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Calibration and Measurement of Dielectric Properties of Finite Thickness Composite Sheets with Open-Ended Coaxial Sensors

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Abstract— **The application of open-ended coaxial sensors for dielectric measurement of finite thickness composite sheets is studied. Expressions for calculation of the complex aperture admittance for two geometries are presented. These expressions are used to calculate the dielectric constant of infinite half-space as well as finite thickness slabs. A more efficient method of such calculations, using a personal computer, for low to medium loss dielectrics is demonstrated. The question of when a dielectric layer may be considered as infinitely thick is also addressed, and examples are presented. A different calibration technique (compared to the conventional ones) is described and successfully implemented. This calibration technique utilizes a dielectric sheet with known dielectric properties and thickness. Measurements for different airgaps between the open-ended coaxial line and the dielectric sheet are used to perform and enhance the calibration. The results of this calibration technique and several subsequent measurements are presented and discussed.**

I. Introduction

OPEN-ENDED coaxial line sensors have been widely used for nondestructive measurement of material dielectric properties [1]–[28] since they offer a relatively small interrogation area and possess wide band characteristics. Usually, open-ended coaxial sensors are utilized in medicine for in-vivo measurement of biological tissue properties. They are also used for dielectric property characterization of composites in process and quality control applications [22], [23]. The dielectric material under test is often considered to be infinitely thick when using this probe for dielectric property measurements. This is primarily due to the fact that unlike other probes, such as open-ended waveguides, the radiation characteristics of an open-ended coaxial line does not provide for considerable radiation into a generally lossy dielectric material [29], [30], [33]. However, as will be shown in this paper, the assumption of an infinitely thick sample may not always hold true.

A finite thickness dielectric material may consist of several layers of different dielectrics. Moreover, the existence of an airgap between the open-ended sensor and the material under test may substantially increase measurement sensitivity (particularly when measuring thickness of a dielectric) [26], [30]. These are why the study of a multilayered dielectric composite is important. It is also a well known fact that it is difficult to obtain a good contact between the coaxial sensor and a dielectric sheet when making these types of measurement. The introduction of a fixed airgap between the two alleviates this problem as long as the presence of the airgap is theoretically accounted for. Thus, the consideration of a dielectric composite made of several layers (one being an airgap) is important. Also, measuring and monitoring local dielectric property variations may be used to detect voids, porosity and delamination in composite materials (other examples of a multilayered dielectric). Moreover, once the dielectric properties of a sheet material is known, it is possible to detect its thickness variation [29].

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In this paper dielectric property characterization of finite thickness dielectric composites along with an improved calibration procedure for open-ended coaxial sensors are described. A technique to speed up the calculation process for measuring the dielectric properties is also presented. A calibration procedure using multiple measurement points corresponding to different airgap distances is described and successfully implemented. Finally, measurement results for several finite thickness dielectric specimens are reported.

II. Calculation of the Dielectric Constant

The detailed underlaying theoretical analysis of radiation from an open-ended coaxial line into stratified dielectrics, which is used here, has been developed by Bakhtiari *et al.*, [29]. Consider a coaxial line filled with a dielectric with permittivity ε_{r_c} and with an inner conductor radius a and an outer conductor inner radius b as shown in Fig. 1. The coaxial line is radiating into a layered dielectric composite. Fig. 1 shows the specific geometry pertinent to the discussion of this paper. A dielectric layer with finite thickness is preceded by an airgap and followed by an infinite half-space of another dielectric (free-space). A common infinite half-space is realized when $d_1 = 0$ and $d_2 = \infty$ with a dielectric constant of $\varepsilon_{r_2} = \varepsilon_r$. Neglecting higher order modes, the complex aperture admittance of an open-ended coaxial line radiating into an N-layer dielectric composite is given by the following general expression [29]:

$$y_S = \frac{1-R}{1+R} = \frac{\varepsilon_{r_1}}{\sqrt{\varepsilon_{r_c}}\ln\left(\frac{b}{a}\right)}\int_0^\infty \frac{\left[J_0(k_0\zeta b) - J_0(k_0\zeta a)\right]^2}{\zeta}\mathcal{F}(\zeta)d\zeta \quad (1)$$

