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Dana M. Hughes

R. Zoughi
Missouri University of Science and Technology, zoughi@mst.edu

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A Method for Evaluating the Dielectric Properties of Composites Using a Combined Embedded Modulated Scattering and Near-Field Microwave Nondestructive Testing Technique

Dana Hughes and Reza Zoughi
Department of Electrical and Computer Engineering
University of Missouri – Rolla
Rolla, MO 65401 USA
Phone +1 573 341-4728 Fax +1 573 341-4532
E-Mail: zoughi@ece.umr.edu, URL: http://www.ece.umr.edu

Abstract ***– Investigation into the derivation of the dielectric property of a material with an embedded modulated PIN diode-loaded dipole is described, using an open-ended rectangular waveguide as the irradiating source. Previous measurements of the curing of a mortar specimen show the sensitivity of this combined technique and its potential for inspecting composite structures. Modification of previous algorithms for back calculating the dielectric properties of a material with a conductor backing is considered. The modification would involve replacing the reflection at the conductor with the reflection at a modulated dipole antenna. For this, comparisons between the reflection coefficients of dipole antenna and an infinite conducting plate are made. These results are analyzed, and the necessary considerations are discussed.***

I. INTRODUCTION

Evaluation of the dielectric properties of composite materials is of great interest in various industries. There are several applications that benefit from such evaluation, including:

- resin cure monitoring in composite manufacturing,
- cure monitoring in cement-based structures,
- detection and evaluation of chloride ingress in concrete,
- detection and evaluation of impact damage severity in composites, and
- detection and evaluation of disbond and delamination in thick sandwich composites.

For the above applications, the measured dielectric properties (at microwave frequencies) of a material are correlated to the presence of a defect (e.g. disbond), the cure state of a resin, or the gradual ingress of foreign materials (e.g. chloride). Also, changes in a material due to damage or curing are generally subtle at the onset of the change, and become pronounced only after severe damage has been caused or curing has been completed. Therefore, a sensitive nondestructive testing and evaluation approach would be beneficial for these applications.

Microwave nondestructive testing (NDT) techniques have already shown great potential for evaluating non-conducting (i.e. insulating or dielectric) materials [1]. Microwave NDT techniques have also been used to accurately measure the thickness of various composites and ceramics [2], as well as detecting the presence of local voids and evaluating distributed porosity in dielectric mixtures consisting of several constituents [3,4]. Recently, investigations have also demonstrated the capability of microwaves to detect the state and degree of curing in several different materials in which curing takes place [5-8].

II. BACKGROUND

Modulated scattering techniques are based upon measuring the backscattered signal generated from a reflector, which is illuminated by a plane (far field) or spherical (near field) wave at microwave frequencies. The measured reflected signal can then be used to reconstruct the electric field anywhere in space, including the space between the reflector and the illuminating source [9].

For the purpose of near field microwave measurements, the reflector used is a PIN diode-loaded dipole antenna, whose length is $\lambda/2$ (resonant) in the material in which it is embedded. The PIN diode is then modulated with alternating forward and reverse biased voltages (i.e. a pulse train) at a very low frequency (0.5 Hz to a few Hz) known as the modulation frequency. When the diode is forward biased, it acts as a near short resistive impedance, thus the dipole is connected to a near short. When the diode is reverse biased, it presents high reactive impedance, and the dipole is connected to a near open in this case. The resulting backscattered signal is modulated between two different reflections, one from the short circuited dipole, and one from the open circuited dipole. The near-field measurements were conducted using an open-ended rectangular waveguide, at various fixed frequencies, in conjunction with an HP8510B vector network analyzer.

There are several advantages in using modulated scattering techniques in conjunction with near-field microwave measurements using open-ended rectangular waveguides. These include high signal-to-noise/clutter ratio, high sensitivity of microwave signals to material changes particularly curing, and the fact there is no need for accurate knowledge of the location of the dipole within a material. Preliminary investigations using this combined technique have shown great potential for evaluating the dielectric properties of several diverse materials [10-11].

