A New Approach to Estimate Complex Permittivity of Dielectric Materials at Microwave Frequencies Using Waveguide Measurements

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***Abstract*—In this paper, a simple waveguide measurement technique is presented to determine the complex dielectric constant of a dielectric material. The dielectric sample is loaded in a short-circuited rectangular waveguide. Using a network analyzer, the reflection coefficient of the waveguide is measured. Using the finite-element method (FEM) the exact reflection coefficient of this configuration is determined as a function of the dielectric constant. The measured and calculated values of the reflection coefficient are then matched using the Newton–Raphson method to estimate the dielectric constant of a material. A comparison of estimated values of the dielectric constant obtained from simple waveguide modal theory and the FEM approach is presented. Numerical results for dielectric constants of Teflon and Plexiglas measured at the X- and Ku-bands are presented. Numerical inaccuracies in the estimate of the dielectric constant due to: 1) the presence of airgaps between sample and sample holder waveguide surfaces and 2) inaccuracy in the sample dimensions are also discussed.**

***Index Terms*—Dielectric constant, finite-element method.**

I. Introduction

APPLICATION of materials in the aerospace, microwave, microelectronics, and communication industries requires the exact knowledge of material parameters such as permittivity and permeability. Over the years many methods have been developed and used for measuring permittivity (ϵ_r', ϵ_r'') and permeability (μ_r', μ_r'') of materials [1], [2]. The most widely used methods are: 1) free-space techniques; 2) cavity perturbation techniques; and 3) transmission line of waveguide methods. Each technique has its own advantages and limitations. The free-space methods are employed when the material is available in a big sheet form. These measurements are less accurate because of unwanted reflections from surrounding objects, difficulty in launching a plane wave in a limited space, and unwanted diffraction from the edges of the sample. However, with use of focusing lenses these problems in the free-space measurements can be minimized. The resonant cavity measurement or cavity perturbation techniques are more accurate [3]. However, they are applicable only over a narrow frequency band. Furthermore, in the cavity measurement technique it is necessary to design a resonator for the given frequency range. For measurements of permittivity and permeability of material over a wide range of frequencies, transmission line, or waveguide methods are widely used [3], even though these methods are less accurate than the resonant cavity technique. In a one-port measurement technique the input reflection coefficient of a sample holder loaded with an isotropic material sample is measured using a network analyzer. Assuming that the material sample occupies the total sample–holder length and has the same cross section as the sample holder, the input reflection coefficient of the sample holder is calculated using a simple waveguide modal expansion method. Using the inverse procedure, constituent parameters of a material sample are determined by matching calculated and measured values of the input reflection coefficient of the sample holder. The material sample used in these measurements is usually of a cross section which is the same as that of the transmission line. The uniform cross section of the sample is preferred so that a dominant mode analysis is sufficient and accurate for determining the material constants. However, when the sample selected is not of a uniform cross section or the sample occupies a part of the transmission-line cross section, then the complete modal analysis is required to accurately determine the material properties. The complete modal analysis is quite complicated, if not impossible. In such cases, when the sample cross section is different from that of the transmission line, a numerical method such as the finite-element method (FEM) instead of the modal analysis is much easier to implement to determine material properties [4].

In this paper, the FEM is proposed to estimate the complex permittivity of a material using a terminated rectangular waveguide. The method described here may be easily extended to estimate the complex permeability of material. The material sample of specific length, but of arbitrary cross section, is assumed to be present in a short-circuited rectangular waveguide. The reflection coefficient at some arbitrarily selected reference plane in the rectangular waveguide is measured at a given frequency. Since only permittivity is required, a single reflection-coefficient measurement suffices. The reflection coefficient at the given frequency is also calculated as a function (ϵ_r', ϵ_r'') using the FEM technique. From the calculated and measured values of reflection coefficients and the use of the Newton–Raphson Method [5], the complex primitivities of the given material is then determined. The complex permittivity of Teflon and Plexiglas at X- and Ku-band obtained using the

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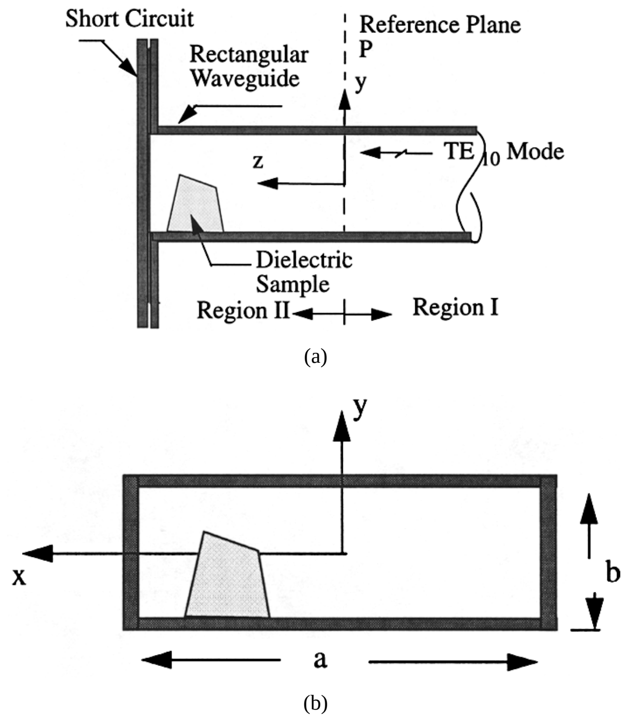


Fig. 1. Geometry of rectangular waveguide excited by TE_{10} mode. (a) Longitudinal view of rectangular waveguide with dielectric sample. (b) Cross-sectional view of rectangular waveguide.

present technique are compared with the values obtained using the standard software available with the hp-8510 Network Analyzer.