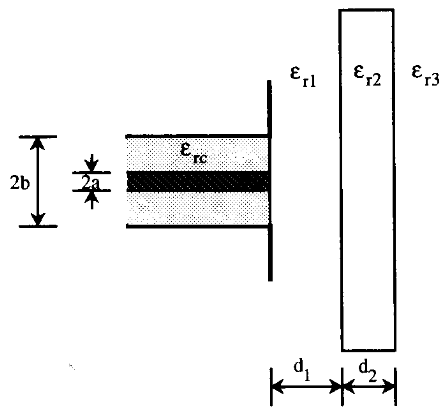

Fig. 1. Cross section of coaxial line radiating into a two-layer media terminated by infinite half-space.

where $\mathcal{F}(\zeta)$ is an unknown function which is to be evaluated by forcing the boundary conditions, ζ is the integration variable, R is the complex reflection coefficient ($R = \Gamma e^{j\phi}$), k_0 is the free-space wave number, and $\varepsilon_{r_1} = \varepsilon'_{r_1} - j\varepsilon''_{r_1}$ is the relative complex dielectric constant of the first layer (closest to the aperture).

A. Infinite Half-Space Case

The case of radiation into an infinite half-space of a dielectric with $d_1 = 0$, $d_2 = \infty$ and with dielectric constant $\varepsilon_{r_2} = \varepsilon_r$ will be considered first. This case represents an important part of practical measurements and calibration procedures. The function $\mathcal{F}(\zeta)$ in this case takes the following simple form:

$$\mathcal{F}(\zeta) = \frac{1}{\sqrt{\varepsilon_r - \zeta^2}}. \tag{2}$$

Calculating the value of the dielectric constant, ε_r, from the measured complex reflection coefficient, R, is referred to as an inverse problem. The speed with which (1) can be numerically integrated dictates how quickly the dielectric constant can be estimated. For the dielectric constants of generally lossy materials which are within the scope of this study, the integration can be carried out efficiently on a personal computer.

To speed up the calculation time a procedure similar to the one described in [30] may be used. To illustrate this consider Fig. 2(a) and (b) which show the return loss ($\mathrm{RL} = -20\log\Gamma$) and phase of the reflection coefficient, ϕ, for an open-ended coaxial line with $a = 1.18$ mm and $b = 3.62$ mm as a function of the loss tangent ($\tan\delta = \varepsilon'_r/\varepsilon''_r$) for several values of the real part of the dielectric constant (ε'_r). All of the forthcoming calculations and measurements are performed with this coaxial line and at a frequency of $f = 5$ GHz. Considering Fig. 2(a), it may be concluded that for high values of ε'_r, the RL changes negligibly with increasing $\tan\delta$, while for low and medium dielectric constants this change is substantial. Fig. 2(b) shows that ϕ is quite constant for $\tan\delta$ values of up to ≈0.4 irrespective of the value of ε'_r. As a result, an initial

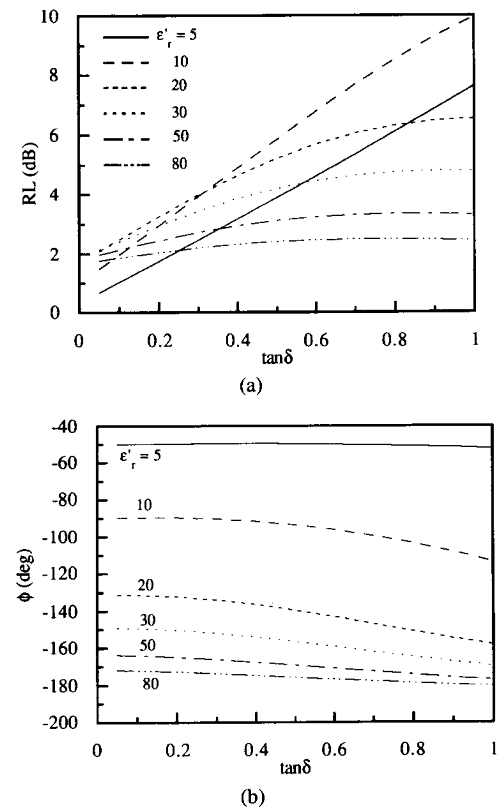

Fig. 2. Return loss (a) and phase (b) versus loss tangent for different values of the real part of the dielectric constant. The dielectric is considered with infinite thickness.

