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Dielectric Plug-Loaded Two-Port Transmission Line Measurement Technique for Dielectric Property Characterization of Granular and Liquid Materials

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***Abstract*—There are numerous dielectric property characterization techniques available in the microwave regime each with its own uniqueness, advantages and disadvantages. The two-port completely-filled waveguide (transmission line) technique is a robust measurement approach which is well suited for solid dielectric materials. In this case, the dielectric material can be relatively easily machined to fit inside the waveguide and the subsequent measurement of the scattering parameters of this two-port device renders the dielectric properties of the material filling the waveguide. However, this technique is not well suited for measuring the dielectric properties of granular and liquid materials. These materials are used in the production of various composites which are increasingly replacing the use of metals in many environments. If this technique is directly applied to these types of materials, several approximations either in the measurement apparatus or the formulation must be made. To overcome this problem, this paper describes a modification to this measurement technique utilizing two dielectric plugs which are used to house the granular or the liquid dielectric material. In this approach no approximation to the measurement apparatus is made while the presence of the plugs are fully accounted for in the derivations. Using this technique, the dielectric properties of cement powder, corn oil, antifreeze solution and tap water, constituting low- and high-loss dielectric materials (granular and liquid) were measured. In addition, the important issue of measurement uncertainty associated with this technique is also fully addressed. The issue of optimal choice of various measurement parameters is also discussed as it relates to the measurement uncertainty.**

***Index Terms*— Dielectric constant, granular, liquid, measurement uncertainty, scattering parameters.**

I. INTRODUCTION

IN THE microwave and millimeter wave regime, the interaction of an electromagnetic wave with a dielectric medium is strongly influenced by the frequency dependent electrical and magnetic properties of the medium. With the ever increasing utilization of composite materials, there is a growing industrial demand for dielectric characterization of these materials and their constituents for design, manufacturing and quality control purposes. By knowing the dielectric properties of a material, it is possible to deduce information about its physical and chemical properties. Conversely, by knowing the dielectric properties of the constituents of a composite material (e.g., resin binder, epoxy and glass in glass reinforced composites) one may be able to monitor for the desired dielectric properties of the composite during its manufacturing. Therefore, there is an ever increasing demand for accurate dielectric characterization techniques capable of robust measurement of the dielectric properties of various composite constituents including liquids and granular materials.

Currently, there are numerous available microwave dielectric property measurement techniques. Several open-ended rectangular waveguide [1]–[4] and coaxial line [5]–[8] techniques have been developed for the nondestructive determination of the dielectric properties of infinite half-space materials (solids and liquids) and finite-thickness layered materials. In these cases a planar measurement surface is required. Moreover, improper contact between the probe aperture and the material surface can result in significant errors in measuring its dielectric properties. Also, for relatively low-loss materials the infinite half-space size requirements may be difficult to achieve, particularly when using open-ended waveguide apertures. For low-loss or lossless materials resonant cavity methods render accurate measurement results, however these methods require meticulous sample preparation, and are conducted in a narrow range of frequency [9]. Conversely, cavity methods are not well suited for relatively lossy materials. A more general approach, to overcome these limitations, is short-circuited or two-port transmission line techniques in which a dielectric specimen is inserted in a section of a short-circuited or a two-port transmission line. Of these, the extensively used coaxial line [10]–[12] and rectangular waveguide [13]–[16] techniques are noteworthy. In general, these techniques make use of the reflected and/or transmitted waves by and through a dielectric-filled transmission line in order to analytically or numerically determine the dielectric properties of the material. These techniques are straightforward when applied to solid dielectric specimens, and can be conducted over a relatively large frequency range. Solid dielectric specimens can be relatively easily cut to fit inside transmission lines such as waveguides. However, when measuring granular and liquid

