ULTRA-WIDEBAND CHARACTERIZATION OF LOSSY MATERIALS: SHORT-PULSE MICROWAVE MEASUREMENTS

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Abstract - Planar antennas are switched photoconductively to generate picosecond bursts of freely-propagating radiation with usable spectral amplitudes in the 5 to 85 GHz frequency range. This radiation is used to measure the frequency-dependent, complex index of refraction of dispersive materials in reflection and transmission; new deconvolution techniques are also demonstrated for extracting frequency-domain information from time-domain measurements. Experimental results are presented for the particular case of water, and a discussion is included on the relative merits of reflection and transmission time-domain measurements on materials.

I. INTRODUCTION

Over the last several years many researchers have used lasers to switch planar antennas photoconductively. Depending on the laser and antenna used, one can generate freely propagating radiation of picosecond to subpicosecond duration, with commensurate bandwidth extending from microwave to terahertz frequencies, respectively. This radiation has been used to characterize the dispersive properties of various materials [1]-[4] as well as to perform scattering measurements on several canonical targets [5]. In the work reported here we focus on the application of these short microwave pulses for ultra-wideband characterization of high-loss, dispersive materials.

Almost all previous short-pulse measurements of the dispersive properties of materials have been performed in transmission [1]-[3]. Such measurements are restricted to either low-loss materials or to high-loss substrates which are very thin. In both cases, the transmitted signal undergoes a time delay and attenuation dictated primarily by, respectively, the real and imaginary parts of the material's index of refraction. For high-loss substrates, an analysis container is obviously needed to hold the sample. The permittivity of the holder will thus affect the measurements. To avoid confusion between the permittivity of the holder (assumed known or measured in advance) and that of the liquid (unknown, to be measured), we will refer to the permittivity of the holder in terms of dielectric constant and the permittivity of the liquid in terms of index of refraction.

The remainder of this paper is organized as follow. The experimental setups for ultra-wideband reflection and transmission measurements are discussed in Sec II. In Sec. III we describe the theory for the deconvolution scheme involved in a time-domain reflection and transmission measurement of lossy materials. Experimental results are presented in Sec. IV where we compare the accuracy of the two measurement configurations. Conclusions from this work are addressed is Sec. V.

II. EXPERIMENTAL SETUP

We use a mode-locked, pulse-compressed, frequency-doubled, cw Nd-YLF laser to generate 527 nm optical pulses of approximately 5 ps duration at a 76 MHz repetition rate and 200 mW average power. These optical pulses are used to photoconductively switch coplanar-strip horn antennas which are fabricated on a silicon-on-sapphire substrate [1]. The transmitting antenna is connected to a dc battery and the receiving antenna is connected to a current pre-amplifier and then to a lock-in amplifier. The received signal is measured coherently, in a standard pump-probe fashion [1]-[6].

Our laser-antenna system is used to routinely generate and detect microwave pulses of less than 15 ps duration convolved, full-width-half-maximum (FWHM), with usable bandwidth extending from 5 to over 85 GHz. A 55 mm diameter fused silica hemispherical lens is used after the transmitting antenna to produce a pulse beam and a second identical lens is used to focus the radiation onto the receiving antenna. The use of these lenses significantly improves the signal-to-noise ratio and the lens on the transmitter also produces a pulsed beam that has a quasi-planar phase front along its axis [5]. The cross section of the pulsed beam was measured to have a diameter of approximately 3 cm [5], and all materials used in the technique was introduced [4] that determines the complex index of refraction of these materials from time-domain transmission measurements. However, the deconvolution scheme required one to perform transmission measurements for several sample thicknesses. Consequently, this increases errors due to unavoidable amplitude variations in the transmitted field caused by laser power drifts; errors due to power drifts become more severe as the data acquisition time increases. One of the purposes of this paper is to present an alternative analysis technique that does not require multiple transmission measurements and its inherent consequences.

High loss materials must be very thin such that an appreciable signal can be measured in transmission. For

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thick, lossy materials, transmission measurements are difficult and it is advantageous to perform the measurements in reflection. As will be shown, the deconvolution scheme for reflection measurements is far simpler than that for transmission measurements. However, this simplification in the deconvolution process is compensated by the need to perform very accurate measurements (due to the problems associated with amplitude fluctuations in radiation source). Since in reflection there is no time delay to be measured (as in transmission measurements), the amplitude fluctuation in the laser strongly affects the real and imaginary part of the measured complex index of refraction. Ultra-wideband reflection measurements have been performed previously on doped semiconductors, but results were given only in the form of a real reflection coefficient amplitude [6].