II. Theory

A. Direct Problem

In this section, the FEM will be used to determine the reflection coefficient of a short-circuited rectangular transmission line loaded with an arbitrarily shaped dielectric material. Fig. 1 shows a terminated rectangular waveguide with a dielectric sample of arbitrary cross section. It is assumed that the waveguide is excited by a dominant TE_{10} mode from the right and the reflection coefficient is measured at the reference plane P as shown in Fig. 1(a). For the purpose of analysis the problem is divided into two regions; Region I ($z < 0$), and Region II ($z > 0$). Using the waveguide vector modal functions, the transverse electromagnetic field in Region I is expressed as [6]

$$\vec{E}^I(x, y, z) = \vec{e}_0(x, y)e^{-j\gamma_0 z} + \sum_{p=0}^{\infty} a_p \cdot \vec{e}_p(x, y)e^{j\gamma_p z} \quad (1)$$

$$\vec{H}^I(x, y, z) = \vec{h}_0(x, y)Y_0 e^{-j\gamma_0 z} - \sum_{p=0} a_p \cdot \vec{h}_p(x, y)Y_p e^{j\gamma_p z}. \quad (2)$$

In deriving (1) and (2) it is assumed that only the dominant mode is incident on the interface P and the a_p are the amplitudes of reflected modes at the $z = 0$ plane. Y_p and γ_p appearing in (1) and (2) are, respectively, the characteristic admittance and propagation constant for the pth mode and are defined in [6]. The unknown complex modal amplitude a_p may be obtained in terms of the transverse electric (TE) field over the plane P as follows:

$$1 + a_0 = \iint_S \vec{E}\Big|_{\text{over S}} \bullet \vec{e}_0 dso \quad (3)$$

$$a_p = \iint_S \vec{E}\Big|_{\text{over S}} \bullet \vec{e}_p ds \quad (4)$$

where S is the surface area over the plane P.

The electromagnetic field inside Region II is obtained using the FEM formulation [7]. The vector-wave equation for the $\vec{E}^{II}$ field is given by

$$\nabla \times \left(\frac{1}{\mu_r} \cdot \nabla \times \vec{E}^{II}\right) - (k_0^2 \epsilon_r)\vec{E}^{II} = 0. \quad (5)$$

Using the weak form of the vector-wave equation and some mathematical manipulation [7], (5) may be written as

$$\begin{aligned} \iiint_V \left(\nabla \times \vec{T} \bullet \left(\frac{1}{\mu_r} \cdot \nabla \times \vec{E}^{II}\right) - (k_0^2 \epsilon_r)\vec{E}^{II} \bullet \vec{T}\right) dv \\ = 2(j\omega\mu_0) \cdot Y_0 \cdot \iint_S \vec{T} \bullet \vec{e}_0(x, y) ds \\ - (j\omega\mu_0) \cdot \sum_{p=0}^{\infty} Y_p \left(\left(\iint_S \vec{T} \bullet \vec{e}_p(x, y) ds\right)\right. \\ \left.\cdot \left(\iint_S \vec{E}^{II}\Big|_{\text{over S}} \bullet \vec{e}_p(x, y) ds\right)\right). \end{aligned} \quad (6)$$

In order to solve (6), the volume enclosed by Region II is discretized by using first-order tetrahedral elements. The electric field in a single tetrahedron is represented as

$$\vec{E}^{II} = \sum_{m=1}^{6} b_m \cdot \vec{W}_m \quad (7)$$

where b_m are the six complex coefficients of the electric field associated with the six edges of the tetrahedron, and $\vec{W}_m(x, y, z)$ is the vector basis function associated with the mth edge of the tetrahedron. A detailed derivation for the expressions for $\vec{W}_m(x, y, z)$ is given in [7].

