Point source terahertz optics

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We demonstrate an ultrafast 10 μm sized, electric dipole source of terahertz radiation closely coupled to a 1 cm spherical mirror. This optical approach has the advantages of subpicosecond response times with essentially complete collection efficiency. Using this technique, we have generated and detected subpicosecond freely propagating electrical pulses.

The idea of using a transient electric dipole as a source of broadband radiation goes back to the original work of Hertz,[1] described in standard textbooks on electromagnetic theory. A modern integrated circuit version of Hertz's experiment has been performed by Auston *et al.*[2] using fast photoconductive switches on silicon-on-sapphire (SOS) wafers as the dipole sources and detectors. This work demonstrated the generation and detection of 1.6 ps pulses of radiation freely propagating through the SOS wafer.

The experiments by Ketchen *et al.*[3] describe the generation of extremely short-lived electric dipoles by the "sliding contact" method of shorting charged, micron-sized, coplanar transmission lines with ultrashort laser pulses. The extremely fast response time was mainly due to the fact that the field pattern of the electric dipole created by the sliding contact excitation matched the field pattern of the propagating TEM mode of the transmission line.[4] Therefore, in addition to the freely propagating radiation produced by the creation of the electric dipoles, the essentially perfect coupling to the line resulted in the production of two counterpropagating subpicosecond electrical pulses on the coplanar transmission line. By adding an impedence matched antenna to the coplanar line geometry, DeFonzo and Lutz have transmitted and detected freely propagating 10 ps electrical pulses.[5] Subpicosecond pulses have been generated, transmitted, and detected by Smith *et al.*[6] who fabricated ultrafast dipolar antennas terminated by coplanar transmission lines.

The above approaches using antennas extend radio and microwave techniques into the terahertz regime. In this letter we demonstrate an alternative approach, whereby optical techniques are adapted to terahertz frequencies. Our approach is distinguished by excellent time resolution and essentially complete collection of the radiation. We use an ultrafast point dipole source (Hertzian dipole) with dimensions small compared to any of the radiated wavelengths. This source is located at the focal point of a spherical lens or mirror which can focus the radiated pulse on a detector or collimate the emission to produce a beam of freely propagating ultrashort electrical pulses. Our method has extremely high coupling efficiency in that we capture essentially all of the dipolar radiation. In addition, our excellent focusing properties preserve the subpicosecond response times of the source.

The experimental geometry illustrated in Fig. 1(a), used to generate the transient electric dipole responsible for the terahertz radiation emitted into the sapphire substrate, is similar to that used earlier for transmission line studies.[3,4] Here, the subpicosecond electric dipoles are created by photoconductive shorting the charged coplanar transmission line with 70 fs pulses from a colliding-pulse, mode-locked dye laser. For short propagation distances, the electrical pulse coupled to the transmission line has the same time

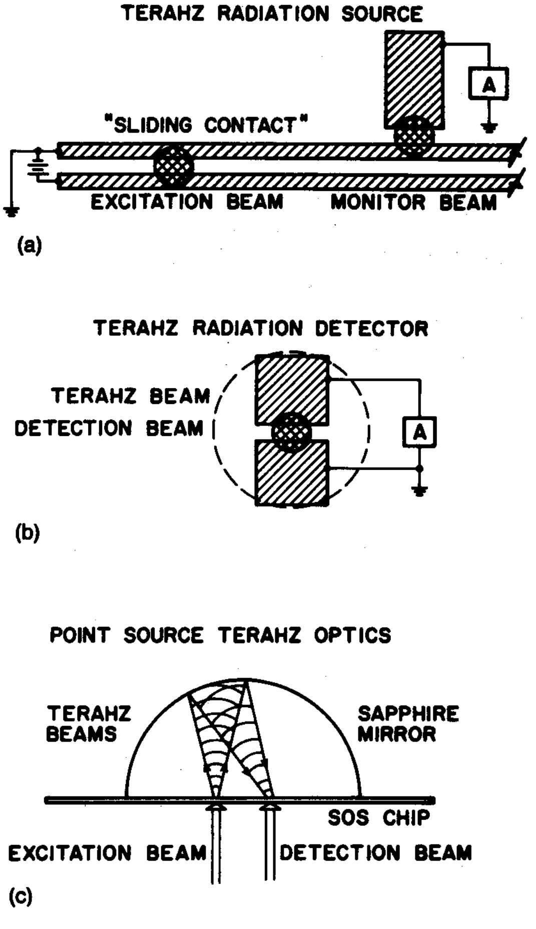

FIG. 1. (a) Schematic diagram of the charged coplanar transmission line. The laser excitation beam spot defines the location of the transient electric dipole. The monitor beam measures the electrical pulse coupled to the line. (b) Schematic diagram of the terahertz detector. The laser detection beam spot is shown centered on the gap in the focal spot of the terahertz radiation. (c) Schematic diagram of the focusing optics consisting of a gold-coated, solid-hemispherical sapphire mirror with a diameter of 9.5 mm in contact with the backside (sapphire side) of the SOS chip.

dependence as the transient electric dipole responsible for the terahertz radiation.[4] 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 100 Ω and consisted of two parallel 5-μm-wide, 0.5-μm-thick aluminum lines separated from each other by 10 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 wafer, which was heavily implanted to ensure the required short carrier lifetime.[7] The measurements were made with the standard excite and probe arrangement for the beams of optical pulses.

