Ultra-Wideband Transient Microwave Scattering Measurements Using Optoelectronically Switched Antennas

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Abstract—**Ultra-wideband transient microwave scattering measurements are performed using optoelectronically switched planar antennas. The laser-based system produces freely propagating bursts of picosecond duration electromagnetic radiation, with a bandwidth extending from 5 to over 70 GHz. Measurements are presented for scattering from one and two conducting strips and from a conducting sphere. All measurements are compared to theoretical computations.**

I. Introduction

PHOTOCONDUCTIVE switching of planar antennas has been used extensively to transmit and receive ultra-wideband (UWB) transient electromagnetic (EM) radiation [1] (a commonly accepted definition of a UWB signal is one with bandwidth at least 25% of its center frequency [2]). Early work in the development of photoconductively switched antennas involved the generation and detection of transient EM energy using simple dipole antennas [3]. Recently, more sophisticated antenna structures have been developed [4]–[6]. All of these antennas are operated by taking advantage of the recent developments in ultra-short pulsed lasers, from which stable picosecond and subpicosecond optical pulses can be generated routinely.

A desirable quality of this time domain technique is that UWB data can be obtained in a single measurement. One application of these antenna systems is for UWB spectroscopy. Ultra-wideband characteristics of isotropic and anisotropic dielectrics [7], [8], doped semiconductors [9], and superconductors [10] have been investigated. Another application of such a pulsed antenna system is for UWB time domain scattering measurements. Some scattering results have been presented by Arjavalingam and co-workers; specifically, scattering from conducting cylinders [11] and infinite gratings [12]. In this paper we present time domain scattering results from one and two conducting strips as well as from a conducting sphere, with the measured results compared to computed data. The experimental system used here is similar to Arjavalingam's in that the antennas, developed by DeFonzo and Lutz [4], are used with a lens at the transmitter, which results in the generation of a collimated pulsed beam. However, unlike in [11] and [12], we have chosen not to put a lens in front of the receive antenna. This, as will be discussed further, is because it is felt that such a lens reduces the angular resolution of the measurement system.

The remainder of this paper is organized as follows. The experimental details are discussed in Section II, followed by a comparison of theoretical and experimental results in Section III. In Section IV sources of experimental error are discussed. Concluding remarks as well as future improvements are discussed in Section V.

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II. Experiment

A. Measurement System

The antennas used in the experiments are aluminum coplanar strip horn antennas printed on silicon-on-sapphire (SOS) wafers. In conjunction with an ultrafast laser, the antennas are used to generate and detect short bursts of freely propagating EM radiation [4]. These antennas are identical to those developed by DeFonzo and Lutz, and the reader is referred to their original paper [4] for a detailed description of the antennas and their operation. This paper will concentrate on the application of these and similar antennas for UWB transient scattering measurements.

Optically switched planar antennas have been used previously for spectroscopy [7]–[10] and scattering [11], [12] measurements. In those experiments, lenses were used to collimate the radiation from the transmitter and to focus the radiation onto the receive antenna. In the work presented here, an ordinary 50 mm focal length lens has been used to collimate the radiation from the transmitter. However, one is often interested in the angular dependence of the scattered field from a given target. Since the lenses used (1 in diameter) have sizes that are comparable to the size of the target as well as the distance from the target to the observation point, it is felt that with a lens on the receive antenna, one loses angular resolution in the measured response. Therefore, in our work we have chosen not to use a lens on the receive antenna. This results in a lower signal-to-noise ratio but should lead to better angular resolution (the receiver acts like a point detector).

Currently, a mode-locked Nd-YLF laser is used to produce 80 ps duration infrared pulses (1054 nm) at a 76 MHz repetition rate and 15 W average power. These pulses are compressed to approximately 5 ps using a fiber-grating pulse compression system, and then are frequency doubled with a KTP crystal to produce approximately 4 ps duration green pulses (527 nm) with 250 mW average power. These optical pulses are used to switch the planar antennas photoconductively in a pump (transmitter)/probe (receiver) configuration.