Substituting (7) into (6), integration over the volume of one tetrahedron results in the element matrix equation

$$[S_{el}] \cdot [b] = [v] \quad (8)$$

where the entries in the element matrices are given by

$$\begin{aligned} S_{el}(m, n) \\ = \frac{1}{\mu_r}\left(\iiint_V (\nabla \times \vec{W}_m \bullet \nabla \times \vec{W}_n - k_0^2 \epsilon_r \vec{W}_n \bullet \vec{W}_m) dv\right) \\ + (j\omega\mu_0) \bullet \sum_{p=0}^{\infty} Y_p \left(\left(\iint_S \vec{W}_m \bullet \vec{e}_p(x, y) ds\right)\right. \\ \left.\cdot \left(\iint_S \vec{W}_n \bullet \vec{e}_p(x, y) ds\right)\right) \end{aligned} \quad (9)$$

$$\begin{aligned} v(m) \\ = 2(j\omega\mu_0) \cdot Y_0 \cdot \iint_S \vec{W}_m \bullet \vec{e}_0(x, y) ds. \end{aligned} \quad (10)$$

These element matrices can be assembled over all the tetrahedral elements in Region II to obtain a global matrix equation

$$[S]\cdot[b]=[v]. \tag{11}$$

The solution vector $[b]$ of the matrix equation (11) is then used in (3) to determine the reflection coefficient at the reference plane P as

$$a_0=-1+\iint_S \vec{E}\bigg|_{\text{over S}} \bullet \vec{e}_0 ds. \tag{12}$$

B. Rectangular Waveguide Measurement System

The reflection coefficient of a rectangular waveguide loaded with a dielectric sample is measured using the standard hp-8510 Network Analyzer setup. Before the measurement, a calibration using a standard waveguide calibration kit is done to measure the reflection coefficient at the reference plane P. The input reflection coefficient a_0' of a terminated rectangular waveguide with a sample is then measured as a function of frequency. Assuming the sample occupies the entire cross section of the waveguide, an algorithm which uses the Nicholson–Ross technique [8] is used to determine the complex permittivity of the sample. However, the algorithm which is based on the Nicholson–Ross technique cannot be used when the sample occupies part of the cross section of the rectangular waveguide. When the dielectric sample is of arbitrary shape the procedure described in the following section is used.

C. Inverse Problem

This section presents computation of the complex dielectric constant of a given sample from a one-port measurement of the reflection. From the given geometry of the sample and its position in the short-circuited rectangular waveguide the reflection coefficient $a_0(\epsilon_r', \epsilon_r'')$ is calculated using the FEM for assumed values of $(\epsilon_r', \epsilon_r'')$. If a_0' is the measured reflection coefficient then the error in calculated value of the reflection coefficient is $a_0(\epsilon_r', \epsilon_r'')-a_0'$. Writing the error in real and imaginary parts we get

$$f_1(\epsilon_r', \epsilon_r'')=\text{real}(a_0(\epsilon_r', \epsilon_r'')-a_0') \tag{13}$$

$$f_2(\epsilon_r', \epsilon_r'')=\text{imag}(a_0(\epsilon_r', \epsilon_r'')-a_0'). \tag{14}$$

If $(\epsilon_r', \epsilon_r'')$ are incremented by small values to $(\epsilon_r'+d\epsilon_r', \epsilon_r''+d\epsilon_r'')$ then the functions $f_1(\ )$ and $f_2(\ )$ may be written in Taylor's series as [5]

$$\begin{aligned} f_1(\epsilon_r'+d\epsilon_r', \epsilon_r''+d\epsilon_r'') &= f_1(\epsilon_r', \epsilon_r'')+\frac{\partial f_1}{\partial \epsilon_r'}d\epsilon_r'+\frac{\partial f_1}{\partial \epsilon_r''}d\epsilon_r'' \\ &\quad +O((d\epsilon_r')^2, (d\epsilon_r'')^2) \end{aligned} \tag{15}$$

$$\begin{aligned} f_2(\epsilon_r'+d\epsilon_r', \epsilon_r''+d\epsilon_r'') &= f_2(\epsilon_r', \epsilon_r'')+\frac{\partial f_2}{\partial \epsilon_r'}d\epsilon_r'+\frac{\partial f_2}{\partial \epsilon_r''}d\epsilon_r'' \\ &\quad +O((d\epsilon_r')^2, (d\epsilon_r'')^2) \end{aligned} \tag{16}$$

where $O((d\epsilon_r')^2, (d\epsilon_r'')^2)$ are the higher order terms in Taylor's series. If the increments to $(\epsilon_r', \epsilon_r'')$ by $(d\epsilon_r', d\epsilon_r'')$ are such that $f_1(\epsilon_r'+d\epsilon_r', \epsilon_r''+d\epsilon_r'')$ and $f_2(\epsilon_r'+d\epsilon_r', \epsilon_r''+d\epsilon_r'')$ are simultaneously zero then we can write the following matrix equation [5]:

$$\begin{bmatrix} \frac{\partial f_1}{\partial \epsilon_r'} & \frac{\partial f_1}{\partial \epsilon_r''} \\ \frac{\partial f_2}{\partial \epsilon_r'} & \frac{\partial f_2}{\partial \epsilon_r''} \end{bmatrix} \begin{bmatrix} d\epsilon_r' \\ d\epsilon_r'' \end{bmatrix} = -\begin{bmatrix} f_1(\epsilon_r', \epsilon_r'') \\ f_2(\epsilon_r', \epsilon_r'') \end{bmatrix}. \tag{17}$$

The matrix elements in the coefficient matrix of (17) are calculated numerically using the FEM procedure. The matrix equation in (17) is then solved for $d\epsilon_r'$, $d\epsilon_r''$. From the solution of (17), new modified values of $(\epsilon_r', \epsilon_r'')$ are obtained as

$$(\epsilon_r')_{\text{new}}=(\epsilon_r')_{\text{old}}+d\epsilon_r' \tag{18}$$

$$(\epsilon_r'')_{\text{new}}=(\epsilon_r'')_{\text{old}}+d\epsilon_r''. \tag{19}$$

