Picosecond Time-Domain Electromagnetic Scattering from Conducting Cylinders

W. M. Robertson, G. V. Kopcsay, and G. Arjavalingam

Abstract—**The microwave scattering properties of conducting cylinders are characterized by measuring their response to picosecond duration electromagnetic pulses. The ultrafast electromagnetic transients are generated and detected with optoelectronically pulsed antennas. The time-domain response gives physical insight into the scattering process. In addition, Fourier analysis is used to obtain the frequency dependence of the scattered amplitude and phase from 15 to 140 GHz.**

THE scattering of radiation by three-dimensional objects is a fundamental problem in electromagnetics [1]. Much theoretical and experimental effort has been invested in this topic both for fundamental reasons and because of a diversity of practical applications in radar engineering and optics [1], [2]. The use of impulse response waveforms for characterizing electromagnetic scattering, as suggested by Kennaugh [3], is an alternative to more traditional continuous-wave techniques. Although the impulse response contains equivalent information to the frequency domain formulation, the time-domain signature is more directly related to the geometrical form of the object, and offers a clearer physical insight into the scattering process [4], [5].

In this letter, we describe picosecond time scale scattering experiments which utilize the ultrashort electromagnetic transients radiated and received by optoelectronically pulsed antennas. The method is based on the coherent microwave transient spectroscopy (COMITS) technique [6] that was used previously to characterize the dielectric properties of materials in the 15–140 GHz frequency range. In addition to its broad frequency coverage, the inherent phase sensitivity and strong polarization selectivity [7] of COMITS offers several advantages for the investigations described here.

The letter is arranged as follows. We describe the experimental set-up and illustrate its application to scattering studies with measurements on a series of conducting cylinders. The measured time-domain waveforms are shown to agree qualitatively with existing theoretical treatments. In addition, good quantitative agreement is found between the complex Fourier transforms of these signals and the theoretically predicted frequency response.

The experimental configuration is shown schematically in Fig. 1. The transmitting and receiving elements are exponen-

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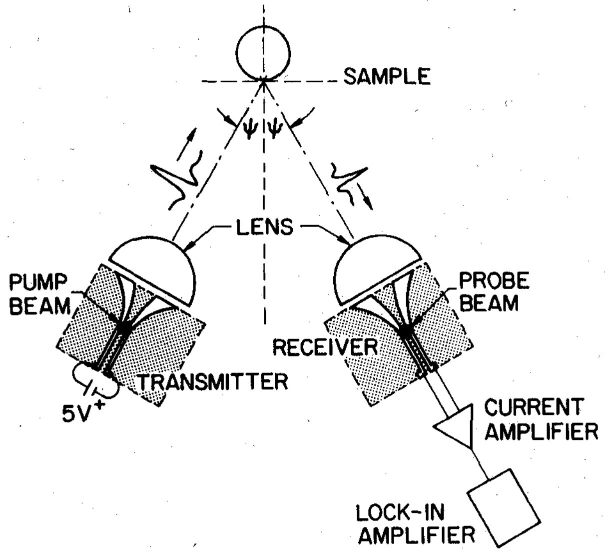

Fig. 1. Schematic of the configuration for scattering experiments.

tially-tapered coplanar stripline antennas photolithographically fabricated on silicon-on-sapphire [8]. The silicon is subsequently ion implanted to reduce the carrier lifetime to less than 1 ps. The dc-biased transmitter is excited, and the signal induced on the receiver photoconductively sampled, by 1.5 ps optical pulses ($\lambda = 527$ nm) from a mode-locked, pulse compressed, and frequency-doubled Nd:YLF laser. The optical pulses are arranged in a pump-probe configuration such that the signal at the receiver is measured as a function of the time delay between the pump and probe pulses [8]. As shown in the Fig. 1, fused silica lenses are used to collimate the electromagnetic transients radiated by the transmitter and to focus the reflected or scattered signal onto the receiver. The collimated microwave beam was determined experimentally to be roughly 3 cm in diameter.

