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A Cherenkov Source for Freely-Propagating Terahertz Beams

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Abstract—**Using a unique cylindrical optical arrangement, we have coupled out a Cherenkov electromagnetic shock wave from the confining dielectric substrate and have used this shock wave as a source to produce freely-propagating terahertz beams. The shock wave is initially generated by a surface-dipole distribution propagating faster than the phase velocity in the underlying dielectric substrate.**

IT IS well known that electromagnetic shock waves are generated when electric charges or charge distributions travel at speeds greater than the phase velocity in a dielectric [1]. An important example of this situation has been discovered by Auston, who created a moving volume electric dipole distribution by driving the optical rectification effect in a nonlinear dielectric material with an ultrashort laser pulse [2], [3]. Because the speed in the dielectric for both the visible light pulse and the volume dipole was much faster than the phase velocity for the terahertz frequencies describing the electric field of the volume dipole, an electromagnetic shock wave was produced. By measuring the change in time dependence of the shock wave as a function of propagation distance, far-infrared spectroscopic measurements of the nonlinear dielectric were obtained [4]. In addition, measurements of the change in the time dependence after a reflection at the surface of the dielectric allowed for measurements of other materials brought in contact with the dielectric surface [5].

Another experimental approach to the generation of electromagnetic shock waves is by creating an electric surface-dipole distribution which propagates faster than the phase velocity in the underlying dielectric substrate [6], [7]. This situation occurs when ultrashort electric pulses propagate on a coplanar transmission line at speeds faster than the phase velocity in the underlying dielectric substrate. Because these electrical pulses propagate as the differential (TEM) mode of the two-line coplanar transmission line, there is a positive pulse on one line and a negative pulse of identical shape on the other. Therefore, the total electric field of the pulse is described by a propagating electrical-dipole distribution. Consequently, as seen from the underlying dielectric, the situation is that of an electric-dipole distribution propagating on the surface faster than the phase velocity in the dielectric. This situation produces an electromagnetic shock wave. The initial observation [6] was the measurement of the frequency-dependent loss due to Cerenkov radiation from the propagating electric pulse. Recent experiments have directly observed the shock wave and measured its time dependence [7].

The general usefulness of these electromagnetic shock waves as sources of terahertz pulses would be greatly enhanced if they could be coupled out of their confining dielectrics and spatially reshaped into collimated freely-propagating beams. In this paper we report the first such result. Using a unique cylindrical optical arrangement, we have coupled out a Cherenkov electromagnetic shock wave from a dielectric substrate and have used this shock wave as a source to produce freely-propagating terahertz beams. The observed subpicosecond time dependence is exceptionally fast and is potentially faster than could be obtained by the direct generation of terahertz pulses by driving a Hertzian dipole with ultrashort laser pulses [8]–[10]. The freely-propagating beams have (10–40 mm) diameters proportional to wavelength but a wavelength-independent divergence of only 30 mrad [10].

The experimental details of the generation of the electromagnetic shock wave from an electric pulse propagating on a coplanar transmission line faster than the phase velocity of the underlying sapphire substrate has been presented earlier [6], [7]. For the experiment described in this paper, the transmission line consisted of two parallel 10 micron wide lines separated from each other by 30 microns. At the midpoint of this 20 mm long transmission line a Hertzian dipole antenna structure was imbedded [10]. This antenna served to excite a significantly larger electrical pulse on the transmission line than by simply shorting out the line with the focused laser pulse [10], [11]. The antenna was driven by photoconductive shorting the antenna gap with 70 fs pulses coming at a 100 MHz rate in a 3 mW beam from a colliding-pulse, mode-locked dye laser.

The optical arrangement used to couple out the Cherenkov shock wave from the sapphire substrate is illustrated in cross section in Fig. 1(a). Here, the location of the laser excitation beam is indicated together with the generated electrical pulse on the line shown after several millimeters of propagation. A section of a crystalline sapphire cylinder, fabricated with the optic axis of the sap-