The reflection coefficient $a_0(\epsilon_r', \epsilon_r'')$ with new values of $(\epsilon_r', \epsilon_r'')$ is again calculated using the FEM procedure. With the new value of $a_0(\epsilon_r', \epsilon_r'')$ computations through (15)–(19) are performed to update $(\epsilon_r', \epsilon_r'')$. The above procedure is repeated until required convergence is obtained (i.e., $d\epsilon_r' \leq \Delta_1$ and $d\epsilon_r'' \leq \Delta_2$, where Δ_1 and Δ_2 are preselected small quantities). The procedure described above will converge faster to the true value of complex permittivity if the first choice of $(\epsilon_r', \epsilon_r'')$ is close to the true value of complex permittivity.

D. Sensitivity Analysis

The sensitivity of the present method to the airgaps that may exist between the common surfaces of the dielectric and waveguide can be obtained numerically. Since these airgaps can be easily modeled with the FEM procedure, the estimate of ϵ_r' with and without airgaps is calculated. The percentage error in the estimation of ϵ_r' may be defined as

$$\%\,\text{Error}=\left[\frac{[(\epsilon_r')_{\text{without airgap}}-(\epsilon_r')_{\text{with airgap}}]}{(\epsilon_r')_{\text{without airgap}}}\right]100. \tag{20}$$

Likewise, the errors in the estimation of ϵ_r' due to inaccuracy in the dimensions of the sample may be defined as (see (21) at the bottom of the page). With the present method, the dielectric constant ϵ_r' for correct dimensions and ϵ_r' for dimensions which are off from the correct dimensions are calculated. The error in the estimation of ϵ_r' is then obtained from (21).

III. Numerical Results

To validate the present technique, the authors first present numerical results for the direct problem. The input-reflection coefficient of a short-circuit rectangular waveguide loaded with the Teflon ($\epsilon_r' = 1.95$, $\epsilon_r'' = 0.001$) dielectric sample as shown in Fig. 2 is calculated using the expression (14) and is presented in [3] along with the measured results. To check the numerical convergence, the calculations were performed for two different discretizations with a number of unknowns equal to 870 and 1559. It is clear from the results in Fig. 3

$$\%\,\text{Error}=\left[\frac{[(\epsilon_r')_{\text{exact dimensions}}-(\epsilon_r')_{\text{with small changes in dimensions}}]}{(\epsilon_r')_{\text{exact dimensions}}}\right]100 \tag{21}$$

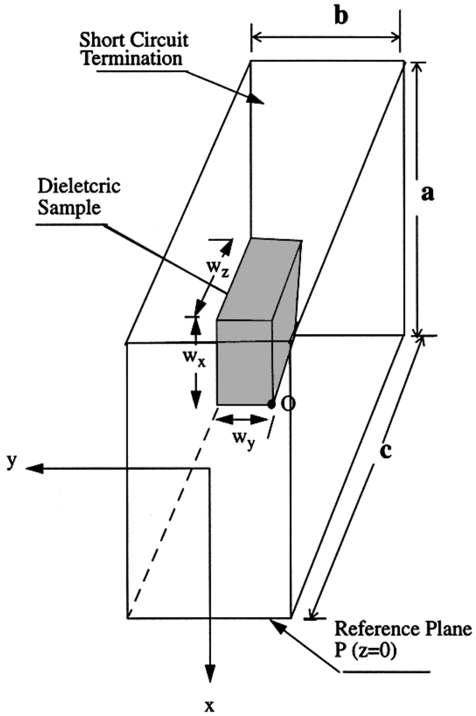


Fig. 2. Geometry of the X-band rectangular waveguide ($a = 2.29$, $b = 1.02$, $c = 0.958$) holding Teflon dielectric sample ($w_x = 1.58$, $w_y = 0.785$, $w_z = 0.632$). Coordinates of point $O(x = 1.145$, $y = -0.275$, $z = 0.326)$. (All dimension are in centimeters.)

