Photoconductively switched antennas for measuring target resonances

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(Received 1 November 1993; accepted for publication 18 February 1994)

Coplanar-strip horn antennas are switched photoconductively to generate picosecond bursts of freely propagating electromagnetic energy with bandwidth covering 15–75 GHz. The antennas are fabricated on GaAs grown by molecular beam epitaxy at low substrate temperatures. These antennas are used to perform transient scattering measurements from slit-coupled circular and coaxial cavities; Prony's method [IEEE Trans. Antennas Propagat. **23**, 777 (1975)] is used to extract cavity resonances from the measured late-time scattered signal.

When an electromagnetic pulse first encounters a target, specular reflection occurs from relatively flat surfaces and nonspecular reflection occurs from scattering centers such as edges, corners, bends, etc. Such specular and nonspecular reflections are usually manifested at the receiver in the form of a series of pulses and are termed the "early-time" response. After the incident pulse has interrogated the entire target, energy bounces around on its surface between scattering centers and/or within cavities inside the target, again leading at the receiver to a series of pulses. This second series of pulses produces a damped oscillatory signal, referred to as the "late-time" response, which can be expressed collectively in terms of the target's resonant modes.[1] The early-time response is difficult to use as a target signature because its characteristics depend strongly on the incident pulse shape, the angle of incidence, and the angle of observation. The late-time response, on the other hand, is characterized by unique complex resonant frequencies which are determined only by the properties of the target.[1] Thus, the late-time response is referred to as being "aspect independent" and the extracted target resonant frequencies provide a useful target signature.

In this letter we report the first use of photoconductively switched antennas for measuring the late-time resonant frequencies from targets. The measurements are performed using coplanar-strip horn antennas[2] fabricated on GaAs grown via molecular beam epitaxy (MBE) at low substrate temperature (LT-GaAs).[3,4] We have chosen to use LT-GaAs [as opposed to, for example, oxygen-bombarded silicon on sapphire[5] (SOS)] because when grown properly, LT-GaAs produces superior performance as a photoconductive substrate for picosecond applications. In particular, we have compared coplanar strip horn antennas fabricated on LT-GaAs and SOS photoconductors and have found that—for picosecond applications—antennas fabricated on LT-GaAs radiate waveforms with more than ten times greater intensity than antennas fabricated on SOS, with minimal sacrifice with regard to pulse duration (bandwidth).[6] The scattered field is usually much weaker than the incident field and therefore it is critical to radiate as strong as pulse as possible.

In our scattering measurements the antennas are separated by a 45° angle and fused silica hemispherical lenses are placed in front of the transmitting and receiving antennas; the lens on the transmitter leads to a well collimated pulsed beam and the lens on the receiver enhances the signal-to-noise ratio significantly.[7] The transmitting antenna is charged by a dc battery and the receiving antenna is connected to a current preamplifier and then to a lock-in amplifier. In the measured results presented below, both the transmitting and receiving antennas were fabricated on LT-GaAs MBE grown at 270 °C; post-growth anneals at 800 and 700 °C were applied to the LT-GaAs used for the transmitting and receiving antennas, respectively. The antennas are switched photoconductively by a continuous-wave (cw) Nd-YLF laser which is mode locked, pulse compressed, and frequency doubled to produce approximately 5 ps duration optical pulses at a 527 nm wavelength, 200 mW average power, and 76 MHz repetition rate (the pump beam, which switches the transmitting antenna, is mechanically chopped at 1 kHz). To characterize the signal generated by the transmitter, an aluminum plate is positioned such that the specularly reflected wave is directed toward the receiver, where a reference pulse is measured (Fig. 1).

The late-time scattered signal is usually very weak, so for these initial measurements we have selected targets for which the late-time response is as strong as possible. In particular, we have considered scattering from slit-coupled circular cavities (see Fig. 2). The first measurement was performed using a hollow slit-coupled cylindrical cavity which was fabricated by cutting a 15° slit along the axis of a 1.49-cm-diam (hollow) aluminum cylinder. With our antennas, we currently have a time window of approximately 300 ps which provides a resolution of 3.33 GHz in the frequency domain; the cylinder diameter was therefore selected to assure that the resonant frequencies were separated far enough in frequency such that we could measure them accurately. The horns of the transmitting and receiving antennas were positioned 15 and 13 cm, respectively, from the cylinder axis and the electric field was polarized along the cavity axis; viewing this as an idealized two-dimensional scattering problem, we expect the cavity resonant frequencies for this polarization to correspond to the cutoff frequencies of the transverse magnetic (TM) modes in a hollow circular waveguide (ignoring perturbations due to the slit).