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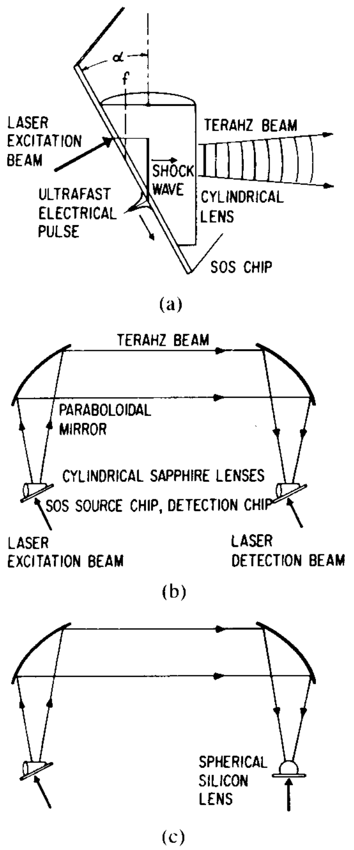

Fig. 1. (a) Cross-sectional view of the optical system used to couple out the Cherenkov radiation pulse; f is the focal line of the cylindrical lens. (b) Terahertz beam system with the Cherenkov source and detector. (c) Terahertz beam system with the Cherenkov source and standard detector using a spherical focusing lens.

phire parallel to the cylindrical axis, is in contact with the back side (sapphire side) of the silicon-on-sapphire (SOS) chip. The 5 mm diameter cylinder has been cut so that the cylindrical axis makes an angle of $\alpha = 48°$ with respect to the coplanar transmission line. The angle α is related to the shock wave propagation direction θ_c [3] by the relationship $\alpha = 90° - \theta_c$. In addition, the SOS wafer has the sapphire optic axis oriented so that it is parallel to the cylindrical axis. Consequently, in the cross section shown, the ordinary shock wave propagates perpendicular to the cylindrical axis. From inspection of Fig. 1(a), it can be seen that at a unique point, the focal line of the cylindrical lens intersects the transmission line. Therefore, the shock wave emanating from this point will be reshaped by the lens into a collimated beam in the plane normal to the cylindrical axis. For the experiment, the electrical pulse is generated slightly upstream from this point to keep a short propagation distance and to thereby minimize broadening of the electrical pulse. The collimated beam from the cylindrical lens is recollimated by a paraboloidal mirror with a 4 cm aperture and a 6.6 cm focal length, as shown in Fig. 1(b). The output face of the cylindrical lens is located slightly beyond the focus of the paraboloidal mirror. The collimated beam from the mirror can now be propagated hundreds of centimeters with little loss in signal due to diffraction. The beam is immediately useful for all the applications previously proposed for terahertz beams [8]-[10]. For the detection scheme depicted in Fig. 1(b), the beam is refocused by a second matched paraboloidal mirror onto an identical cylindrical focusing lens in contact with another identical SOS chip driven by a sampling laser pulse, as described previously [8]-[10]. Another method of detection is illustrated in Fig. 1(c), where a spherical 9.5 mm diameter silicon lens with a 7 mm focal length is used to focus the terahertz beam onto the detecting chip [10]. For both Figs. 1(b), and (c) the total terahertz beam path length was 28 cm.

The measured terahertz pulse from the Cherenkov source with the optical arrangement of Fig. 1(b) is shown in Fig. 2(a). This high signal-to-noise measurement was made in a single 2 min scan of the relative time delay between the excitation and detection pulses. The measured signal strength of 1.5 mV is of the same magnitude as obtained with our high-brightness terahertz source (10), driven with a transient Hertzian dipole. Similarly, the measured 0.78 ps (FWHM) pulsewidth of the main pulse compares well with our best result of 0.68 ps from the Hertzian dipole source (10). The persistent structure shown after the main pulse is mainly due to the absorption and dispersion of water vapor in the laboratory air [9]. In order to better compare the Cherenkov source with the previously-used Hertzian dipole source, we used a spherical lens to focus the terahertz beam on the detector, as illustrated in Fig. 1(c). Here we see that the signal strength is of the same order of magnitude as that of Fig. 2(a). The measured pulse shown in Fig. 2(b) has a pulsewidth of 0.64 ps (FWHM), significantly shorter than for Fig. 2(a). Most of this improvement can be attributed to the silicon lens which has less high-frequency absorption than sapphire. It is informative to note that we have tried the three crystalline materials, sapphire, MgO, and high-resistivity silicon for terahertz lenses. As noted above, the strong birefringence of sapphire gives severe technical problems. In addition, the absorption of sapphire at terahertz frequencies is higher than MgO and high-resistivity silicon. Both MgO and silicon are optically isotropic, and their index at terahertz frequencies is relatively close to that of sapphire, thereby giving a small reflection at the SOS wafer-lens interface. Because the frequency dependence of the index of refraction is much less for silicon than for MgO, silicon is the preferred lens material. Our silicon lens was fabricated from high-resistivity (greater than 10 kΩ · cm) float-zone, silicon obtained from Topsil. The amplitude absorption coefficient of this material at 1 THz is less than 0.2 cm^{-1}, as measured in our laboratory by time-domain spectroscopy with a high-brightness terahertz beam [10], [12].