value of ε'_r may be estimated from the measured phase fairly accurately. ε''_r may then be obtained from the measured value of RL. In summary, the real part of the dielectric constant is estimated from the measured phase value. Then, the imaginary part of the dielectric constant is calculated from the return loss measurement utilizing the already found real part of the dielectric constant. This iterative process is repeated until a prescribed accuracy is reached. This calculation is shown to converge very rapidly (usually after three iterations).

For the case of very lossy materials, for which ϕ can no longer be considered constant, another technique should be applied. Consequently, the following system of equations must be solved simultaneously:

$$\begin{cases} \mathrm{RL}(\varepsilon_r) - \mathrm{RL}_m = 0 \\ \phi(\varepsilon_r) - \phi_m = 0 \end{cases} \tag{3}$$

where the index m denotes the measured values, and $\mathrm{RL}(\varepsilon_r)$ and $\phi(\varepsilon_r)$ are calculated from (1). A good practice is to find the values of the dielectric constant that best fit (3) instead of trying to find an exact solution for the system. Of course, this procedure is slower than the previous case, but it still may be executed on a personal computer reasonably quickly. These numerical techniques may also be used for finite thickness dielectrics as it will be discussed later. For such cases the speed of calculations will also depend on the thickness of the dielectric layer.

An important conclusion may be drawn when considering the infinite half-space case. Fig. 3(a) and (b) show the RL and ϕ as a function of ε_r' for different values of $\tan\delta$. It is evident that for high values of ε_r' there is hardly any change in the values of the RL and ϕ. Hence, calibration of open-ended coaxial probes with liquids having high ε_r' may not render high degree of accuracy. Application of high dielectric liquids is the prominent calibration practice for open-ended coaxial lines. As it will be discussed later, one way to improve calibration accuracy is to use multiple thicknesses of a dielectric sheet or to vary the airgap.

B. Finite Thickness Case

In many practical environments dielectric layers with finite thicknesses are encountered. This is depicted in Fig. 1 with the dielectric layers having thicknesses d_1 and d_2 with corresponding dielectric constants of ε_{r_1} and ε_{r_2}. The explicit expression for $\mathcal{F}(\zeta)$ when the third layer is an infinite half-space extending in the z-direction with a dielectric constant of ε_{r3} is given by

$$\mathcal{F}(\zeta) = \frac{1}{\sqrt{\varepsilon_{r_1} - \zeta^2}} \left(\frac{1+\rho_1}{1-\rho_1} \right) \tag{4}$$

where

$$\rho_1 = \frac{\kappa_1 - \beta_2}{\kappa_1 + \beta_2} e^{-j2k_0 d_1 \sqrt{\varepsilon_{r_1} - \zeta^2}}$$

$$\kappa_1 = \frac{\varepsilon_{r_2}\sqrt{\varepsilon_{r_1} - \zeta^2}}{\varepsilon_{r_1}\sqrt{\varepsilon_{r_2} - \zeta^2}}$$

$$\beta_2 = \frac{1 - \rho_2 e^{j2k_0 d_1 \sqrt{\varepsilon_{r_2} - \zeta^2}}}{1 + \rho_2 e^{j2k_0 d_1 \sqrt{\varepsilon_{r_2} - \zeta^2}}}$$

$$\rho_2 = \frac{\kappa_2 - 1}{\kappa_2 + 1} e^{-j2k_0 (d_1 + d_2)\sqrt{\varepsilon_{r_2} - \zeta^2}}$$

$$\kappa_2 = \frac{\varepsilon_{r_3}\sqrt{\varepsilon_{r_2} - \zeta^2}}{\varepsilon_{r_2}\sqrt{\varepsilon_{r_3} - \zeta^2}}.$$