III. SAMPLE RESULTS

To demonstrate the potential of this technique, an 8" x 8" x 8" mortar specimen with water-to-cement ratio of 0.5 and sand-to-cement ratio of 1.5 was produced. The specimen was allowed to cure for one day in a hydration room, and was then in ambient temperature and low humidity thereafter. Two PIN diode-loaded dipoles, both resonant at 5 GHz in mortar, were embedded in the specimen, one at about 1.3 cm from the surface, and the other at about 2.6 cm from the surface. The use of two probes at different depths facilitates the calculation of the reflection properties of the probe, and provides a means for factoring this out from the dielectric property calculations. This experiment demonstrated the sensitivity of resonant dipole probes to the curing of mortar. These measurements were conducted using an open-ended rectangular waveguide in contact with the surface of the specimen, and an HP8510 vector network analyzer.

The measurements produced two distinct reflection coefficients, one for when the dipole was shorted, and another from when the dipole was open, as shownin Fig. 1. The overall reflection coefficient was though to consist of the combination of a static reflection from the surface of the block, and a dynamic reflection from the modulated dipole. The static reflection was removed by coherently subtracting the average reflection between the two points. This produced two points that were 180° out of phase, centered on the origin. The magnitude and phase of dynamic reflection coefficient were then taken as those of one of the points.

The dynamic reflection coefficient from the probe was measured daily for the first 28 days of curing. Fig. 2a and Fig. 2b show the magnitude and phase of the dynamic reflection coefficient from these two dipoles as a function of curing time (days). It is known that as the specimen cures, some of its free water evaporates and some becomes bound to cement through a hydration process [7]. Clearly, the effect of loss of free water through hydration and evaporation can clearly be seen through the temporal increase in the magnitude of dynamic reflection coefficients. The consistent difference in magnitude and phase between the two dipoles is directly related to the difference in depths of the two probes.

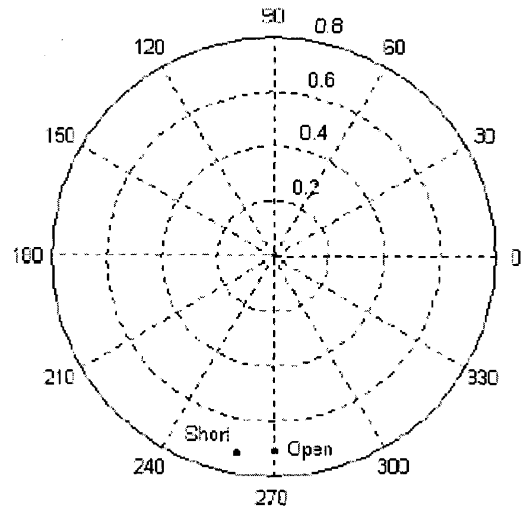

Fig. 1. Polar representation of measured reflection coefficient from modulated dipole embedded in mortar sample.

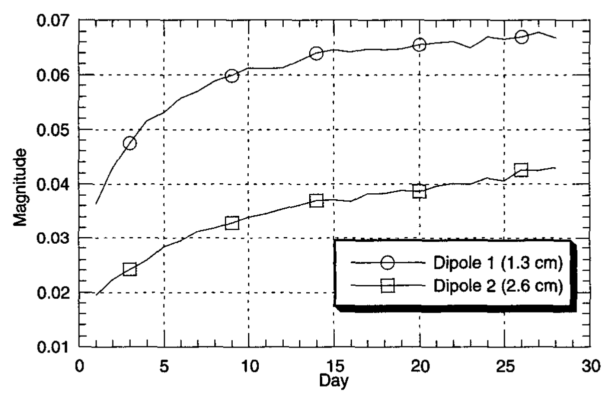

Fig. 2a. Magnitude of dynamic reflection coefficient from the dipole probes. Dipole 1 was 1.3 cm below the surface of the block, and Dipole 2 was 2.6 cm below the surface of the block.

