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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

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***Abstract*—The use of combined embedded modulated scattering technique and near-field microwave nondestructive testing techniques is investigated as a novel method for evaluating the dielectric properties of a material. The forward formulation for determining the reflection coefficient at the aperture of a waveguide radiating into a dielectric half-space in which a PIN diode-loaded dipole (i.e., modulated scattering technique probe) is embedded was presented in Part I of this paper. Here, in Part II, the recalculation of the dielectric properties, using the results of the forward model, is presented along with some associated experimental results.**

***Index Terms*—Dielectric material characterization, embedded sensors, microwave nondestructive testing, modulated scattering technique.**

I. INTRODUCTION

THE first part of this investigation formulated the forward model for determining the reflection coefficient at the aperture of a waveguide radiating into a generally lossy dielectric material, in which a modulated scattering technique (MST) probe is embedded [1]. This formulation was based on calculating the near-field coupling between the waveguide radiator and the MST probe, and comparisons between the measured and calculated reflection coefficient values for an MST probe in free-space and when embedded in fine sand were used to verify the validity of this model.

For nondestructive testing and evaluation (NDT&E) applications, it is more practical to determine the dielectric properties of a material from the measured (modulated) reflection coefficient. Thus, it is of practical importance to apply a root-solving technique to the forward formulation in order to determine the dielectric properties of the material in which an MST probe is embedded. For this, a function minimization algorithm, such as the downhill simplex method may be used, as described in this paper.

II. THE DOWNHILL SIMPLEX METHOD

The downhill simplex method is a multivariable function minimization algorithm, which, while it may not be the most efficient of all routines, it provides for a method that is easily and rapidly applied to a function [2], [3]. Unlike the conjugate gradient method or Powell's method, this method requires only the direct calculation of the function to be solved for [3]. However, the method is not as efficient in terms of the required number of iterations as the aforementioned techniques.

The complete description of this method is given elsewhere [2]. However, a brief description of it is presented here. In this technique, the simplex represents a geometric figure consisting of $N+1$ vertices, where N is the number of variables to be solved for. In this investigation, the permittivity and loss factor are the two variables to be solved for, thus the simplex is a figure consisting of three vertices. Each vertex in the simplex contains a set of data consisting of a set of variables to be solved for (i.e., permittivity and loss factor), and the corresponding solution to the forward model using the values of the variables (i.e., the recalculated value of the reflection coefficient). The simplex routine then attempts to determine the permittivity and loss factor that would recalculate the actual measured reflection coefficient.

The vertices of the initial simplex is either assigned or guessed. During each subsequent iteration, the simplex is redefined through a series of operations [3]. The simplex transverses the region of every possible permittivities and loss factors, and defines the vertices of the simplex to reduce the error between the recalculated and actual reflection coefficients (i.e., the magnitude of the difference between the two). When expressed as this error, the goal of the algorithm is to move the simplex "downhill" to the lowest point possible. The algorithm attempts to move the simplex in this manner, through the following steps.

1) The high and low vertices are initially determined. The high point represents the vertex whose recalculated reflection coefficient is furthest from the actual reflection coefficient, while the low point represents the vertex whose recalculated reflection coefficient is closest to the actual solution.

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2) The high point is reflected through the opposite face of the simplex. Essentially, the high point attempts to move downhill toward a lower point.
3) If the reflection operation produces a new low vertex, the vertex is expanded again in this direction, in an attempt to obtain a better result in this direction. This corresponds to moving the simplex even further downhill.
4) If the reflection does not produce a better result, the original high point is instead contracted toward the opposite face. This occurs if the reflection operation moves the simplex up an opposite hill.
5) In the event that the high vertex cannot be improved upon by any of the above steps, the entire original simplex is contracted around the low vertex. This is the same as pulling the simplex around the best point, in an attempt to move it down a sharp decline.

This method may be customized or optimized by changing the coefficients for the reflection, expansion and contraction operations, which determine the weight of each.

The simplex algorithm continues until a minimum is obtained. For a function that produces a single solution, this may be the determined by assigning a tolerance limit for the error between the actual and recalculated solutions. This is the case for when using either the forward- or reverse-biased state of the MST probe only. For more complex functions, as when using both states of the probe as a measurement criterion, the root mean square of the overall error may be used as a criterion for convergence. The minimum is obtained when this error is sufficiently small. However, due to the potential presence of a local minima in the solution region, the simplex may converge to an inaccurate point. In this instance, the algorithm must be reinitialized with an updated set of vertices in an attempt to move the simplex out of a local minimum.