The calculation of the dielectric constant for this case may be speeded up for low and medium lossy dielectrics in a similar manner as described for the infinite half-space case. In this case the speed of calculation and scope of applicability will not only depend on the coaxial line geometry, frequency of operation and the dielectric constant, but also on the range of thicknesses of the dielectric layer. For layers with high dielectric constants (both real and imaginary parts) the system described in (3) must be solved in the same manner as explained earlier.

III. Airgap Backed by a Finite Thickness Dielectric Versus Airgap Backed by an Infinitely Thick Dielectric

A basic question, in measurements and calculations, is whether the sample under test has a finite thickness or whether it may be considered as an "*infinite*" sample. This may be checked experimentally by placing a shorting plate behind the sample and monitoring any changes in the measured quantities. It is obvious that the "*finiteness*" is a function of the coaxial line geometry, frequency and the dielectric constant of the sample. For a given coaxial line sensor and an operating frequency (or range of frequencies) it is possible to perform calculations for a range of dielectric constants and arrive at a thickness that may be large enough to be considered an infinite half-space.

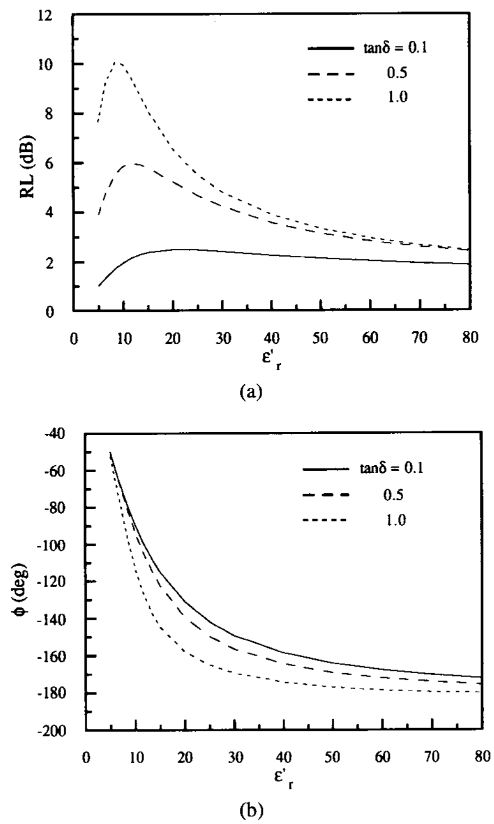

Fig. 3. Return loss (a) and phase (b) versus the real part of the dielectric constant for different loss tangents. The dielectric is considered with infinite thickness.

An illustration of such a calculation is given here for which the complex reflection coefficient versus an airgap distance between the coaxial sensor and the dielectric sheet with $\varepsilon_{r_2} = 5.8 - j0.4$ is calculated (this material is used in the measurements later on). The geometry in this case is that of Fig. 1 where the first and the third dielectric layers are free-space, and the second layer is the dielectric (ε_{r_2}). The RL and the ϕ as a function of the airgap distance for several thicknesses of the dielectric sheet are presented in Fig. 4(a) and (b), respectively. From these figures it may be concluded that return loss approaches its infinite half-space value for larger values of d_2 than does the phase. Obviously, for this sample a thickness of around 5 mm can not be considered as an infinite half-space. A convenient way to determine which thickness may be considered as an infinite half-space for this type of measurements is to perform the calculations for fixed, small airgaps values ($d_1 = 0.127$ mm and $d_1 = 0.254$ mm which were used in our actual measurements) and a changing thickness of the dielectric layer (d_2). Such a calculation is necessary only for the return loss since it defines the infinite half-space thickness [Fig 4(a)]. Fig. 5 shows the return loss

