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N. Qaddoumi

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

Sasan Bakhtiari

Stoyan I. Ganchev

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Microwave Noncontact Examination of Disbond and Thickness Variation in Stratified Composite Media

Sasan Bakhtiari, Nasser Qaddoumi, Stoyan I. Ganchev, and Reza Zoughi

Abstract—Numerical and experimental results of a microwave noncontact, nondestructive detection and evaluation of disbonds and thickness variations in stratified composite media are presented. The aperture admittance characteristics of a flange mounted rectangular waveguide radiating into a layered, generally lossy dielectric media backed or unbacked by a conducting sheet is modeled. The theoretical implementation is based on a Fourier transform boundary matching technique to construct the field components in each medium, coupled with a stationary form of the terminating aperture admittance of the waveguide. The model can serve as a reliable test bed for real-time examination of layered composite media. Experimental results for several cases are presented which show good agreement with the theoretical findings. This is a versatile technique for near-field in situ interrogation of stratified composite media which provides for high resolution measurements.

I. INTRODUCTION

NONCONTACT nondestructive evaluation (NDE) of disbonds, delaminations and minute thickness variations in stratified composite materials is of great interest in many industrial applications. Good examples would be thickness variations, disbonds and delamination detection in ceramic, synthetic rubber, and honeycomb composite structures. In many instances, the layered structure is backed by a conducting plate, or it is a dielectric coating on top of a conducting sheet. Noncontact microwave NDE techniques have demonstrated tremendous potential in such applications although they have not received the acknowledgement of other conventional techniques such as ultrasonic, eddy currents, and X-rays. The ability of microwaves to penetrate inside a dielectric medium and their sensitivity to the presence of a boundary between two dissimilar layers make them suitable for this type of measurements [1]-[3].

Much work has been done on rigorous theoretical analysis of a rectangular waveguide radiating into a layered media. The applications at which these works have been aimed at are just as diverse. Most of the earlier literature have addressed the problem of plasma covered aperture antennas [4]-[7]. More recent rigorous analysis have been presented mostly in application to measurement of dielectric properties of materials and field interactions with biological tissues [8]-[12]. Considering typical measurement resolutions and accuracies in near-field examination of generally lossy composite media, most rigorous numerical results offer little practical advantage when taking into account the necessary computation time and difficulties involved in replicating the results by means of well-controlled experimental setups.

The approach adopted here was originally applied in [6] in application to radiation from plasma covered aperture antennas. It is assumed that the aperture field distribution is that of the dominant mode. This approach was first implemented and tested for the practical case of thickness measurement and variation detection of lossy dielectric slabs backed by a conducting plate [13]. In this work the solution is expanded to include general N-layer stratified dielectric media which may be terminated by a conducting sheet or an infinite half-space. This is done using a Fourier transform boundary matching technique to construct the field solutions in the layered medium outside the waveguide. A variational expression for the terminating aperture admittance in an infinite ground plane is used to construct the desired solution. Furthermore, the numerical results have been compared with several experimental measurements using a precise mechanical device built specifically for this purpose. Some important observations regarding both the numerical and experimental results have been acknowledged.

II. THEORETICAL FORMULATION

Fig. 1 shows a rectangular aperture in an infinite flange. Variational expression for the terminating admittance of the waveguide can be written as [6]

\[
Y = G + jB = \frac{\iint_{\text{aperture}} [E(x, y, 0) \times W(x, y)] \cdot \hat{a}_0 \, dx \, dy}{\left[ \iint_{\text{aperture}} E(x, y, 0) \cdot \hat{E}_0(x, y) \, dx \, dy \right]^2} \tag{1}
\]

where,

\[
W(x, y) = \bar{H}(x, y, 0) + \sum_{i=1}^{\infty} Y_i \bar{h}_i(x, y)
\]

\[
\iint_{\text{aperture}} \bar{E}(\eta, \xi, 0) \cdot \bar{E}_i(\eta, \xi) \, d\eta \, d\xi
\]

and \(\bar{E}(x, y, 0)\) and \(\bar{H}(x, y, 0)\) represent the aperture field distributions. \(G\) and \(B\) are the aperture conductance and susceptance respectively. This admittance expression is constructed using transverse vector mode functions and their orthogonal properties [14]. \(\bar{E}_i\) and \(\bar{h}_i\) are the ith vector mode functions and \(Y_i\) is the characteristic admittance of the the
ith waveguide mode. It has been shown that (1) is stationary with respect to variations of the aperture E-field about its exact value [6], [15], [16]. Thus, a reasonable approximation for the electric field results in a good estimate of the aperture admittance. It must be noted that as standard practice, a square flange with sides greater than $l_{X_0}$ is a good approximation to the theoretical assumption of an infinite flange for near-field measurements [17].

