Terahertz beams

Ch. Fattinger and D. Grischkowsky
IBM T. J. Watson Research Center, P. O. Box 218, Yorktown Heights, New York 10598

(Received 10 October 1988; accepted for publication 29 November 1988)

We have generated freely propagating, diffraction-limited beams of single-cycle 0.5 THz electromagnetic pulses from a 5-mm-diam coherent source. After propagating 100 cm in air, there was little change in the measured subps pulse shape, even though the signal strength was reduced by 20 times compared to the strength at 10 cm.

The importance of integrated circuit versions of the Hertzian dipole as generators and detectors of terahertz radiation was first demonstrated by Auston *et al.*[1] In a recent paper an optical approach was introduced to focus and to manipulate the terahertz radiation emitted by the Hertzian dipole source with an ultrafast time dependence.[2] The dipole had small dimensions compared to any of the radiated wavelengths and was produced by shorting a charged coplanar transmission line with an ultrashort laser pulse. When this dipole source was located at a focal point of a spherical mirror, essentially all of the emitted radiation was captured by the mirror and could be focused on an ultrafast optically driven photoconductive switch. Besides the extremely high coupling efficiency, the excellent focusing properties preserved the subps time dependence of the source. This approach represents an alternative and complementary method to recent works extending radio and microwave techniques into the terahertz regime through the use of antennas.[3,4]

In this letter we report the application of the optical technique to the generation of diffraction-limited terahertz beams with a relatively large source size, by locating the ultrafast dipole source at the focal point of a collimating lens. This technique allowed us to produce, for the first time, diffraction-limited beams of single-cycle 0.5 terahertz pulses from a coherent source (the time dependence is much faster than the transit time across the source) of 5 mm diameter. Because of their relatively low divergence, the single-cycle pulses were easily measured after a propagation distance of 100 cm. The detection was accomplished by focusing the terahertz beam on a photoconductive switch driven by a subpicosecond laser pulse.

The terahertz radiation source is similar to that used before[2,5,6] and is illustrated in Fig. 1(a). Here, the 20 μm sized subps electric dipoles are created by photoconductive shorting of the charged coplanar transmission line with 70 fs pulses from a colliding-pulse, mode-locked dye laser. As described previously, the electrical pulse coupled to the transmission line has the same time dependence as the transient electric dipole responsible for the terahertz radiation.[6] This electrical pulse on the line was measured by a fast photoconductive switch (driven by the monitor beam, a time-delayed beam of the same 70 fs laser pulses), which connected the transmission line to the electrical probe. The 20-mm-long transmission line had a design impedance of 125 Ω and consisted of two parallel 5-μm wide, 0.5-μm-thick aluminum lines separated from each other by 15 μm. The measured dc resistance of a single 5 μm line was 10 Ω/mm. The transmission line was fabricated on an undoped silicon-on-sapphire (SOS) wafer, which was heavily implanted to ensure the required short carrier lifetime.[7]

The terahertz radiation detector shown in Fig. 1(b) is simply a photoconductive gap of 5 μm spacing with a width of 25 μm. This gap was fabricated as above on a separate SOS chip. One side of the gap is grounded, and a current amplifier is connected across the gap as indicated. During operation the gap is biased by the incoming terahertz radiation pulse polarized across the gap. The measurement is made by shorting the gap via the 70 fs ultrashort optical pulses in the detection beam and measuring the collected charge (current) versus the time delay between the excitation and detection pulses.

The terahertz optics illustrated in Fig. 1(c) consist of two crystalline sapphire, spherical lenses contacted to the backside (sapphire side) of the SOS chips. For the radiation