In this work we use photoconductively switched antennas to characterize the ultra-wideband dispersive properties of water; the measurements are first performed in reflection and then in transmission. The particular example of water is a difficult test case because both the real and imaginary part of its index of refraction are large at microwave and millimeter-wave frequencies. The deconvolution schemes and accuracy of the transmission and reflection measurements are compared. It is also explained how our deconvolution scheme for data measured in transmission is far simpler than a technique presented previously [4]. All results are compared with published data.

When performing measurements on liquids, a measurements had cross sectional areas large compared to the beam cross section (to avoid edge effects).

III. MEASUREMENT TECHNIQUE

A. Reflection

For reflection measurements a reference pulse r(t) is measured (reflection from a good reflector) and then we measure the reflected signal m(t) off a material. In our measurements, the transmitting and receiving antennas are separated by 90° (45° angle of incidence and observation). The measured impulse response for reflection from the material is therefore given, in the frequency domain, as $H(\omega)=-M(\omega)/R(\omega)$, where $M(\omega)$ and $R(\omega)$ are the Fourier transforms (calculated via a Fast Fourier Transform (FFT)) of the measured m(t) and r(t), respectively. We can express the theoretical, frequency-domain scattered-field impulse response for a semi-infinite material in terms of its (unknown) complex index of refraction $n(\omega)$. This analysis is simplified greatly by the experimentally verified assumption [5] that the problem can be treated approximately as an obliquely incident, linearly polarized plane wave. When the material under investigation is a liquid, it must obviously be placed inside a container, as shown in Fig. 1. We do not measure any multiple reflections from within the liquid, so in the theory we assume L_2 is infinite and we consider scattering from a semi-infinite "slab" of water. Equating the measured and theoretical $H(\omega)$, it can easily be shown that the material's unknown index of refraction $n(\omega)$ can be given explicitly in terms of the measured $H(\omega)$. The dielectric constant of the container walls ϵ_r is measured in transmission [1], where, as will be shown below, the accuracy is generally better than what can be obtained in reflection.

B. Transmission Measurements

As in reflection measurements, we refer to the reference measurement as r(t) (the transmission measurement with no material), and the signal transmitted through the material under test as m(t). By applying an FFT to the time-domain measurements r(t) and m(t), we again obtain $R(\omega)$ and $M(\omega)$. The measured impulse response for transmission through the material is given by $H(\omega)=[M(\omega)/R(\omega)]\exp(-jk_oT)$, where $T=2L_1+L_2$ is the total thickness of the material (water) and its container, and k_o is the free-space wavenumber. Assuming a plane wave normally incident on the face of the transmission cell, one can derive a theoretical expression for $H(\omega)$ where the complex index of refraction of the material under test is the unknown parameter. We again equate the measured and theoretical $H(\omega)$, obtaining a transcendental equation for the index of refraction. For the transmission measurements we cannot express the material's index of refraction in terms of $H(\omega)$ explicitly; the transcendental equation for the index of refraction is solved via the Muller Method. The effectiveness of our technique lies in the fact that the frequency dependent index of refraction can be determined based on frequency-domain data obtained from only one time-domain transmission measurement, whereas the technique in [4] required several transmission measurements.

IV. RESULTS

A. Reflection Measurements

If $k_oL_1\sqrt{\epsilon_r-\sin^2\theta_i}<1$, it can be shown that the reflection problem in Fig. 1 reduces to the simpler case of a semi-infinite medium with unknown index of refraction, without a dielectric slab (wall of the sample cell) present. To simplify the deconvolution, we initially used a low-dielectric-constant plastic with a thickness of less than .5 mm (leading to the simulation of a "slab" of water in free space since the container thickness is so small electrically that it can be ignored in the deconvolution). In all cases considered experimentally, the container held enough water such that there were no multiple reflections from within the water. Results are shown in Fig. 2 which compare the measured reflected signal (points) with a theoretical time-domain result using tabulated [4] values for the dispersive index of refraction over the frequency band (5-85 GHz) of our waveform. The theoretical curve was calculated by convolving a measured reference pulse r(t) with the theoretical impulse response for reflection off a semi-infinite "slab" of liquid water in free space (the results are actually computed through multiplication in the frequency domain and subsequent conversion to the time domain via a FFT). One sees that the accuracy of the measurement in the time domain is very good when compared to theory and it should be noted that this quality is very repeatable. Steam-distilled water was used in all measurements.