With the $TE_{10}$ mode incident on the aperture, a symmetrical electric field distribution over the large dimension can be written as

$$E_y(x, y, 0) = \bar{E}_0(x, y)$$

$$= \begin{cases} \frac{2}{a} \cos \left( \frac{\pi x}{a} \right) & \text{Over Aperture} \\ 0 & \text{Elsewhere} \end{cases} (3)$$

where $a$ and $b$ are the large and small dimensions of the waveguide cross section respectively, and the distribution is normalized so that a Fourier transform boundary matching technique is used to construct the field solutions in an $N$-layer stratified generally lossy dielectric medium. The transverse field components are expanded in each layer in terms of Fourier integrals. Subsequently, appropriate boundary conditions across each interface is enforced to solve for the unknown field coefficients in each medium. Fig. 1(a) and (b) depict the cross section of an open-ended waveguide radiating into a layered medium which is terminated into an infinite half-space and a perfect conducting sheet respectively. Each layer is assumed to be homogeneous and nonmagnetic with relative complex dielectric constant $\varepsilon_r$. The fields outside the waveguide may be constructed using a single vector potential. In each layer, denoted by layer number $n$, fields must satisfy the source-free wave equation

$$\mathbb{E}_n(x, y, z) = -\nabla \times \mathbb{H}_n$$

$$\mathbb{H}_n(x, y, z) = \frac{1}{j\omega \mu_0} \left[ k_n^2 \mathbb{E}_n + \nabla \times \mathbb{H}_n \right] (4a)$$

where, $\mathbb{H}_n = \Phi_n \hat{a}_x + \Psi_n \hat{a}_y$

General solutions of (4a) and (4b) may be expressed in terms of integrations over the entire mode space as

$$E_n^\pm(x, y, z) = \frac{j k_m}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty}$$

$$\left[ \mp A_n^{\pm} e^{-jk_{m} x} \pm A_n^{-\pm} e^{jk_{m} x} \right]$$

$$e^{-j(k_{m} x + b_{m} y)} dk_{x} dk_{y} (5a)$$

$$H_n^\pm(x, y, z) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty}$$

$$\left[ \mp A_n^{\pm} e^{-jk_{m} x} \pm A_n^{-\pm} e^{jk_{m} x} \right]$$

$$e^{-j(k_{m} x + b_{m} y)} dk_{x} dk_{y} (5b)$$

where $k_m$ is the complex propagation constant for the $n$th layer, and

$$k_m = \sqrt{k_n^2 - k_0^2 - k_0^2} (6)$$

is taken as $k_m = \| \Re(k_{m}) \| - j \| \Im(k_{m}) \|$ to comply with the appropriate direction of propagation. Referring to Fig. 1(a), only positively travelling waves exist in the $N$th layer which is unbounded in $+z$ direction. Thus, for the the field components in this region only those terms in (5a) and (5b) which are associated with positive direction of propagation remain. Using Fourier properties of the field components in (5) and enforcing the continuity of the tangential field components at each interface, the unknown field coefficients for each layer can be determined. Following the treatment given in the Appendix, the admittance expression $A^\pm$ once normalized with respect to guide admittance can be expressed as

$$y_s = g_s + j b_s = \frac{j 2}{(2\pi)^2} \int_{0}^{\infty} \int_{0}^{\infty}$$

$$\left[ \varepsilon_r - (\mathcal{R} \cos \theta) \right] \left[ 2 A_{g,1}^\pm + j \mathcal{G}(\mathcal{R}, \theta) \right]$$

$$- 2 R^2 \sin \theta \cos \theta A_{g,2}^\pm \right] G(\mathcal{R}, \theta) d\theta d\mathcal{R} (7)$$

where,

$$\mathcal{G}(\mathcal{R}, \theta) = \frac{2a^4 (4\pi)^2 \cos^2 \left( \frac{\alpha R \cos \theta}{2} \right)}{\mathcal{V} \left( \mathcal{R} \sin \theta \right)} \left[ \frac{\alpha R \sin \theta}{\mathcal{V} \left( \mathcal{R} \sin \theta \right)} \right] (8)$$

with $\mathcal{R}$ and $\theta$ as the new variables of integration given by (A9) and $a'$ and $b'$ are the normalized waveguide dimensions. Calculation of the normalized field coefficients $A_{g,1}^\pm$ and $A_{g,2}^\pm$ in (7) is outlined in the Appendix. Lossless stratified media is not the focus of this work, however, for such a case one encounters singularities in (7). This can be resolved by contour integration around singular points of the integrand located on
the real axis and take into account the residue. In application to a composite medium which contains generally lossy layers, which is the case addressed here, the poles of the integrand move off of the real axis and the integrand becomes smooth. This allows quick and efficient numerical integration schemes such as a Gauss quadrature method (used here) to be applied.