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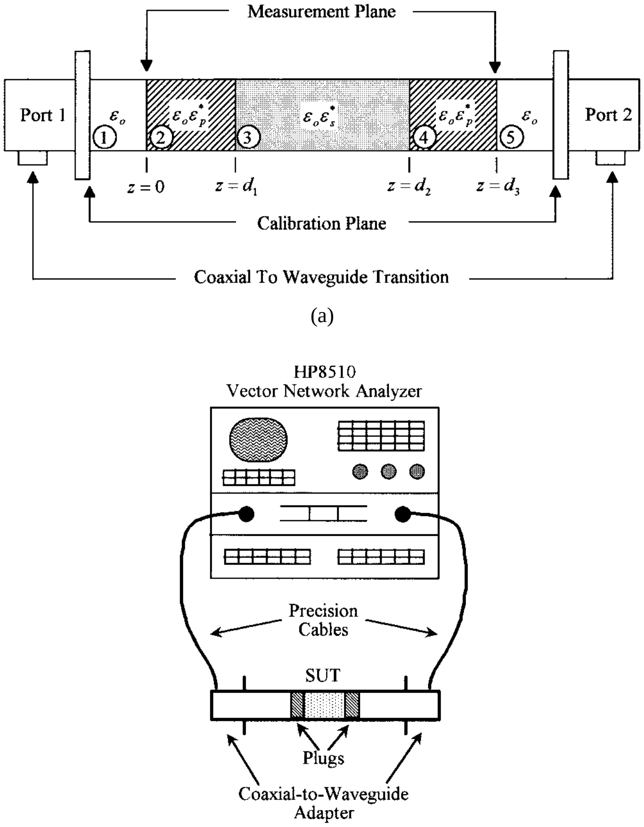
materials, these techniques generally require some form of approximation in the physical nature of the measurement apparatus and its subsequent forward and inverse problem formulations, or they require that the dielectric specimen be low-loss [12]. In most attempts at measuring the dielectric properties of liquids using these techniques, the measurement setup is commonly fixed in a vertical position or a dielectric plug possessing properties close to that of air is used [16], [17]. Subsequently, the influence of the dielectric plug, on the measurements, is assumed to be negligible and is not taken into account in the theoretical formulation of the problem [16]. When the measurement setup is vertically positioned to hold liquid specimens, a meniscus can form at the top, thereby deforming the measurement plane and contributing to an additional source of measurement error [17]. For the case of granular specimens, planar measurement planes within the transmission line may not also be easily achieved, since it is tedious to compact the material in such a way that the measurement plane is exactly normal to the direction of propagation of the incident wave. This also results in errors when calculating the dielectric properties of the granular material. Other methods combining coaxial waveguides feeding circular waveguides have been successfully used to measure the dielectric properties of liquid materials [18], [19]. However, the dynamic range of the reflection coefficient measurement, used to determine the properties of the dielectric material, is very small (e.g., $0.96 < |\Gamma| < 1$) [18]. Hence, small errors in the reflection coefficient measurement due to calibration, the precision of the measurement setup (e.g., network analyzer) and accurate machining of the coaxial sample holder can result in significant errors when determining the dielectric properties of a specimen.

To overcome the difficulties mentioned here, and yet obtain accurate dielectric properties of granular and liquid dielectric materials, a waveguide-based two-port transmission line technique is developed which uses two identical dielectric plugs, one on each side of the liquid or granular dielectric sample, so that there is no meniscus or irregularities in the measurement plane [20], [21]. Unlike previous approaches, the presence of the plugs is fully taken into account in the formulation, and there is no requirement for the plugs to have dielectric properties close to that of air. In addition, this type of measurement setup has the advantage of using “off-the-shelf” waveguide components, and does not require tedious machining similar to that encountered when using coaxial resonators. In this paper, an overview of the theoretical derivation of this dielectric plug-loaded two-port transmission line measurement technique, and the important issue of measurement uncertainty analysis are presented.



(a)

(b)

Fig. 1. (a) Geometry of the measurement setup for the two-port plug-loaded transmission line technique and (b) S-parameter measurement setup using HP8510B vector network analyzer.

II. THEORETICAL APPROACH

The geometry of the problem is shown in Fig. 1(a). In this setup, two dielectric plugs possessing identical lateral dimensions (equal to the rectangular waveguide cross-section), length and relative dielectric properties (ε_p^*) are used. The air-filled waveguide sections (regions 1 and 5) are included here, in order to take into account any possible offset between the calibration plane and the measurement plane. However, the measured scattering parameters can easily be referenced back to the measurement plane. In this fashion, the geometry is symmetrical about the measurement planes, which greatly facilitates the derivation of the forward formulation. The specimen, whose relative dielectric properties are to be measured (ε_p^*), is then pressed between the two plugs producing no air gap, meniscus or irregularities in the measurement plane. The dielectric properties of the plugs and their lengths should be chosen such that they cause minimal reflection of the wave incident on the specimens under test (SUT).

As the incident electromagnetic wave travels from one port of the setup to the other, it encounters four discrete boundaries produced by the five distinct regions shown in Fig. 1(a). At each boundary, the incident wave is partially reflected and partially transmitted through. The amplitude and phase of the reflected and transmitted waves in each region vary as a function of the dielectric properties of each of the materials filling that region, its length and the frequency of operation. Hence, the first step in this theoretical derivation is to express the measurable scattering parameters (e.g., the S-parameters), as a function of the dielectric properties and lengths of the SUT and the plugs and the frequency of operation. This is done through appropriate matching of the tangential electric and magnetic fields at all boundaries. Once the S-parameters are solved for, a sequence of algebraic operations is performed to express the electrical properties of the SUT as a function of the measured S-parameters. It is important to note that since it is assumed that both the SUT and the plugs completely fill the waveguide cross-section (i.e., no air gaps present between the specimen and the walls of the waveguide), no higher-order modes need to be considered in the formulation.