B. Measurement Technique and Data Deconvolution

In the scattering experiments, a measurement is made first for signal propagation from the transmitter to the receiver directly, without a target present. Call this signal $s_1(t)$. The waveform $s_1(t)$ can be expressed as a cross correlation [7] between the current induced on the receiver and the effects of the photoconductive sampling process. A second measurement is then taken with a scatterer placed between the transmitter and receiver. The second measured signal $s_2(t)$ can be expressed as a convolution of $s_1(t)$ with the impulse response $(h(t))$ of the target at the point of observation. Once $s_1(t)$ and $s_2(t)$ have been measured, several different techniques are available to deconvolve $h(t)$ from $s_2(t)$. The simplest approach is to divide the Fourier transform of $s_2(t)$ by that of $s_1(t)$. This gives the impulse response in the frequency domain, which can be converted back to the time domain if desired.

In the above considerations, it has been assumed that the incident waveform on the scatterer is the same signal that was incident on the receive antenna for the measurement of $s_1(t)$. To achieve this, the distance between the transmitter and receiver for the measurement of $s_1(t)$ must be the same as the distance from the transmitter to the target when measuring $s_2(t)$. However, if all significant frequency components in the pulse decay approximately at the same rate with distance, this distance criterion may not be critical. In this case, if the distances discussed above are not adhered to, one would measure a scaled (in amplitude) version of $h(t)$. A measurement was performed to determine the decay rate of the EM pulse with distance. It was found that as the distance from the transmitter to receiver was varied, the pulse shape remained essentially unchanged, but the amplitude scaled. The peak amplitude of each measured pulse is plotted in Fig. 1 as a function of distance. It is seen that the pulse exhibits approximately a $1/r$ dependence, with r the distance from the transmitter. Although this is what is expected of an EM beam, it is important that it be verified experimentally in light of recent theoretical studies of EM missiles [13].

It should be pointed out that the use of a lens on the transmitter significantly increased the signal strength measured on the receiver. The use of the lens produces a collimated pulsed beam, and in the far field of the lens a $1/r$ signal decay is expected. The use of the lens effectively increases the aperture from which the energy radiates, thus increasing the distance from the transmitter to the Fraunhofer far field. If one were to use a lens on the receiver, and the rate of diffraction was such that the beam energy existed predominantly within the diameter of the lens, then the measured pulse would be independent of distance (assuming the lens efficiently focuses all the EM energy onto the antenna). Examples such as this, for which the use of a focusing lens on the receiver camouflages physical effects associated with EM radiation (diffraction in this case), are why a lens was only used on the transmitter. It should be noted that in material measurements, the interest of [7]–[10], the problems caused by a lens on the receiver are not an issue, and the significant enhancement in signal-to-noise (see Section V) afforded by such a lens is obviously desirable.

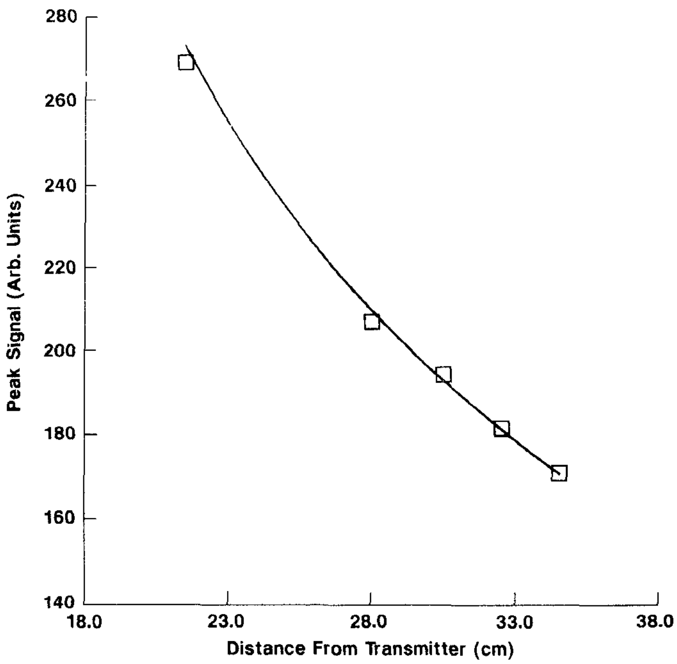

Fig. 1. Peak signal as a function of distance from the transmitter. The points represent measured data and the line represents a theoretical $1/r$ variation, where r is the distance from the transmitter. The line was computed by using one measured point (at 34.5 cm), and assuming a $1/r$ variation for all other distances.

