A Technique for Dielectric Measurement of Cylindrical Objects in a Rectangular Waveguide

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Abstract— **In this paper, the inverse scattering problem of a homogeneous dielectric post in a rectangular waveguide is considered. A novel inversion algorithm, based on the method of moments and eigen analysis, for computation of the dielectric constant of the post (ϵ) from the measured voltage reflection coefficient is introduced. In this method the integral equation for the polarization current induced in the dielectric post is cast into a matrix equation, and then the contribution of ϵ to the resulting reflection coefficient is expressed explicitly using the eigen analysis. It is shown that the dielectric constant can be obtained from the solution of a complex polynomial function which in turn can be obtained numerically using the conjugate gradient method. Practical aspects of dielectric measurement using this technique are discussed. The HP-8510 network analyzer is used to measure the reflection coefficient of dielectric posts in an X-band waveguide sample holder. Metallic and known dielectric posts are used to determine the accuracy of the dielectric measurement technique.**

I. Introduction

With advances in technology, synthetic aperture radars have become the most promising remote sensing tool in retrieving the biophysical parameters of a vegetation stand [1], [2]. For this reason in the past two decades considerable effort has been devoted to measurement and characterization of the dielectric constant of vegetation [3]–[8]. All existing methods for dielectric constant measurement of vegetation are destructive: that is, the samples must be cut to shape to fit in the sample holder. Therefore natural variation of the dielectric constant as a function of temperature and water content cannot be measured. Moreover, the existing methods of dielectric measurement are suitable for broad leaves, and a reliable dielectric measurement technique for pine needles does not exist. Motivated by the need for an accurate method to measure the complex dielectric constant of pine needles at microwave frequencies both *in situ* and *in vivo* conditions, the problem of scattering from a dielectric post in a rectangular waveguide is considered.

The dielectric measurement technique proposed in this paper is based on the reflection coefficient measurement from cylindrical obstacles in a rectangular waveguide. A slot or a small hole in a waveguide wall that does not interrupt the flow of currents on the walls does not couple energy to the outside: hence the internal fields remain undisturbed. For example, a hole whose diameter is much smaller than both the cutoff and guide wavelengths made on the broad walls parallel to the narrow walls and perpendicular to the axis of a waveguide does not disturb the surface currents of a TE_{10} mode. If a pine needle (or any dielectric object) is inserted through the hole, part of the incident wave will be scattered back towards the generator. The reflected wave is a function of both the dielectric constant and the geometry of the cylinder cross section. The idea is to measure the reflection coefficient of a cylinder with known cross section and then calculate its dielectric constant.

Analytical scattering solutions for cylindrical posts in a rectangular waveguide are limited to metallic circular posts of small diameters [9], [10]. A more complicated solution based on a grating formulation for a metallic circular cylinder can also be found [11]; however, the solution seems to be excessively complex and has limited potential for combination with other structures. For larger metallic cylinders or, in general, dielectric cylinders of arbitrary cross section one must resort to numerical techniques. In [12] a numerical solution for metallic circular cylinders of arbitrary diameter in a rectangular waveguide is given. In this paper a numerical solution for the scattering problem of a homogeneous dielectric cylinder in a rectangular waveguide supporting a TE_{10} mode is sought with the emphasis on the inverse scattering solution. Using a vector network analyzer and dielectric posts with known cross section and dielectric constant both the forward and inverse scattering formulations are verified.

II. Forward Scattering Formulation

Suppose a homogeneous dielectric cylinder with a known geometrical cross section is placed vertically in a rectangular waveguide. The post has a uniform cross section, and its position in the waveguide is also known. The width of the rectangular waveguide is a and its height is b. The geometry of the problem and the coordinate system used are shown in Fig. 1. It is assumed that the waveguide can only support the dominant TE_{10} mode which is propagating in the positive z-direction. The incident wave induces a polarization current in the dielectric cylinder which becomes the source of the scattered field in the waveguide. The scattered field can be expanded in terms of waveguide modes where the reflected and transmitted waves (away from the cylinder) can be evaluated by retaining only the first mode. Since the reflection and transmission coefficients in a rectangular waveguide can be measured with a high degree of accuracy [8], a numerical solution for the induced polarization current is sought in order to establish the relationship between ϵ and Γ.

