Superluminal terahertz pulses

Klaas Wynne and Dino A. Jaroszynski

Femtosecond Research Centre, Department of Physics and Applied Physics, University of Strathclyde, Glasgow G4 0NG, UK

Received August 5, 1998

In femtosecond terahertz-pulse (T-ray) imaging of metal structures with dimensions of the order of the wavelength, it is observed that the T rays propagate faster than the vacuum speed of light. In the case of apertures this can be understood as a waveguide effect in which superluminal velocities are expected close to the cutoff frequency. However, the effect is also observed close to knife edges and in propagation past thin metal wires. © 1999 Optical Society of America

OCIS codes: 320.2250, 320.0320, 320.5540, 110.3080, 350.5500.

The technique of generation and detection of free-space terahertz (THz) pulses (T rays) has undergone major developments over the past few years. The discovery that nonlinear crystals of the zinc blende type, such as ZnTe,[1,2] can be used for electro-optic sampling of T rays through the Pockels effect has led to huge improvements in signal-to-noise ratio, detection speed, and bandwidth.[2] The wavelength range that is typically accessible to T rays (from a few millimeters to ~100 μm) is relatively unexplored and can provide information on the structure of materials. Several successful attempts have been made to use T rays for imaging, including T-ray tomography and real-time imaging,[3] typically with a resolution of the order of a millimeter. A near-field method for improving spatial resolution in T-ray imaging has been reported[4] in which a metal aperture was used to improve resolution to 140 μm. In this Letter an alternative method of achieving subwavelength spatial resolution in T-ray imaging is demonstrated. An optical beam is focused to a small spot in an optical rectification crystal, resulting in T rays emerging in a beam that in the near-field region has a subwavelength diameter. If the sample is placed directly on the generation crystal, it can be imaged in the far infrared with $\lambda/4.3$ resolution. This experimental setup was used to image metal structures with dimensions of the order of the T-ray wavelengths. Evidence is found that the propagation speed of the T rays can exceed the vacuum speed of light. Because our T-ray setup gives access to all the pertinent information on the pulse traveling through these structures, we have been able to analyze the propagation characteristics fully. It is found that, although the phase velocity becomes superluminal, the group velocity is at all times subluminal.

In our experiment T-rays are generated through optical rectification of femtosecond pulses in ZnTe.[1] The laser source is a commercial Ti:sapphire oscillator and regenerative amplifier producing 120-fs pulses at 800 nm with a repetition rate of 250 kHz and an average power of ~1 W. Figure 1 shows a schematic of the setup used for T-ray imaging. Approximately 280 mW of power is focused by an $f = 5$ cm lens onto a 10 mm $\times$ 10 mm aperture ZnTe crystal (Uni-Export) with a thickness of either 1 mm or 500 μm and is cut perpendicular to the $\langle 110 \rangle$ crystallographic axis. The crystal is mounted upon an $x-y$ translation stage that allows translation over 25 mm in the plane perpendicular to the beam, with a resolution of 10 nm. The T rays that are emitted by the ZnTe crystal are collimated and focused with two 44.5-mm-diameter off-axis parabolic mirrors, each with a focal length of 38.1 mm. The second off-axis parabolic mirror has a hole drilled through it, which allows an 800-nm gating beam to overlap with the T-ray beam in another $\langle 110 \rangle$ ZnTe crystal with a thickness of 500 μm. The gating beam has an average power of 8 mW, is temporally delayed by a fast-scanning (6-Hz) optical delay line, and is focused into the detection crystal with an $f = 10$ cm lens. The Pockels effect in the ZnTe detection crystal causes the ellipticity of the gate beam to change in proportion to the instantaneous field strength of the T-ray pulse.[1,2] We measure this time-delay-dependent change in ellipticity by sending the gate beam through a quarter-wave plate, and a Glan–Thompson polarizer and by balanced detection by a pair of photodiodes wired to give zero current for balanced

