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Microwave Nondestructive Detection and Evaluation of Disbonding and Delamination in Layered-Dielectric-Slabs

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***Abstract*—A microwave nondestructive technique for detection and evaluation of disbonding and delamination in layered-dielectric-slabs backed by a conducting plate is discussed. The theoretical development begins by considering an incident wave illuminating such a medium and then formulating the characteristics of the wave reflected by the metal plate. An effective reflection coefficient is determined in this way whose phase characteristics are used in the detection and evaluation of delaminations in the media. The characteristics of this phase as a function of several parameters such as delamination dielectric constant and thickness, slab dielectric constant, and thickness and the frequency of operation are investigated. The description of an experimental apparatus is given and it is used to perform several experiments to test and verify the theory. Very good agreement was obtained between the theoretical and experimental results.**

I. Introduction

MATERIALS composed of layered-dielectric-slabs, which are manufactured by adhesively bonding several layers of dielectric slabs, are used in many facets of industry. A delamination between any two slabs caused by the absence of an adhesive compound can cause major failure wherever these layered-slabs are used. In most applications, such as the aerospace and construction industries, these materials are backed by a conducting plate which limits the access to the plates to only one side of the material. Clearly, it is desirable to develop a noncontacting technique for detecting and evaluating such delaminations (disbondings). This paper discusses the development of a technique which utilizes the phase properties of reflection coefficient of a microwave signal as it passes through the dielectric plates and is reflected by the donducting plate. Zoughi, *et al.* have used a similar approach to determine thicknesses of dielectric slabs and their permittivities at microwave frequencies [1]. Other investigators have also used microwaves for delamination detection using amplitude sensitive reflectometers [2], [3]. Layered dielectric media have been the focus of the attention of many investigators, particularly in determining impedances and reflection coefficients of these materials [4]–[6]. The technique outlined here can also be used to evaluate the thickness of adhesive layers if their permittivities are known which provides adhesive thickness-uniformity information during the manufacturing process.

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Relative permittivities of dielectric slabs are generally complex; $\epsilon = \epsilon' - j\epsilon''$, where ϵ' is known as the relative dielectric constant and ϵ'' is the loss factor. For lowloss material, ϵ'' is much smaller than ϵ'. The technique outlined in this paper is applicable to generally lossy material, provided the loss does not prevent reasonable signal penetration into the material. ϵ' is the primary cause of signal phase variation, whereas ϵ'' is primary cause of signal attenuation as it travels through the material. As will be seen shortly, we are only concerned with phase measurements, therefore the absolute level of the received signal is not of interest. Therefore, for the purpose of our discussions, we consider lossless material (slabs whose permittivities are real). Also, this technique is applicable to multilayer slabs, but we limit our discussion to media consisting of two dielectric slabs and one layer of delamination.

II. Approach

The problem of transmission and reflection of uniform plane waves from a multilayer dielectric medium has been investigated by many investigators [7]–[8]. An incident signal, E_{io}, is transmitted into the layered medium and once reflected by the conducting plate, it is detected as E_{ro}. The ratio of these two signals gives the effective reflection coefficient of the medium. The phase difference between the reflection coefficient for a nondelaminated and a delaminated medium is related to the thickness (d) and the dielectric constant (ϵ) of the delamination layer. If ϵ is known then d can be calculated via the knowledge of the difference in the phase of the reflection coefficients. Fig. 1 illustrates a medium consisting of two layers of dielectric plates and a layer of delamination all backed by a conducting plate. Calculation of the effective refleciton coefficient for such a medium involves the derivation of the forward and backward traveling electric and magnetic field components in each layer based on a known incident field and the application of appropriate boundary conditions at each interface. Referring to Fig. 1, field expressions in each layer are given by the following expressions, respectively (subscripts i and r denote incident and reflected fields, + and − subscripts represent forward and