III. FORWARD-BIASED RECALCULATIONS

Recalculations for the dielectric properties of the sand used in Part I [1] were made based on the measurements and calculations for a half-space of fine sand. As in Part I, the dielectric constant of the sand was measured using a two-port filled waveguide technique [1], [4]. The average value over S-band (i.e., 2.6–3.95 GHz) for sand was measured to be $\varepsilon_r = 2.76 - j0.03$. Because of the low-loss nature of the sand, recalculation of the exact loss factor is difficult. Furthermore, slight variations in such a small value will result in a large percentage in error between the recalculated and actual vales for loss factor. Thus, the convergence of permittivity will determine the potential use of the inversion routine here.

Table I summarizes the recalculated dielectric properties from the *measured* forward-biased reflection coefficient at 3 GHz. This includes the recalculated dielectric constant, the percent variation between the measured and recalculated reflection coefficient (i.e., the error in reflection coefficient), the required number of iterations to reach this solution, and the percent error from the actual permittivity and loss factor as calculated using a two-port technique. As can be seen, the measured and recalculated permittivity values agree quite well. The error in the loss factor is relatively large; however, this is attributed to the low-loss nature of sand, as mentioned earlier. The results for loss factor, although not close percentage wise, are still close from an absolution point of view. However, the former result is expected to significantly improve for materials with larger loss factors. For this material, however, the actual value for loss factor is small, making it difficult to converge to an accurate value. Table II summarizes the recalculation of the dielectric constant of sand at 3 GHz using the forward-biased state of the probe, as in Table I. However, the *calculated* reflection coefficient was used, rather than the measured value, as the solution criterion for the technique. Table III summarizes the recalculation of the dielectric constant of sand at 3.5 GHz using the forward-biased state of the probe from the *measured* reflection coefficient, while Table IV summarizes the recalculation of dielectric constant at 3.5 GHz using the forward-biased state of the probe from the *calculated* reflection coefficient. The same conclusions are observed here as with the recalculations using 3 GHz.

TABLE I
RECALCULATED DIELECTRIC CONSTANT OF SAND FROM *MEASURED* FORWARD-BIASED REFLECTION COEFFICIENT AT 3 GHZ

Γ_{fwd} (meas)		$0.364\angle -169.09°$	
# Iterations	8	%error Γ	0.02%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.916	ε_r''(recalc)	-0.021
%error ε_r'	5.52%	%error ε_r''	18.3%

TABLE II
RECALCULATED DIELECTRIC CONSTANT OF SAND FROM *CALCULATED* FORWARD-BIASED REFLECTION COEFFICIENT AT 3 GHZ

Γ_{fwd} (calc)		$0.377\angle -169.23°$	
# Iterations	15	%error Γ	0.03%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.762	ε_r''(recalc)	-0.027
%error ε_r'	0.03%	%error ε_r''	7.2%

TABLE III
RECALCULATED DIELECTRIC CONSTANT OF SAND FROM *MEASURED* FORWARD-BIASED REFLECTION COEFFICIENT AT 3.5 GHZ

Γ_{fwd} (meas)		$0.356\angle -161.79°$	
# Iterations	15	%error Γ	1.73%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.768	ε_r''(recalc)	-0.034
%error ε_r'	0.19%	%error ε_r''	34.9%

TABLE IV
RECALCULATED DIELECTRIC CONSTANT OF SAND FROM *CALCULATED* FORWARD-BIASED REFLECTION COEFFICIENT AT 3.5 GHZ

Γ_{fwd} (calc)		$0.361\angle -160.68°$	
# Iterations	6	%error Γ	0.07%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.763	ε_r''(recalc)	-0.024
%error ε_r'	0.07%	%error ε_r''	4.9%

IV. REVERSE-BIASED RECALCULATIONS

Tables V and VI show the recalculation of the dielectric constant of sand from the *measured* and *calculated* reflection coefficient, respectively, at 3 GHz using the reverse-biased state of the probe. Tables VII and VIII show the recalculated dielectric constant of sand using the reverse-biased state of the probe at

TABLE V
Recalculated Dielectric Constant of Sand From *Measured* Reverse-Biased Reflection Coefficient at 3 GHz

Γ_{rev} (meas)		$0.384\angle{-167.89}^\circ$	
# Iterations	11	%error Γ	0.81%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.92	ε_r''(recalc)	-0.020
%error ε_r'	5.57%	%error ε_r''	19.2%

TABLE VI
Recalculated Dielectric Constant of Sand From *Calculated* Reverse-Biased Reflection Coefficient at 3 GHz

Γ_{rev} (calc)		$0.385\angle{-167.24}^\circ$	
# Iterations	11	%error Γ	0.02%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.762	ε_r''(recalc)	-0.032
%error ε_r'	0.03%	%error ε_r''	25.3%

TABLE VII
Recalculated Dielectric Constant of Sand From *Measured* Reverse-Biased Reflection Coefficient at 3.5 GHz

Γ_{rev} (meas)		$0.312\angle{-164.76}^\circ$	
# Iterations	14	%error Γ	0.86%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.713	ε_r''(recalc)	-0.011
%error ε_r'	1.81%	%error ε_r''	58.3%