Unfortunately, we have found that the deconvolution scheme discussed in Sec. IIIA is not very accurate when applied to time-domain measurements such as those displayed in Fig. 2 (using a container of infinitesimal electrical thickness). The reason for these inaccuracies is easily understood. The reflection off the water is very strong at the microwave and millimeter-wave frequencies used in our measurement. Due to the large mismatch between the water and free space, the reflection is very large. For a material with such a high index of refraction, it is difficult to obtain the fidelity in the time domain needed to obtain accurate frequency-domain results. Essentially, since the water is so reflective at microwave frequencies, it is difficult to distinguish its experimentally measured reflected signal from what would be measured from any other good reflector (such as a good metal conductor). To make such distinctions, the tolerances needed with regard to the accurate measurement of the reflected amplitudes in the time-domain waveform are beyond what is achievable in our setup.

We have used a very simple technique to overcome this problem. Instead of using a very thin, low dielectric-constant container to simplify the deconvolution, we use a relatively thick, high-dielectric constant material for the container. The dielectric constant of the container is selected such that it is between that of free space and that of water. In our case, we used a container with 2.78 mm thick walls and a dielectric constant $\epsilon_r=6.29$. The dielectric constant was measured in transmission [1] to be nearly dispersionless over the frequency band of interest, with negligible loss. By using this container, there is not such a large mismatch between the material under test (the water) and the immediate surrounding environment (the container). There is of course a trade off in that there is now a reflection at the air-dielectric interface, which reduces the signal that hits the water. However, in our tests so far we have not found this to be a significant problem.

We next performed a measurement similar to that considered in Fig. 2 except now we used a 2.78 mm thick dielectric container of $\epsilon_r=6.29$ in front of the water. In the time domain, the agreement between the theory and experiment was found to be similar to that found in Fig. 2. However, as will be shown below, the frequency domain results from these new measurements can be used to accurately measure the frequency-dependent, complex index of refraction of water while this was not possible using time-domain results such as those in Fig. 2. A typical frequency-domain result is shown in Fig. 3. Notice that the real part of the index of refraction agrees very well with previous results [4]. The general shape of the imaginary part of the index of refraction agrees with previous results, but it is slightly smaller. This type of agreement was not possible using measured results such as those in Fig. 2, even though agreement in the time domain appears to be quite good. The type of agreement shown in the frequency domain plot of Fig. 3 is typical and is very repeatable, and it shows that a simple technique can be used to accurately measure the frequency-dependent properties of high-loss materials in reflection. Note that in reflection our results were only good to about 60 GHz.

B. Transmission Measurements

The measurement of the complex index of refraction of materials with high loss requires very thin substrates. It was necessary to perform transmission measurements with water samples of .495 mm thickness in order to measure a usable signal (for this thickness, the peak transmitted amplitude was approximately nine times smaller than that of the reference). It was necessary that all detectable multiple reflections between the walls of the container and the sample occurred within our time window (200 ps). In this way we avoid introducing frequency-domain errors caused when a FFT is applied to an incomplete time-domain signal. In order to minimize this error, the walls of the water container were designed such their electrical length was short. For this purpose 1.5 mm plexiglass was used. The dielectric constant of the plexiglass was characterized in transmission [1], and was determined to be nearly lossless and dispersionless over the pulse bandwidth, with $\epsilon_r=2.4$.

The real and imaginary part of the index of refraction calculated from measured transmission data for water are displayed in Fig. 4. We see in Fig. 4 that the agreement between results reported by other methods [4], and the experimental values are very good. We observe that the results differ a little at the low end of the spectrum. This error is associated with the fact that wavelengths at these frequencies are too large for the lenses to provide proper collimation and focusing. However, at the high end we have much better agreement than what was obtained for reflection. Furthermore, transmission measurements yield good results up to 85 GHz rather than just 60 GHz for reflection measurements. As a practical issue, it should be noted that the solution for the complex index of refraction was found to be relatively independent of the starting point for the Muller Method.