In a fashion similar to that developed by Nicolson–Ross [13] and Weir [14] (known as the NWR procedure), appropriate matching of the tangential electric and magnetic fields at all boundaries yields the following relationships:

$$S_{21} + S_{11} = \frac{(T_1^2\Gamma_2 + T_1^2T_2 + T_2\Gamma_1\Gamma_2 + \Gamma_1)}{(T_1^2T_2\Gamma_1 + T_1^2\Gamma_1\Gamma_2 + T_2\Gamma_2 + 1)} = V_1 \quad (1)$$

$$S_{21} - S_{11} = \frac{(T_1^2\Gamma_2 - T_1^2T_2 - T_2\Gamma_1\Gamma_2 + \Gamma_1)}{(T_1^2T_2\Gamma_1 - T_1^2\Gamma_1\Gamma_2 + T_2\Gamma_2 + 1)} = V_2 \quad (2)$$

$$\Gamma_1 = \frac{Z_p + Z_o}{Z_p - Z_o} \quad (3)$$

$$\Gamma_2 = \frac{Z_s - Z_p}{Z_s + Z_p} \quad (4)$$

$$T_1 = \exp^{-\gamma_p d_p} \quad (5)$$

$$T_2 = \exp^{-\gamma_s d_s} \quad (6)$$

where $S_{11} = |S_{11}|e^{j\theta_{11}}$ and $S_{21} = |S_{21}|e^{j\theta_{21}}$ are the reflection and transmission scattering parameters which can readily be obtained from (1) and (2); Γ_1 and Γ_2 are the reflection coefficients at the air-plugs and the plug-SUT boundaries, respectively; T_1 and T_2 are the exponential propagation coefficients in the plugs and the SUT, respectively; (γ_o, Z_o), (γ_p, Z_p) and (γ_s, Z_s) represent the propagation constants and the wave impedances of the air, plug and SUT-filled regions, respectively; λ_o and λ_c correspond to the free-space and the waveguide cutoff wavelengths; $d_p = d_1$ and $d_s = d_2 - d_1$ are the lengths of the plugs and the SUT; and (ε_p^*, μ_p^*) and (ε_s^*, μ_s^*) are the complex relative to free-space electromagnetic properties of the plug and the SUT, respectively. In this paper, the plugs and the SUT are assumed to be nonferromagnetic (i.e., $\mu_s^* = \mu_p^* = 1$). Also, the complex relative to free-space dielectric properties of the plug and the SUT can be further expressed by their usual real (relative permittivity) and imaginary (relative loss factor) parts (i.e., $\varepsilon_p^* = \varepsilon_p' - j\varepsilon_p''$ and $\varepsilon_s^* = \varepsilon_s' - j\varepsilon_s''$).

III. SOLVING FOR THE ELECTRICAL PARAMETERS

The S-parameters of this dielectric plug-loaded two-port transmission line setup are measured using an HP8510B vector network analyzer, as shown in Fig. 1(b). Each S-parameter measurement is subsequently referenced back from the calibration plane [see Fig. 1(a)] to the measurement plane (i.e., $z = 0$ and $z = d_3$). The dielectric properties of the SUT are then calculated in a two-step process.

Step 1: ε_s^* is calculated via the NWR [13], [14] procedure, shown in (7)–(12) at the bottom of the page.

Step 2: The complex value of ε_s^* obtained from Step 1 is then used as an initial value for a mean square error solving of the following equation [15]:

$$S_{21}^2 - S_{11}^2 = V_1V_2 \quad (13)$$

where V_1 and V_2 are functions of ε_s^* and S_{11}, S_{21} are the measured scattering parameters. The combination of these two steps is designed to alleviate certain numerical instabilities in the dielectric property recalculation process [15], and will hereafter be referred to as the NWR/Baker–Jarvis procedure.

IV. UNCERTAINTY ANALYSIS

In any measurement procedure, there is an inherent error margin associated with the results. This error margin is de-

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S_{11}, S_{21} : measured scattering parameters

$$\Downarrow$$

$$X = \frac{1}{2}\frac{(1 - \Gamma_1^2S_{21}^2 + \Gamma_1^2S_{11}^2 - 2\Gamma_1S_{11})T_1^4 + \Gamma_1^2 - 2\Gamma_1S_{11} + S_{11}^2 - S_{21}^2}{T_1^2(\Gamma_1 - \Gamma_1S_{21}^2 + \Gamma_1S_{11}^2 - \Gamma_1^2S_{11} - S_{11})} \quad (7)$$

$$\Gamma_2 = -X \pm \sqrt{X^2 - 1} \quad (8)$$

$$T_2 = \frac{T_1^2\Gamma_2 + \Gamma_1 - V_1(1 + T_1^2\Gamma_1\Gamma_2)}{V_1(\Gamma_2 + T_1^2\Gamma_1) - T_1^2 - \Gamma_1\Gamma_2} \quad (9)$$

$$\frac{1}{\Lambda^2} = \left[\frac{-j}{2\pi d_s}\ln\left(\frac{1}{T_2}\right)\right]^2 \quad (10)$$

$$\mu_s^* = \mu_p^*\frac{1 + \Gamma_2}{(1 - \Gamma_2)\Lambda\sqrt{\frac{\mu_p^*\varepsilon_p^*}{\lambda_o^2} - \frac{1}{\lambda_c^2}}} \quad (11)$$

$$\varepsilon_s^* = \frac{\lambda_o^2}{\mu_s^*}\left(\frac{1}{\Lambda^2} + \frac{1}{\lambda_c^2}\right) \quad (12)$$