In important point to make here is that it should be possible, by using the same approach as described above, to couple out and convert to a freely-propagating terahertz beam the conical Cherenkov shock wave generated by optical rectification in a nonlinear dielectric [3], [4]. In lithium tantalate, for example, the angle α is only 22°. The low anisotropy of both its optical and terahertz dielectric

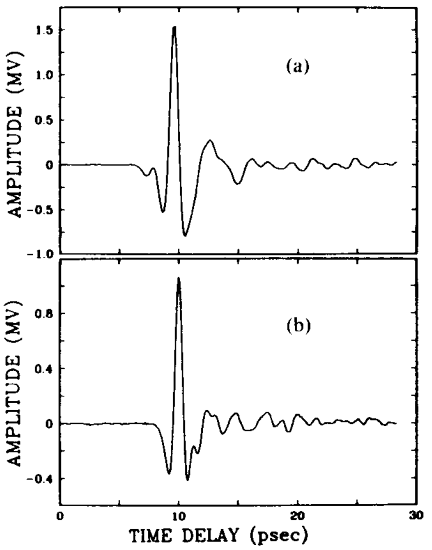

Fig. 2. (a) Measured transmitted pulse from the Cherenkov source and detected with the cylindrical sapphire focusing lens. (b) Measured transmitted pulse from the Cherenkov source and detected with the spherical silicon focusing lens.

constants (0.2 and 0.5 percent, respectively) makes the crystal ideally suited for this technique.

In summary, we have demonstrated a new type of source of freely-propagating terahertz pulses; the source is not based on the excitation of transient Hertzian dipoles or antennas.

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Christof Fattinger was born in Brazil on October 3, 1954. He received the M.S. degree in physics and the Ph.D. degree from the Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, in 1980 and 1987, respectively.

In 1980 he joined the Optics Laboratory at ETH, where he was employed as a Research Assistant. His experimental and theoretical dissertation work involved laser spectroscopic investigations of molecules near surfaces and interfaces. In 1987 he received a postdoctoral fellowship from the IBM Research Division at the IBM T. J. Watson Research Center, Yorktown Heights, NY. His recent work in the field of ultrafast optoelectronics involved experimental and theoretical studies of the electromagnetic radiation processes associated with the excitation and propagation of subpicosecond electrical pulses on integrated-circuit transmission lines. This work led to the development of techniques for the generation of diffraction-limited beams of single-cycle electromagnetic pulses in the terahertz regime. Since 1989 he has been with F. Hoffmann-La Roche Ltd., Basel, Switzerland, where he is engaged in research on microoptical sensors for biomedical applications.

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In 1969 he joined the IBM Research Division at the IBM T. J. Watson Research Center, Yorktown Heights, NY, where he now manages the Ultrafast Science with Lasers Group. His initial experimental and theoretical research involved studying the interaction between near-resonant light and the two-level system. The "adiabatic following model," which he originally proposed as a result of these studies subsequently explained the observed effects of self-focusing, self-defocusing, self-steepening, and slow group velocities in vapors of two-level systems (alkali metals). His experimental and theoretical studies of the nonlinear propagation of picosecond laser pulses in single-mode optical fibers led to the concept of "enhanced frequency chirping" and the associated optical-fiber pulse compressor, and the experimental observations of gray solitons, and optical intensity shocks. His most recent work has involved the generation and applications of subpicosecond electrical pulses on transmission lines. An important part of this work has been the observation of terahertz radiation from the generation site and Cerenkov radiation from the propagating electrical pulses. These studies have resulted in a new source of pulsed terahertz beams.

Dr. Grischkowsky is a Fellow of the Optical Society of America and the American Physical Society. An outgrowth of his work was the invention of the optical fiber pulse compressor, for which he was awarded The Boris Pregel Award for Applied Science and Technology (1985) by The New York Academy of Sciences. He was awarded The R. W. Wood Prize (1989) of the Optical Society of America for pulse propagation studies in optical fibers and their use for generating ultrashort pulses of light.