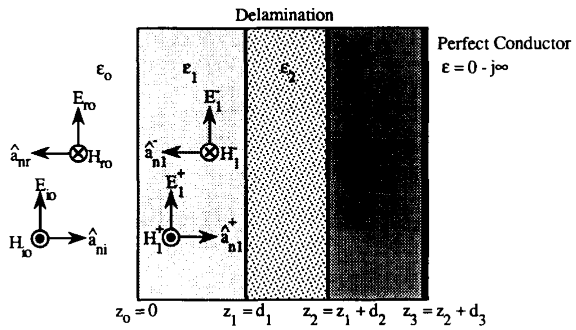

Fig. 1. Incident and reflected fields for a medium consisting of two layers of dielectric plates (ϵ_1 and ϵ_3) and a layer of delamination (ϵ_2), all backed by a conducting plate.

backward traveling waves, respectively, n represents the layer number, and bold characters denote vectors quantities):

$$\boldsymbol{E}_n = \hat{a}_x\,(E_{in}e^{-j\beta_n z} + E_{rn}e^{j\beta_n z}) \tag{1}$$

$$\boldsymbol{H}_n = \hat{a}_y \frac{1}{\eta_n}\,(E_{in}e^{-j\beta_n z} - E_{rn}e^{j\beta_n z}) \tag{2}$$

where

$$n = 0, \cdots, 3$$

$$\beta_o = \frac{2\pi}{\lambda_o} \quad (\text{rad/m})$$

$$\beta_n = \beta_o\sqrt{\epsilon_n} \quad (\text{rad/m})$$

$$\eta_n = \sqrt{\frac{\mu_o}{\epsilon_o\epsilon_n}}$$

and λ_o is the wavelength in free space, and μ_o and ϵ_o are the permeability and permittivity of free space, respectively.

Boundary conditions at $z_3 = d_1 + d_2 + d_3$ forces the tangential E-field on the surface of the perfect conductor to be zero, $\boldsymbol{E}_3(z_3) = 0$. Thus

$$E_3^+ e^{-j\beta_3 z_3} + E_3^- e^{j\beta_3 z_3} = 0$$

or

$$E_3^- = -E_3^+ e^{-j2\beta_3 z_3}. \tag{3}$$

Substituting (3) into (1) and (2) for layer 3 give

$$\boldsymbol{E}_3 = \hat{a}_x[E_3^+ e^{-j\beta_3 z} - E_3^+ e^{j\beta_3(z-2z_3)}] \tag{4}$$

$$\boldsymbol{H}_3 = \hat{a}_y \frac{1}{\eta_3}\,[E_3^+ e^{-j\beta_3 z} + E_3^+ e^{j\beta_3(z-2z_3)}]. \tag{5}$$

By applying the boundary conditions at $z_2 = d_1 + d_2$, and $z_1 = d_1$ the effective reflection coefficient and its phase can be written as

$$\Gamma = \frac{E_{ro}}{E_{io}} = \frac{\frac{\eta_1}{\eta_o}D - 1}{\frac{\eta_1}{\eta_o}D + 1} \tag{6}$$

$$\phi = \tan^{-1}\left[\frac{\text{Im}\{\Gamma_e\}}{\text{Re}\{\Gamma_e\}}\right] \tag{7}$$

where

$$D = \frac{1 + Ce^{-j2\beta_1 d_1}}{1 - Ce^{-j2\beta_1 d_1}} \tag{8}$$

$$C = \frac{\frac{\eta_2}{\eta_1}B - 1}{\frac{\eta_2}{\eta_1}B + 1} \tag{9}$$

$$B = \frac{1 + Ae^{-j2\beta_2 d_2}}{1 - Ae^{-j2\beta_2 d_2}} \tag{10}$$

$$A = \frac{\frac{\eta_3}{\eta_2}\tan\beta_3 d_3 - 1}{\frac{\eta_3}{\eta_2}\tan\beta_3 d_3 + 1}. \tag{11}$$

The difference between this phase and the one for a nondelaminated case can now be measured for various values of delamination thickness, dielectric constant, and frequency. Thus

$$\Delta\phi = \phi_{\text{nondel.}} - \phi_{\text{del.}}. \tag{12}$$

III. Experimental Apparatus

The derivation given in Section II assumes that the field inside all dielectric layers are uniform plane waves. The practical implication of this assumption is that the dielectric medium must be placed in the far-field of any antennas used to experimentally verify the results of this derivation. The measurement apparatus is shown in Fig. 2. A microwave sweep oscillator (HP8350B) is used to generate a continuous wave (CW) signal at a given frequency. This signal is passed through an isolator to prevent reflections from reaching the oscillator. The signal is then split into a test and a reference signal. The reference signal becomes the input signal to the reference channel of a microwave network analyzer (HP8410A). The test signal is fed through another isolator which prevents reflections from corrupting the reference signal and then it irradiates the multilayered medium under test via a small transmitting horn antenna. The signal propagates through the medium and once reflected by the conducting plate is then picked up by another small receiving horn antenna and is subsequently fed into the test channel of the network analyzer. The network analyzer compares the amplitude and the phase of the test signal with those of the reference signal and their differences are indicated.