With a knowledge of the EM pulse decay rate, the signals $s_1(t)$ and $s_2(t)$ are measured as follows. The transmitter and receiver are placed at the positions desired for a given scattering measurement. A good reflector (an aluminum plate in our experiments) is positioned just in front of the location at which the scatterer will be placed. The pulse specularly reflected off the plate is measured at the receiver. Using the distances from the plate to the receiver and from the transmitter to the receiver, this measured pulse is easily scaled in amplitude to its value at the plate's surface. Therefore, the scaled signal (now used as $s_1(t)$) will approximate very closely the signal actually incident on the scatterer cross correlated with the response of the receiver. The plate is then replaced with the scatterer, and $s_2(t)$ is measured.

III. Results

Measured data are presented for scattering from one and two conducting strips, as well as from a conducting sphere. The experimental results are compared to computed theoretical data. For both the strip and sphere calculations, the theoretical data were computed in the frequency domain, and a unit amplitude linearly polarized plane wave is assumed incident. We therefore compute the impulse response in the frequency domain, which is then multiplied by the Fourier transform of $s_1(t)$ (which is measured). This frequency domain product is converted into the time via a Fourier transform, arriving at a theoretical calculation of $s_2(t)$. For scattering from conducting strips, a spectral domain moment method procedure was used [14]; for scattering from a conducting sphere, a standard spherical harmonic expansion [15] was applied. The experimental results represent data that can be measured routinely, and the agreement shown between theory and experiment is typical but not the best (or worst) that can be achieved.

A. Strip Scattering

The strips are 5 mm wide and are separated by 5 mm (for the two strip case). In the experiment, the strips are made of thin aluminum and are sufficiently long such that the strip length is much larger than the beam cross section. The antennas are arranged such that the angle of incidence and observation are both 42°, with the angles measured from a (fictitious) line normal to the strip width. The electric field is approximately polarized (see Section IV) parallel to the length of the strips (TE). The transmitter and receiver are placed 12.5 and 9 cm, respectively, from the front surface of the strips. Fig. 2 shows a typical reference pulse measured at the receiver after reflecting off the aluminum plate. Also shown in Fig. 2 is the Fourier transform of the reference pulse. It is evident that the pulse contains significant EM energy at frequencies spanning from 5 to over 70 GHz. This bandwidth is limited by the laser, and can be extended by using shorter duration optical pulses [11], [12]. Figs. 3 and 4 show the pulse after scattering from one and two aluminum strips, respectively. In Figs. 3 and 4, the points represent measured data and the curves represent computed results. Notice that the scattered signal off a single strip is approximately a scaled version of the reference pulse at the angle of observation chosen. This can be understood by realizing that since the angles of incidence and observation are equal, we are observing predominantly specular reflection (which is weakly dispersive). For the two strip case, destructive and constructive interference is expected from the pulses reflected from each individual strip. Notice that this results (both experimentally and theoretically) in an enhanced second dip in the scattered waveform.

B. Sphere Scattering

The steel sphere used in the experiments had a 2.5 cm diameter. The transmitting and receiving antennas were placed 7.0 and 5.5 cm, respectively, from the center of the sphere, separated by an angle of 75°. The antennas were situated such that the coplanar strips of the two antennas were facing one another (not in the same plane). In this transmitter–receiver arrangement, the creeping wave excited is very small in magnitude, much smaller than the initial wavefront. Fig. 5 shows the theoretical and experimental data for this structure. The agreement between theory and experiment is quite respectable, although noise causes a slight corruption in the early- and late-time response of the experimental data. The reference pulse used for the sphere (not shown) is different than that for the strip measurements since a different reference pulse is measured for each experiment.