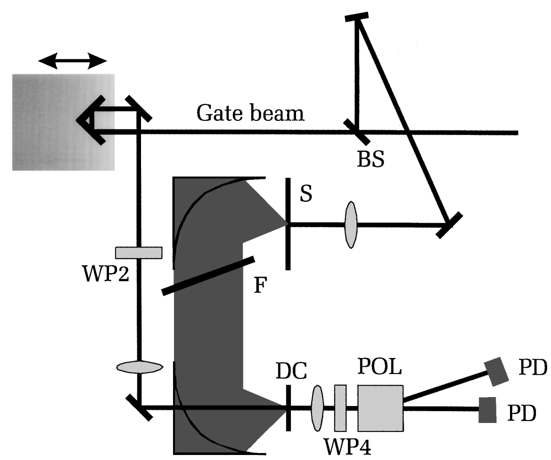

Fig. 1. Schematic diagram of the near-field T-ray imaging setup: The T rays are generated by optical rectification of a beam of 120-fs pulses at 800 nm in $\langle 110 \rangle$ ZnTe. The sample is positioned on the back of the generation crystal, in the near field of the T rays. BS, beam splitter; S, sample and generation crystal on an $x-y$ translation stage; F, Teflon filter; WP2, WP4, wave plates; DC, detection crystal; POL, polarizer; PD's, photodiodes.

0146-9592/99/010025-03$15.00/0

power. The signal current is sent to a preamplifier (Stanford Research Systems SR570) for amplification and filtering. This signal and a signal proportional to the instantaneous temporal delay are digitized by a fast analog–digital converter (Data Translation Model T112). The T rays have approximately three cycles and a spectrum that extends from $\sim$5 to 100 cm^{-1}, as described previously.[5]

To obtain the highest spatial resolution one would like to focus the 800-nm T-ray generation beam to the smallest possible spot size. As ZnTe is used as the optical rectification crystal, the minimum spot size is determined by two-photon absorption and is approximately 200 μm. For smaller spot sizes there is a catastrophic loss of signal intensity and green emission from the crystal. To determine the resolution of the imaging system, we scanned a knife edge consisting of a piece of aluminum foil mounted directly on the ZnTe generation crystal through the beam. At each position, we took multiple time scans over $\sim$20 ps to determine the time dependence of the T rays ($\sim$1 s of averaging; signal-to-noise ratio, 300). We then Fourier transformed these data to obtain the position-dependent transmission spectra. The transmission is determined as $T_{\text{field}}(\omega) = E(\omega, x)/E(\omega, 0)$, where $E(\omega, 0)$ is the complex amplitude spectrum of the field at a position at which the knife-edge does not absorb. The advantage of defining the transmission in this manner is that the noise has a symmetric distribution, unlike in the case of a ratio of intensities. The wavelength- and position-dependent transmission profiles were fitted by error functions. The intensity FWHM of the T-ray beam derived from the fits to error functions varies from 110 $\pm$ 13 μm and 80 cm^{-1} ($\lambda = 125$ μm) to 232 $\pm$ 85 μm at 10 cm^{-1} ($\lambda = 1$ mm). The uncertainties given are the 1σ joint confidence intervals. At the longer wavelengths the spatial resolution is more than 2.6 times better than the free-space diffraction limit of 0.61 λ for the intensity FWHM. As the refractive index of ZnTe is 3.1 at these wavelengths, this result is not proof of resolution enhancement owing to a near-field effect. However, there appears to be no reason why the resolution could not be enhanced further by this technique, with an unamplified laser and tighter focusing into the ZnTe crystal.

For fast imaging of samples an algorithm is employed that searches for the maximum in the THz trace, assumes that this maximum corresponds to the peak of the THz pulse, and fits the trace to a second-order polynomial over a 300-fs interval. Thus one can plot the variation of T_{field}, the transit time of the pulse, or the curvature on the peak of the pulse. When the ZnTe generation crystal (with no contacted metal features) is scanned several millimeters perpendicularly to the generation beam, little variation of the T-ray field strength ($\pm$10%) or the transit time ($\pm$5 fs over short distances; see below) is observed. Because the amplified laser system is relatively noisy, $\sim$1 s of averaging is required for each pixel in the image.