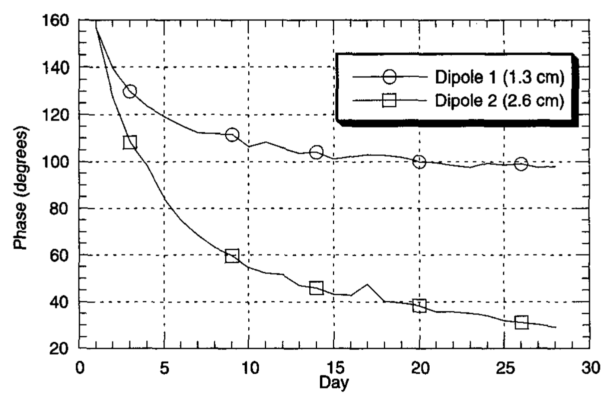

Fig. 2b. Phase of dynamic reflection coefficient from the dipole probes. Dipole 1 was 1.3 cm below the surface of the block, and Dipole 2 was 2.6 cm below the surface of the block.

IV. MODELING APPROACTH

While the sensitivity of modulated scattering technique has been shown, it is necessary to model the interaction of the probe with the waveguide aperture in order to calculate the dielectric properties of the material being tested. For this purpose, measurements were made at 10 GHz, with an HP8510B vector network analyzer, in air. The dipole probes used were 3 cm in length ($\lambda/2$ in free-space).

Since the measurements were performed in the near field of an open-ended waveguide, it was not possible to assume plane wave propagation. Thus, the potential for modification of previous code generated in the Applied Microwave Nondestructive Testing Laboratory (*amntl*) was investigated [2,12]. The codes in references 2 and 12 back calculate the dielectric constant of a material from reflection coefficients measured using open-ended rectangular waveguides. Reference [2] assumes the material to have a conducting back plate, while reference [12] assumes an infinite half space. These algorithms will be modified to include the presence of a modulating dipole probe. However, before this can be done, the relation between the dipole probe and the conducting plate need to be considered.

Measurements were first performed on the reflection from a dipole in free-space as a function of distance away from the waveguide aperture. The magnitude and phase of reflection coefficient for both the forward and reverse biased cases are shown in Fig. 3a and Fig. 3b. The effects of multiple reflections between the waveguide and dipole can clearly be seen, as well as a consistent attenuation in the signal due to the distance increase between the dipole and the waveguide aperture.

The mounting used to position the dipole in front of the waveguide was then measured without the presence of the dipole. While very small in magnitude in comparison to the dipole, the mounting produced a similar signal to that in Fig. 3a. Thus, while small, the mounting affected the measurements in Fig. 3a and Fig. 3b. To compensate for this, this signal was coherently subtracted from the measurements. This subtraction also removed static reflection at the aperture of the waveguide. The remaining signal displayed only the interaction between the dipole and the waveguide aperture. The magnitude and phase can be seen in Fig. 4a and 4b.

In order to investigate the feasibility of modifying the above-mentioned models in reference [2] and reference [12], similar measurements were performed on a conducting plate. Unlike the measurements with the dipole, the mounting did not show significant impact on the measurements. Consequently, for comparison, only the reflection of the waveguide into air was coherently subtracted from the measured signal.

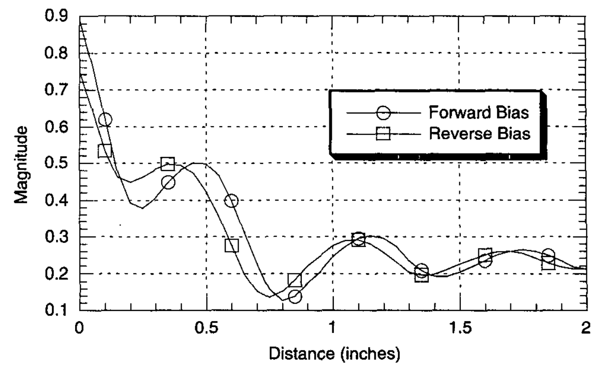

Fig. 3a. Magnitude of reflection coefficient of the forward and reverse biased PIN diode-loaded modulated dipole. The signals include multiple reflections between the waveguide and dipole.

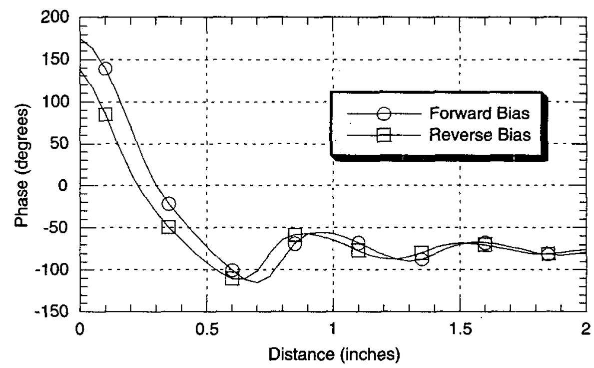

Fig. 3b. Phase of reflection coefficient of the forward and reverse biased PIN diode-loaded modulated dipole. The signals include multiple reflections between the waveguide and dipole.