III. THEORETICAL AND EXPERIMENTAL RESULTS AND OBSERVATIONS

The complex reflection coefficient, \( R \), is related to normalized complex admittance, \( y_d \), by \( R = (1 - y_d)/(1 + y_d) \). Thus, the magnitude and phase of \( R \) can be measured directly from VSWR and shift in the location of the standing wave null compared to a short circuited waveguide \([18]\). The apparatus utilized to conduct experimental measurements incorporated a slotted line and a mechanical setup with two sliding sample holders which allowed precise adjustment of the sample positions, via two micrometers, in front of the waveguide aperture. Fig. 2(a) and (b) depict the two basic geometries examined by this apparatus. The measurements presented here were performed at a frequency of 10 GHz using dielectric sheets with permittivity and loss tangent of \( \epsilon_r' = 8.4 \) and \( \tan \delta = 0.107 \) (synthetic rubber sheets). The experimental results presented here are the average value of several independent measurements.

A. Termination of Layered Media into an Infinite Half-Space

To examine the validity and limitations of the numerical results, initially variations of VSWR and phase were monitored as a function of distance between the aperture and the sample (air gap) using a single slab terminated into free-space. The geometry configuration of the measurement is derived from Fig. 2(a) with a dielectric sample thickness of \( d_2 = 7.55 \) mm, and with \( d_3 \) and \( d_4 \) equal to zero. The measured slab thickness using a micrometer thickness gauge, is the mean value over the aperture area. The results of the theoretical and measured VSWR and phase for a range of air gap values are shown in Fig. 3 over a distance of \( \lambda_0/2 \) from the aperture. There is a good agreement between the measurement and numerical results. As expected, the air gap size dictates the degree of the field coupling into the dielectric slab and can be manipulated for measurement purposes.

Next, variations of VSWR and phase were investigated as a function of the slab thickness for a fixed arbitrary air gap distance \( d_1 \). Once again Fig. 2(a) illustrates the geometry for this case with \( d_3 \) and \( d_4 \) equal to zero. Figs. 4 and 5 show the numerical results at 24 GHz along with both the numerical and experimental results at 10 GHz for different slab thicknesses. Figs. 4(a) and (b) show variations of VSWR and phase respectively for an air gap of \( d_1 = 2 \) mm. The numerical results of phase variation at 24 GHz shows a change of around 120 degrees over the first 4.5 mm range of slab thickness. This indicates that for this case thickness variations as small as 0.04 mm may be detected since the measurement apparatus used here may resolve a change of one degree. Figs. 5(a) and (b) display the results for an air gap of \( d_1 = 5 \) mm. The measured phase at 10 GHz, which is also predicted by the theory, shows significant variation over this thickness range. Due to greater signal attenuation at larger air gaps and increase in electrical length of the lossy sample at higher frequencies, variations of VSWR and phase are expected to degrade as shown for the 24 GHz results in Fig. 5. Such observations are made to indicate that the measurement resolution (accuracy) may be maximized by using the theory to optimize the air gap distance and the operating frequency based on the sample thickness and its dielectric properties. Moreover, having such resolutions at X-band suggests that one may not need to go to much higher frequencies to achieve high resolutions for examination of the type of dielectric samples used here, although higher frequencies may eventually render better accuracies for thin and low-loss materials.

To examine the effect of disbond in a stratified composite medium an experiment was conducted in which the separation between two slabs of the same dielectric material (disbond) was varied for a fixed air gap. Once again, Fig. 2(a) depicts the geometry of this case for \( d_2 = 5.15 \) mm, \( d_4 = 7.55 \) mm, and with both slabs having the same dielectric constant as before. Layers 1, 3, and the infinite half-space in the back have free-space permittivity. Fig. 6 shows the numerical and experimental results for \( d_1 = 5 \) mm as \( d_3 \) varies over a
Fig. 4. (a) Comparison of numerical results at 10 and 24 GHz along with experimental results at 10 GHz for VSWR as a function of slab thickness for an arbitrary air gap of \(d_1 = 2\) mm. (b) Comparison of numerical results at 10 and 24 GHz along with experimental results at 10 GHz for phase as a function of slab thickness for an arbitrary air gap of \(d_1 = 2\) mm.