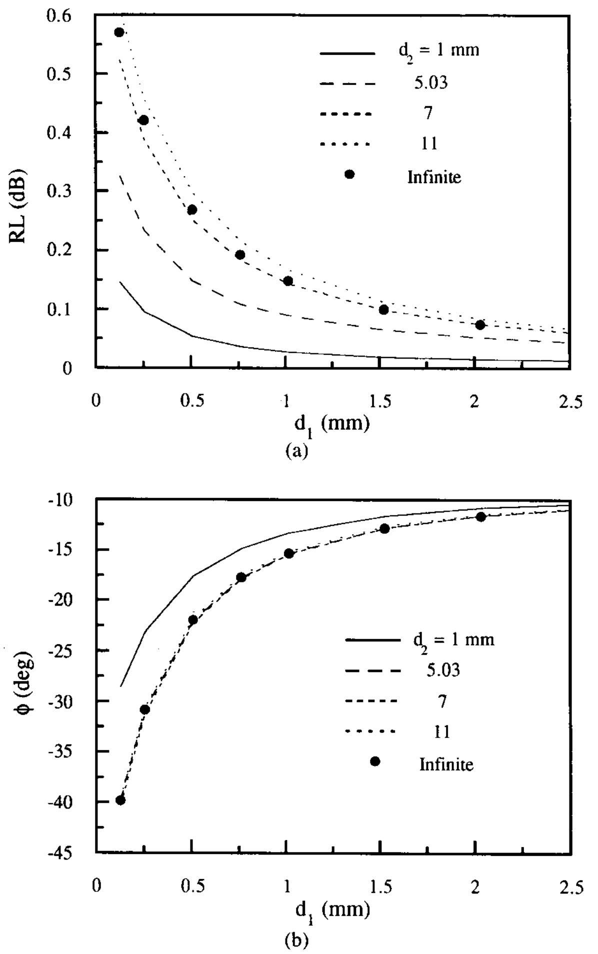

Fig. 4. Return loss (a) and phase (b) versus air gap (d_1) for different thicknesses (d_2) of the dielectric layer ($\varepsilon_r' = 5.8 - j0.4$).

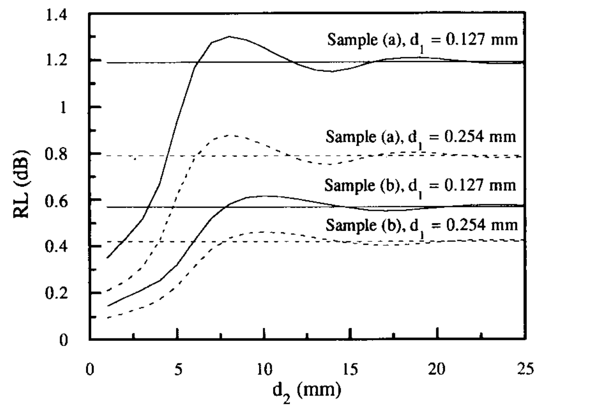

Fig. 5. Return loss versus air gap (d_1) for two fixed air gaps $d_1 = 0.127$ mm and $d_2 = 0.254$ mm and two dielectric constants: (a) $\varepsilon_r' = 9.08 - j1.05$; (b) $\varepsilon_r' = 5.8 - j0.4$.

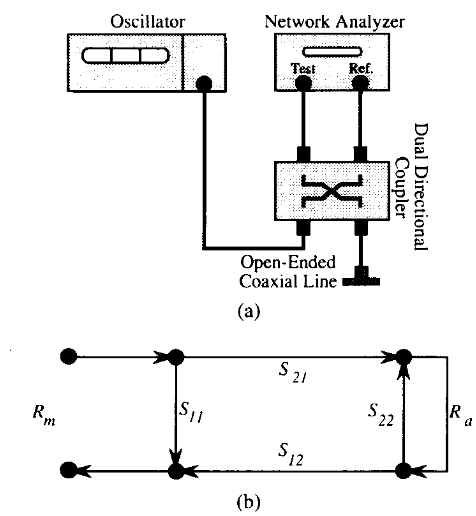

Fig. 6. (a) Measurement apparatus. (b) Simplified flow graph of the measurement apparatus.