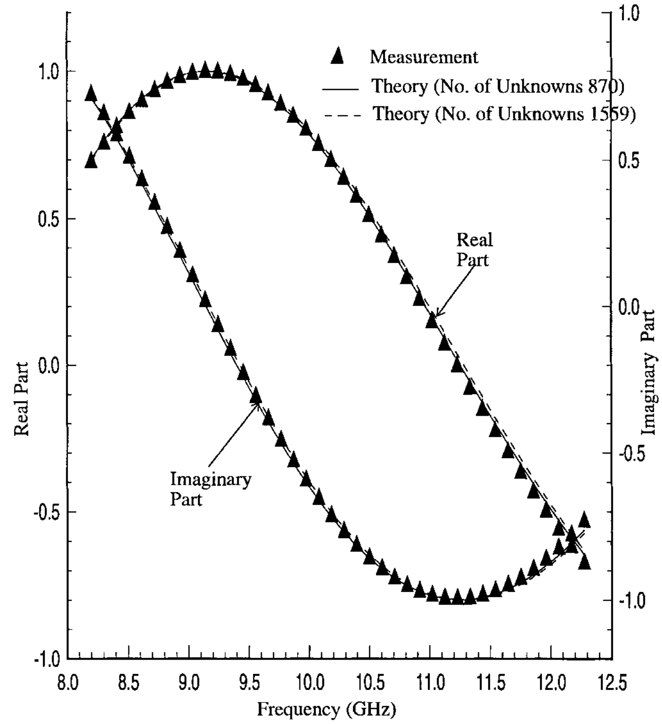


Fig. 3. Comparison of measured and calculated reflection coefficient of a rectangular waveguide loaded with a Teflon dielectric sample as shown in Fig. 2.

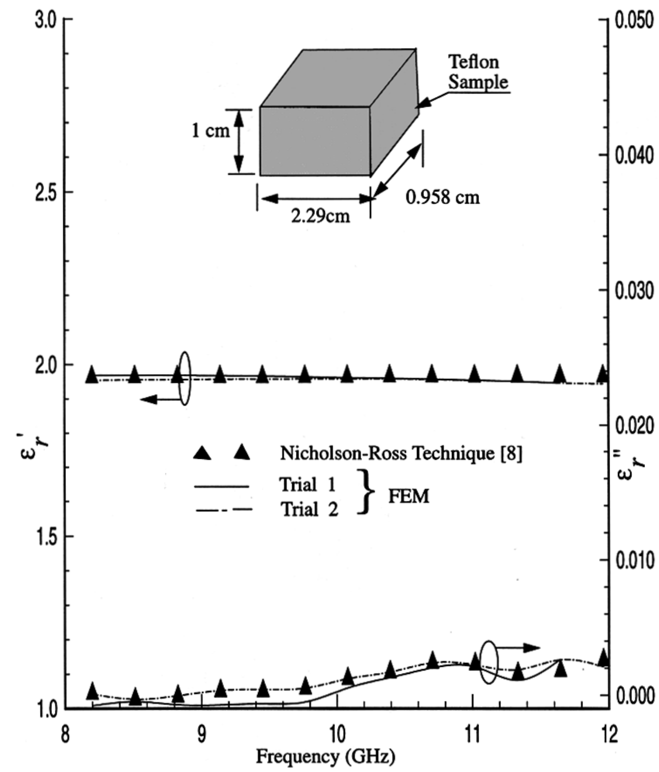


Fig. 4. Complex permittivity of a Teflon sample over the X-band calculated using two different methods.

that the discretization level with 870 unknowns is sufficient to achieve convergence. The excellent agreement between the calculated and measured reflection coefficient establishes the validity of the present approach for the direct problem.

For the inverse problem, samples made from Teflon and Plexiglas materials are considered. Samples having the same cross section as that of the sample holder waveguide are considered first. This is done for the purpose of comparing results obtained by the present technique and the results obtained by standard software available with the hp-8510 Network Analyzer. The software available with hp-8510 uses the Nicholson–Ross technique which requires the cross section of the sample and the sample–holder waveguide to be identical. Numerical results obtained for a sample having a cross section different from that of the sample–holder waveguide are also presented.

First, two samples of rectangular shape with dimensions $w_x = 2.29$ cm, $w_y = 1.0$ cm, and $w_z = 0.958$ cm, were cut from a Teflon sheet. The reflection coefficient (over the frequency band 8.2–12.40 GHz) at reference plane P was measured by placing one of the samples in an X-band rectangular waveguide and using a hp-8510 Network Analyzer. Using the procedure described in Section II, and setting $\Delta_1 = 0.01$, $\Delta_2 = 0.001$, the complex permittivity of the Teflon material was calculated and shown in Fig. 4. To check repeatability, the complex permittivity of the Teflon material using the second sample was also determined and presented in Fig. 4. The close agreement between the results for two samples suggest high repeatability of these measurements. For the same sample, complex permittivity using the Nicholson–Ross technique is also calculated and is presented in Fig. 4 for the sake of comparison. Because of very low loss characteristic of the Teflon material, the measurement of the imaginary part of

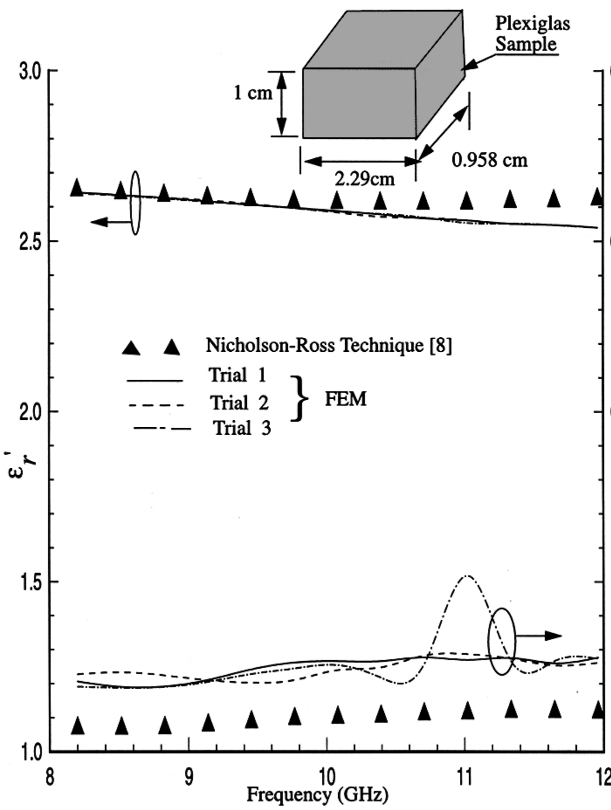


Fig. 5. Complex permittivity of a Plexiglas sample over the X-band calculated using two different methods.

