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Gabriel S. Freiburger

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

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DETERMINATION OF MICROWAVE DIELECTRIC PROPERTIES OF MATERIALS USING A UNIQUE APPLICATION OF EMBEDDED MODULATED SCATTERER TECHNIQUE

G. Freiburger and R. Zoughi

Applied Microwave Nondestructive Testing Laboratory (amntl)
Electrical and Computer Engineering Department
University of Missouri-Rolla, Rolla, MO 65409 USA

ABSTRACT. The embedded modulated scatterer technique has been investigated in the past as a means of determining the dielectric properties of a material of interest using an open-ended rectangular waveguide and an embedded PIN diode-loaded dipole probe. This technique has been further explored in a unique application utilizing the complex ratio of dynamic reflection coefficients for the two states of the modulated dipole probe. By utilizing this ratio, the calculation of dielectric properties becomes independent of measurement parameters such as distance, orientation, and location of the dipole probe relative to the waveguide radiator. This paper explores this unique application of the embedded modulated scatterer technique and presents both theoretical and experimental results for evaluating complex dielectric properties of materials.

INTRODUCTION

Microwave nondestructive testing and evaluation (NDT&E) is increasingly being explored for use in applications such as process-control, material characterization, and health monitoring of critical structures [1]. The embedded modulated scatterer technique (MST) is a unique material characterization method that may be effectively used for determining the microwave dielectric properties of materials and detecting slight variations in dielectric properties. This technique involves embedding a PIN diode-loaded dipole in a dielectric material of interest and modulating the diode load between two states. A rectangular waveguide at the surface of the material provides an incident impinging microwave signal on the embedded dipole and measures the reflection coefficient at its aperture for each of the two states of the modulated dipole [2]. The measured reflection coefficient information and known measurement system parameters can then be used to calculate the complex dielectric properties of the material [3,4]. The complex dielectric properties can then be correlated to the physical, chemical, and mechanical state of the material [5]. Such a modulated scatterer can be embedded at critical locations in a structure and provide highly localized measurements. Reflection coefficient measurements

corresponding to a particular state of the modulated dipole may be coherently averaged to improve the measurement signal-to-noise ratio. Embedded MST may also be used for rapid data collection over an extensive area with use of multiple scatterers. Furthermore, this method may be enhanced by utilization of the complex ratio of dynamic reflection coefficients corresponding to the two states of the modulated probe. Inverse calculations of dielectric properties based on this ratio are independent of the distance, orientation, and location of the dipole probe relative to the waveguide radiator [6]. In this paper, the complex ratio of dynamic reflection coefficients will be investigated as a means for determining complex dielectric properties both theoretically and experimentally.

APPROACH

Embedded MST is employed using a cylindrical dipole antenna of known physical length and diameter that is centrally loaded with a PIN diode and embedded in a material whose dielectric properties are sought, as shown in Figure 1. By using thin resistive wires to modulate the diode load with a pulse train, the load alternates between two impedance states, namely a forward state and a reverse state, which are independent of the dielectric properties of the material. These alternating impedance load values are dependent on the diode characteristics, applied bias voltage and current, and frequency of operation. The embedded modulated dipole is then irradiated by a microwave signal at a particular frequency by a rectangular waveguide radiator, resulting in the scattered field being effectively modulated. The total system reflection coefficient, composed of both the static and dynamic reflection coefficients, is measured at the aperture of the waveguide. Reflection coefficient measurements related to each state can be coherently averaged to improve the signal-to-noise ratio. The static reflection coefficient due to the material interface is then subtracted from the system reflection coefficient for each state to obtain the dynamic reflection coefficients due to each state of the loaded dipole. These dynamic reflection coefficients can then be used to calculate the dielectric properties of the material.
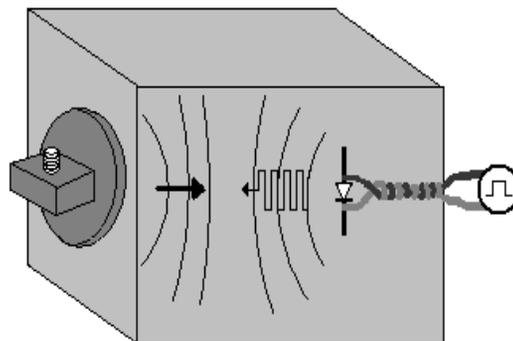
FIGURE 1. Schematic of an embedded loaded dipole probe in dielectric material irradiated by an open-ended rectangular waveguide.