versus the thickness of the dielectric sheet for two fixed airgaps and two different dielectric constants, namely sample (a) with $\varepsilon_{r_2} = 9.08 - j1.05$ and sample (b) with $\varepsilon_{r_2} = 5.8 - j0.4$. These dielectric samples were later used in our measurements. The horizontal lines represent the infinite thickness value for each dielectric constant. This value is calculated using the two layer model, e.g. the first layer is the airgap, and the second (infinite) layer is the dielectric sample. Depending on the desired accuracy the "*infinite*" thickness may be considered when d_2 is at least 20 mm. The conclusion from this numerical simulation is that for an unknown dielectric layer it is better to use the finite thickness formulation.

IV. Calibration

Fig. 6(a) shows an experimental setup that was used in our measurements. It is well known that the measured reflection coefficient is different from the actual (or true) reflection coefficient (of the measured dielectric sample) at the reference plane [31]. The reflection coefficient, R_m, measured by the network analyzer is different than the desired (actual) reflection coefficient, R_a, at the open-ended plane of the coaxial line. To calculate the actual reflection coefficient the S-parameters should be determined using a calibration procedure. The widespread calibration procedure includes measurement of a short circuit, open circuit and some known load which is usually a liquid with well-known dielectric properties. It is recognized that the choice of the reference liquid affects the measurement uncertainty in any subsequent dielectric measurements [4]. Usually this is attributed to the frequency dependence of the calibration liquid dielectric properties. Furthermore, the calibration accuracy when using a high dielectric and high loss material is less than when using a medium or low loss dielectric or liquid [see Fig. 3(a) and (b)].

One way to accomplish a more precise calibration with one known load, is multiple measurements using different distances between the sensor and a short-circuiting plate immersed in the liquid [20]. However, as the results of our investigation indicated, it is also possible to use a finite thickness dielectric layer with a known dielectric constant and conduct multiple measurements using a varying airgap between the sensor and the dielectric layer.

V. Measurement Results

The measurements were performed using an HP-8410 network analyzer at a frequency of 5 GHz with a coaxial sensor

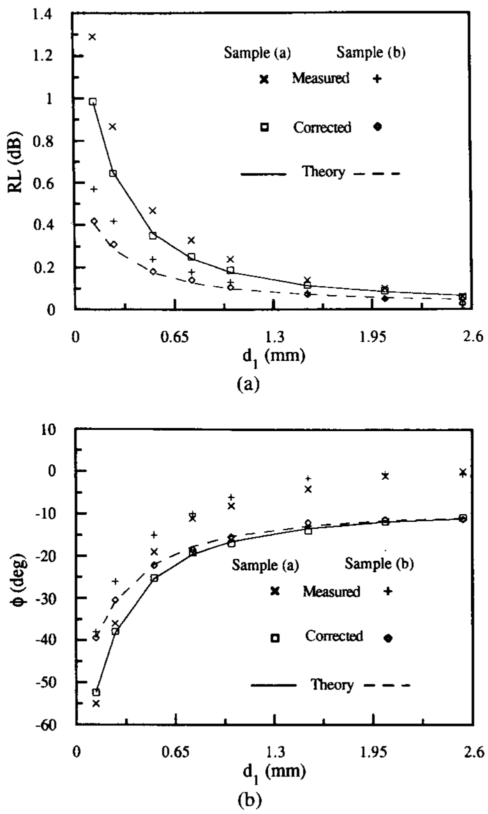

Fig. 7. Return loss (a) and phase (b) versus air gap (d_1) for the two samples (a) and (b). The measurement points are denoted with (x,+), the corrected points are denoted with (square, diamond) and the theoretical curves (solid, dash).