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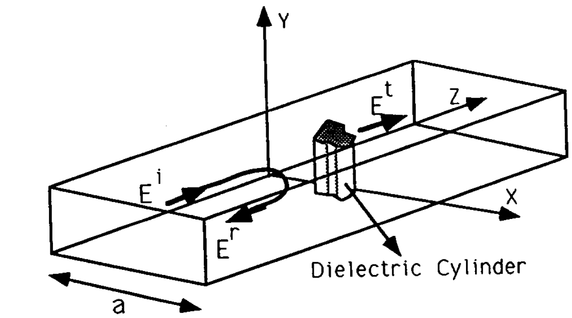

Fig. 1. Geometry of the scattering problem of a dielectric post in a rectangular waveguide.

The incident field and the cross section of the scatterer in this problem are independent of y which implies that the induced polarization current is also independent of y. Moreover, the incident field is along $\hat{y}$ and as mentioned $\delta/\delta y = 0$ for all field components; therefore the induced polarization current is along $\hat{y}$ as well. This simplifies the problem drastically because using the image theory, the top and lower waveguide walls can be removed provided that the dielectric rod is replaced by an infinite cylinder of the same dielectric constant and cross section placed in the resulting parallel-plate waveguide. To set the integral equation Green's function for the problem is required. Suppose an infinite current filament of magnitude I_0 is located at (x', z') parallel to the walls of the parallel-plate waveguide. Again by applying the image theory, the waveguide plates can be removed by replacing the filament current with two periodic arrays of filament currents of the same magnitude and 180° phase difference. Summing the contribution from all filaments:

$$G = -\frac{k_0 Z_0}{4} I_0 \sum_{n=-\infty}^{+\infty} H_0^1(k_0\rho_n^-) - H_0^1(k_0\rho_n^+)$$

where $\rho_n^- = \sqrt{(x - x' - 2na)^2 + (z - z')^2}$, $\rho_n^+ = \sqrt{(x + x' - 2na)^2 + (z - z')^2}$ and k_0 and Z_0 are, respectively, the propagation constant and the characteristic impedance of the free space. H_0^1 is the Hankel function of zeroth order and first kind. The convergence rate of this series is very poor; thus its numerical evaluation is very inefficient. A better representation for Green's function can be obtained using the Poisson summation formula [11] and is given by

$$G = -\frac{k_0 Z_0}{a} \sum_{n=1}^{\infty} \frac{\sin(\frac{n\pi}{a}x')\sin(\frac{n\pi}{a}x)e^{ik_{zn}|z-z'|}}{k_{zn}} \tag{1}$$

where k_{zn} is defined by

$$k_{zn} = \sqrt{k_0^2 - \left(\frac{n\pi}{a}\right)^2}.$$

Suppose a TE_{10} mode with field distribution

$$\boldsymbol{E}^i = \hat{y}\sin\left(\frac{\pi}{a}x\right)e^{ik_{1z}z}$$

is illuminating the cylinder, inducing a volumetric polarization current $J(x, z)$ in the cylinder. The induced current is proportional to the total electric field inside the cylinder and is given by

$$\boldsymbol{J}(x, z) = -ik_0 Y_0(\epsilon - 1)(\boldsymbol{E}^s + \boldsymbol{E}^i)$$

where $\boldsymbol{E}^s$ is the scattered field given by

$$\boldsymbol{E}^s(x, z) = \hat{y}\int_s J(x', z')G(x, z; x', z')dx'dz'.$$

Therefore the integral equation for the induced current is of the following form:

$$J(x, z) = -ik_0 Y_0(\epsilon - 1)\left[\sin\left(\frac{\pi}{a}x\right)e^{ik_{1z}z} + \int_s J(x', z')G(x, z; x', z')dx'dz'\right]. \tag{2}$$