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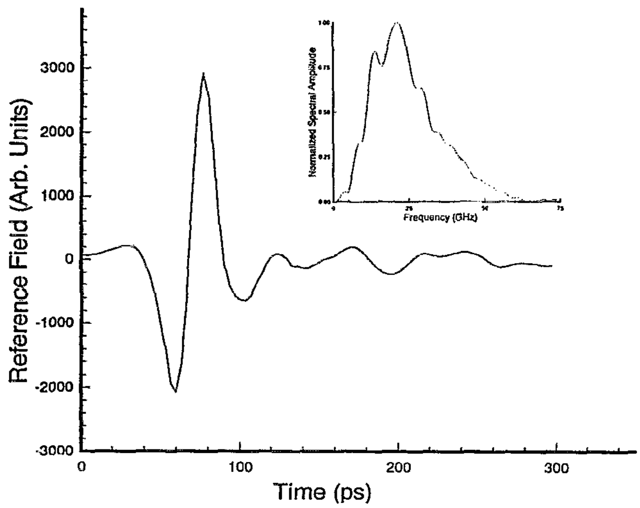

FIG. 1. Reference electromagnetic pulse measured in absence of target and its Fourier transform (inset). The small ripples after the main pulse are attributed to slight ringing in the transmitting antenna.

A typical scattered field measured from the slit-coupled hollow circular waveguide cavity is shown in Fig. 3. One sees clearly the strong early-time signal due to specular reflection from the waveguide outer surface plus nonspecular diffraction from the edges of the slit. At later times we measure the anticipated damped oscillatory waveform. To extract the resonant frequencies of the cavity from this measured late-time response, we use Prony's method.[8] This technique expresses the late-time response $f(t)$ as a sum of damped exponentials

$$f(t) \sum_{m=1}^{\infty} A_m \exp(s_m t), \quad t>0, \tag{1}$$

where $s_m = i\omega_m + \sigma_m$ and A_m represent, respectively, the complex frequency and amplitude (residue) of the mth mode. The number of resonant frequencies which can be extracted from measured data is limited by the bandwidth of the incident waveform and, because $f(t)$ is a real function, the complex resonant frequencies s_m come in complex conjugate pairs and are in the left half of the complex s plane. Prony's method is one of the simplest techniques available for resonant frequency extraction and it is well known to be highly susceptible to noise. Nevertheless, it is seen from Table I that we are able to accurately extract seven resonant frequencies from the late-time response in Fig. 3. The theoretical imaginary part of the resonant frequency ω_m in Table I was calculated in two ways: (i) From the cutoff frequencies of the TM modes in a hollow circular waveguide[9] ignoring the slit (identified as "waveguide" in Table I) and (ii) by applying Prony's method to theoretical time-domain scattering data calculated for an incident pulsed plane wave (the theoretical scattering data was calculated via the finite difference time domain[10] and the corresponding resonant frequencies are identified as FDTD in Table I). The agreement in Table I was found to be quite repeatable for several measured waveforms. The incident waveform in the measurements is a pulsed beam, and therefore the scattering problem is three

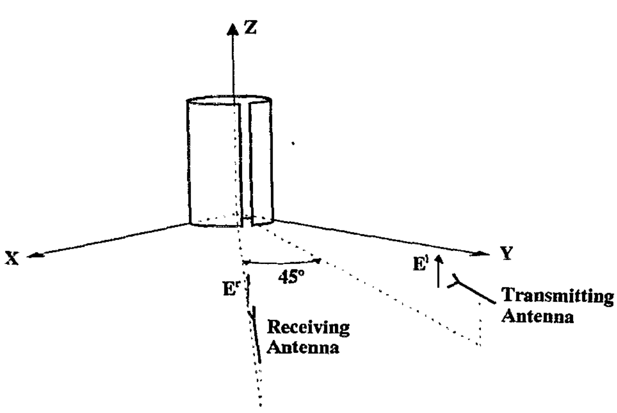

FIG. 2. Experimental setup for scattering measurements from slit-coupled cylindrical cavities. The electric field was polarized parallel to the axis of the cylinder.