pendent on the uncertainty associated with the measurement of each measurable parameter (i.e., how well one can measure the phase and magnitude of S_{11}, L_s, etc.). To evaluate the total measurement error, a thorough sensitivity analysis needs to be conducted on the measurement procedure so that one can estimate the influence of the measurement uncertainties (i.e., measurement limitations of the technique), and optimize the technique by operating at optimal parameters to minimize measurement error. Based on the theoretical derivation of this technique, it is seen that the measured scattering parameters, the length of the SUT, the dielectric properties and the length of the plugs all contribute to the calculation of the dielectric properties of the SUT. Thus, the sensitivity analysis conducted here is used to analyze the influences of all these variables on the accurate measurement of the dielectric properties of the SUT. Here, sensitivity refers to variation in the solution of ε_s^* given a certain variation in any one of the measurable parameter (e.g., the variation of ε_s^* with respect to any slight variation in $|S_{11}|$), and is mathematically expressed using partial derivatives (e.g., $\partial\varepsilon_s^*/\partial|S_{11}|$). On the other hand, uncertainty refers to the precision with which any single parameter can be measured (e.g., measurement precision for the length of the SUT).

The uncertainty analysis of this dielectric plug-loaded two-port filled-waveguide technique can be accomplished by following a procedure previously used to perform the uncertainty analysis of a two-port transmission line technique by Baker–Jarvis *et al.* [22], which assumes that there are no air gaps between the waveguide walls and the SUT. In the present case, the independent variables contributing to the measurement error associated with ε_s^* are $|S_{11}|$, $|S_{21}|$, θ_{11}, θ_{21}, length of the plug (L_p), length of the SUT (L_s), and the relative permittivity and loss factor of the plug (i.e., ε_p' and ε_p''). Thus, the total contribution of these independent variables to the measurement error of ε_s^* with respect to the relative permittivity and loss factor of the SUT can be expressed as shown in (14) and (15) shown at the bottom of the page, where $\Delta|S_{i1}|$ and $\Delta\theta_{i1}$ are the measurement uncertainty in the magnitude and phase of the scattering parameters, L_1 corresponds to L_p or the length of the plug, and L_2 corresponds to L_s or the length of the SUT, and ΔL_i is the corresponding uncertainty in measuring the plug and the SUT lengths, respectively. The latter values are operator dependent and nowadays, with the more advanced length measurement techniques, these measurement uncertainties can be reduced considerably. In addition, the uncertainties in the scattering parameters ($\Delta|S_{i1}|$ and $\Delta\theta_{i1}$) are dependent upon the specifications of the particular network analyzer used. The detailed mathematical analysis of (14) and (15) can be found in [23].

The total relative uncertainties shown in (14) and (15) can be plotted as a function of the normalized SUT length, with respect to the wavelength in the SUT-filled waveguide, λ_m, for a given frequency of operation. In this way optimal SUT length, resulting in minimal measurement uncertainty, can be determined. Similar results can also be obtained as a function of frequency for a given SUT. In this way, one may optimally choose the measurement parameters (i.e., the sample length or the frequency) which result in maximum measurement accuracy and minimum measurement uncertainty.

When measuring the dielectric properties of solid materials, the preferred method is still that proposed by Baker–Jarvis, *et al.* [22]. This is due to the fact that for a solid SUT there is no need for the plugs, which introduce additional measurement parameters whose corresponding measurement uncertainties must be accounted for. But since it is not practical to measure granular and liquids using this two-port waveguide transmission-line technique, the present technique incorporating two dielectric plugs is preferred for these cases.

V. EXPERIMENTAL UNCERTAINTY ANALYSIS

In this uncertainty analysis, the dielectric properties of cement powder, an antifreeze solution and corn oil were measured at X-band (8.2–12.4 GHz). The dielectric properties of tap water were also measured using this technique at 3 GHz (S-band), and the results were compared to those predicted by well established expressions. These specimens were chosen since they include granular and liquid dielectric materials while possessing a broad range of permittivity and loss factor. Cement powder and corn oil are in the family of low-loss dielectrics since their loss tangent (i.e., $\tan\delta = \varepsilon_s''/\varepsilon_s'$) is much less than one [20]–[23], while antifreeze solution and water are in the family of high-loss materials with greater loss tangent values [24].

A. Uncertainty Analysis for Low-Loss Materials

The dielectric properties of commercially available Portland cement (type II) powder were measured by employing this dielectric plug-loaded two-port transmission line technique. The cement powder was compacted to fill an X-band waveguide sample holder with a length of 10.86 cm which was plugged at both ends with two identical Plexiglass plugs each with a length of 1 cm each resulting in the cement powder sample length of 8.86 cm.

