01 May 2005

Dielectric Material Characterization by Complex Ratio of Embedded Modulated Scatterer Technique States

Gabriel S. Freiburger

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

IMTC 2005 – Instrumentation and Measurement
Technology Conference
Ottawa, Canada, 17-19 May 2005

Dielectric Material Characterization by Complex Ratio of Embedded Modulated Scatterer Technique States

G. Freiburger and R. Zoughi
Applied Microwave Nondestructive Testing Laboratory (*amntl*)
Electrical and Computer Engineering Department, University of Missouri-Rolla, Rolla, MO 65409 USA
Phone: +1 573 341-4728, Fax: +1 573 341-4532
Email: zoughi@ece.umr.edu, URL: http://www.ece.umr.edu/amntl

Abstract *– The embedded modulated scatterer technique (MST) is an innovative tool which can be used for microwave dielectric characterization of infrastructure and composite structures. By impinging a microwave signal on a loaded thin dipole antenna embedded in a material whose dielectric properties are sought, the resulting reflection data can be used to inversely solve for the dielectric properties of interest. Previous investigations utilized reflection information from a single loaded dipole and required known system parameters, such as radiator polarization vs. dipole alignment and relative distance between radiator and probe, to solve for the sought-for dielectric properties. This paper explores a unique application of embedded MST in which the ratio of the reflection coefficients for two independent states of a PIN diode-loaded dipole probe is utilized to significantly simplify the method for calculating dielectric properties.*

Keywords *– modulated scatterer technique, dielectric characterization, embedded sensors, nondestructive testing*

I. INTRODUCTION

Cement-based infrastructure, newly designed and manufactured composite structures, and composite retrofitted infrastructure are constantly subjected to loads and loading cycles beyond their design limitations and lifetimes. Moreover, long-term environmental stresses (such as exposure to freeze thaw cycles, chloride ion ingress, seismic events, etc.) result in additional and significant degradation of these structures. Nondestructive inspection (NDI) of complex and varied infrastructure, including those employing composite components, for the purpose of process-control and health monitoring is continuously receiving more attention. The embedded modulated scatterer technique (MST) is an innovative NDI technique for microwave dielectric characterization of infrastructure and composite structures [1-2]. Subsequently, dielectric properties of the material may be correlated to physical, chemical, and mechanical properties. To employ this technique, a PIN diode-loaded dipole antenna, embedded in a material whose dielectric properties are sought, is illuminated with a plane (far-field) or spherical (near-field) wave at microwave frequencies [3]. The PIN diode is connected to a simple modulation circuit that provides an alternating bias voltage across the diode. This forward or reverse bias causes the impedance of the PIN diode to alternate between two states, namely *high* and *low* states producing corresponding impedances of Z_{high} and Z_{low}, respectively. These two impedances are determined by the solid state properties of the particular PIN diode used and its packaging characteristics, the frequency of operation, and the modulation biasing voltage and current. The PIN diode ideally acts like a short circuit when forward biased and like an open circuit when reversed biased. Consequently, once a wave is incident upon the dipole, the reflected wave from it will also be modulated by its reflection coefficient which is directly related to its impedance and the impedance of the PIN diode, and hence to the modulation rate. The measured reflected or scattered field from the dipole can then be used to reconstruct the electric field anywhere in space, including the space in between the dipole and the illuminating source [3-5]. Figure 1 shows the schematic of an embedded PIN diode-loaded dipole antenna in a material with a relative complex dielectric constant of ε_r, while an incident electric field, produced by an open-ended rectangular waveguide aperture.

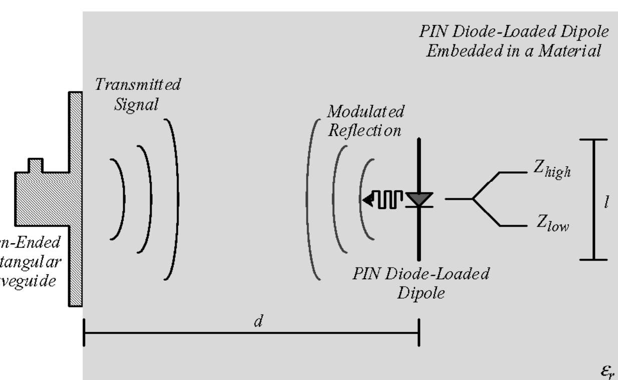

Fig 1. Schematic of an embedded MST probe irradiated by an open-ended rectangular waveguide.