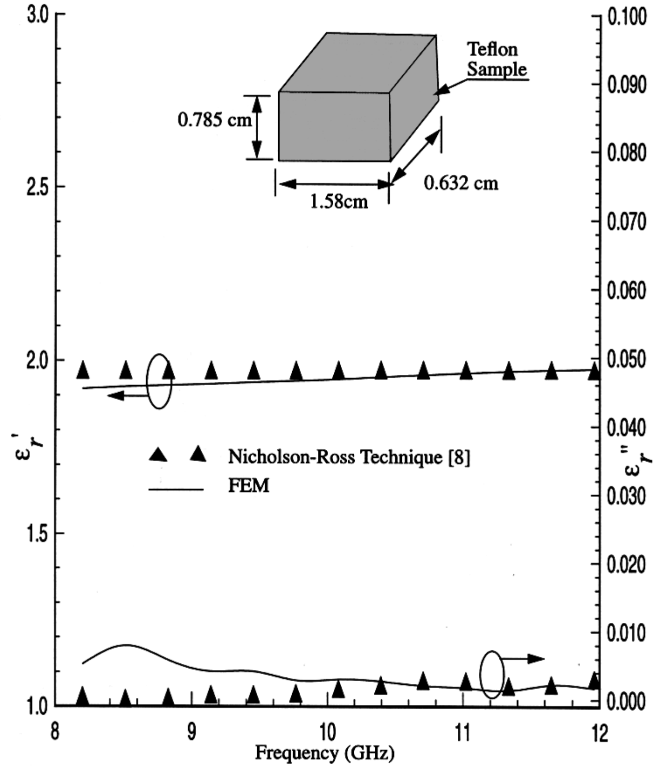


Fig. 6. Complex permittivity of a Teflon material obtained using an undersized sample. ▲ indicates complex permittivity of the same material obtained using the sample size as shown in Fig. 4.

complex permittivity may not be very reliable. Using the same procedure as described above, the complex permittivity of Plexiglas is also obtained using the present procedure and is shown in Fig. 5 along with the results obtained by the Nicholson–Ross technique [8]. The results in Fig. 5 are in good agreement with each other at lower frequencies compared to those at higher frequencies. Also the estimate of ϵ_r'' shown in Fig. 5 disagrees with the estimate from the Nicholson–Ross technique. However, because of the low loss nature of this material these estimates may not be very reliable. The close agreement between the results for three samples suggests high repeatability of these results.

The central processing unit (CPU) time for a single estimation at one frequency depends upon the number of unknowns involved in (11). For the example considered above, with the number of unknowns equal to 870 a single estimation at one frequency took 265 s CPU time on a Convex C220. In the first estimate, for the starting frequency the initial guess for the dielectric constant was $\epsilon_r' = 1.0$ and $\epsilon_r'' = 0.001$. However, for the estimation at subsequent frequencies the initial guess for ϵ_r' and ϵ_r'' were the final values of ϵ_r' and ϵ_r'' obtained at the previous frequency, and hence, it took only 4 s of CPU time on a Convex C220. Though the FEM procedure takes considerable CPU time compared to the time taken by the Nicholson–Ross technique, its versatility to easily handle a complex-shaped material makes the FEM technique more useful than the Nicholson–Ross technique.

In order to validate the present method for a material sample whose cross section is different from that of a sample–holder waveguide a Teflon sample with dimension $w_x = 1.58$ cm, $w_y = 0.785$ cm, $w_z = 0.632$ cm was cut from a Teflon sheet. The sample was then placed in a rectangular waveguide for measurement of the reflection coefficient as shown in Fig. 2. From the measured value of the reflection coefficient and following the procedure described in Section II, the complex permittivity was calculated and presented in Fig. 6. For comparison, the complex permittivity obtained using the full-size sample (i.e., $w_x = 2.29$ cm, $w_y = 1.0$ cm, $w_x = 0.947$ cm) is also presented in Fig. 6. Good agreement between the two results in Fig. 6 suggests that the FEM procedure can be used to determine the complex permittivity of a dielectric material using an arbitrarily shaped sample.

To study the sensitivity of the present method as far as the airgaps are concerned, the authors consider the sample as shown in Fig. 2. Using the FEM procedure, $(\epsilon_r')_{\text{without airgap}}$ and $(\epsilon_r')_{\text{with airgap}}$ are estimated for various airgaps. The percentage error in the estimation of ϵ_r' is calculated using (20) and presented in Fig. 7. From Fig. 7 it is clear that the presence of airgaps introduces errors in the estimation of ϵ_r'. The percentage error increases with the size of the airgap.