Equation (16) shows that $\partial\varepsilon_s^*/\varepsilon_p^*$ is inversely proportional to the square root of the dielectric properties of the plug. Thus, it

$$\frac{\Delta\varepsilon_s'}{\varepsilon_s'} = \frac{1}{\varepsilon_s'}\sqrt{\sum_{i=1}^{2}\left[\left(\frac{\partial\varepsilon_s'}{\partial|S_{i1}|}\Delta|S_{i1}|\right)^2 + \left(\frac{\partial\varepsilon_s'}{\partial\theta_{i1}}\Delta\theta_{i1}\right)^2 + \left(\frac{\partial\varepsilon_s'}{\partial L_i}\Delta L_i\right)^2\right] + \left(\frac{\partial\varepsilon_s'}{\partial\varepsilon_p'}\Delta\varepsilon_p'\right)^2} \tag{14}$$

$$\frac{\Delta\varepsilon_s''}{\varepsilon_s''} = \frac{1}{\varepsilon_s''}\sqrt{\sum_{i=1}^{2}\left[\left(\frac{\partial\varepsilon_s''}{\partial S_{i1}}\Delta|S_{i1}|\right)^2 + \left(\frac{\partial\varepsilon_s''}{\partial\theta_{i1}}\Delta\theta_{i1}\right)^2 + \left(\frac{\partial\varepsilon_s''}{\partial L_i}\Delta L_i\right)^2\right] + \left(\frac{\partial\varepsilon_s''}{\partial\varepsilon_p''}\Delta\varepsilon_p''\right)^2} \tag{15}$$

seems that the higher are the dielectric properties of the chosen plug, the less is the sensitivity to this parameter.

$$\frac{\partial\varepsilon_s^*}{\partial\varepsilon_p^*} = \frac{1}{2}\frac{\left(\dfrac{1}{\Lambda^2}+\dfrac{1}{\lambda_c^2}\right)}{(1+\Gamma_2)\sqrt{\dfrac{\varepsilon_p^*}{\lambda_o^2}-\dfrac{1}{\lambda_c^2}}}\Lambda(1-\Gamma_2). \qquad (16)$$

However, one must also consider the fact that in this approach low-loss plugs are desired so that most of the microwave energy reaches the SUT without much of the power being absorbed by the plugs, minimizing the error associated with S_{21} measurement [23]. This is also the justification why high-loss plugs are not desirable for this system. Conversely, a plug with very high permittivity and low loss factor (e.g., ceramics) would present significant reflection at the air-plug interface, resulting into less microwave energy reaching the SUT.

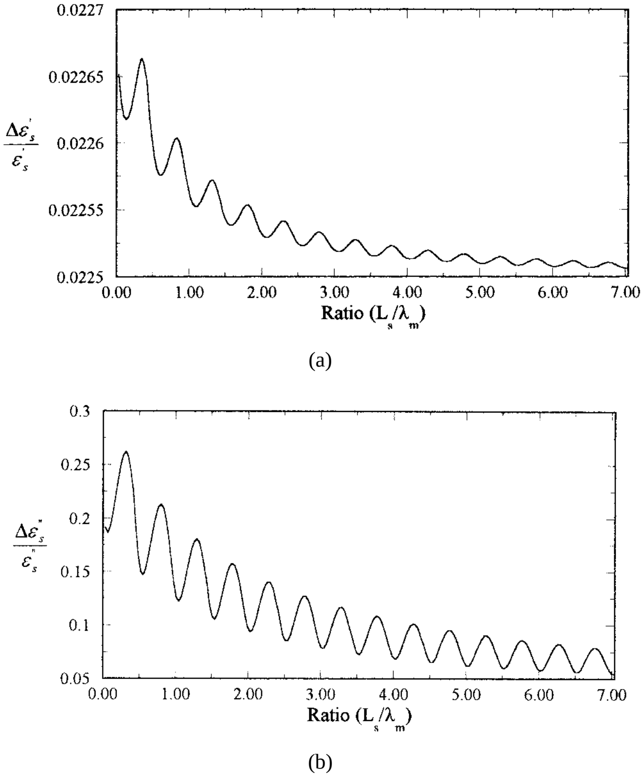
Since it is known that Plexiglass is a low permittivity and low-loss material, it was chosen as the plugs for this system. However, the technique described in this paper is general and can accommodate different plugs (when considering their mechanical properties for cutting and fitting inside a waveguide). Prior to this measurement, using the technique developed in [22], the dielectric properties of the Plexiglass plugs were measured (at 10 GHz $\varepsilon_p' = 2.602$ and $\varepsilon_p'' = 0.0184$), in addition its uncertainty analysis were conducted as well. This information was then used in the dielectric property measurement and the uncertainty analysis of the granular and liquid materials.

In addition, (17) shows that $\partial\varepsilon_s^*/\partial L_p$ is proportional to the negative exponential of the length of the plug. Hence, a longer plug is preferred in order to minimize its respective measurement uncertainty

$$\frac{\partial T_1}{\partial L_p} = -\gamma_p e^{-\gamma_p L_p}. \qquad (17)$$

However, the plug length should also be optimized so that the microwave signal is adequately able to penetrate the whole system. In other words, to choose the dielectric plugs for this technique, the power of the microwave signal, the dielectric properties and the length of the plugs need to be selected such that the signal is still able to penetrate through the whole system. Hence, there is a compromise between minimizing the uncertainty due to the addition of the plugs and increasing the measurement uncertainty due to more ambiguous S-parameters measurements.