Fig. 2(a) shows the specularly reflected signal from a gold mirror (an essentially perfect reflector at microwave frequencies) which is used as the reference waveform to determine calibrated scattering functions. It has a 6.5-ps wide central peak, and an amplitude spectrum with components extending to 150 GHz [9]. The planar antenna structures emit linearly-polarized radiation (polarization ratio 60:1) with the E-field in the plane of the antenna [7]. For all the results described here the transmitter and receiver were oriented such that the E-field lay in the plane of scattering. The angle, ψ, defined in Fig. 1 was 33°. More complete details of the underlying principles of the COMITS technique and its application to

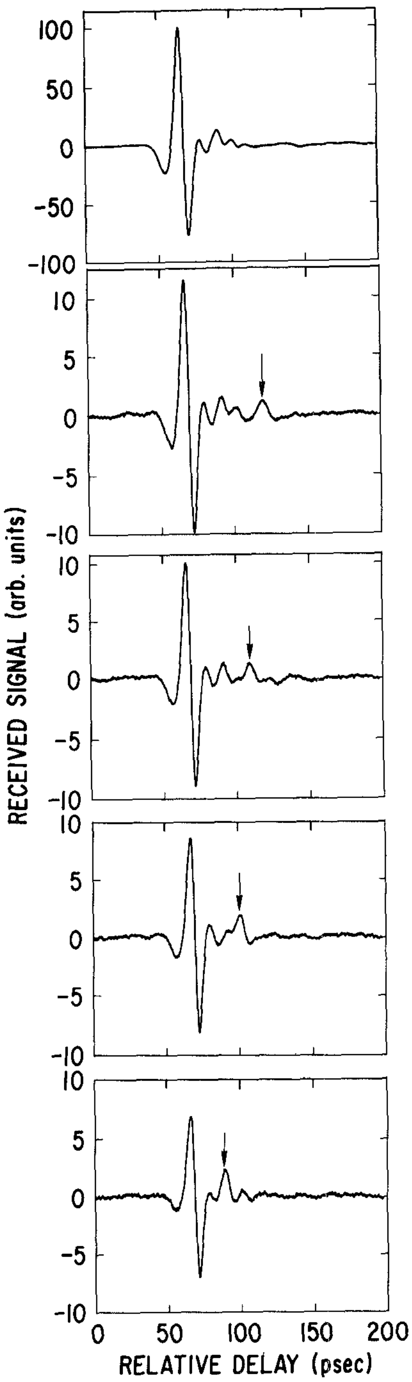

Fig. 2. Time-domain waveforms recorded for scattering from a series of aluminum cylinders. (a) Specular reflection from a gold mirror used as a reference signal. Scattered waveforms from cylinders of diameters. (b) 0.800 cm. (c) 0.635 cm. (d) 0.488 cm. (e) 0.317 cm.

transmission and reflection spectroscopy can be found in [6], [9].

The measured waveforms due to scattering from a series of aluminum cylinders with a range of diameters are shown in Figs. 2(b)–(e). The cylinders, all of which were much longer than the microwave beam diameter of 3 cm, were oriented with their axes perpendicular to the plane of Fig. 1. Each waveform in Figs. 2(b)–(e) consists of two pulses. There is an initial strong pulse and a second weaker pulse (marked with an arrow in Fig. 2) which is delayed with respect to the first pulse by a time which scales with the diameter of the cylinder. The two pulse structure can be qualitatively understood in impulse response terms. The first pulse is a specular reflection from the illuminated surface of the cylinder and, as expected, the amplitude of this specular pulse decreases with decreasing diameter. The second pulse is due to radiation from a surface wave that propagates around the rear of the cylinder as a "creeping wave".[1] Because this pulse is a superposition of a wide range of frequencies which undergo different amounts of loss and dispersion in the surface wave propagation, both a decrease in amplitude and a temporal broadening are clearly observed with increasing diameter. The time delay Δt_d between the peaks of the two pulses is plotted versus cylinder diameter in Fig. 3. As mentioned previously, Δt_d scales proportionally with diameter in the range characterized. The same behavior was observed in a numerical simulation of the scattering process using the frequency-domain model described in the next paragraph, and an inverse Fourier transform. In the simulation we found that for a particular rod diameter the precise value of Δt_d varies by a few picoseconds depending on the form of the input pulse, with lower values for narrow pulses (i.e., for broad-frequency bandwidths) and higher for wide pulses. However, the relation Δt_d versus diameter remains linear in all cases with essentially the same slope. The variation of Δt_d with different incident pulses reflects the dispersion and attenuation of the surface wave propagation previously mentioned.