V. CONCLUSIONS

Reflection and transmission techniques have been presented for the ultra-wideband measurement of the dispersive properties of high-loss materials, with results presented for the particular case of water. We have shown that the frequency-domain results from transmission measurements are generally of better accuracy than reflection measurements, although reflection measurements are required for thick lossy samples. We also obtained good results over a significantly wider bandwidth in transmission than were obtained in reflection. Additionally, our deconvolution scheme for transmission measurements is far simpler than that developed previously, and it yields very accurate results.

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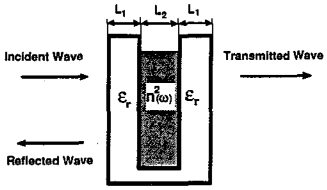


Figure 1. Material with unknown index of refraction n(ω) (dielectric constant $n^2(\omega)$) in a container of known dielectric constant ϵ_r. The container has walls of thickness L_1 and holds material of thickness L_2. For reflection measurements L_2 is made thick enough such that, during the usable time window (200 ps) of the measurements, no multiple reflections are measured from within the material under test.

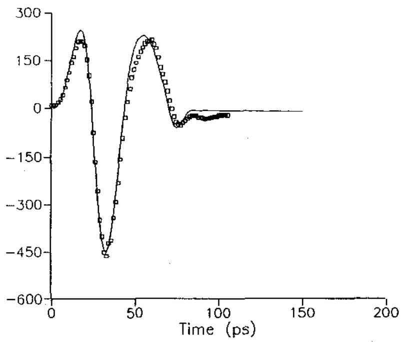
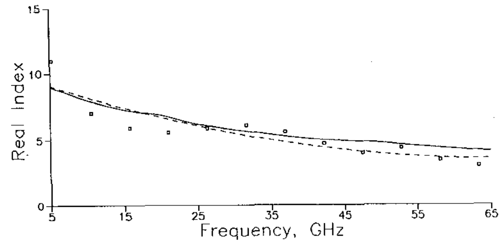


Figure 2. Measured (points) and computed (curve) reflected waveform from steam-distilled water inside a container that has walls of infinitesimal electrical thickness over the bandwidth of the incident waveform ($L_1/\lambda < 1$ over the 5-85 GHz bandwidth, where λ is the wavelength in the container walls). The curve was computed using tabulated values for the index of refraction of water [4] over the pulse bandwidth, and using a measured reference pulse as the incident waveform.



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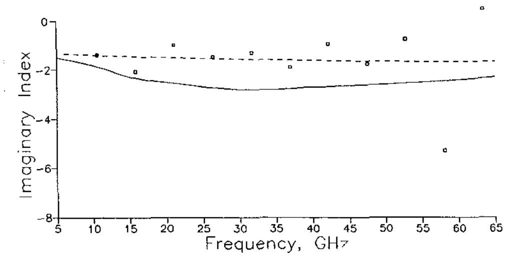
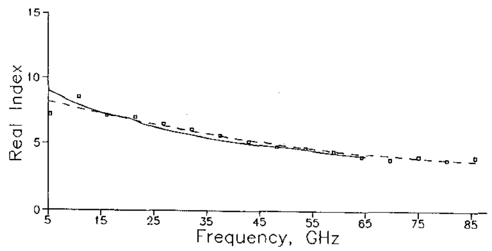


(b)

Figure 3. Measured (points) complex index of refraction for water calculated from measured time-domain reflection data. The solid line represents the results in [4] and the dashed line is a best-fit curve of our results. (a) Real part, (b) Imaginary part



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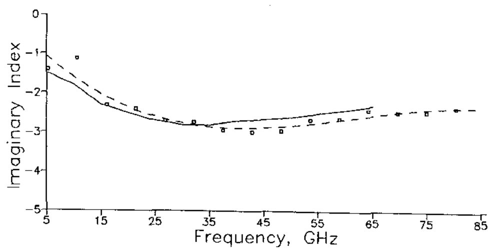

(b)

Figure 4. Measured (points) complex index of refraction for water computed from measured time-domain transmission data. The solid line represents the results in [4] and the dashed line is a best-fit curve of our results. (a) Real part, (b) Imaginary part