Following the procedure outlined in [20], the dielectric properties of the cement powder were measured as a function of frequency. Subsequently, using the measured results at 10 GHz, the total uncertainty was calculated as a function of the ratio of the sample length to the wavelength in the SUT-filled waveguide, λ_m. At 10 GHz, the measured dielectric properties of cement powder were measured to be $\varepsilon_s^* = 3.7031 - j0.0224$ using the procedure outlined in Section III. Fig. 2 shows that the total relative uncertainty for the relative permittivity and the loss factor associated with cement powder tend to decrease as a function of increasing sample length. The uncertainty minima appear when the SUT length is at every multiples of half-wavelength. This is due to the fact that at these points, $|S_{11}|$ approaches zero and $|S_{21}|$ approaches one. Clearly, the behavior of the scattering parameters is oscillatory as a function of frequency and hence these two uncertainties. Therefore, around the points where the local minima of $|S_{11}|$ and local maxima of $|S_{21}|$ occur, any measurement error will not have as significant of an influence as it may have in the other sharper regions of the S_{11} and S_{21} curves.



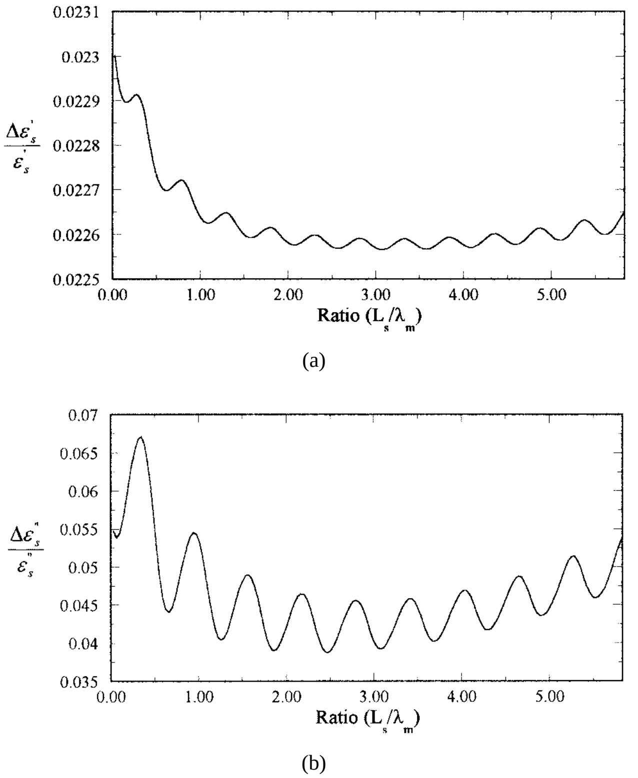
(a)

(b)

Fig. 2. (a) Relative total uncertainty of ε_s' and (b) the relative total uncertainty ε_s'' as a function of normalized length for cement powder.

The results also show that the uncertainties continue to decrease as a function of increasing length (with respect to the wavelength in the SUT in the waveguide) even beyond $7\lambda_m$. This demonstrates the fact that at this relative sample length, the microwave signal still penetrates through the entirety of the system, indicating the low-loss nature of the cement powder. This observation is supported by the fact that cement powder is a very low-loss material, since its loss tangent is quite small (at 10 GHz, the loss tangent of cement powder is calculated to be 0.006 38). Based on the results from these figures, at a given frequency (i.e., at 10 GHz), a longer sample is preferred to give less measurement uncertainty and the length of the sample needs to be chosen such that it results in minimum uncertainty (according to the results shown in Fig. 2).

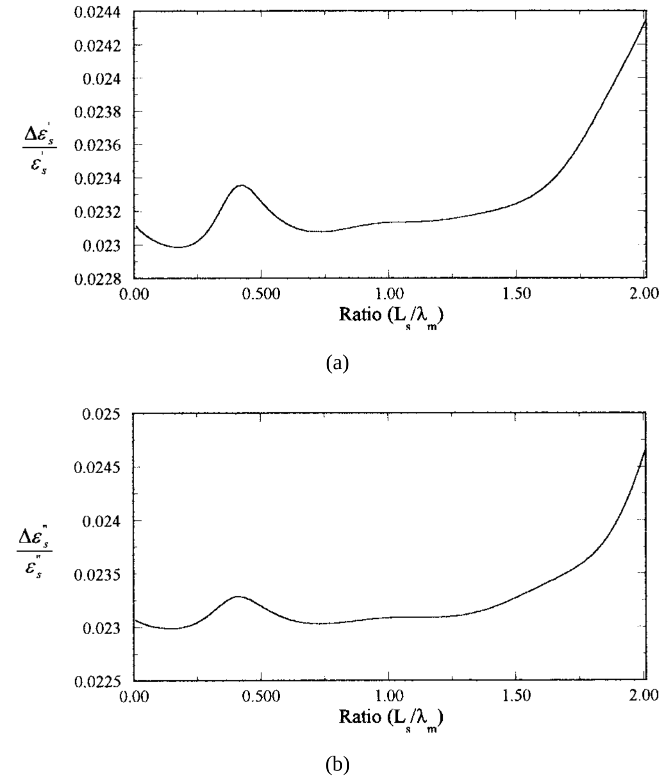
For dielectric measurement of liquids, commercially available corn oil was chosen to represent a low-loss liquid. This corn oil was poured to completely fill a 10 cm-long X-band waveguide sample holder which was plugged at both ends with the two identical Plexiglass plugs each with a length of 0.5 cm resulting in the SUT length of 9 mm. At 10 GHz, the measured dielectric properties of corn oil were measured to