\(\lambda_0/10\) range. The measurement outcomes, which are in good agreement with the theory, clearly indicate that for this specific case, the phase of the reflection coefficient shows much more sensitivity to the disbond dimension than VSWR. The phase drops around 15 degrees over the first 0.5 mm variation of disbond in the layered medium.

**B. Termination of Layered Media into a Conducting Sheet**

Similar measurements were performed for the case where the medium is backed by a conducting plate. Referring to Fig. 2(b), a slab with thickness of \(d_2 = 7.55\) mm was first placed flush against a metal plate \((d_3 = 0)\), and \(d_1\) varied over a \(\lambda_0/2\) distance. The numerical and experimental results for VSWR and phase are shown in Fig. 7. Comparing VSWR in Fig. 7 with its counterpart in Fig. 3 where the conductor is not present one can clearly observe the effect of strong reflection from the surface of the metal plate causing slower damping of the VSWR variation in Fig. 7. Similarly comparison between phase of these two cases shows the strong influence of the conductor backing both in terms of a shift in position and change of slope in the phase variation.

Fig. 8 displays variations of VSWR and phase as a function of disbond thickness variation, \(d_3\), between the dielectric sheet and the metal plate for an air gap of \(d_1 = 5\) mm. Both VSWR and phase values, which are in close agreement with the theory, display significant change over the \(\lambda_0/10\) range. Comparing the phase shown in Fig. 8 with that of Fig. 7, it is clear that the presence of the conducting sheet in the back enhances the measurement sensitivity. Such an
effect is expected due to a strong reflection at the interface between the dielectric slab and the surface of conducting plate. These results clearly illustrate the utility of this approach for detecting a disbond at its early stages of development.

To further stress the effect of air gap on the measurement resolution, the numerical results of VSWR and phase of Fig. 7 (disbond \(d_3 = 0\)) were compared against a case where a disbond of \(d_3 = 0.1\) mm exists between the dielectric sheet and the metal plate. The results of this test are shown in Fig. 9. The solid line displays the difference between the magnitude of VSWR (in dB) and the dashed line is the phase difference between the two cases. The results clearly indicate a resolvable difference as a result of a 0.1 mm disbond between the dielectric slab and the conductor surface. The maximum difference of the VSWR and phase occurs at different air gaps. Such tests demonstrate that the theory may render important information on the air gap for the position of maximum separation of either the VSWR or the phase for optimization of measurement resolution and accuracy.

### IV. Conclusion

A theoretical model along with experimental results have been presented in application to microwave in situ NDE of layered dielectric media terminating into either free-space or a conducting sheet. The theoretical analysis is based on a Fourier transform boundary matching technique to construct the field components in a layered media outside an open-ended rectangular waveguide coupled with the variational form of the terminating admittance of the flange-mounted aperture. The integrity of the numerical results have been examined by conducting several measurements using a precise mechanical device built specifically to duplicate the geometry of the theoretical model. The measurements presented here were performed at 10 GHz using generally lossy slab-like samples. Variation of VSWR and phase of the reflection coefficient
as a function of parameters such as the air gap between
the sample and the waveguide, and sample thickness were
investigated. Furthermore, numerical and experimental results
were presented demonstrating the possibility for detection of
small disbond thicknesses in a layered media. The experi-
mental results showed good agreement with the numerical
outcomes. These results clearly indicate that high resolutions
may be achieved in examination of generally lossy dielectric
samples without the need to operate at very high frequencies.
Furthermore, they demonstrate the sensitivity of such versatile
NDE technique as it applies to the interrogation of layered
composite media, and the importance of a fast and reliable
numerical model as a tool to gain real time a priori knowledge
of the underlying process. It is concluded that the theoretical
model can render important information for optimization of
such measurement parameters as position of the sensor and
operating frequency leading to better resolutions.