IV. Theoretical Results

$\Delta\phi$ variations, as a function of delamination thickness (d_2) for four different cases at 10 GHz for $\epsilon_1 = \epsilon_3 = 3.5$, are shown in Fig. 3(a)-(d). Fig. 3(a) and (b) show the

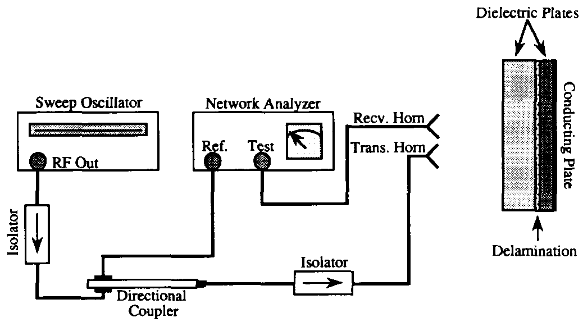

Fig. 2. The experimental apparatus.

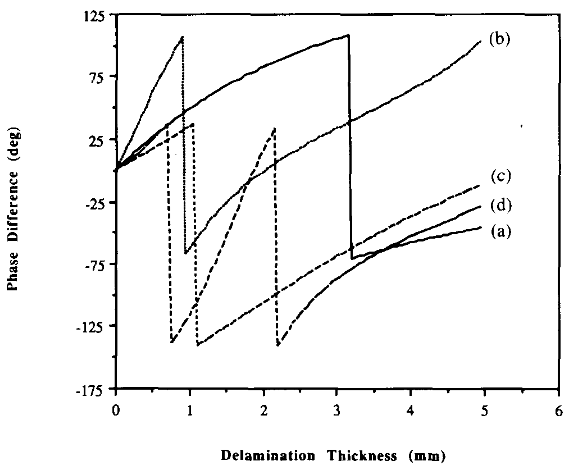

Fig. 3. Phase difference vs. delamination thickness at 10 GHz, ϵ_1 and ϵ_3 = 3.5 for (a) $d_1 = d_3 = 50$ mm, $\epsilon_2 = 1$, (b) $d_1 = d_3 = 50$ mm, $\epsilon_2 = 6.5$, (c) $d_1 = d_3 = 25$ mm, $\epsilon_2 = 1$, and (d) $d_1 = d_3 = 25$ mm, $\epsilon_2 = 6.5$.

results for a medium consisting of two 50 mm-thick dielectric plates with air ($\epsilon_2 = 1$) and epoxy ($\epsilon_2 = 6.5$) as their respective delamination layer. In both cases $\Delta\phi$ increases as the delamination thickness increases and both cases experience the sharp 180° phase reversal due to the nature of the $\tan^{-1}$ function in (7). The period of this variation shortens for an increasing delamination dielectric constant value. The maximum and minimum levels of $\Delta\phi$ for both cases remain fairly constant. Changing the thicknesses of the dielectric plates to 25 mm (cases (c) and (d)) produces faster $\Delta\phi$ variations compared to the two previous cases. As before, more $\Delta\phi$ variations occur when the delamination dielectric constant increases.