To study the sensitivity of the present approach to the tolerance in the sample dimensions, the authors estimate $(\epsilon_r')_{\text{exact dimensions}}$ and $(\epsilon_r')_{\text{with small changes in dimensions}}$ using the FEM procedure by introducing small changes in the dimensions of the sample shown in Fig. 2. The percentage error in the estimation of ϵ_r' is then calculated using (21) and

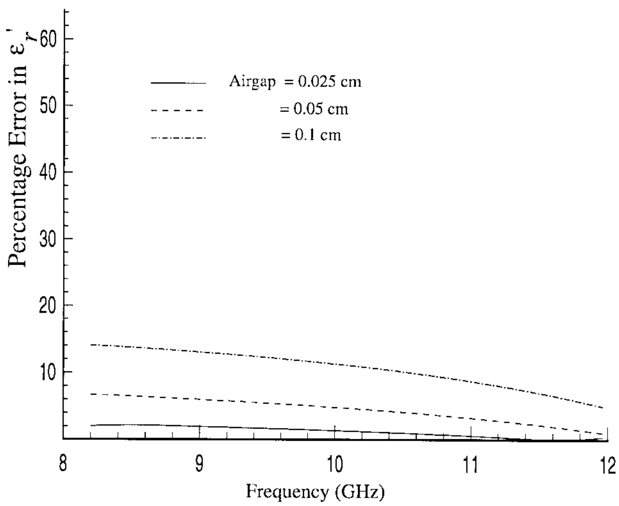


Fig. 7. Percentage error in the estimation of ϵ_r' of a Teflon sample (shown in Fig. 2) as a function of frequency for three sizes of airgaps between sample and waveguide wall surfaces.

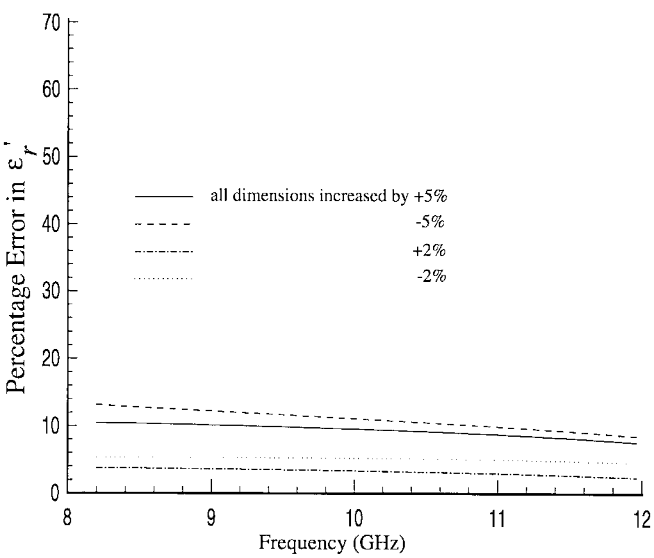


Fig. 8. Percentage error in the estimation of ϵ_r' of a Teflon sample (shown in Fig. 2) as a function of frequency for various tolerances in the sample dimensions.

presented in Fig. 8, where an estimate of the percentage error due to error in the sample dimensions is given.

Fig. 9 shows the complex permittivity of Plexiglas obtained using a sample with dimension $w_x = 1.58$ cm, $w_y = 0.785$ cm, $w_z = 0.632$ cm and placed in a rectangular waveguide as shown in Fig. 2. The complex permittivity of Plexiglas obtained using three different measured data sets agrees well with each other.

The FEM procedure was also used to determine the dielectric constant of Teflon at Ku-band. The dielectric constant of Teflon at Ku-band was measured using two configurations as shown in Fig. 10(a) and 10(b). The complex dielectric constant of Teflon at Ku-band estimated using the measurement performed with configurations shown in Fig. 10(a) and 10(b) is shown in Fig. 11. The estimated value is very close to the value 1.95–2.1 specified by the manufacturer.

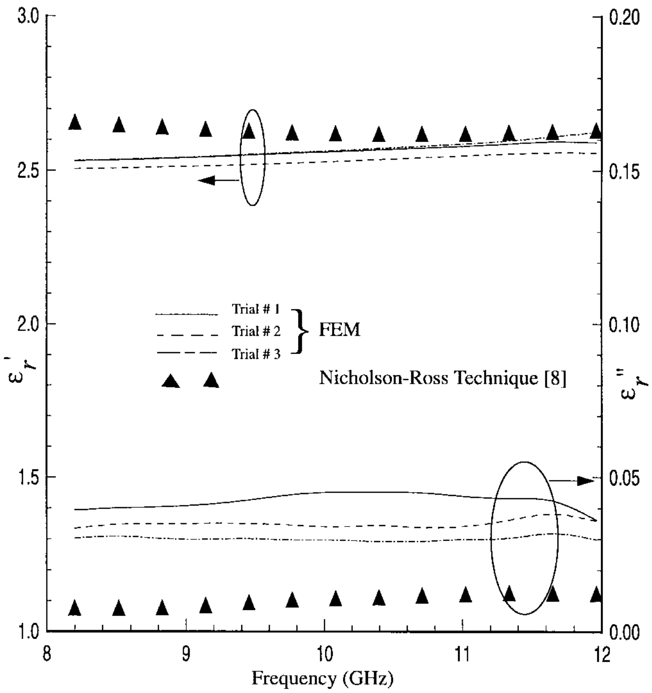
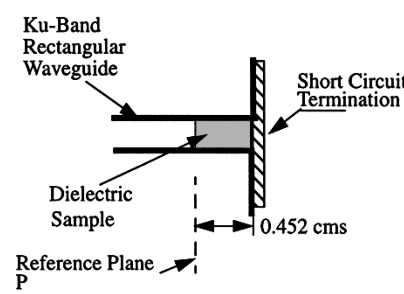