Figure 2 shows a T-ray image of a silicon-on-sapphire chip that was designed for the generation of T rays by use of Hertzian dipole antennas. This chip consists of high-resistivity silicon and has aluminum contacts patterned on it with a thickness of 510 $\pm$ 10 nm. However, the area shown in the figure contains not the antenna but the characters "ÅU1." In Fig. 2(a) the T-ray pulse field transmission is plotted, which varies from 1 at the edges of the plot to 0.1 in the center of the letters. In Fig. 2(b) the pulse delay is plotted, with zero delay defined as the delay that the T-ray pulse experiences when it is transmitted through the silicon-on-sapphire chip far away from any of the metal contacts. Cursory inspection of the two images suggests that the spatial resolution is much higher in delay imaging than in transmission imaging. Closer inspection of Fig. 2(b) shows something odd: In the narrow spaces between the letters, the relative delay of the T-ray pulse is negative. In other words, the pulse appears to travel faster than the vacuum speed of light, c, when it is squeezed through a narrow aperture such as that formed by the metal letters. The largest negative delay of -110 fs is observed in the bottom of the U. To the right of the 1 ($x = 10.6$, $y = 18.5$) and to the left of the Å the delay is also slightly negative at ~ -25 fs. As it would take light 1.7 fs to travel through 500 nm of air, it follows that the peak of the THz pulse emerges from the aperture before entering it. It was shown previously[6] that these effects are not necessarily in conflict with causality.

Similar effects were observed in metal wires. Figure 3 shows a one-dimensional scan through a tinned-copper wire with a diameter of 100 μm by use of T rays polarized parallel [Fig. 3(a)] and perpendicular [Fig. 3(b)] to the wire. Figure 3(b)

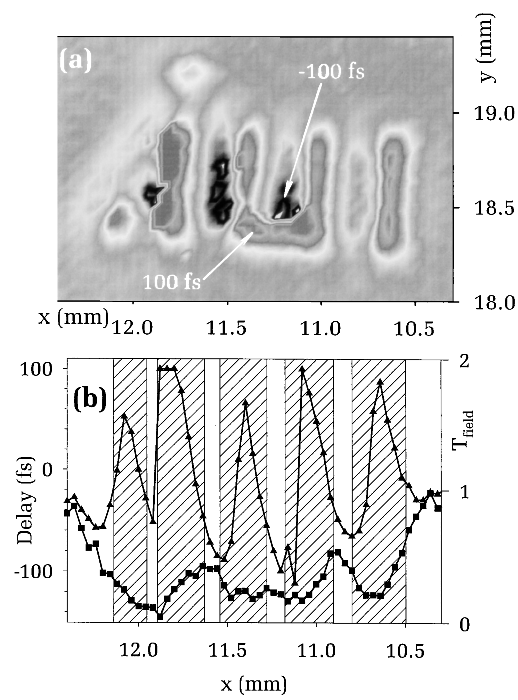

Fig. 2. T-ray images of 500-nm-thick aluminum lettering on a silicon-on-sapphire chip. (a) Image generated when the relative transit time of the pulse is plotted. The T rays are polarized parallel to the y axis. (b) Cross section at $y = 18.48$ mm. The hatched areas indicate the position of the metal. Triangles, delay; squares, transmission.

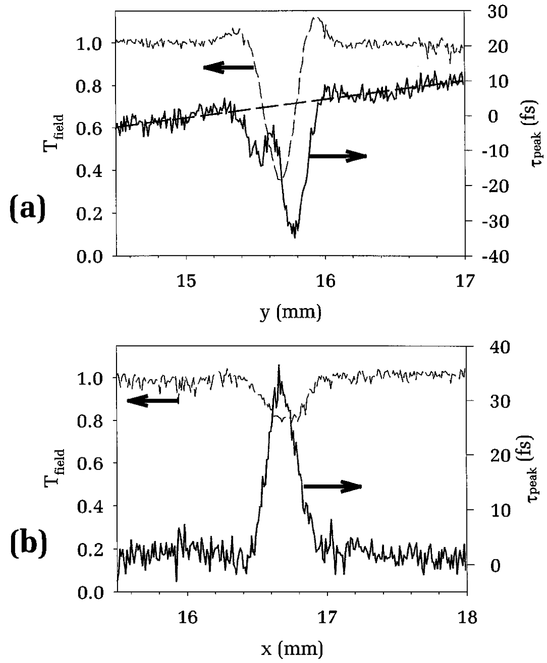

Fig. 3. T-ray image of a 100-μm-diameter tinned-copper wire. (a) T-ray polarization parallel to the wire (the dashed line is the delay drift that is due to thickness variation in the ZnTe crystal). (b) Perpendicular polarization.

