High-brightness terahertz beams characterized with an ultrafast detector

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We have significantly improved the emission and detection of electromagnetic beams of single-cycle 0.5 THz pulses, through the use of new dipolar antenna structures. The frequency response was extended to well beyond 1 THz, and the beam power was increased by more than 15 times. The antennas were located at the foci of sapphire lenses and were photoconductively driven by ultrafast laser pulses. An additional collimation by a paraboloidal mirror produced a beam with a 25 mrad divergence, and subsequent focusing by a second identical mirror improved the coupling between the transmitting and receiving antenna by orders of magnitude.

Since the initial experiments of Hertz,[1] the Hertzian dipole has been known to be an important emitter and receiver of radiation with wavelengths large compared to the dipole. Modern integrated circuit techniques have now made possible the precise fabrication of micron-sized dipoles, which when driven with subpicosecond excitation can radiate well into the terahertz regime. The importance of these integrated circuit versions of the Hertzian dipole as generators and detectors of terahertz radiation was first demonstrated by Auston *et al.*[2] Recent work has introduced an optical technique to collect, collimate, and focus the terahertz radiation emitted by Hertzian dipoles,[3,4] produced by shorting a charged coplanar transmission line with ultrashort laser pulses.[5] When these dipole sources were located at the foci of spherical mirrors or lenses, most of the emitted radiation was captured and could be focused on detectors or collimated to produce relatively large diameter diffraction limited beams. Besides the high coupling efficiency, the excellent focusing properties preserved the subpicosecond time dependence of the source.

The above optical approach represents an alternative and complementary method to recent works extending radio and microwave techniques into the terahertz regime through the use of antennas.[6–10] For example, Mourou *et al.*[6] used a subpicosecond laser pulse to trigger a GaAs photoconductive switch driving a coaxial cable terminated by a millimeter-sized dipole antenna. This combination produced a microwave transient of several picoseconds. Later, Heidemann *et al.*[7] demonstrated the importance of planar antennas by exciting a larger, exponentially tapered, slot-line antenna with a laser-driven photoconductive switch to obtain nanosecond bursts of radiation. As discussed in their paper, this planar design is readily adaptable to integrated circuit fabrication with a consequent increase in bandwidth as the size is reduced. Defonzo *et al.*[8] demonstrated picosecond performance of an integrated circuit version of an antenna similar to that of Ref. (7). Later, Defonzo *et al.* developed and demonstrated an improved impedance-matched antenna consisting of an exponentially flared transmission line.[9] This design reduced antenna reflections and produced clean 10 ps bursts of radiation. In the most recent work, subpicosecond pulses have been generated, transmitted, and detected by Smith *et al.*,[10] who used integrated circuit techniques to fabricate ultrafast dipolar antennas terminated by coplanar transmission lines.

In this letter we report the use of a new ultrafast dipole antenna structure, optimized for photoconductive excitation, as the radiation source for the optical method.[3,4,11] Using this antenna we achieve an increase in transmitted beam power of more than 15 times, compared to the earlier work.[4] The antenna was located at the focus of a collimating sapphire lens in contact with the sapphire side of an ion-implanted,[12] silicon-on-sapphire (SOS) chip on which the antenna was fabricated. In addition, when the simple gap structure initially used for detection[3,4] was replaced with this antenna, the frequency response was significantly extended. In fact, we show that the signal measured by the antenna is the time derivative of the signal measured by the gap. Through the use of paraboloidal collimating and focusing mirrors, we have obtained a frequency-independent divergence of only 25 mrad and have increased the coupling between the transmitter and receiver by orders of magnitude. This tight coupling is evidenced by the fact that we measure electrical signals of many millivolts after a free-flight path of 80 cm.

The terahertz radiation source is illustrated in Fig. 1(a). Because this antenna directs all of the photocurrent into the antenna arms, it performs somewhat better than a dipole antenna at the end of a transmission line.[10] For comparable dimensions, more power is radiated and the noise level is lower due to the larger separation between the lines. A simple scaling argument compares the efficiency of the new antenna with that achieved by the earlier "sliding contact" technique[3,4] of simply shorting-out a coplanar transmission line. For this case the photocarrier density is inversely proportional to the area of the focused laser spot with a diameter approximately equal to the spacing between the lines. The area of contact of the photoconductive spot with the lines is proportional to the diameter of the laser spot. Consequently, with the same electric field between the lines, the photocurrent is inversely proportional to the line separation. Therefore, the main advantage of the new antenna design is that the total photocurrent from a 5 μm gap is put into a 30 μm antenna. Directly shorting a coplanar line with 30 μm separation between the two lines and with a six times higher bias voltage, would produce a current only 1/6 of that obtained by the antenna. The 20-μm-wide antenna structure was located in the middle of a 20-mm-long transmission line consisting of two parallel 10-μm-wide, 1-μm-thick, 5 Ω/mm, aluminum lines separated from each other by 30 μm. The antenna was driven by photoconductive shorting the 5 μm antenna gap with 70 fs pulses coming at a 100 MHz rate in a