The PIN diode impedances, corresponding to the two states, do not change as a function of the dielectric properties of the material in which the MST probe is embedded. However, the radiation impedance of the dipole antenna is directly and strongly influenced by the complex dielectric properties of the material in which it is embedded [2]. Thus, the reflected signal can then be used for material

0-7803-8879-8/05/$20.00 ©2005 IEEE

characterization, anomaly (disbond and delamination) detection, detection of excessive microcracking (porosity), etc [2,4,6-7]. In addition, the MST probe can be strategically embedded in a critical region of a material or a composite, and a number of MST probes can be dispersed in a structure during construction enabling the inspection of a large area of the structure. Previously, reflection information from one of the two states was used to inversely evaluate the dielectric properties of the material in which the probe was embedded, where the distance from the probe to the radiator and radiator polarization vs. dipole alignment were explicitly taken into account [1-2]. However, with reflected signal from two independent states of the PIN diode available, their complex ratio can be used to effectively eliminate the need to know the exact distance between the radiating source and the MST probe (e.g., the PIN diode-loaded dipole) and the relative orientation between the radiating source electric field polarization vector and the primary axis of the MST dipole. The complex ratio of the reflection coefficients from two states of a PIN diode-loaded dipole probe provides for a significantly simpler and more robust measurement approach than that used previously for evaluating the dielectric properties of the material in which the dipole is embedded [1-2].

II. THEORETICAL APPROACH

A. Ratio Derivation

The following symbolic expression is used to demonstrate the relationship between the incident and reflected electric fields for a loaded dipole probe as a function of all measurement parameters:

$$E_r = C_o e^{-2\gamma(\varepsilon_r)d}\Gamma(Z_{load}, Z_{dipole}(l, f, \varepsilon_r))E_i\,. \qquad (1)$$

In this expression, C_o is a complex constant representing the portion of the incident field coupled into the probe. The exponential term represents wave propagation and attenuation. In addition, the reflection coefficient Γ is a function of the dipole load impedance Z_{load} and the impedance of the unloaded dipole Z_{dipole}. The dipole input impedance Z_{dipole} is itself a function of the dipole length l, the frequency of operation f, and the relative dielectric constant of the material ε_r. In a measurement system such as the one shown in Fig. 1, C_o accounts for the polarization of the probe relative to that of the radiator, and d represents the distance between the probe and radiator. In previous investigations utilizing a single load, it was therefore necessary to explicitly consider each of these dipole orientation parameters when solving for the relative dielectric constant of the material using Equation (1). However, if the dipole load can be changed (i.e. by modulating a PIN diode load), reflection measurements can be taken for two states while the dipole location and orientation parameters remain the same. By utilizing two different load values, Z_{high} and Z_{low}, a ratio can be made from the two states to form the following expression:

$$\frac{E_{r,high}}{E_{r,low}} = \frac{\Gamma_{high}(Z_{high}, Z_{Dipole}(l, f, \varepsilon_r))}{\Gamma_{low}(Z_{low}, Z_{Dipole}(l, f, \varepsilon_r))}\,. \qquad (2)$$

The C_o, E_i, and $e^{-2\gamma(\varepsilon_r)d}$ terms, which are identical in both states, cancel out to leave a complex ratio independent of the orientation of the dipole and distance between the dipole probe and radiator. With known load impedances, Z_{high} and Z_{low}, dipole length l, and frequency of operation f, the only unknown remains to be the relative permittivity. Therefore, for an experimentally determined complex ratio of reflection coefficients, an inverse formulation can then be utilized to determine the unknown ε_r.

B. Theoretical Model

To model a measurement system which utilizes an open-ended waveguide radiator such as in Fig. 1, a two-port impedance network model can effectively be used. In Equation (2), reflection coefficients for each state of the loaded dipole probe are assumed to be the effect of the MST probe only. However, when utilizing a rectangular waveguide radiator, the reflection coefficient measured at the aperture of the waveguide will also include the effect of mutual coupling between the two antennas. In an impedance network model, the coupling between the waveguide aperture and the dipole probe can be represented as an effective mutual impedance Z_{12}. For linear materials, the mutual impedances are reciprocal ($Z_{12} = Z_{21}$). The input impedance of the waveguide is represented as Z_{11}, while the input impedance of the unloaded dipole probe is expressed as Z_{22}. The term Z_L represents the impedance of the load on the dipole, as shown in Fig. 2:

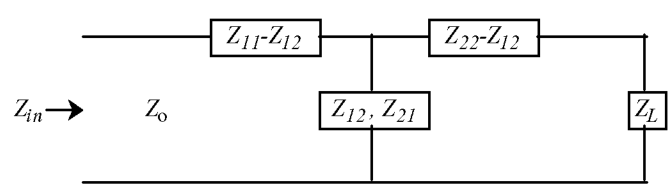

Fig 2. Two port network circuit model for a waveguide and loaded dipole probe system.