An analytical solution for this integral equation is not known; however, an approximate numerical solution can be obtained using the method of moments. By subdividing the cross section of the cylinder into sufficiently small rectangular cells over which the induced current can be assumed constant, the integral equation can be cast into a matrix equation. If the discretized polarization current is denoted by a column vector $\mathcal{J}$, then

$$\boldsymbol{Z}\mathcal{J} = \boldsymbol{V} \tag{3}$$

where $\boldsymbol{V}$ is the excitation vector given by

$$v_i = \sin\left(\frac{\pi}{a}x_i\right)e^{ik_{1z}z_i}$$

and (x_i, z_i) is the Cartesian coordinate of the ith cell. In (3) $\boldsymbol{Z}$ is the impedance matrix whose elements can be computed from

$$z_{ij} = \begin{cases} \dfrac{k_0 Z_0}{a}\displaystyle\sum_{n=1}^{\infty} \dfrac{4\sin\left(\frac{n\pi x_i}{a}\right)\sin\left(\frac{n\pi x_j}{a}\right)\sin\left(\frac{n\pi\Delta x}{2a}\right)\sin\left(\frac{k_{nz}\Delta z}{2}\right)}{ik_{nz}^2\left(\frac{n\pi}{a}\right)} \times e^{ik_{nz}|z_i - z_j|} & z_j \neq z_i \\ \dfrac{k_0 Z_0}{a}\displaystyle\sum_{n=1}^{\infty} \dfrac{4\sin\left(\frac{n\pi x_i}{a}\right)\sin\left(\frac{n\pi x_j}{a}\right)\sin\left(\frac{n\pi\Delta x}{2a}\right)}{ik_{nz}^2\left(\frac{n\pi}{a}\right)} \times \left(e^{ik_{nz}\Delta z/2} - 1\right) & z_j = z_i \end{cases}$$

$$z_{ii} = \frac{i}{k_0 Y_0(\epsilon - 1)} + \frac{k_0 Z_0}{a}\sum_{n=1}^{\infty}\frac{4\sin^2\left(\frac{n\pi x_i}{a}\right)\sin\left(\frac{n\pi\Delta x}{2a}\right)}{ik_{nz}^2\left(\frac{n\pi}{a}\right)}\left(e^{ik_{nz}\Delta z/2} - 1\right)$$

where Δx and Δz are the pixel dimensions. Once the polarization current is obtained, by inverting (3), the scattered field can be calculated easily. Since the waveguide can only support the TE_{10} mode, only the first term of Green's function is needed to compute the reflected or transmitted wave. For example, away from the dielectric cylinder the reflected wave is given by

$$E^r = -\frac{k_0 Z_0}{ak_{1z}}\sin\left(\frac{\pi x}{a}\right)e^{-ik_{1z}z}\int_s J(x', z')\sin\left(\frac{\pi x'}{a}\right)dx'dz'.$$

Therefore, the reflection coefficient, defined as the ratio of the reflected wave to the incident wave at $z = 0$, in vector notation is given by

$$\Gamma = -\frac{k_0 Z_0}{a k_{1z}} \Delta x \Delta z \boldsymbol{V}^t \mathcal{J} \tag{4}$$

where $\boldsymbol{V}^t$ is the transpose of the excitation vector. In a similar manner the transmission coefficient can be obtained from

$$\tau = 1 - \frac{k_0 Z_0}{a k_{1z}} \Delta x \Delta z \tilde{\boldsymbol{V}} \mathcal{J}$$

where $\tilde{\boldsymbol{V}}$ is the conjugate transpose of $\boldsymbol{V}$.