TABLE VIII
Recalculated Dielectric Constant of Sand From *Calculated* Reverse-Biased Reflection Coefficient at 3.5 GHz

Γ_{rev} (calc)		$0.317\angle{-164.20}^\circ$	
# Iterations	12	%error Γ	0.13%
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.762	ε_r''(recalc)	-0.017
%error ε_r'	0.05%	%error ε_r''	33.1%

TABLE IX
Recalculated Dielectric Constant of Sand From *Measured* Modulated Reflection Coefficient at 3 GHz

Γ_{fwd} (meas)		$0.364\angle{-169.09}^\circ$	
Γ_{rev} (meas)		$0.384\angle{-167.89}^\circ$	
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.92	ε_r''(recalc)	-0.020
%error ε_r'	5.52%	%error ε_r''	22.3%

TABLE X
Recalculated Dielectric Constant of Sand From *Calculated* Modulated Reflection Coefficient at 3 GHz

Γ_{fwd} (calc)		$0.377\angle{-169.23}^\circ$	
Γ_{rev} (calc)		$0.385\angle{-167.24}^\circ$	
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.759	ε_r''(recalc)	-0.025
%error ε_r'	0.02%	%error ε_r''	3.8%

TABLE XI
Recalculated Dielectric Constant of Sand From *Measured* Modulated Reflection Coefficient at 3.5 GHz

Γ_{fwd} (meas)		$0.356\angle{-161.79}^\circ$	
Γ_{rev} (meas)		$0.312\angle{-164.76}^\circ$	
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.758	ε_r''(recalc)	-0.026
%error ε_r'	0.19%	%error ε_r''	0.18%

TABLE XII
Recalculated Dielectric Constant of Sand From *Calculated* Modulated Reflection Coefficient at 3.5 GHz

Γ_{fwd} (calc)		$0.361\angle{-160.68}^\circ$	
Γ_{rev} (calc)		$0.317\angle{-164.20}^\circ$	
ε_r' (actual)	2.76	ε_r''(actual)	-0.026
ε_r' (recalc)	2.762	ε_r''(recalc)	-0.025
%error ε_r'	0.04%	%error ε_r''	3.6%

3.5 GHz from *measured* and *calculated* reflection coefficients, respectively. Again, the same observations may be made as with the recalculations using the forward-biased state of the probe.

V. Combined Forward- and Reverse-Biased Recalculations

As mentioned above, it is possible to utilize multiple solutions from a single function as criteria for convergence by taking the error function as the root mean square value of the overall error. Thus, it is possible to utilize both the forward- and reverse-biased reflection coefficient (i.e., modulated) measurements at the same time in this method.

Tables IX–XII summarize the recalculation of the dielectric constant of sand at 3 and 3.5 GHz using the *measured* and *calculated* reflection coefficient values, as with the forward- and reverse-biased recalculated results.

Similar results were obtained using modulated state of the MST probe as with the forward- or reverse-biased state. However, the results presented in Tables IX–XII seem to show much better results in terms of error in permittivity and loss factor. This is due to using both states of the probe for the criterion for convergence and indicates that more accurate results may be obtained from this. From the measured reflection coefficients at 3 GHz for the forward-biased, reverse-biased, and both modulated states, the recalculated permittivity was found to be approximately $\varepsilon_r{}' = 2.91$. As this value was recalculated consistently for all states of the probe, this technique implies that the permittivity is slightly higher at 3 GHz than the average value over S-band.

From the above results, it is clear that the use of an iterative technique to determine the dielectric constant of the material from measured reflection coefficient values provides for quite accurate results. Furthermore, as the recalculated values converged to the actual dielectric constant of the material for both calculated and measured reflection coefficients, the cases above provide for a strong indication that the forward formulation presented above is valid.

VI. Conclusion

The inverse problem of determining the dielectric constant of the material from modulated reflection coefficient measurements is of a great practical importance for the embedded MST technique. The application of the downhill simplex method, a function minimization routine used to determine the correct set of parameters for a given solution, was employed. This method allows for determination of the permittivity and loss factor of the dielectric material under investigation from measured reflection coefficients. It must be noted that in the microwave material characterization regime, special measurement precautions may be necessary when measuring the loss factor of low loss materials. Some of the results shown in this paper indicate high percentage of error associated with the loss factor recalculations. The calculated percent error is with respect to a small value to begin with; therefore a slight difference causes large errors. Additionally, for very low loss materials another method may be used (e.g., resonant cavity method).

Use of the inversion routine for determining the dielectric constant of sand produces results that converge very well with the permittivity of sand, as measured from a separate technique, for both the measured and calculated values. This is very encouraging, as it shows the validity of the forward model, the ability of applying an inversion routine to this, and the potential for using this technique in the investigation of dielectric materials.

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Dana Hughes, photograph and biography not available at the time of publication.

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