By modeling the antennas and mutual coupling as impedances, the system can be evaluated by simple circuit analysis. The impedance Z_{in} seen at the aperture of the waveguide can be found and used to solve for the reflection coefficient of the system with a particular load impedance Z_L. The reflection coefficients at the aperture of the waveguide for load impedances Z_{high} and Z_{low} can be expressed as:

$$\Gamma_{high} = \frac{Z_{in,high} - Z_o}{Z_{in,high} + Z_o} \quad (3)$$

$$\Gamma_{low} = \frac{Z_{in,low} - Z_o}{Z_{in,low} + Z_o}. \quad (4)$$

In addition, the measured reflection coefficient at the aperture will contain a static reflection, Γ_{static}, composed of the reflection of the aperture/air interface. Since this reflection is coherently added in each state, static reflection does not cancel out and therefore must be subtracted from each reflection coefficient measurement. Once properly subtracted from each state, the complex ratio of Equation (2) is obtained. The effect of mutual coupling is significantly reduced with the increasing relative distance between the radiating source and the loaded dipole. The mutual interaction therefore can be assumed negligible at some distance. The limit at which the effect of mutual impedance Z_{12} decreases, reduces this ratio to:

$$\lim_{Z_{21}\to 0} \frac{\Gamma_{high} - \Gamma_{static}}{\Gamma_{low} - \Gamma_{static}} = \frac{Z_{22} + Z_{L,high}}{Z_{22} + Z_{L,low}}. \quad (5)$$

After a distance at which the effect of mutual impedance was negligible, the complex ratio of reflection coefficient is shown to converge to a constant value.

III. EXPERIMENTAL RESULTS

To demonstrate the validity of the ratio measurements, as described above, reflection coefficient data was collected using an S-band rectangular waveguide in conjunction with an HP8510C vector network analyzer. Both the waveguide and PIN diode-loaded dipole probe were contained in an anechoic chamber to minimize the effects of unwanted reflections. Any present undesired reflections were then accounted for by coherently subtracting the static reflection, Γ_{static}, composed of both the reflection of the waveguide aperture/air interface and other environmental reflections, leaving only reflection due to the dipole probe. This static reflection was easily measured in the absence of the dipole probe. The measured magnitude and phase of reflection coefficient, at 3 GHz, for a PIN diode-loaded dipole in air with static reflections coherently subtracted are shown in Figs. 3 and 4 as a function of increasing distance between the waveguide and probe (i.e., d in Fig. 1). Both the magnitude and phase of the complex ratio are also in these figures indicating their convergence to a constant value, as expected. The oscillation in the magnitude is directly related to the influence of the mutual interaction between the radiating open-ended waveguide aperture and the loaded dipole.

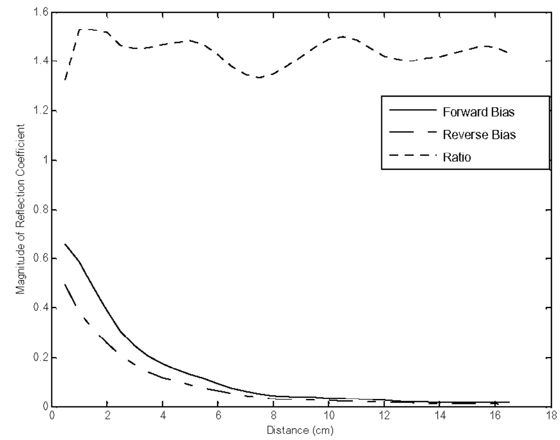

Fig 3. Magnitude of reflection coefficient for PIN diode at 3 GHz as a function of distance.