The dynamic reflection coefficient for each state of the loaded dipole can be expressed as the ratio of the reflected electric field to the incident electric field on the dipole:

$$\Gamma_{dipole,high} = \frac{E_{r,high}}{E_i} \tag{1}$$

$$\Gamma_{dipole,low} = \frac{E_{r,low}}{E_i}. \tag{2}$$

The reflected or scattered fields for each state differ based on the changing impedance characteristics of the modulated dipole. However, since the relative orientation of the measurement system remains the same for both states of the modulated dipole, the external electric field applied by the waveguide and incident on the dipole is the same for each state. By taking the ratio of the dynamic reflection coefficients in (1) and (2), the incident electric field term cancels and the ratio reduces to:

$$\frac{\Gamma_{dipole,high}}{\Gamma_{dipole,low}} = \frac{E_{r,high}}{E_{r,low}}. \tag{3}$$

This ratio is independent of the incident field and is thus independent of the distance, orientation, and location of the dipole relative to the waveguide [6]. Furthermore, the observation point, transmission medium, and frequency are identical for each of the two states of the modulated MST probe; therefore, the ratio of reflected electric field values from the two states of the dipole can consequently be reduced to a ratio of maximum dipole currents in each of the states. Finally, the dipole current maximum for each state is inversely related to the dipole input impedance for the state, resulting in an equivalent relationship between the ratio of dynamic reflection coefficients and the dipole impedance characteristics. However, the mutual impedance between the waveguide radiator and the dipole antenna must be considered, as coupling has some effect on the outcome of the ratio. A limit evaluated as the effect of mutual impedance decreases results in the following expression:

$$\lim_{Z_{mutual} \to 0} \frac{\Gamma_{dipole,high}}{\Gamma_{dipole,low}} = \frac{Z_{self} + Z_{load,low}}{Z_{self} + Z_{load,high}}. \tag{4}$$

The alternating impedance load values, $Z_{load,low}$ and $Z_{load,high}$, are known, and the reflection coefficients due to each state of the dipole, $\Gamma_{dipole,high}$ and $\Gamma_{dipole,low}$, are measured experimentally. Thus, the remaining unknown self impedance of the dipole Z_{self} can easily be solved. Using this calculated self impedance, along with the known parameters of frequency of operation and dipole physical length and diameter, the dielectric properties of the material can be solved numerically in an inverse algorithm.

THEORETICAL RESULTS

Simulations were used to verify the utility of this ratio technique for determination of dielectric properties. Using a forward formulation [4], theoretical results were obtained for a dipole of length 2.4 cm with central alternating impedance loads, Z_{high}=5+j50 and Z_{low}=10-j20, and embedded in each of sand (ε_r = 2.7-j0.03), free space (ε_r = 1), and mortar (ε_r = 4.3-j0.37). Figure 2 shows the magnitude and phase of the complex ratio obtained as a function of distance between the waveguide and embedded dipole at 3 GHz.
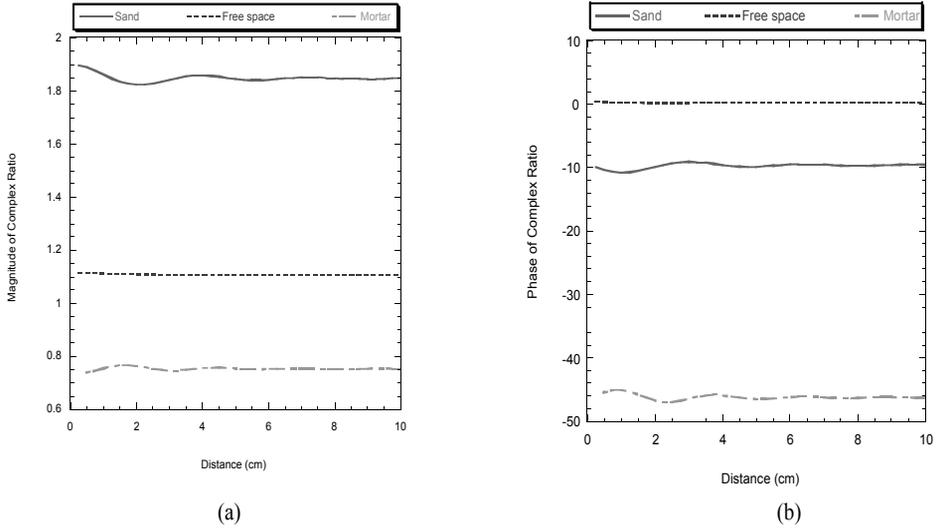
FIGURE 2. a) Magnitude of complex ratios and b) phase of complex ratios of dynamic reflection coefficients for embedded dipole in sand, free space, and mortar, as a function of distance.