APPENDIX
The boundary value problem was solved by introducing the
following normalized (with respect to \( k_0 \)) parameters inside
the formulation

\[
\alpha_i' = k_0 \alpha_i, \quad \beta_i' = k_0 \beta_i, \quad \gamma_n = k_0 \sum_{i=1}^{n} d_i, \quad A_i^+ = \frac{k_0}{k_0} A_i^+ \quad (A1)
\]

where \( n = 1, 2, \ldots, N \), \( d_i \) is the thickness of the \( i^{th} \) layer, and
the index \( I \) refers to \( \Psi \) or \( \Phi \) component of the vector potential.
Taking inverse transform of both components of (5a) at the
aperture results in the following relations between the field
coefficients in layer 1

\[
A_{\Psi 1}^+ = A_{\Psi 1}^- \quad (A2)
\]

\[
A_{\Phi 1}^+ - A_{\Phi 1}^- = \frac{4\pi}{jK_1} \sqrt{\frac{2\alpha_1' \cos (K_{\alpha 1}' \Delta) \sin (K_{\alpha 1}' \Delta)}{K_{\alpha 1}' \pi^2 - (K_{\alpha 1} a')^2}} \quad (A3)
\]

where \( G \) is chosen to simplify the notation. Forcing the
appropriate boundary conditions, namely continuity of the
transverse \( E \) and \( H \) field components across each interface
and vanishing tangential \( E \)-field component over the conducting
surface results in the following set of relations between the field
coefficients of adjacent layers

\[
A_{\Psi m+1}^- + A_{\Psi m}^+ - A_{\Psi m}^- e^{-\frac{jK_{\Psi m} \gamma_n}{2}} e^{jK_{\Psi m} \gamma_n} = \frac{K_{m+1}}{K_m} \left[ A_{\Psi m+1}^+ - A_{\Psi m+1}^- e^{-\frac{jK_{\Psi m+1} \gamma_n}{2}} e^{jK_{\Psi m+1} \gamma_n} \right] \quad (A4)
\]

\[
\left( \varepsilon_{m+1} - \varepsilon_{m} \right) \left[ A_{\Psi m+1}^+ e^{-\frac{jK_{\Psi m+1} \gamma_n}{2}} e^{jK_{\Psi m+1} \gamma_n} + A_{\Psi m+1}^- e^{-\frac{jK_{\Psi m+1} \gamma_n}{2}} e^{jK_{\Psi m+1} \gamma_n} \right]
- (K_{\Psi m} K_{\Psi m+1}) \left[ A_{\Psi m}^+ e^{-\frac{jK_{\Psi m} \gamma_n}{2}} e^{jK_{\Psi m} \gamma_n} + A_{\Psi m}^- e^{-\frac{jK_{\Psi m} \gamma_n}{2}} e^{jK_{\Psi m} \gamma_n} \right] \quad (A5)
\]

where \( m = 1, 2, \ldots, (N - 1) \) is the layer number. Consequently,
when the medium is terminated into an infinite half-space the
contribution of negative travelling field components drops out of (A4) and (A5). For a layered media
terminating into a conducting sheet, the vanishing tangential
\( E \)-field components over the conductor surface renders an
additional set of relations between the field coefficients in the
\( N \)th layer as

\[
A_{\Psi N}^- = e^{-j2K_{\Psi N} z_N} A_{\Psi N}^+ \quad (A6)
\]

Solving simultaneously a system of 4N - 2 equations for the
\( N \)-layered case terminated into an infinite half-space results
in the sought for field coefficients. Similarly, a system of
4N equations has to be solved for the case of \( N \)-layer
medium terminated into a conducting sheet. Application of
Parseval's theorem allows the construction of the numerator
of admittance expression (1) as

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [E(x, y, 0) \times \mathcal{W}(x, y, 0)] \cdot \hat{n} dx dy
= \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P_y^+(k_x, k_y) \mathcal{H}_y^+(k_x, k_y) d k_x d k_y \quad (A7)
\]

where the \( E \) and \( \mathcal{H} \) on the right hand side of (A7) are the
transformed field components of layer 1 from (5a) and (5b) and
* represents the complex conjugate notation. Upon calculation
of the field coefficients in layer 1 and use of (A7) the following
admittance expression results from (1)

\[
Y_n = \frac{j}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ [\varepsilon_{\alpha 1} - K_1^2] \left[ 2A_{\Psi 1}^- + \frac{jG(K_{\alpha 1}, K_y)}{K_1} \right] - 2K_1 K_{\Psi 1} A_{\Psi 1}^- \right\} G(K_{\alpha 1}, K_y) d K_x d K_y \quad (A8)
\]

where subscript \( n \) denotes normalization with respect to the
free-space characteristic admittance. By applying a polar co-
ordinate transformation of the form

\[
K_x = R \cos \theta, \quad K_y = R \sin \theta \quad (A9)
\]

with transformation Jacobian \( \mathcal{R} \) to (A8), which has two
infinite integrals, the terminating aperture admittance may be
evaluated by a double integral having only one unbounded
range of integration as given by (7).
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