IV. Sources of Discrepancy

The experimental results are in good agreement with the theoretical computations. There are some discrepancies, however, and it is important that their sources are understood. In the computations, it has been assumed that the incident field was linearly polarized. Although the radiation produced by the coplanar strip antennas is known to be highly linearly polarized [8], the incident radiation will have some cross-polarization components. Additionally, the theory assumes the strips and sphere are perfectly conducting; and in the case of the strips, it is assumed that the conductors are infinitesimally thin. Obviously, these conditions can only be approximated experimentally. Perhaps the largest source of discrepancy,

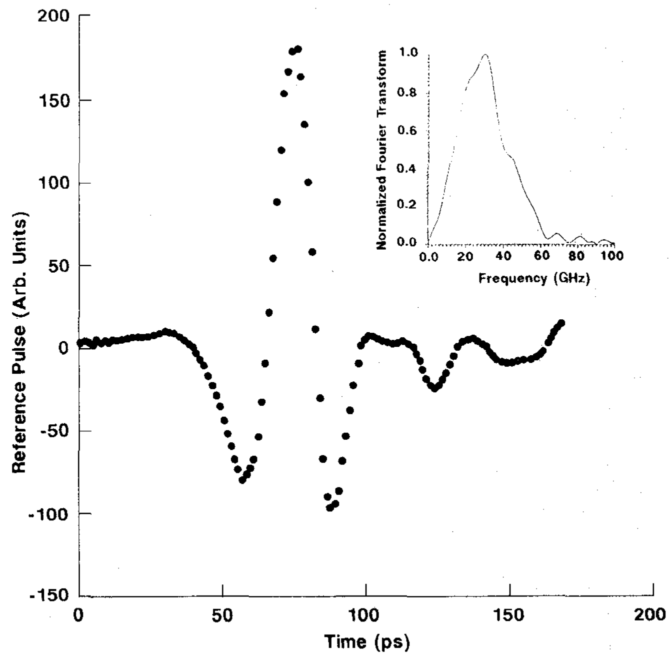

Fig. 2. The measured reference pulse and its associated numerical Fourier transform (inset).

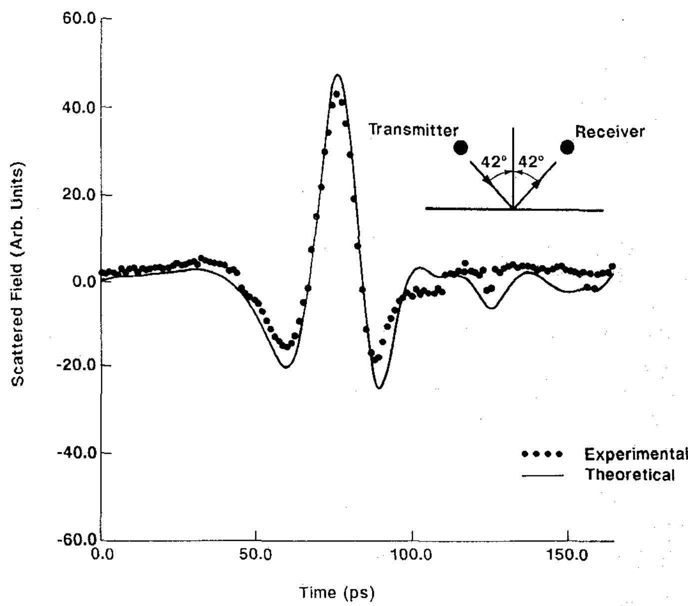

Fig. 3. Measured and computed scattered signal, $s_2(t)$, from a single aluminum strip of 5 mm width. The points represent measured data and the line represents computed results. The transmitter and receiver are 12.5 and 9 cm, respectively, from the strip. The transmitter and receiver are both positioned at 42° angles with respect to the strip (see inset).