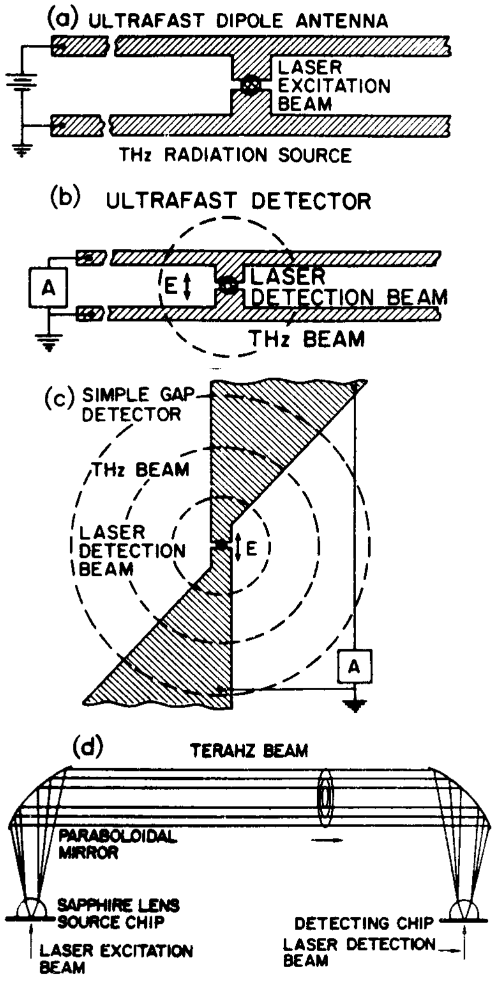

FIG. 1. (a) Ultrafast dipolar antenna terminated by the charged coplanar transmission line. (b) Ultrafast antenna used a a detector centered in the focal disk of the incoming 1.2 THz radiation. (c) Simple gap detector centered in the overlapping focal disks of the incoming 0.4, 0.6, and 1.2 THz radiation. (d) Collimating and focusing optics consisting of crystalline sapphire lenses in contact with the SOS chips, near the foci of paraboloidal collimating and focusing mirrors.

1.5 mW beam from a colliding-pulse, mode-locked dye laser.

We have used two different terahertz radiation detectors. The one shown in Fig. 1(b) uses the same ultrafast antenna and terminating transmission line as the transmitter. Via the transmission line one side of the antenna is grounded, and a current amplifier is connected across the antenna. During operation the antenna is driven by the incoming terahertz radiation pulse polarized parallel to the antenna; this excitation causes a time-dependent voltage to appear across the antenna gap. This induced voltage is measured by shorting the antenna gap with the 70 fs optical pulses in the detection beam and monitoring the collected charge (current) versus the time delay between the excitation and detection laser pulses. The detector shown in Fig. 1(c) has a simple photoconductive gap of $10\,\mu$m spacing, an initial width of $25\,\mu$m, and a total length of 1 mm. This detector is similar to those used previously[3,4] and has some similarity to the bow tie antenna.[11,13] The measurements made using the simple gap are performed in the same manner.

The terahertz optics illustrated in Fig. 1(d) consist of two matched crystalline sapphire, spherical lenses contacted

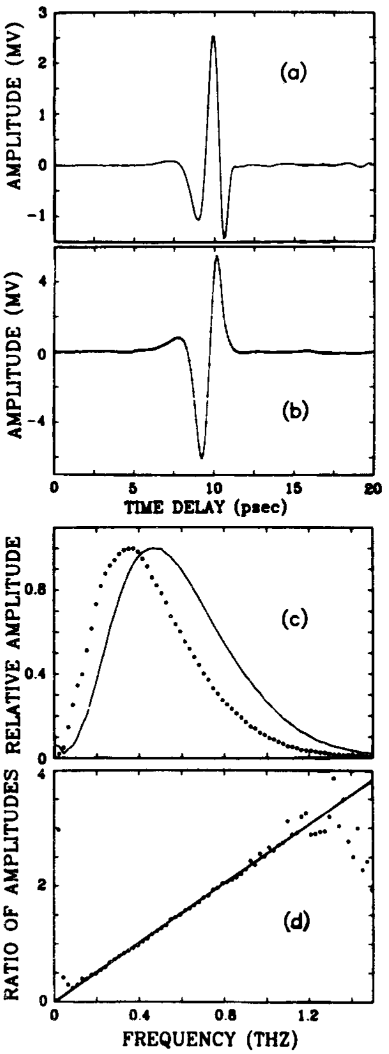

FIG. 2. (a) Measured electrical pulse of the freely propagating terahertz beam with the ultrafast dipolar antenna detector. (b) Measured electrical pulse of the freely propagating terahertz beam with the simple gap detector. (c) Amplitude spectra of the measured pulse shapes shown in (a) (solid line) and (b) (dots). (d) Ratio of the spectral amplitudes of (c).