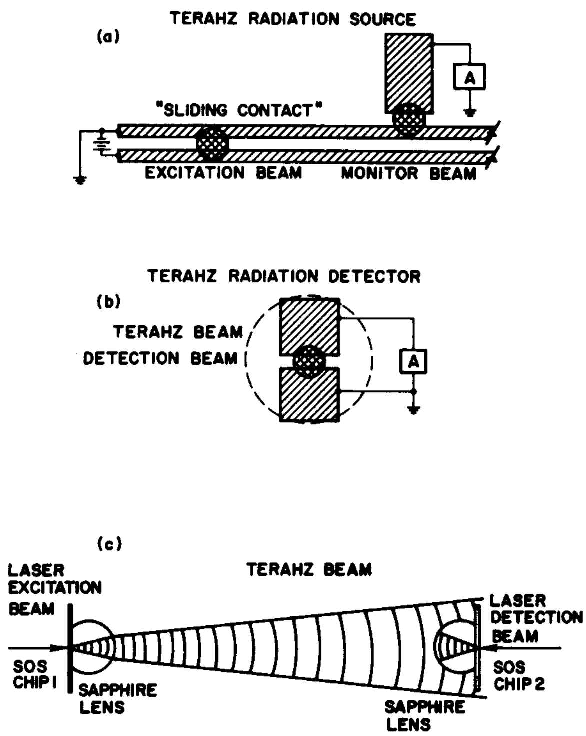

FIG. 1. (a) Schematic diagram of the charged coplanar transmission line. The laser excitation beam spot defines the location of the transient electric dipole. The monitor beam measures the electrical pulse coupled to the line. (b) Schematic diagram of the terahertz detector. The laser detection beam spot is shown centered on the gap in the focal spot of the terahertz radiation. (c) Schematic diagram of the collimating and focusing optics consisting of crystalline, sapphire lenses in contact with the backside (sapphire side) of the SOS chips.

 0003-6951/89/060490-03$01.00

source the center of the truncated 9.5-mm-diam sphere (lens) is 2.3 mm above the Hertzian dipole located at the focus of the lens. The same situation holds for the detector where the photoconductive switch is at the focus of the lens. For both lenses the C axis of the sapphire is perpendicular to the optical axis of the lens. For the source lens and the source chip the C axes are oriented parallel to the transmission line, while for the detecting lens and the detecting chip the C axes are perpendicular to the gap (parallel to the 25 μm dimension of the gap). Consequently, for both generation and detection the C axes are perpendicular to the polarization of the terahertz radiation. These orientations of the C axes are required in order to generate and detect the cleanest and shortest terahertz pulses. It is important to note that, because of the relatively high dielectric constant of approximately 10 of sapphire, most of the radiation emitted from the transient electric dipole is contained in a 40° full angle cone normal to the surface of the SOS chip and directed into the sapphire.[8] This situation gives exceptionally good collection and collimation of the terahertz radiation, because the central portion of the spherical lens captures essentially all of the emitted radiation. After collimation we obtain a beam diameter of 5 mm with a diffraction-limited divergence. Thus, we have changed the effective source size from 20 μm to 5 mm while at the same time preserving the ultrafast time response.

The generated electrical pulse on the line is shown in Fig. 2(a). This measurement was made in a single 2 min scan of the relative time delay between the excitation and monitor pulses. For this result the spatial separation between the sliding contact excitation spot and the monitor gap was 200 μm so that propagation effects were negligible. The measured full width at half maximum (FWHM) as shown is 0.95 ps. Taking into account the response time of the monitor gap, we consider that the actual pulse width of the transient dipole was 0.6 ps.

Figures 2(b) and 2(c) display the detected terahertz radiation pulses after propagation distances of 10 and 100 cm, respectively. The indicated amplitude scales are normalized with respect to the electrical pulse on the transmission line [Fig. 2(a)]. As can be seen, the signal strength dropped by about 20 times as the propagation distance was increased from 10 to 100 cm, indicating a full angle beam divergence of about 100 mrad. This is an average value with respect to the frequency content of the pulse, because the diffraction angle and the divergence are proportional to the wavelength. Both of these high signal-to-noise measurements of the freely propagating pulses were made in single 2 min scans of the relative time delay between the excitation and detection pulses.

With the exception of the initial dip in the observed pulse shape, the measured time dependence roughly approximates the time derivative of the transient dipole source. However, the response time of the detector is believed to be limiting the observed fast time dependence of the signal. One effect that we did not observe was an expected changing of the pulse shape as the detector was moved away from the source. This effect would have been due to a selective spectral filtering, caused by the wavelength-dependent diffraction angle, enhancing the higher frequency components of the pulse. As illustrated in Fig. 2 the main component of the signal was independent of propagation distance for distances greater than 10 cm, corresponding to the far field of the 5-mm-diam source. However, the oscillations on the trailing edge [observable in Fig. 2(c)] increased with propagation distance. We have determined that these oscillations are due to absorption by water vapor. When the 100 cm space between the source and the detector was filled by a large plastic bag inflated with helium, the oscillations disappeared. But, when a water soaked sponge was placed in the bag, the oscil-