Fig. 4(a)-(d) show the results of $\Delta\phi$ variations as a function of the delamination dielectric constant when $\epsilon_1 = \epsilon_3 = 3.5$ and a delamination layer thickness of 1 mm. At 10 GHz, Fig. 4(a) and (b) show this variation for $d_1 = d_3 = 50$ mm and $d_1 = d_3 = 25$ mm, respectively. For the thicker dielectric plates (case (a)) the 180° phase reversal occurs for a higher value of delamination dielectric constant compared to that of the thinner plates (case (b)). For these same two cases at 5 GHz (cases (c) and (d), the 180° phase reversal occurs for much higher values of de-

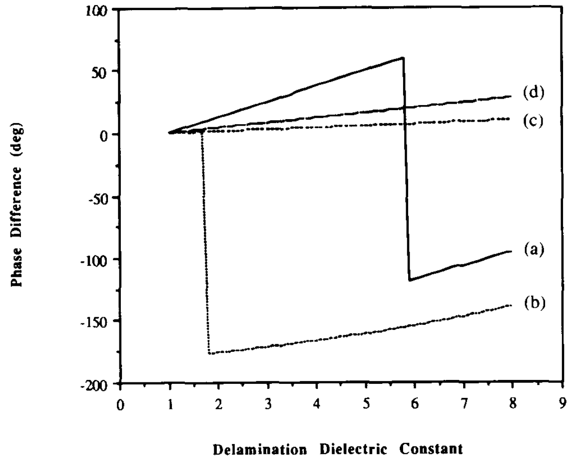

Fig. 4. Phase difference versus delamination dielectric constant for $\epsilon_1 = \epsilon_3 = 3.5$, $d_2 = 1$ mm, (a) $f = 10$ GHz, $d_1 = d_3 = 50$ mm, (b) $f = 10$ GHz, $d_1 = d_3 = 25$ mm, (c) $f = 5$ GHZ, $d_1 = d_3 = 50$ mm, and (d) $f = 5$ GHz, $d_1 = d_3 = 25$ mm.

lamination dielectric constant and $\Delta\phi$ variations at this frequency are not as pronounced when comparing thicker dielectric plates with thinner ones. This indicates that if the dielectric constant is to be determined for a given delamination thickness, higher frequencies render better results.

From these results it is apparent that due to the repetitive nature of $\Delta\phi$ versus delamination thickness, a unique delamination thickness may not be obtained. There are at least three remedies for this problem which are as follows.

1) The knowledge of the possible relative range of the delamination thickness reduces this ambiguity. For example, if two 2 cm-thick dielectric slabs are bonded together with epoxy, it would be safe to assume that any potential delamination will not be more than a few millimeters (otherwise a visual inspection would be sufficient). Having known this, the above ambiguity is eliminated.
2) Lower frequencies render less repetition in $\Delta\phi$ characteristics. Thus for a given medium it is possible to choose a frequency for which $\Delta\phi$ characteristic curve does not repeat for a large range of delamination thickness values.
3) Dual frequency operation can also aid in reducing this ambiguity. This would require solving (7) for two different frequencies. This solution is more complex than the previous two.

V. Experimental Results

Several experiments were conducted (taking multiple samples in each case) using precision measuring devices to test the validity of the theoretical findings. At 10 GHz, an experiment was conducted using a synthetic rubber

TABLE I
COMPARISON OF THE THEORETICAL AND EXPERIMENTAL RESULTS FOR SYNTHETIC RUBBER AND PLEXIGLASS PLATES BACKED BY A CONDUCTING PLATE.

Delamination Thickness, d_2 (mm)	Theoretical $\Delta\phi$ (deg)	Measured $\Delta\phi$ (deg)
1	17.34	17.00 $\mp$ 2.58
2	36.03	36.75 $\mp$ 2.99
3	56.95	58.00 $\mp$ 2.83
4	81.07	72.25 $\mp$ 2.06

TABLE II
COMPARISON OF THE THEORETICAL AND EXPERIMENTAL RESULTS FOR TWO PLEXIGLASS PLATES BACKED BY A CONDUCTING PLATE

Delamination Thickness, d_2 (mm)	Theoretical $\Delta\phi$ (deg)	Measured $\Delta\phi$ (deg)
1	32.16	40.00 $\mp$ 2.00
2	59.33	66.00 $\mp$ 1.73
3	82.06	80.67 $\mp$ 1.15
4	101.47	100.67 $\mp$ 1.16
5	118.73	120.67 $\mp$ 1.15
8.7	-1.23	-2.93 $\mp$ 5.08