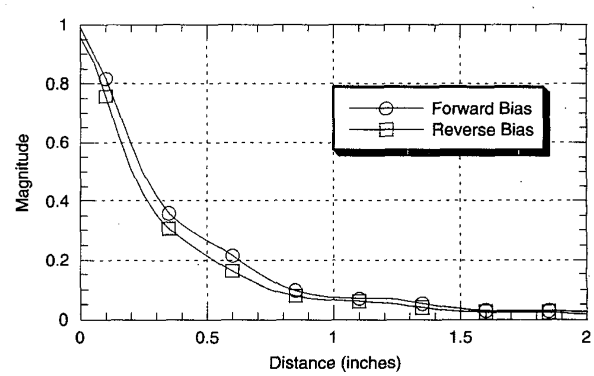

Fig. 4a. Magnitude of reflection coefficient of the forward and reverse biased PIN diode-loaded modulated dipole. The signals have the reflection from the waveguide coherently removed.

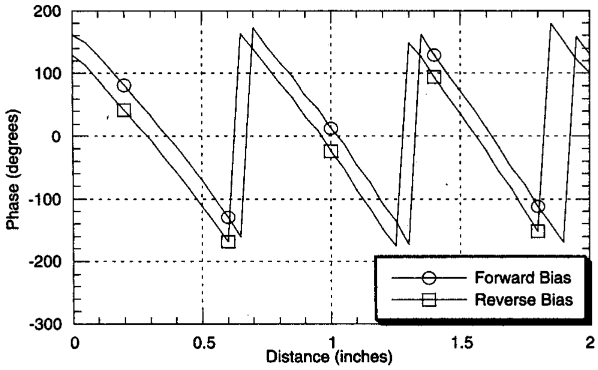

Fig. 4b. Phase of reflection coefficient of the forward and reverse biased PIN diode-loaded modulated dipole. The signals have the reflection from the waveguide coherently removed.

The magnitude of the measured reflection coefficient from a metal plate, without the waveguide reflection removed, is shown in Fig. 5a. The magnitude shows the effects of multiple reflections, similar to the dipole. However, this signal is attenuated much less, due to the larger extent of the metal plate. The phase of the signal, shown in Fig. 5b, does not appear to relate to that of the dipole.

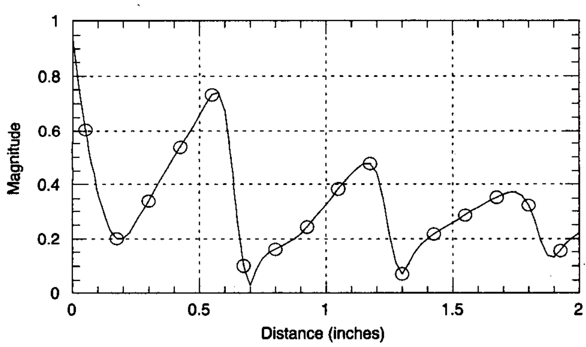

Fig. 5a. Magnitude of reflection coefficient of a metal plate as a function of distance. The signals include multiple reflections between the waveguide and plate.

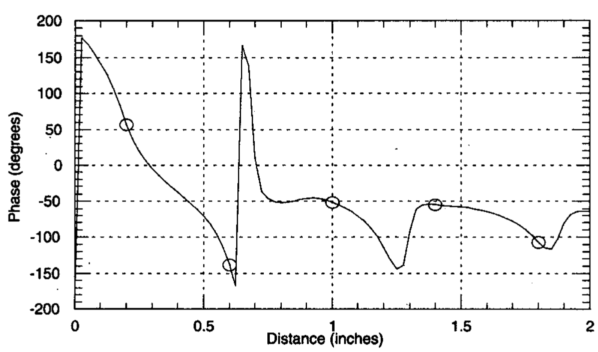

Fig. 5b. Phase of reflection coefficient of a metal plate as a function of distance. The signals include multiple reflections between the waveguide and plate.