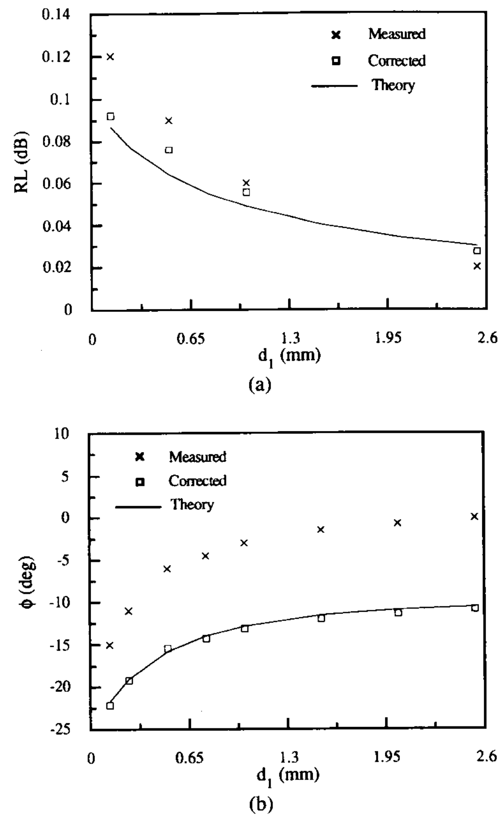

Fig. 8. Return loss (a) and phase (b) versus air gap (d_1) for Plexiglass. The measurement points are denoted with (x), the corrected points are denoted with (square) and the theoretical curves (solid).

with $a = 1.18$ mm and $b = 3.62$ mm. In these measurements three samples were used:

a) a resistive strip (carbon black rubber) with thickness 5.15 mm and $\varepsilon_r' = 9.08 - j1.05$,
b) a resistive strip with thickness 5.03 mm and $\varepsilon_r' = 5.8 - j0.4$ and
c) a Plexiglass plate with thickness 25.8 mm and $\varepsilon_r' = 2.6 - j0.02$.

The dielectric constants of samples (a) and (b) were measured with the technique described in [32], and for the purpose of this investigation they are called "*actual values*". For the calibration procedure the airgap distance between the coaxial sensor and the samples was changed to obtain multiple measurement points using a precise mechanical device (described in [33]). For each airgap the complex reflection coefficient, R_m, was measured. A measurement point for a large airgap constitutes an open-circuit load which is usually considered as a standard load for calibration.

Fig. 6(b) shows a simplified flow graph of the measurement setup [31] which results in (5) once a short-circuit load is used to eliminate the explicit influence of S_{12} and S_{21} from (5):

$$R_a = \frac{R_m - S_{11}}{1 + S_{11} + S_{22}(1 + R_m)}. \quad (5)$$

The finding of the remaining S-parameters was based on obtaining the best fit of the measured values of the reflection coefficient R_m to the calculated (actual) ones R_a. Fig. 7(a) and (b) depict the results of the calibration procedure using sample (a) as the calibrating load. Subsequently, the S-parameters were obtained. Then, the actual values for the RL and ϕ were recalculated (corrected) from the measured values of samples (a) and (b) and compared to the theoretical curves obtained by using the actual values of ε_r. The deviation of the recalculated measurement points around the theoretical curves for sample (a) gives an indication of the calibration accuracy [which is very good as indicated in Fig. 7(a) and (b)]. The results further indicate the validity of calibration using one load, and obtaining good results for a different finite thickness dielectric load. The same results for Plexiglass are presented in Fig. 8, and once again good agreement between the theoretical and corrected [i.e. calibrated with sample (a)] results is obtained. Plexiglass, which has a well-known dielectric constant, is not a good calibrating load for this calibration technique since it offers very little change of the return loss as a function of airgap.

Finally, the dielectric constants of the samples were obtained using the fitting procedure which involves finding the best fit of the dielectric constant value to the theoretical RL and ϕ using R_a. This provides for averaging of the measured quantities which results in improved measurement confidence. The speed of this fitting routine depends on the number of measurement points (i.e. airgap distances). Table I shows the results of the above procedure, once using sample (a) as the calibrating load and another time using sample (b).