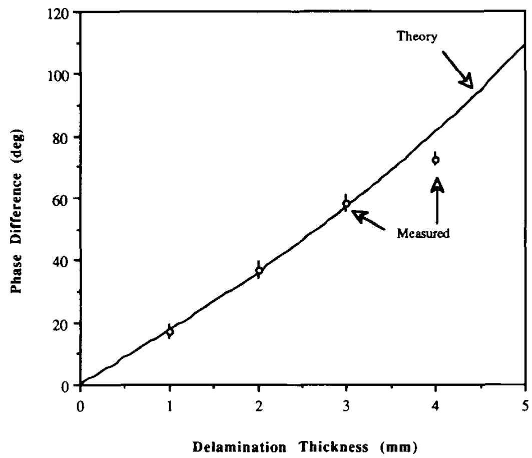

Fig. 5. Comparison of theory and experimental results at 10 GHz, d_1 = 25.45 mm, ϵ_1 = 3.32 (synthetic rubber), d_3 = 26.2 mm, ϵ_3 = 2.53 (plexiglass), and ϵ_2 = 1 (air).

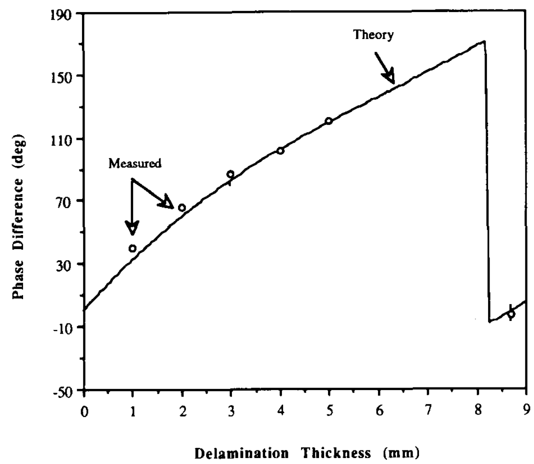

Fig. 6. Comparison of theory and experimental results at 10 GHz, d_1 = d_3 = 26.2 mm, ϵ_1 = ϵ_3 = 2.35 (plexiglass), and ϵ_2 = 1 (air).

plate of thickness d_1 = 25.45 mm with a dielectric constant of ϵ_1 = 3.32 and a plexiglasss plate of thickness d_3 = 26.2 mm with a dielectric constant of ϵ_3 = 2.53 backed by a metal plate. Using the experimental setup discussed earlier, $\Delta\phi$ was measured as a function an air gap (ϵ_2 = 1) thickness between these two plates. Table I shows the comparison between the theoretical and experimental results.

Fig. 5 illustrates the results shown in Table I (the vertical lines through the circles indicate the measurement standard deviations), and clearly the agreement between the theory and measurement is very good.

In the second experiment at 10 GHz, two identical plexiglass plates similar to that used in the first experiment were used to test the 180° phase reversal associated with $\Delta\phi$. Table II shows the comparison of the theoretical and experimental results for this case.

Fig. 6 illustrates the results shown in Table II, and again a very good agreement between the theory and measurements is obtained.

These results illustrate the potential of this technique for detection and evaluation of delaminations. The difference between the theoretical and measured results can be reduced by conducting more measurements (i.e., obtaining more independent samples), and by a more accurate knowledge of the dielectric slab permittivities. Fig. 6 shows that if the delamination thickness happens to be where the transition in the $\Delta\phi$ versus delamination thickness curve occurs (i.e., at ~8.2 mm), one may not be able to determine the thickness correctly. In this case it will be necessary to vary the frequency of operation slightly to alleviate this problem.

VI. CONCLUSIONS

The theoretical development of a microwave nondestructive technique for detection and evaluation of disbonding and delamination in layered-dielectric-slabs backed by a conducting plate was given. Using the properties of the phase of the effective reflection coefficient for a signal illuminating such a medium and reflected by the metal plate, it was shown that delaminations of very small thicknesses can be detected and evaluated. The characteristics of this phase as a function of delamination dielectric constant and thickness, slab dielectric constant and thickness, and frequency was explored. In general it was concluded that higher frequencies, thicker dielectric plates, and lower values of delamination dielectric constants tend to produce better results for evaluating the nature of a delaminated layer. The results of several experiments that were conducted, showed very good agreement with the theory. This technique is simple and easily applicable to environments where these types of layered-slabs are used.

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