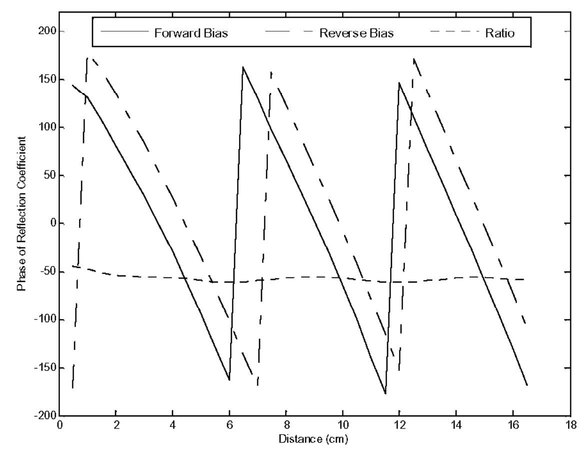

Fig 4. Phase of reflection coefficient for PIN diode at 3 GHz as a function of distance.

Additional experiments were also conducted in which the influence of the relative rotation angle between the radiating electric field polarization and the dipole primary axis was investigated. Figure 5 shows the schematic of the orientation angle between these two parameters. In these experiments, the dipole probe was fixed in a plane parallel to the waveguide aperture at a fixed distance of 16 cm while the orientation angle was changed. Figure 6 shows the magnitudes of the two states, while Fig. 7 shows their ratio. In addition, Fig. 8 shows the phases of the two states of the dipole probe, while Fig. 9 indicates their difference (i.e., complex phase ratio).

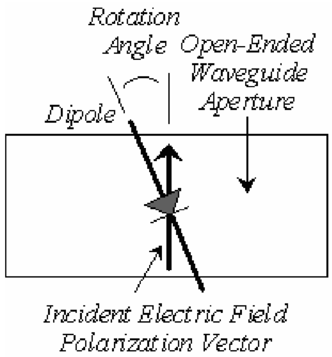

Fig 5. Schematic of the relative angle (i.e., rotation angle) between the radiating electric field polarization and the dipole primary axis.

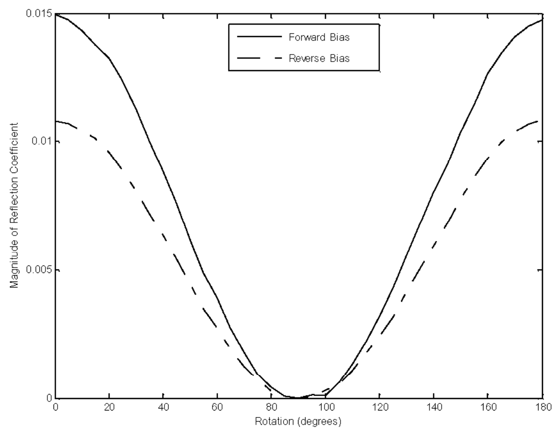

Fig 6. Magnitude of reflection coefficient for PIN diode at 3 GHz as a function of polarization angle.

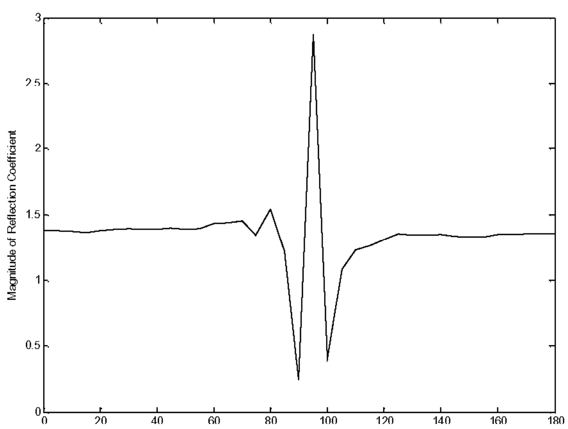

Fig 7. Magnitude of complex ratio for PIN diode at 3 GHz as a function of polarization angle.

As the probe is rotated near ninety degrees, the probe becomes perpendicular to the radiating electric field polarization. For this reason, reflection data near ninety degrees does not accurately reflect the complex ratio of interest. However, as expected, the complex ratio as a function of polarization angle matches that seen as a function of distance (i.e., remaining constant).