The effect of the presence of the waveguide was then removed by coherently subtracting the measured reflection coefficient of the waveguide in air. As mentioned earlier, the mounting for the metal plate displayed no effect on the measured signal, and was thus not considered. The magnitude of the reflection coefficient without the presence of the waveguide is shown in Fig. 6a. Although the potential for multiple reflections was thought to be removed, there still remains a periodic hump in the signal. However, despite these, the results resemble those from the dipole measurements. The corresponding corrected phase signal is shown in Fig. 6b. As with the dipole, a distinct linear phase is present, which corresponds well with that of the dipole.

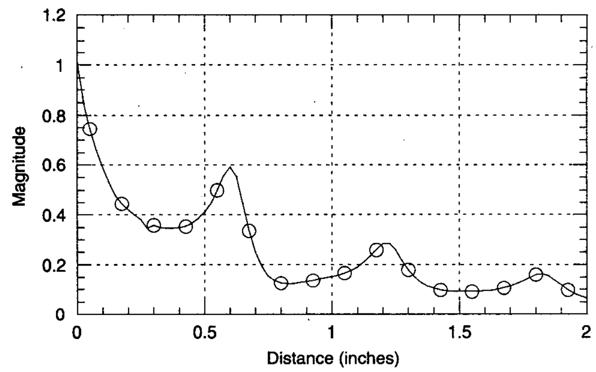

Fig. 6a. Magnitude of reflection coefficient of a metal plate as a function of distance. The signal has the reflection from the waveguide coherently removed.

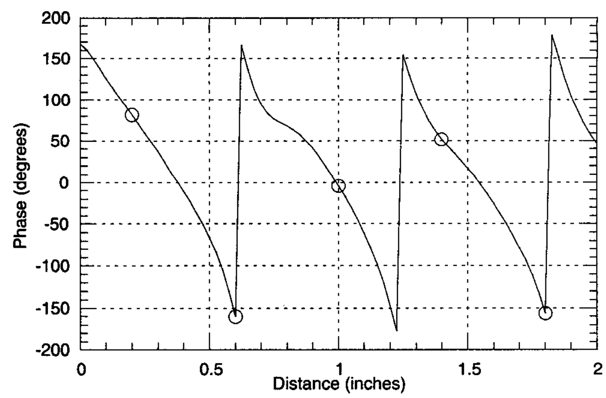

Fig. 6b. Phase of reflection coefficient of a metal plate as a function of distance. The signal has the reflection from the waveguide coherently removed.

V. ANALYSIS

Due to the similarities of the corrected reflection coefficients of the dipole and metal plate, it appears that the potential for modifying the algorithms mentioned in the references is quite high. The corrected magnitude of reflection coefficient for the metal plate still contains humps, which are not present in the dipole signal. This is possible due to the increased reflection from the metal plate. It is clear that the effect of multiple reflections between the waveguide and the plate is much more pronounced than that for the dipole. It may be that, while removing the reflection from the waveguide corrected the reflection coefficient for the dipole, it may not be sufficient for the metal plate. However, assuming this to be the case, similarities between the dipole and the metal plate can be made. The magnitude of reflection coefficient for the metal plate will still need to be adjusted to account for the increased attenuation as a function of distance for the dipole.

The phase of reflection coefficient, after corrections, shows an almost distinct match for a metal plate and a modulated dipole. Also, the linear quality of both measurements shows that the phase is dependent only on distance from the waveguide and the phase constant of the material.

It seems that the reflection from a dipole and a metal plate correlate enough to allow for the modification of the algorithms previously mentioned to accommodate a modulated scattering technique for calculation of dielectric properties of a material.

CONCLUSION

Modulated scattering technique, in conjunction with near-field microwave nondestructive testing techniques, has shown to produce high sensitivity to changes in dielectric properties in a material. Modeling of an embedded dipole probe by modification of previous code is suggested. To this end, comparisons between the reflection of a dipole and a conducting plate were made. The high correlation between these two suggests that modifying the aforementioned code to be viable.

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