to the sapphire side of the SOS chips located near the foci of two identical paraboloidal mirrors. For both the radiation source and the detector, the center of the truncated 9.5-mm-diam sphere (lens) is 2.3 mm above the ultrafast dipolar antenna located at the focus of the lens. The orientations of the *c* axes of the sapphire lenses and SOS chips have been described earlier.[4] Due to the relatively high dielectric constant of approximately 10 for sapphire, most of the radiation emitted from the ultrafast antenna is contained in a 60° full angle cone normal to the surface of the SOS chip and directed into the sapphire.[13,14] This situation gives good collection and collimation of the terahertz radiation, because the central portion of the spherical lens captures most of the emitted radiation. After collimation we obtain a beam diameter of 5 mm; the calculated field pattern shows a strongly defined structure.[13] Although the 70 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. After recollimation by the mirror, we obtained beam diameters (10–70 mm) proportional to the wavelength; therefore, all of the frequencies propagated with the same 25 mrad divergence. After freely propagating 50 cm to the second mirror, all the frequencies were focused to the same 5-mm-diam spot at the entrance to the second sap-

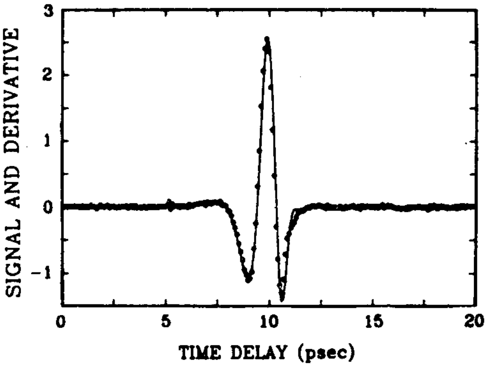

FIG. 3. Numerical derivative (dots) of the measured pulse with the simple gap [Fig. 2(b)] compared to the measured pulse (solid line) with the ultrafast dipolar antenna [Fig. 2(a)].

phire lens. This lens then focused the beam onto the ultrafast dipolar antenna or the simple gap. To first order the collection efficiency of the emitted radiation is almost complete and is independent of frequency. However, a detailed calculation shows a slight frequency dependence for the beam divergence and the resulting coupling between the transmitter and receiver. The total path length was 80 cm from transmitter to detector; 75 cm of this path was in an enclosure purged with dry nitrogen in order to prevent absorption of the terahertz beam by water vapor in the laboratory air. Because the focal diameters produced by the lens are proportional to wavelength, the focus can be considered as a series of concentric overlapping disks of increasing diameters corresponding to the increasing wavelengths.

Figures 2(a) and 2(b) display the detected terahertz radiation pulses measured with the ultrafast antenna and the simple gap, respectively. Both of these high signal-to-noise measurements of the transmitted pulses, after 80 cm of free propagation, were made in single 2 min scans of the relative time delay between the excitation and detection pulses. The measured voltages were calibrated by comparing the time-resolved signal with the photocurrent generated with a known dc bias voltage applied to the receiver. When the antenna was used as the transmitter, the signal strength increased by four times (with no loss in speed), compared to the "sliding contact" emitter, for which a charged coplanar transmission line with 15 μm separation was photoconductively shorted by the laser pulses.[4] This increase was due to the higher photocurrent and larger transient dipole moment of the antenna. Because the signal strength is proportional to the electric field, the factor of four increase in signal corresponds to the transmitter radiating 16 times more power. Compared to the previous demonstration,[4] which used only the sapphire lenses, the addition of the collimating paraboloidal mirror reduced the beam divergence to 25 mrad from an average divergence of 100 mrad. This together with the focusing paraboloidal mirror increased the power incident on the sapphire lens at the detector by another factor of 200. Consequently, as evidenced by the several millivolt amplitudes of the measured signals, the power incident on the detector has been increased by more than 3000 times compared to the earlier work.[4]

Because the spatial extent of the ultrafast detector depicted in Fig. 1(b) is small compared to the focal spot diameter of the shortest wavelength, this detector measures the incident electric field. There is an enhancement in the measured signal of the short-wavelength components due to the fact that their relative focal spot diameters are smaller and their focused electric fields are stronger. This situation is not true for the simple gap whose length is large compared to the focal spot diameter of the longest wavelength. Consequently, the long simple gap integrates over all the focal spots and the frequency enhancement disappears. This is similar to the bow tie antenna, which (theoretically) has a flat frequency response.[11,13] Although the signal strengths from the two detectors are almost the same, the response of the simple gap is clearly slower. A comparison in Fig. 2(c) of the amplitude spectra of the two signals shows that for the ultrafast antenna the spectrum peaks at 0.5 THz and extends well beyond 1.2 THz, compared to the maximum at 0.35 THz for the gap.

It is instructive to take the ratio of these spectra as shown in Fig. 2(d), where the feature at low frequency is an artifact and can be ignored. The linear frequency dependence indicated by the solid line agrees with the above description of the linear frequency enhancement of the antenna. This result, combined with the phase shift of $\pi/2$ of the frequency components of Fig. 2(a) compared to those of Fig. 2(b), leads to the conclusion that the signal measured by the ultrafast antenna is equal to the time derivative of the signal measured by the gap. This conclusion is confirmed by the result shown in Fig. 3, where the calculated time derivative of the gap signal is compared with that measured by the ultrafast antenna, and excellent agreement is obtained.

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