III. Retrieval of Dielectric Constant from Reflection Coefficient

The main goal of this analysis is the calculation of the dielectric constant of the dielectric cylinder from its measured reflection coefficient. As the analysis of the previous section shows there is no simple relationship between the dielectric constant ϵ and the reflection coefficient Γ. The only case where an analytical solution for ϵ can be obtained is when the cylinder is electrically thin, i.e., $k_0 d \ll 1$ with d being a typical dimension of the cylinder cross section. In this case the polarization current can be assumed constant, and it can be shown that

$$\epsilon = 1 + \frac{ia}{k_0^2 \left[\frac{\Delta S \sin^2 \frac{\pi x_0}{a} e^{2ik_{1z} z_0}}{k_{1z}\Gamma} \right] - A} \tag{5}$$

where ΔS is the area of the cross section of the thin cylinder, (x_0, z_0) is the coordinate of the cylinder center, and A is given by

$$A = \sum_{n=1}^{\infty} \frac{1}{k_{zn}} \sin\left(\frac{n\pi x_0}{a}\right) \int_{\Delta S} \sin\left(\frac{n\pi x'}{a}\right) e^{ik_{zn}|z_0 - z'|} dx' dz'.$$

Since the summation is slowly converging, the contribution of higher order terms, which are varying over the cylinder cross section, to the integral is significant; therefore the integral for each term must be evaluated carefully.

Direct retrieval of ϵ from $\Gamma(\epsilon)$ for thick cylinders is not possible. However, brute force numerical search methods such as Newton–Ralphson or conjugate gradient can be used to find the dielectric constant that satisfies

$$\Gamma(\epsilon) - \Gamma_m = 0$$

where Γ_m is the measured reflection coefficient, and $\Gamma(\epsilon)$ is the calculated reflection coefficient for a given dielectric constant and cross section geometry. Search routines, depending on the initial guess, usually require the calculation of $\boldsymbol{Z}^{-1}$ many times. The calculation of $\Gamma(\epsilon)$ using (4) is very slow which makes the search routine inefficient.

In what follows a procedure for the calculation of $\Gamma(\epsilon)$ is presented which does not require evaluation of $\boldsymbol{Z}^{-1}$ for different values of ϵ. The search routines can be made efficient by noticing that the dielectric constant appears only in the diagonal elements of the impedance matrix. The effect of ϵ in $\boldsymbol{Z}^{-1}$ can be made explicit by splitting the impedance matrix into two matrices:

$$\boldsymbol{Z} = \boldsymbol{W} + \beta \boldsymbol{I}$$

where $\boldsymbol{I}$ is the identity matrix, $\beta = i/(k_0 Y_0(\epsilon - 1))$, and $\boldsymbol{W}$

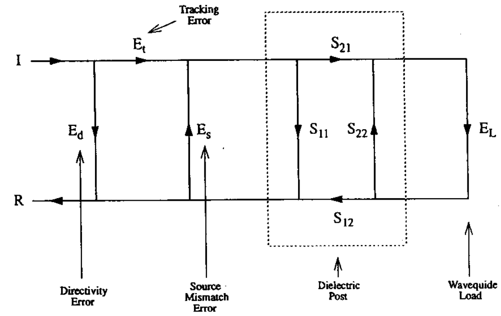

Fig. 2. The signal flow diagram of the measurement setup and the sample holder.

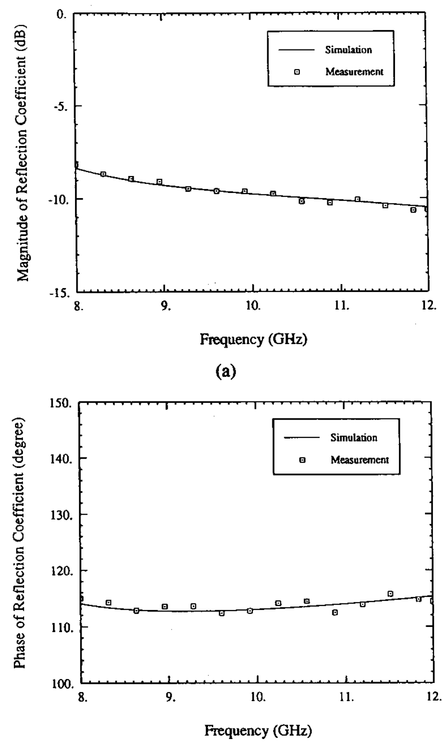

Fig. 3. Magnitude (a) and phase (b) of the reflection coefficient of a circular Teflon post with diameter $d = 0.7$ cm and $\epsilon = 2 + i0.005$ in a WR90 waveguide.