TABLE I
MEASURED ε_r OF THREE SPECIMENS CALIBRATED WITH SAMPLES (A) AND (B)

Dielectric Sample	Actual Value	Calibrated w/ (a)	Calibrated w/ (b)
Sample (a)	9.08 - j1.05	-	9.01 - j0.98
Sample (b)	5.80 - j0.4	5.85 - j 0.45	-
Plexiglass	2.60 - j0.02	2.64 - j0.024	2.64 - j0.018

There are several sources of errors in this type of measurements. First it should be noted that errors in calibration will result in erroneous dielectric constant measurements. Therefore, calibration must be checked prior to each measurement cycle. The tip of the coaxial sensor should be flat and perpendicular to the axis of the coaxial line. Temperature variation may also cause the inner (or outer) conductor to extend beyond the aperture of the coaxial line. Depending on the way the coax has been manufactured, this effect may be permanent as reported in [21]. In the approach used in this paper, the contact problem associated with the way these measurements are normally made is alleviated (i.e., an existing airgap). However, one must be careful when measuring the airgap distance since this could now become a source of measurement error. This error is minimized by averaging several measurements for each airgap. We also accounted for the errors associated with the apparatus by adding the measurement uncertainties for the RL (0.006 dB) and ϕ (0.3°) [13], [31] and subsequently recalculated the dielectric constant. To illustrate the effect of these errors the dielectric constant of sample (b), calibrating with sample (a), was recalculated to be $\varepsilon_r = 5.846 - j0.4058$ (compared to $\varepsilon_r = 5.80 - j0.4$). The result show that for the real part the difference is negligible and for the imaginary part is less than 2 percent. It must be noted that this error will be larger for materials with lower dielectric constants.

VI. CONCLUSION

Different aspects of measurement of dielectric properties with an open-ended coaxial sensor were discussed. Depending on the coaxial line geometry and frequency of operation, for low to middle loss dielectrics it is possible to accelerate considerably the routine for finding the dielectric constant. Discussion of when a finite thickness dielectric layer may be considered to be an infinite half-space was addressed. A different calibration technique using a single dielectric sheet was implemented. The calibration was performed by measuring the complex reflection coefficient at the sensor aperture for multiple airgap distances. The measurement apparatus S-parameters were found from the calibration measurements using a simple best fit procedure. Subsequently, dielectric measurements were performed on three dielectric specimens, and the results compared well with their actual values. Several sources of errors in this type of measurement were discussed. The influence of these errors on the measurements showed to be insignificant.

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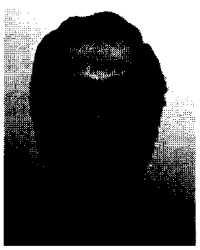

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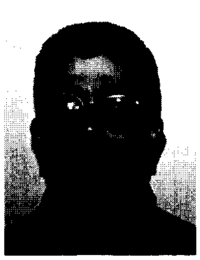

Nasser Qaddoumi was born January 24, 1996, in Nablus in Palestine, and received the B.S.E.E. degree in electrical engineering from the United Arabs Emirates University and the M.S.E.E degree form Colorado State University where he is currently pursuing the Ph.D. degree.

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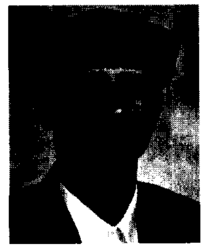
Mr. Qaddoumi is a member of Eta Kappa Nu.



Sasan Bakhtiari (S'89–M'91–SM'94) was born in 1962 in Tehran, Iran. He received the B.S.E.E. degree from Illinois Institute of Technology, Chicago in 1983, the M.S.E.E. from the University of Kansas, Lawrence in 1987 and the Ph.D. degree in electrical engineering from the Colorado State University, Ft. Collins in 1992.

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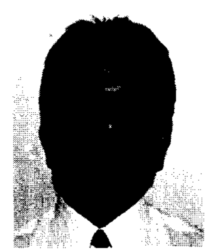

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