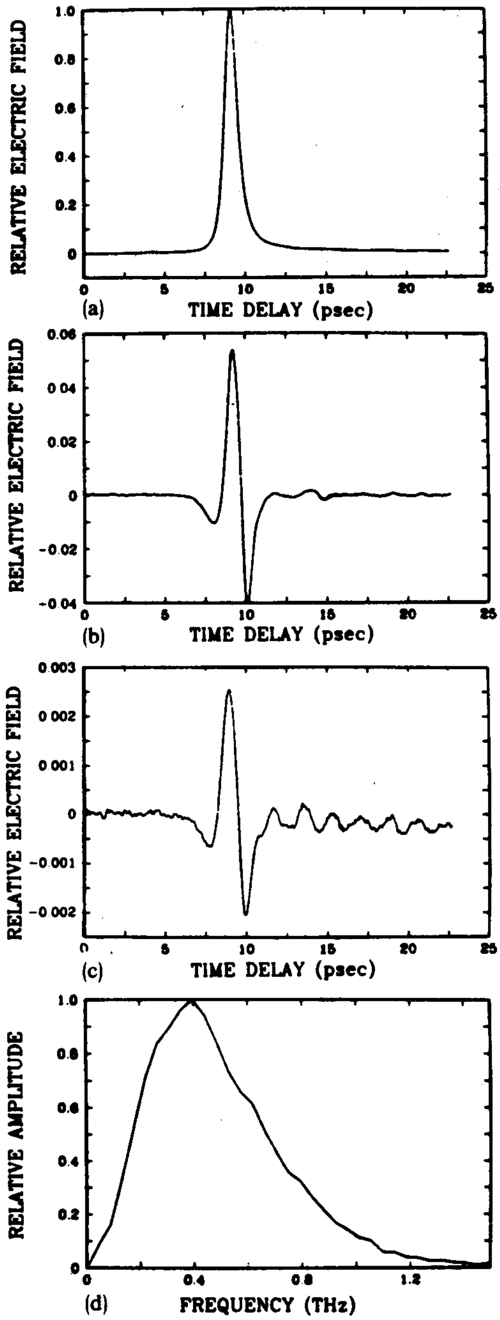

FIG. 2. (a) Measured electrical pulse on the transmission line with 200 μm separation between the excitation and monitor beams. (b) Measured electrical pulse of the freely propagating terahertz beam with the detector located 10 cm from the source. (c) Measured electrical pulse of the freely propagating terahertz beam with the detector located 100 cm from the source. (d) Amplitude spectrum of the transmitted pulse shown in (b).

lations increased in size until equilibrium was reached corresponding to 100% relative humidity.

The amplitude spectrum of the measured pulse of Fig. 2(b) is displayed in Fig. 2(d), where it is seen that the spectrum peaks at approximately 0.4 THz and extends from low frequencies up to above 1 THz. Consequently, these beams are immediately useful for transmission spectroscopy, where by Fourier analysis of the input and transmitted pulses the absorption and disperison of the investigated materials can be obtained. The importance of this conclusion is demonstrated by the water vapor observation. Finally, the wide bandwidth of these beams shows their enormous capacity as a potential communications channel.

This research was partially supported by the U.S. Office of Naval Research.

[1]D. H. Auston, K. P. Cheung, and P. R. Smith, Appl. Phys. Lett. **45**, 284 (1984).
[2]Ch. Fattinger and D. Grischkowsky, Appl. Phys. Lett. **53**, 1480 (1988).
[3]A. P. DeFonzo, M. Jarwala, and C. R. Lutz, Appl. Phys. Lett. **50**, 1155 (1987); A. P. DeFonzo and C. R. Lutz, Appl. Phys. Lett. **51**, 212 (1987).
[4]P. R. Smith, D. H. Auston, and M. C. Nuss, IEEE J. Quantum Electron. **24**, 255 (1988).
[5]M. B. Ketchen, D. Grischkowsky, T. C. Chen, C-C. Chi, I. N. Duling III, N. J. Halas, J-M. Halbout, J. A. Kash, and G. P. Li, Appl. Phys. Lett. **48**, 751 (1986).
[6]D. Grischkowsky, M. B. Ketchen, C-C. Chi, I. N. Duling III, N. J. Halas, J-M. Halbout, and P. G. May, IEEE J. Quantum Electron. **QE-24**, 221 (1988).
[7]F. E. Doany, D. Grischkowsky, and C-C. Chi, Appl. Phys. Lett. **50**, 460 (1987).
[8]W. Lukosz, J. Opt. Soc. Am. **69**, 1495 (1979).