The time-domain data can be converted to the more familiar frequency response by numerically Fourier transforming the scattered temporal waveforms. To express the frequency-domain data as a calibrated reflection function, this result is divided by the Fourier transform of the corresponding specular reflection from a gold mirror. Because the receiving antenna measures the received signal voltage—rather than intensity—phase information is preserved. For example, the frequency-dependent amplitude and phase reflection spectra for scattering from the 0.635 cm diameter cylinder are presented as the points in Fig. 4. The lines in Fig. 4 are theoretical calculations of the relative scattered electric field amplitude and phase. They were obtained using the well-known expansion in cylindrical harmonics of the two-dimensional boundary value solution for plane wave scattering from an infinite conducting cylinder [10]. Good agreement is obtained between the theoretical and experimental results, except for a small linear increase in the scattered amplitude that is measured experimentally. Possible sources for this discrepancy include the following. 1) The experimental configuration is not truly two-dimensionally invariant due to the finite beam width, and possible amplitude variation across the incident beam. 2) Diffraction loss increases at lower frequencies where the aperture of the collimating lens is only a few wavelengths in diameter, and the curvature of the diverging cylindrical wavefront is only approximately 20 × the wavelength.

In summary, the microwave scattering properties of con-

[1] For an interesting discussion of this subject, see [1, pp. 685–698].

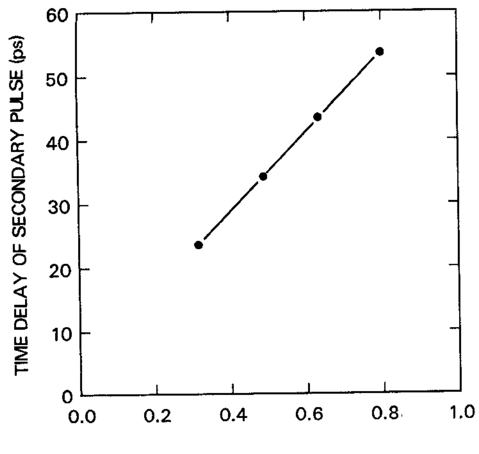

Fig. 3. Time delay (picoseconds) between the two peaks in Fig. 2(b)–2(e) plotted against the cylinder diameter (cm). Line is a guide to the eye.

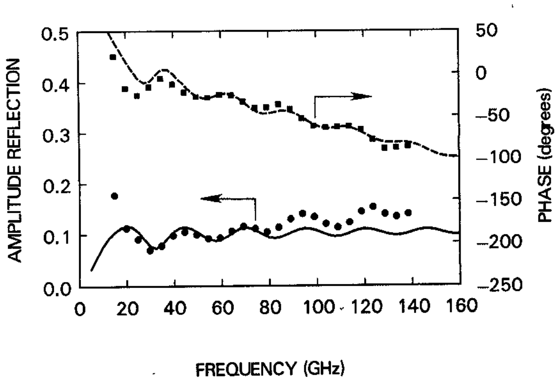

Fig. 4. Amplitude (circles) and phase (squares) scattered from 0.635 cm cylinder plotted as a function of frequency. Lines are theoretical predictions for scattering from a perfectly conducting cylinder [10].

ducting cylinders were investigated with picosecond duration electromagnetic pulses radiated and received by optoelectronically pulsed antennas. The Fourier transforms of the measured signals were in reasonable agreement with theoretical predictions of the frequency response. In addition to the broad-frequency coverage, and the phase and polarization sensitivity, the time-domain measurements described here are advantageous in elucidating the physical mechanisms responsible for scattering from general three-dimensional objects. In conjunction with Fourier analysis they are also particularly suited to the validation of models and simulation routines developed for such investigations.

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