The terahertz radiation detector shown in Fig. 1(b) is simply a photoconductive gap of 10 μm spacing with a width of 25 μm. This gap was fabricated together with the coplanar transmission line on the same SOS chip. With respect to the orientation of the transmission line shown in Fig. 1(a), the detection gap of Fig. 1(b) is located 1.7 mm below the line. 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. 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 point-source terahertz optics illustrated in Fig. 1(c) are quite simple and consist of a gold-coated section of a 9.5-mm-diam hemisphere of sapphire contacted to the backside (sapphire side) of the SOS chip. The center of the hemisphere is located in the plane of the 0.5-μm-thick silicon layer on top of the 0.43-mm-thick SOS chip. This ensures that the terahertz radiation from the transient dipole excited in this plane will be refocused in the plane. Because we work in reflection, alignment is simple in that the focus of the excitation optical beam is imaged at the focus of the terahertz radiation and can be easily observed with an optical microscope. Thus, the hemisphere and the sliding contact are adjusted until the reflected image of the excitation laser focus appears on the gap of the terahertz radiation detector, corresponding to the center of the hemisphere adjusted to be midway between the sliding contact and the detection gap. It is important to note that most of the radiation 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 is a consequence of the relatively high dielectric constant of approximately 10 of sapphire. This situation gives good focusing of the terahertz radiation, because only the central portion of the spherical mirror is involved.

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 120 μm so that propagation effects were negligible. The measured FWHM as shown is 1.0 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.

In Fig. 2(b), the detected terahertz radiation pulse is displayed, where the indicated amplitude scale is normalized with respect to the electrical pulse on the transmission line [Fig. 2(a)]. Again, this measurement was made in a single 2 min scan of the relative time delay between the excitation and detection pulses. The 99 ps time delay shown on Fig. 2(b) with respect to Fig. 2(a) is the measured propagation time from the generation site to the detection gap. For this particular case the radiation detection gap was located 1.7 mm below (with respect to Fig. 1) the sliding contact excitation site with the center of the hemisphere midway between. Thus, the total distance from the excitation point to the surface of hemispherical mirror and back to the gap was 9.7 mm. Using this value we obtain a propagation speed of $c/3.06$ corresponding to a dielectric constant of 9.36 in good agreement with the tabulated value of 9.42 for the ordinary ray in sapphire.[9] This agreement confirms that we have observed the freely propagating radiation pulse.

Although the observed pulse shape approximates the derivative of the time dependence of the transient electric dipole, as predicted by theoretical analysis,[6] it does not agree in detail. This slight disagreement is probably due to a combination of the following three effects. The first effect involves the strong birefringence of the sapphire, the fact that the source is polarized perpendicular to the transmission lines and the feature that the detector measures only the field component perpendicular to the gap. In order to minimize this effect the c axes of the SOS wafer and the sapphire mirror were aligned parallel to the transmission line. Second,

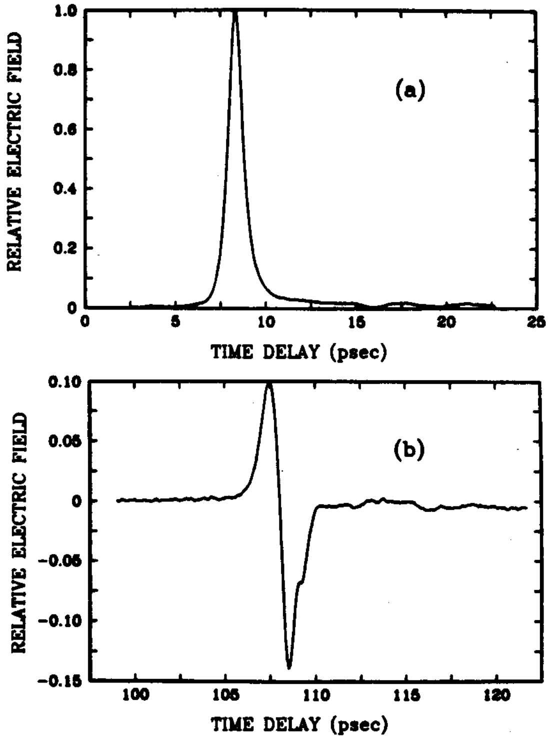

FIG. 2. (a) Measured electrical pulse with 120 μm separation between the excitation and monitor beams. (b) Measured electrical pulse of the focused freely propagating terahertz pulse at the detector.

the detection efficiency is better for higher frequencies. This is due to the fact that the focused spot size is proportional to the wavelength while the much smaller detector size is fixed. Third, we believe that the main reshaping mechanism is due to the dielectric dispersion of the sapphire crystal.[9] This effect reshapes the propagating pulse by delaying the higher frequency components with respect to the lower frequencies. Thus, the more rapid time dependence would occur on the trailing edge of the pulse in agreement with the observation.

The two main features of our method are clearly evidenced by the measurement of Fig. 2(b). First, excellent time resolution is obtained as shown by the 1 ps duration from maximum to the minimum. Second, the collection is extremely efficient. The measured pulse has a good signal-to-noise ratio and is approximately 1/10 the amplitude of the pulse coupled to the lines. Considering that we measure only the central 10-μm-diam of the total 100-μm-diam focal spot of the terahertz radiation, the power in the radiated terahertz pulse appears to be approximately the same as that coupled to the transmission lines. Our experimental results show that, by using standard optical components and techniques combined with point sources of terahertz radiation, it will be possible to generate well collimated beams of freely propagating subpicosecond electrical pulses for a multitude of applications.

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