(a)

(b)

Fig. 3. (a) Relative total uncertainty of ε_s' and (b) the relative total uncertainty ε_s'' as a function of normalized length for corn oil.



(a)

(b)

Fig. 4. (a) The relative total uncertainty of ε_s' and (b) the relative total uncertainty ε_s'' as a function of normalized length for antifreeze.

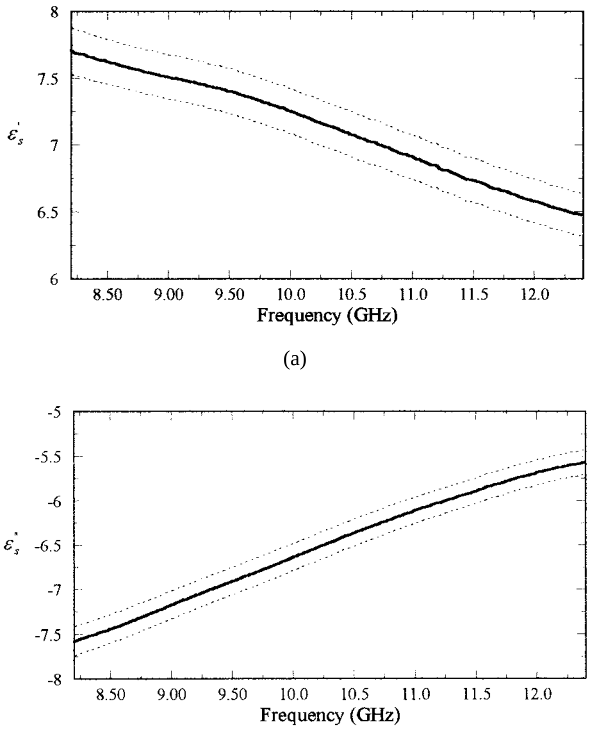
be $\varepsilon_s^* = 2.5260 - j0.1106$ using the procedure outlined in Section III. Fig. 3(a) and (b) show that the total uncertainty for the relative permittivity and the loss factor of this liquid tend to decrease as a function of increasing sample length, and at $2.5\lambda_m$, the uncertainty begins to increase again. The reason for this fact is similar to the cement powder case, in that at these points, $|S_{11}|$ approaches zero and $|S_{21}|$ approaches one. Fig. 3 also shows that the errors increase for a relative SUT length greater than $2.5\lambda_m$. Hence, beyond this length, the incident microwave signal is increasingly absorbed, and a smaller portion of the signal propagates through the whole system, which translates into an increase in S_{21} measurement error. Although corn oil is still considered to be a low-loss material (at 10 GHz, the loss tangent of corn oil is calculated to be 0.0437), its loss tangent is about one order of magnitude larger than that of cement powder. Thus, it makes sense that for cement powder the uncertainties still decrease even when the sample length is beyond $7\lambda_m$ while for corn oil the uncertainties already start to increase again at $2.5\lambda_m$. The uncertainty minima for the permittivity appear at every multiple of half-wavelength of the relative SUT length, as expected.

B. Uncertainty Analysis for High-Loss Materials

To represent high-loss materials, the dielectric properties of a commercially available antifreeze solution were measured using this technique. This antifreeze solution was poured to fill in a 1.5 cm long X-band waveguide sample holder which was plugged at both ends with two identical Plexiglass dielectric plugs with a length of 0.5 cm each resulting in the SUT length of 0.5 cm.

Following the same procedure as that for the low-loss materials and using the measurement results at 10 GHz, the uncertainties were calculated as a function of relative SUT length. At 10 GHz, the dielectric properties of this antifreeze solution was measured to be $\varepsilon_s^* = 7.257 - j6.645$ using the procedure outlined in Section III. Fig. 4(a) and (b) show that the total relative uncertainty for the relative permittivity and loss factor of this antifreeze solution tends to oscillate as the sample length increases until the sample length reaches beyond $1.25\lambda_m$. The uncertainty then begins to increase significantly starting from this point since the measurement error due to S_{21} become more dominant [23]. This is due to the fact that the measurement errors related to the transmission scattering parameter (S_{21}) start to increase significantly when the transmitted signal is less than -40 dB with respect to the reference signal. Hence, when the signal value at port 2 is very small, the noise level becomes comparable to the actual signal, which contributes to a significant increase in the total uncertainty.