is a matrix whose elements are defined as

$$w_{ij} = z_{ij} \quad i \neq j$$

$$w_{ij} = \frac{k_0 Z_0}{a} \sum_{n=1}^{\infty} \frac{4 \sin^2(n\pi x_i/a) \sin(n\pi \Delta x/2a)}{i k_{nz}^2 (n\pi/a)} \times (e^{ik_{nz}\Delta z/2} - 1) \quad i = j.$$

Computing the eigenvalues and eigenvectors of $\boldsymbol{W}$ it can be shown that

$$\boldsymbol{W} = \boldsymbol{Q} \Lambda \boldsymbol{Q}^{-1} \tag{6}$$

where Λ is the diagonal matrix containing the eigenvalues of $\boldsymbol{W}$, and $\boldsymbol{Q}$ is the matrix of eigenvectors; that is, the jth column of $\boldsymbol{Q}$ is the eigenvector of $\boldsymbol{W}$ corresponding to the jth eigenvalue λ_j. Noting that the identity matrix can be written as

$$\boldsymbol{I} = \boldsymbol{Q}\boldsymbol{I}\boldsymbol{Q}^{-1} \tag{7}$$

and using (3), (6), and (7) the polarization current can be computed from

$$\mathcal{J} = \boldsymbol{Q}[\Lambda + \beta \boldsymbol{I}]^{-1}\boldsymbol{Q}^{-1}\boldsymbol{V}.$$

The expression for the reflection coefficient can now be written as

$$\Gamma(\epsilon) = -\frac{k_0 Z_0}{a k_{1z}} \Delta x \Delta z [\boldsymbol{Q}^t \boldsymbol{V}]^t [\Lambda + \beta \boldsymbol{I}] \boldsymbol{Q}^{-1} \boldsymbol{V}. \tag{8}$$

Defining $\boldsymbol{U} = \boldsymbol{Q}^t\boldsymbol{V}$ and $\boldsymbol{U}' = \boldsymbol{Q}^{-1}\boldsymbol{V}$, (8) can be expanded to get

$$\Gamma(\epsilon) = -\frac{k_0 Z_0}{a k_{1z}} \sum_{n=1}^{M} \frac{U_n U_n'(\epsilon - 1)}{\lambda_n(\epsilon - 1) + i k_0 Y_0} \tag{9}$$

where M is the dimension of $\boldsymbol{Z}$. From this expression it is obvious that once the eigenvalues and eigenvectors of $\boldsymbol{Z}$ are obtained, the reflection coefficient can easily be evaluated for any values for ϵ from (9). By setting the right-hand side of (9) equal to the measured reflection coefficient Γ_m, a polynomial of degree M is obtained whose roots are the possibe values of ϵ. The admissible solutions for ϵ must satisfy $\epsilon' \geq 1$ and $\epsilon'' \geq 0$ which can be imposed as a constraint in the search routine. In this paper the conjugate gradient method is used to search for the global minimum of the function

$$f(\epsilon) = |\Gamma(\epsilon) - \Gamma_m|^2$$

subject to the mentioned constraint. For relatively thin cylinders expression (5) can be used as the initial guess.

IV. Numerical and Experimental Results

In this section the applicability and accuracy of the dielectric measurement algorithm described in the previous section are examined. An automatic measurement setup comprised of an HP-8510B vector network analyzer, an HP-8511 test set, and an HP-9000 computer is used to measure the complex reflection coefficient Γ_m of a dielectric cylinder in an X-band waveguide sample holder. The waveguide sample holder consists of a waveguide matched load and a piece of waveguide with a coax-to-waveguide adapter which is connected to the HP-8511. The samples are placed at the junction of the two waveguide pieces ($z = 0$) and centered in the middle of the waveguide cross section ($x = a/2$). Centering the dielectric cylinder in the middle of the waveguide cross section increases the reflected wave, thus improving the signal-to-noise ratio for thin cylinders with low permittivity.