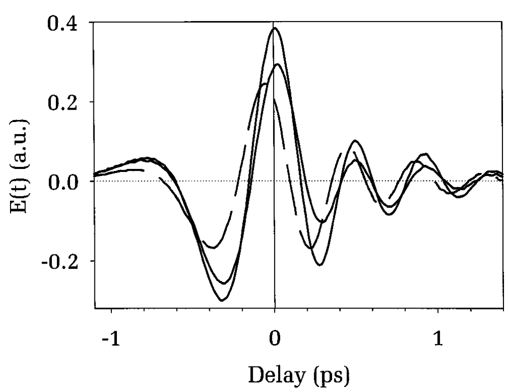

Fig. 4. Time-domain traces of the T-ray pulses used in Fig. 3. Thick solid curve, free-space; dashed curve (shifted toward negative delay times), parallel polarization; solid curve (shifted toward positive delay times), perpendicular polarization.

gives the expected result: The field transmission shows a minimum at the position of the wire, and at the same time the pulse delay tends to a maximum. In the case of parallel polarization, however, the reduction in transmission is twice as large and the pulse delay is negative, exhibiting a peak on either side of the wire. Again, these results indicate that the propagation speed of the T rays is superluminal close to the metal wire. To demonstrate that these superluminal propagation effects are not an artifact of the delay-determination algorithm, in Fig. 4 we show the full time-dependent traces of the T-ray pulses taken at maximum positive–negative delay. It is apparent that the entire waveform appears to shift to positive or negative delay, depending on polarization. From the time-dependent traces shown in Fig. 4, one can calculate the wavelength-dependent phase and the group velocity. It is found that the phase velocity varies from $1.0c$ to $0.87c$ in the case of the perpendicular polarization and from $1.05c$ to $1.43c$ in the case of parallel polarization (assuming that the effect is constant over a 100-μm path). However, the calculated group velocity is not found to be superluminal within the signal-to-noise ratio of the experiment.

These superluminal effects can be understood in terms of the theory of propagation of electromagnetic waves though waveguides. In a cylindrical waveguide the accumulated phase above the cutoff frequency of the TE_{11} mode, $\omega_c = 3.682\ c/d$, is given by[7] $\phi = (\omega_c L/c)[(\omega/\omega_c)^2 - 1]^{1/2}$, where d is the diameter of the waveguide and L is its length. Thus, the waveguide becomes highly dispersive close to cutoff and evanescent below it. As the cutoff frequency is approached, the phase velocity tends to infinity as expected. This theoretical expression does not explain, however, why the propagation velocity becomes superluminal close to the edge of a metal structure.

This research was supported in part by a grant from the Engineering and Physical Sciences Research Council. We are grateful to Søren Keiding for supplying the silicon-on-sapphire chip. K. Wynne's e-mail address is k.wynne@strath.ac.uk.

References

1. A. Nahata, A. S. Weling, and T. F. Heinz, Appl. Phys. Lett. **69,** 2321 (1996).
2. Q. Wu and X. C. Zhang, Appl. Phys. Lett. **71,** 1285 (1997).
3. D. M. Mittleman, R. H. Jacobsen, and M. C. Nuss, IEEE J. Sel. Topics Quantum Electron. **2,** 679 (1996).
4. S. Hunsche, M. Koch, I. Brener, and M. C. Nuss, Opt. Commun. **150,** 22 (1998).
5. R. McElroy and K. Wynne, Phys. Rev. Lett. **79,** 3078 (1997).
6. L. Brillouin, *Wave Propagation and Group Velocity* (Academic, New York, 1960).
7. S. Y. Liao, *Microwave Circuit Analysis and Amplifier Design* (Prentice-Hall, Englewood Cliffs, N.J., 1987).