Fig. 9. Complex permittivity of a Plexiglas material obtained using an undersize sample. ▲ indicates complex permittivity of the same material obtained using the sample size, as shown in Fig. 5.



(a)

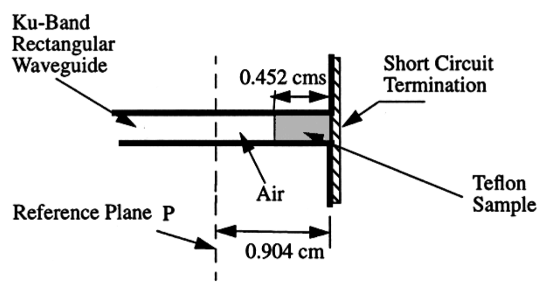


Figure 10(b)

(b)

Fig. 10. (a) Longitudinal view of terminated Ku-band rectangular waveguide ($a = 1.58$ cm, $b = 0.79$ cm) filled with a Teflon plug. (b) Longitudinal view of terminated Ku-band rectangular waveguide ($a = 1.58$ cm, $b = 0.79$ cm) partially filled with a Teflon plug.

IV. Conclusion

A FEM procedure in conjunction with the Newton–Raphson method has been presented to determine complex permittivity of a dielectric material using an arbitrarily shaped sample. The

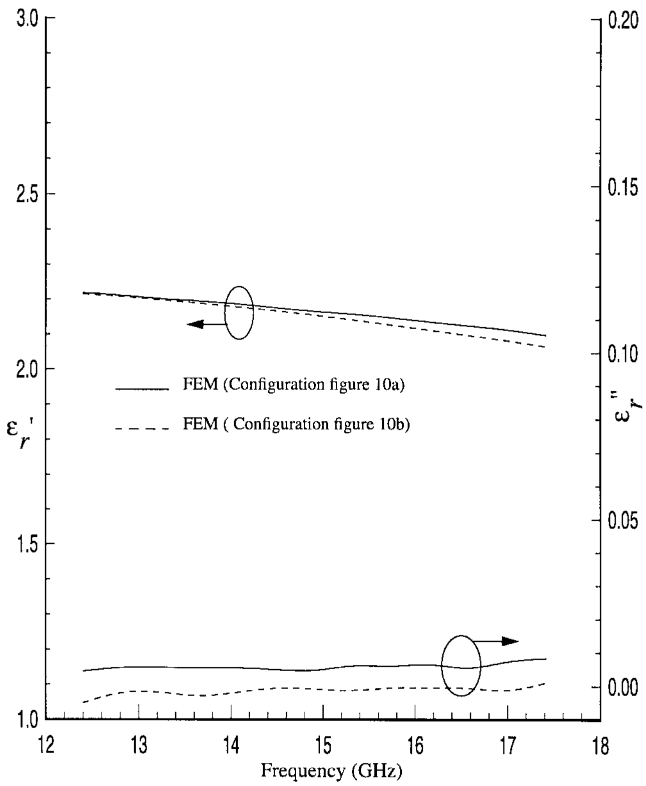


Fig. 11. Complex permittivity of a Teflon sample over Ku-band obtained using two different configurations, as shown in Fig. 10(a) and 10(b).

arbitrarily shaped sampled of a given dielectric material is placed in a terminated rectangular waveguide. The reflection coefficient at a reference plane is measured with a hp-8510 Network Analyzer. For the same configuration of a terminated rectangular waveguide loaded with the sample, the reflection coefficient is calculated as a function of the complex dielectric constant using the FEM technique. The Newton–Raphson method is then used to determine the complex dielectric constant by matching the calculated value with the measured value. The measured values of complex permittivity of Teflon and Plexiglas using the FEM method are in good agreement with the results obtained by the Nicholson–Ross technique. Numerical values of the dielectric constant of Teflon and Plexiglas calculated using the FEM and Newton–Raphson method at X- and Ku-band are in good agreement with the values specified by the manufacturers.

One of the limitations of the present FEM procedure is that it takes considerably more CPU time to estimate the complex dielectric constant compared to the Nicholson–Ross technique. However, its capacity to handle arbitrarily shaped samples gives the user a tremendous advantage over the existing methods.

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