It is also important to determine the upper and lower bounds of measurement uncertainty (i.e., $\pm\Delta\varepsilon_s^*$) associated with the measurement of the dielectric properties of a material at a given sample length as a function of frequency. In this way, one is able to determine the frequency at which the uncertainties are minimum. Using the same apparatus as before, the relative permittivity and the loss factor of antifreeze were measured and the bounds of the uncertainties were calculated as functions of frequency, as shown in Fig. 5. The results



(a)

(b)

Fig. 5. (a) Relative permittivity and (b) loss factor of antifreeze with the upper and lower bound uncertainties.

indicate that as the frequency increases, the uncertainty bounds for the relative permittivity and the loss factor decrease. This is due to the fact that in this measurement the length of the sample is quite short (0.5 cm) compared to the length of the sample of the cement powder and corn oil. Therefore, the sensitivity of the dielectric properties of the sample with respect to the length of the sample and plug dominate the uncertainty bounds. Moreover, in this case, $\partial\varepsilon_s^*/\partial L_s$ and $\partial\varepsilon_s^*/\partial L_p$ decrease as a function of frequency. Thus, we see a decrease in the uncertainty bound as a function of increasing frequency.

Finally, the dielectric properties of tap water, another high loss material, were measured at 3 GHz (S-band) using this dielectric plug-loaded two-port transmission line technique. The dielectric properties of water are well documented and are known to be frequency, temperature and salinity dependent [24]. These measurements were conducted at 19.3 °C and the salinity of the water used here was measured to be at 33 ppm using a HACH C0150 conductivity meter (model 50150). Table I shows the theoretical and measured permittivity and loss factor of this specimen and the calculated measurement error between these two results. The agreement between the predicted and measured results is within 1.1%. Clearly, the results indicate the measurement capabilities of this technique for liquid (as well as granular) dielectric materials.

TABLE I
DIELECTRIC CONSTANT MEASUREMENT OF TAP WATER
(19.3°C, 33 ppm SALINITY) AT 3 GHz (S-BAND)

	Permittivity ε_r'	Loss Factor ε_r''	$\Delta\varepsilon_r'$ (%)	$\Delta\varepsilon_r''$ (%)
Predicted [24]	78.073	13.086	-------	-------
Measured	78.327	12.943	0.324%	1.1%

VI. CONCLUSION

In this paper, a dielectric plug-loaded two-port transmission line technique for measuring the dielectric properties of liquid and granular materials is described. The proposed setup is designed to overcome the limitations of existing filled transmission line measurement techniques when dealing with these types of materials. An overview of the theoretical derivation of the dielectric property measurement, and the important issue of measurement uncertainty analysis were described. In this investigation, the dielectric properties of cement powder, corn oil and antifreeze solution were measured at X-band (8.2–12.4 GHz). The dielectric properties of tap water were also measured using this technique at 3 GHz (S-band). These specimens were chosen since they include granular and liquid dielectric materials while representing a broad range of permittivity and loss factor. Cement powder and corn oil are in the family of low-loss dielectric materials while antifreeze solution and tap water are in the family of high-loss dielectric materials.

It was shown that although $\partial\varepsilon_s^*/\partial\varepsilon_p^*$ decreases as a function of the square root of the dielectric property of the plugs, not much is gained by using high permittivity and high-loss plugs since the former causes significant reflections at the air-plug boundary and the latter causes significant attenuation of the incident microwave signal. In either case the incident microwave signal may not penetrate through the entirety of the SUT. Thus, in this scheme it is preferable to use low permittivity and low-loss plugs so that most of the microwave signal reaches the sample without much of it being absorbed by the plugs. Moreover, for low-loss plugs, a longer SUT is preferred since the total uncertainties decrease in this case. In other words, to choose the dielectric plugs for this technique, the power of the microwave signal, the dielectric properties and the length of the plugs need to be selected such that the signal is still able to penetrate the whole system. Based on the analysis performed, the total uncertainties tend to decrease as the SUT length increases for low-loss materials. However, beyond a certain point where the sample length is too long for the microwave signal to penetrate the whole system, the uncertainties begin to increase (as in the case of corn oil). As mentioned earlier, higher-order modes can be generated as result of imperfect machining of the plugs (e.g., gaps between the plugs and the waveguide walls). In such cases and when the SUT is a material with high permittivity, some propagating higher-order modes may exist whose influences must subsequently be taken into account in the forward and the inverse problem.

For a low-loss material, the results indicated that the minimum uncertainty appears at every multiple of half-wavelength. It was also shown that beyond a certain SUT length, the errors due to the S_{21} measurement tend to dominate the total error (especially in the corn oil case). This is more pronounced for materials with increasing loss factors where the errors due to S_{21} dominate the total uncertainty when the relative SUT length is just greater than λ_m. In this case, the transmitted signal is less than -40 dB with respect to the reference signal, which causes the uncertainty to increase significantly.

It was also noticed that the uncertainty bounds on the dielectric constant measurement for the antifreeze solution decreased as a function of increasing frequency. The reason for this is that the relative length of SUT is shorter at lower frequencies. Here, the sensitivity of the dielectric properties of the sample with respect to the length of the sample and plug dominate the uncertainty bounds.

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