, Whippany, New Jersey 07981.

REFERENCES AND NOTES


13. The ripples after the main pulse at \( z = 0 \) in the timedomain data and the dips in the spectra at \( z = 0 \) may arise from interference with scattered light. This possibility is included in the simulations by addition of a small contribution of background light treated as a plane wave. Without this additional contribution, the simulated data show no ripples or dips.