One difficulty in reflection coefficient measurement is the errors caused by the measurement setup. These errors are known as systematic errors which can be removed by an external calibration procedure. The signal flow diagram of the measurement setup is shown in Fig. 2 where E_d, E_s, E_t, E_l are, respectively, the directivity, source mismatch, frequency tracking, and load errors. The reflection coefficient measured by the network analyzer (Γ_a) before calibration is related to the actual scattering matrix of the cylinder ($\Gamma_m = s_{11}$) by

$$\Gamma_a = E_d + \frac{s_{11} + \frac{s_{12}s_{21}E_l}{1 - s_{22}E_l}}{1 - E_s\left(s_{11} + \frac{s_{12}s_{21}E_l}{1 - s_{22}E_l}\right)} E_t.$$

Calculation of s_{11} from this error model requires the two-port calibration procedure. However, E_l for waveguide loads can be as small as -50 dB and if cylinders with $s_{11} > -20$ dB are concerned, the error in s_{11} measurement would be less than 0.2 dB when E_l is set to zero. In this case the error model reduces to that of a single-port device. To correct for the system errors, the measurement system can be calibrated using three independent loads with known reflection coefficients. For the waveguide sample holder a short, an offset short, and a matched load were chosen to calibrate the system. Since the calibration is done over a frequency range $F^{\min} - F^{\max}$ the length of the offset short (l) must be chosen such that $k_z^{\max} l < \pi$ to assure the independence of the calibration loads.

To check the accuracy of the measurement setup and the forward algorithm, the reflection coefficients of a circular Teflon post with diameter $d = 0.7$ cm and dielectric constant $\epsilon = 2 + i0.005$ and a metallic post with radius $d = 0.63$ cm were measured and compared with the method of moments results. Figs. 3 and 4 show the measured and calculated

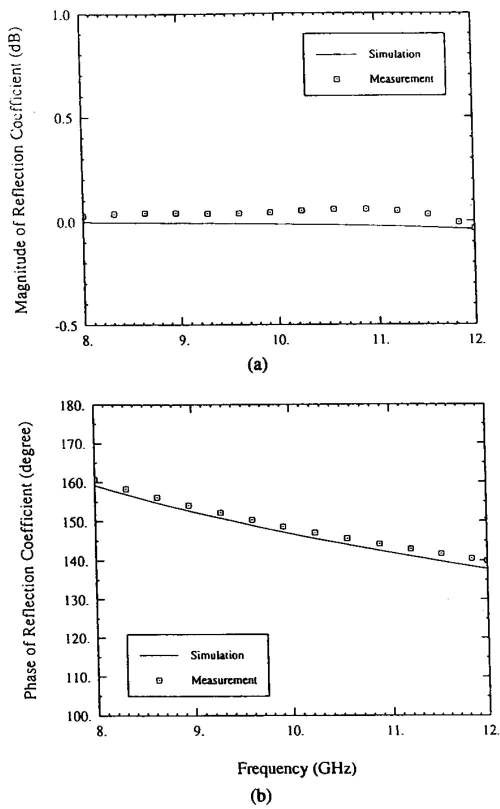

Fig. 4. Magnitude (a) and phase (b) of the reflection coefficient of a circular metallic post with diameter $d = 0.63$ cm in a WR90 waveguide.