The unique complex ratio of the dynamic reflection coefficients in each material converges in the far-field. The varying dielectric properties of the materials result in a varied electrical length of the embedded dipole and corresponding complex ratio. Thus, the same dipole used in each of the materials resulted in a unique ratio of dynamic reflection coefficients.

An inverse algorithm was developed to extract the dielectric properties of the material based on this complex ratio of dynamic reflection coefficients, known impedance loads, and the physical length and radius of the dipole. This numerical algorithm employs an iterative forward approach. The dipole self impedance is calculated using (4) and is compared to the self impedance calculated by the forward algorithm for guessed dielectric properties. The complex dielectric properties are then manipulated in subsequent iterations to minimize the difference in the two impedances. This inverse algorithm was used to calculate dielectric properties based on the ratios obtained from Figure 2, as shown in Table 1.

TABLE 1. Inverse calculations of dielectric properties for theoretical ratios in sand and mortar at 3 GHz.

	Sand		Mortar	
	Relative Permittivity	Loss Factor	Relative Permittivity	Loss Factor
Actual	2.7	-0.03	4.3	-0.37
Calculated	2.705	-0.031	4.304	-0.366
% Error	0.185 %	3.33%	0.093%	1.08%

As expected, the complex ratios obtained theoretically for sand and mortar resulted in inversely calculated dielectric properties with a minimal amount of error in fewer than ten numerical iterations of the inverse algorithm.

EXPERIMENTAL RESULTS

In a previous investigation, embedded MST utilizing the ratio of dynamic reflection coefficients was investigated in free-space [7]. Additional measurements have since been conducted for a dipole probe centrally loaded with a PIN diode and embedded in sand. Reflection coefficient information was recorded for the modulated system using an S-band waveguide operating at 3 GHz, and the resulting ratio of the dynamic reflection coefficients was utilized to inversely calculate the dielectric properties of the sand. The dipole was embedded at a distance such that mutual impedance effects would be minimized. The method resulted in calculated dielectric properties of ε_r=2.34-j0.33. In addition, an alternate method for the determination of dielectric properties was employed for comparison. This alternate method was based on the reflection coefficient at the surface of the material as measured at the aperture of the waveguide on the surface of an assumed infinite half-space of material [8]. Using this technique, a value of ε_r=2.51-j0.11 was obtained for the dielectric properties of the sand. These calculated values are quite similar; however, some variation does exist. The difference in the two values can largely be explained by inaccuracies in the subtraction of the static reflection value from the overall reflection coefficient of the modulated system. Slight variations in static reflection value are potentially quite large relative to the dynamic reflection coefficients of each state. Thus, the accuracy of the static reflection coefficient has a significant impact on the accuracy of the ratio and the resulting calculated dielectric properties. In addition, multiple reflections between the dipole and material interface are not accounted for in the inverse algorithm. This interaction with the surfaces of the material could impact the resulting calculated dielectric property values. Future work will further address each of these issues.

CONCLUSION

The dynamic reflection coefficients due to the two states of a modulated PIN diode-loaded dipole embedded in a dielectric material can effectively be used to inversely calculate the dielectric properties of the embedding material. This unique application of embedded MST is independent of measurement system parameters such as the relative depth, orientation, and location of the dipole probe within the material. Theoretical measurements indicate that a unique complex ratio is obtained for a given probe in various dielectric materials. This complex ratio of dynamic reflection coefficients can be used to calculate the dipole input impedance and the related material dielectric properties. Calculated dielectric properties using this technique for sand compare reasonably well with the dielectric properties calculated using an alternate method. The accuracy of the calculated dielectric properties largely depends on the accuracy of the static reflection coefficient value. In addition, the mutual impedance between the waveguide radiator and dipole probe, as well as multiple reflections with the material interface, effect the accuracy of the ratio obtained.

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