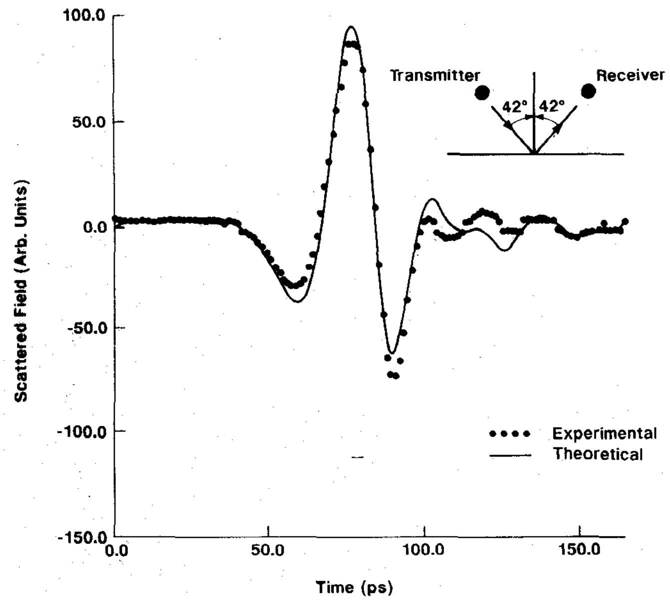

Fig. 4. Measured and computed scattered signal from two coplanar aluminum strips of 5 mm width separated by 5 mm. The points represent measured data and the line represents computed results. The transmitter and receiver are positioned as in Fig. 3.

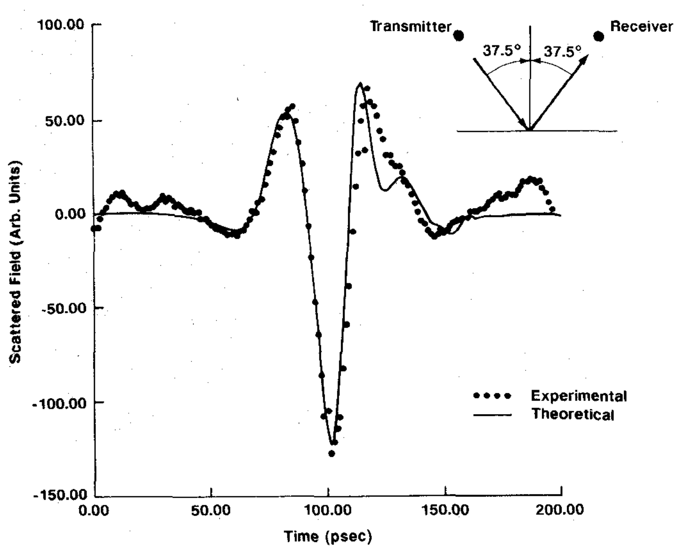

Fig. 5. Measured and computed scattered signal from a 2.5 cm diameter steel sphere. The transmitter and receiver are 7.0 and 5.5 cm, respectively, from the center of the sphere; and are separated by an angle of 75°. The points represent measured data and the line represents computed results.

however, involves the fact that in the theory a pulsed plane wave is assumed incident while in the experiments a pulsed beam is produced. In fact, the theoretical calculations for the case of the strips assume the problem is two dimensional, while in the experiment (due to the diffracting beam, which is only incident on a subsection of the strips) we clearly have three-dimensional scattering. An experiment was performed to evaluate the spatial dependence of the pulsed beam. In Fig. 6 is shown the measured waveform at different places along the beam cross section. Although the pulse is similar at the different points there is a spatial dependence to the measured waveform. It took over 1 hour to measure all the waveforms in Fig. 6. Therefore, due to drifts in the laser power, it is