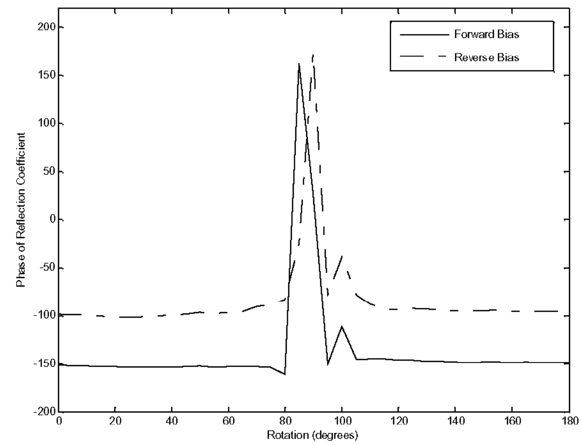

Fig 8. Phase of reflection coefficient for PIN diode at 3 GHz as a function of polarization angle.

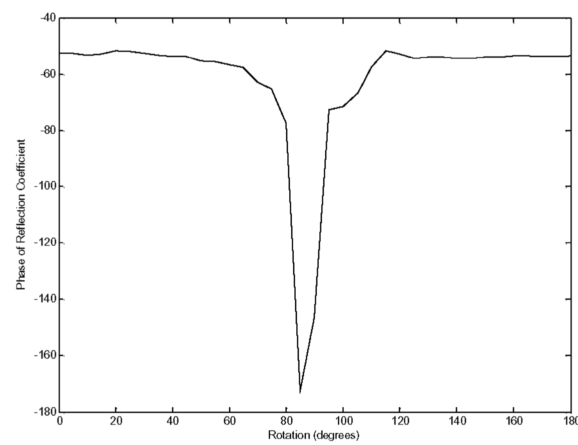

Fig 9. Phase of complex ratio for PIN diode at 3 GHz as a function of polarization angle.

IV. CONCLUSION AND FUTURE WORK

The embedded modulated scatterer technique can be employed to obtain reflection information for a particular dielectric material and inversely calculate the material dielectric properties (not specifically shown here). By using reflection coefficient data from two unique states of a loaded dipole, the measurements can become independent of critical parameters such as the orientation of the dipole and relative distance between the radiator and the dipole resulting in a much more robust measurement. The reflection coefficient data from both states can be carefully measured with static reflections coherently subtracted. Using the experimentally determined complex ratio of two unique states of a PIN diode-loaded dipole probe, dielectric properties can be calculated with theoretical formulations based on a two-port impedance network. In an embedded NDI application, where accurate orientation and distance is not necessarily known, this simplified technique is quite practical. Full theoretical results and the corresponding experimental verification for this technique will appear in the final paper.

REFERENCES

[1] Hughes, D. and R. Zoughi, "A Novel Method for Determination of Dielectric properties of Materials Using a Combined Embedded Modulated Scattering and Near-Field Microwave Techniques. Part I – Forward Model," *IEEE Transactions on Instrumentation and Measurement*, October 2005.

[2] Hughes, D. and R. Zoughi, "A Novel Method for Determination of Dielectric properties of Materials Using a Combined Embedded Modulated Scattering and Near-Field Microwave Techniques. Part II – Dielectric Property Recalculation," *IEEE Transactions on Instrumentation and Measurement*, October 2005.

[3] Bolomey, J.C. and F.E. Gardiol, *Engineering Applications of the Modulated Scatterer Technique*, Artech House, Norwood, MA, 2001.

[4] Hughes, D. and R. Zoughi, "A Method for Evaluating the Dielectric Properties of Composites Using a Combined Embedded Modulated Scattering and Near-Field Microwave Nondestructive Testing Technique," *Proceedings of the IEEE Instrumentation and Measurement Technology Conference*, pp. 1882-1886, Budapest, Hungary, May 21-23, 2001

[5] Hughes, D. and R. Zoughi. "Calculation of the Impedance of a Rectangular Waveguide Aperture in the Presence of a Loaded Dipole Antenna Embedded in a Generally Lossy Material," *Proceedings of the IEEE Instrumentation and Measurement Technology Conference*, pp. 1126-1130, Vail, CO, May 20-22, 2003.

[6] Zoughi, R., N. Bertrand and B. Fosdick, "Potential Application of Embedded Modulated Scatterers in Microwave Near-Field Inspection of Composites," *Proceedings of ICCE/7*, pp. 973-974, Denver, CO, July 2-8, 2000.

[7] Joisel, A., K.J. Bois, A.D. Benally, R. Zoughi and J.C. Bolomey, "Embedded Modulated Dipole Scattering for Near-Field Microwave Inspection of Concrete: Preliminary Investigation," *Proceedings of the SPIE'99 Subsurface Sensors and Applications Conference*, vol. 3752, pp.208-214, Denver, CO, July 18-23, 1999.