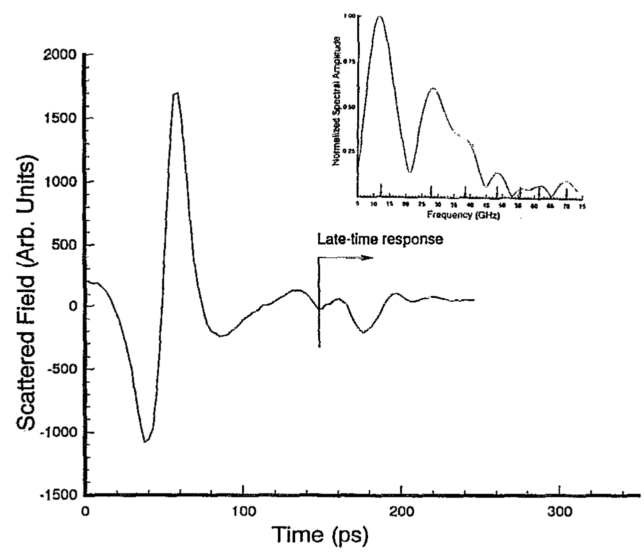

FIG. 3. Measured scattered field from a hollow aluminum cylinder of diameter 1.49 cm with a 15° slit cut parallel to the cylinder axis. The horns of the transmitting and receiving antennas were 15 and 13 cm, respectively, from the axis of the target. Inset is the Fourier transform of the (windowed) late-time data, with arrows marking the anticipated resonant frequencies (Table I). Note the transform is peaked at the predicted target resonances.

TABLE I. Measured and theoretical resonant frequencies (in units of GHz) for the slit-coupled cylindrical cavity considered in Fig. 3. The theoretical frequencies were calculated using two two-dimensional analyses: (i) Cutoff frequencies of the TM modes in a hollow circular waveguide (waveguide) and (ii) poles extracted via Prony's method from theoretical time-domain data computed from the finite difference time domain algorithm (FDTD).

Mode No.	Waveguide	FDTD	Experiment
1	16.43	16.06	18.84
2	26.12	25.96	22.51
3	37.71	38.80	36.60
4	47.91	47.18	44.58
5	57.43	54.21	57.92
6	59.02	61.89	60.81
7	69.42	68.90	68.90

dimensional; however, the resonant frequencies extracted from our measured data agree very well with frequencies calculated using two-dimensional analyses. The difference between the FDTD and the waveguide analyses is that the FDTD data take into account perturbations in the cavity resonances due to diffraction at the slit, which are unaccounted for in the waveguide data.

To further assess the accuracy of our measurements, we centered a 0.475-cm-diam aluminum rod along the axis of the slit-coupled cylinder investigated in Fig. 3, producing a slit-coupled coaxial cavity; the distance between the horns of the transmitting and receiving antennas and the axis of the coaxial target were as for the case of the hollow circular waveguide. Over the bandwidth of the incident waveform the coaxial cavity supports only two resonant TM modes compared to the seven modes in the case of the hollow cavity. We measured a scattered waveform similar to that in Fig. 3 and extracted via Prony's method two resonant frequencies, with the imaginary parts of these frequencies at 37.3 and 71.5 GHz. We were encouraged that our system was able to recognize that there were only two such frequencies, but in this case the agreement between the two-dimensional theory and experiment was not as good (both theoretical models for the resonant frequencies of the TM modes in the slit-coupled coaxial cavity predicted resonant frequencies at 29.6 and 59.1 GHz). The discrepancies between theory and experiment for this case may be due to improper alignment of the inner and outer conductors, which we expect will cause some deviation in the measured results (such alignment was obviously not needed for the hollow cavity). Nevertheless, it was encouraging that the measurements were able to differentiate clearly between the hollow and loaded (coaxial) slit-coupled circular targets.

In summary, we have presented the first results in which photoconductively switched antennas have been used for the extraction of late-time resonances from measured transient scattering data. Prony's method was applied to extract the resonant frequencies from the measured late-time response. For the case of a slit-coupled cylindrical cavity, we accurately measured seven resonant frequencies over our bandwidth. The measured results for the slit-coupled coaxial cavity were encouraging because they showed that we could distinguish between an unloaded and loaded circular-waveguide cavity, but in this case the measured resonant frequencies did not agree as well with the simple theory. We are considering now late-time resonant frequency extraction from three-dimensional targets without cavities (low-Q targets).

This work is supported in part by the National Science Foundation (NSF) under Grant No. ECS-9211353 and by the Air Force Office of Scientific Research under Grant F49620-91-1-0031. A. Rahman was supported during the summer of 1993 by the NSF-sponsored undergraduate summer-research program at Polytechnic University.

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