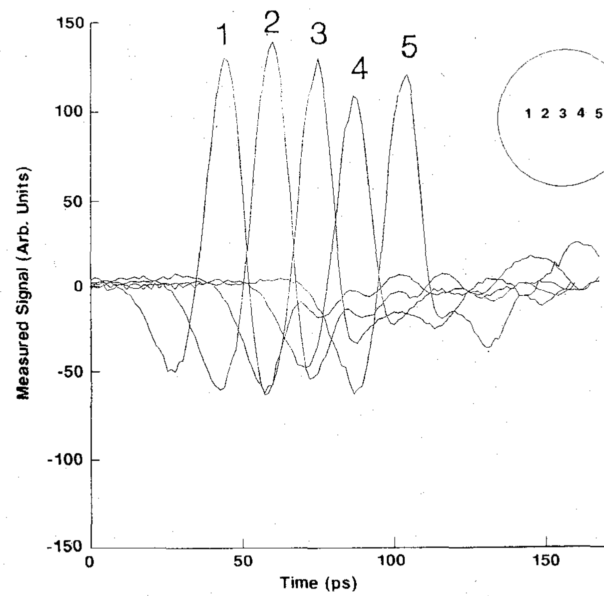

Fig. 6. Experimental characterization of the spatial dependence of the pulsed beam. The measured waveform is shown at five different positions along an axis in the beam's cross section. The distance between each sample location is 0.5 cm.

expected that the spatial variation indicated in Fig. 6 is more severe than what would be expected of a single pulse.

V. Conclusions and Required Improvements

An experimental system has been developed for performing UWB scattering measurements directly on an optical table. The UWB EM radiation was generated and detected by optically switching coplanar strip horn antennas with optical pulses generated by a picosecond laser system. The table-top scattering range was then used to study transient scattering from one and two conducting strips and from a conducting sphere. Upon comparison to theoretical results, good agreement is evident. To further characterize the scattering system, the transverse and longitudinal variation of the pulsed beam has been investigated experimentally. It was found that the pulsed beam decayed in the usual $1/r$ manner, and that the beam cross section is approximately uniform.

The facility discussed above provides a unique technique for performing ultra-wideband transient scattering measurements. The results presented here are in good agreement with theory, but this technology is still relatively new and several improvements are required so that this technique can compete with conventional scattering facilities. Some of these required improvements are discussed below.

The antennas used in this work actually produce (at least) two waveforms [4]. This is due to the fact that the optoelectronically generated current on the antenna is in the form of two pulses: one which travels initially toward the horn antenna, and the other of which travels toward the dc supply. The current pulse that travels toward the horn is partially radiated (and reflected). The other current pulse is reflected at the supply, travels down the transmission line feed, and is also subsequently radiated. The second radiated pulses can be time gated out, but the time duration between the two waveforms limits the time window over which a transient measurement can be performed. With our present antenna design, we have a usable time window of approximately 180 ps. for the low-Q targets investigated in this paper, this window is large enough to obtain good results. However, in transient scattering, often the most important information (complex resonant frequencies) is contained in the late-time response [16]. It is therefore important to develop new types of antennas which give a longer usable time window. For the antenna structure used in this work, this can be achieved easily by making the coplanar strip feed longer. It is also desirable to investigate the design of new types of antennas for short pulse transient applications.

Another shortcoming of the present facility is that the power radiated by the antennas is relatively small. The current measured by the lock-in amplifier is on the order of nanoamps. This also causes problems with regard to measuring the late-time tail since the pulse energies in the late time will be very small and highly susceptible to noise. This is largely due to the fact that most of the energy in the current optoelectronically generated pulses is in the low frequencies, and is not radiated efficiently. New types of switching techniques are required to produce high-power current pulses with peak energies at frequencies that are efficiently radiated. There has already been some progress in this direction [17].

With regard to the power, our system should be compared to a similar system developed by Grischkowsky and co-workers. In [6], a signal-to-noise ratio of $10000 : 1$ is reported. That system is similar to others [6], [7], [9], in which a lens was used on the receiver (as well as on the transmitter). For reasons discussed above, we have chosen not to use a lens on the receiver. However, in tests with a lens at the receiver, we have obtained signal-to-noise ratios of over $1000 : 1$ in the measurement of $s_1(t)$.

We are currently in the process of implementing the discussed improvements, with future work directed at studying scattering from high-Q targets. The scattering facility described in this paper is in its early stages of development, but it is felt that it has great potential for performing scaled ultra-wideband transient scattering measurements.

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