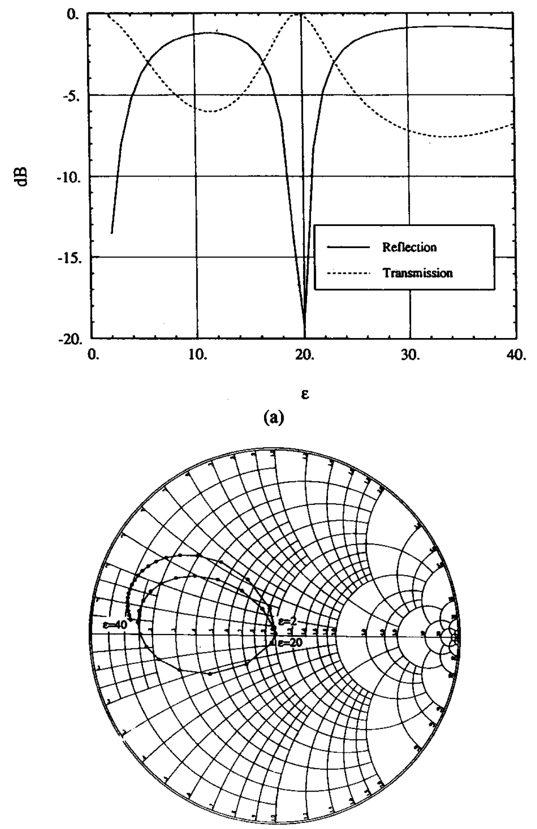

Fig. 5. Magnitude of the reflection and transmission coefficients (a) and complex reflection coefficient versus dielectric constant (b) for a circular cylinder with $d = 0.5$ cm at 10 GHz in a WR90 waveguide.

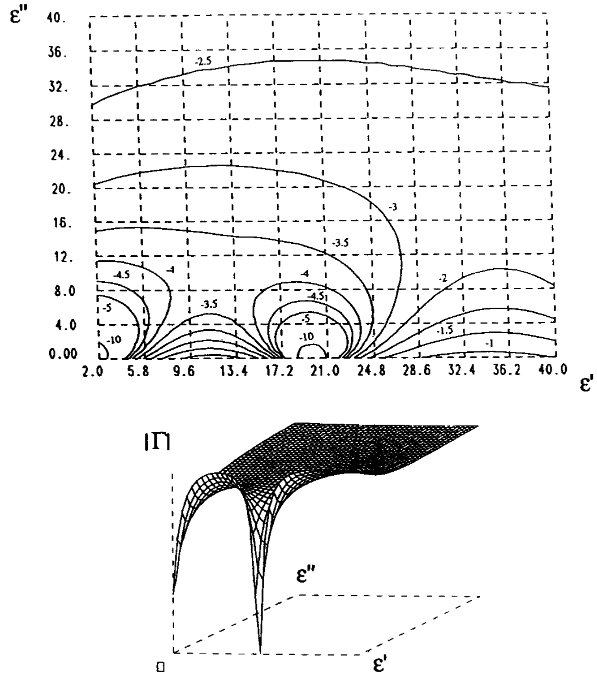

Fig. 6. Sensitivity of magnitude of the reflection coefficient to the real and imaginary parts of the dielectric constant for a circular cylinder with $d = 0.5$ cm at 10 GHz in a WR90 waveguide.

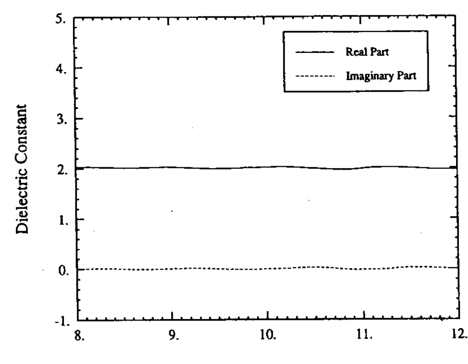

Fig. 7. Calculated real and imaginary parts of the dielectric constant from the measured reflection coefficient of a circularTeflon post with $d = 0.5$ cm.

reflection coefficients of the Teflon and metallic posts over the frequency range 8–12 GHz, respectively. The measured magnitude is within ±0.2 dB of the calculated magnitude, and the measured phase is within ±3° of the calculated phase of the reflection coefficient. With the confidence in the measurement technique, the inversion algorithm is attempted next. First let us examine the sensitivity of the reflection coefficient function to the dielectric constant. Fig. 5(a) shows the magnitude of the reflection and transmission coefficients as a function ϵ for a circular post with $d = 0.5$ cm at 10 GHz. It is noted that for $\epsilon = 20$ a resonance occurs where $s_{11} = 0$ and $s_{21} = 1$, satisfying the conservation of energy. Fig. 5(b) shows the complex reflection coefficient of the same cylinder as a function of the dielectric constant. It is also noted that the dielectric constant can be a multivalued function of the complex reflection coefficient. Due to the complex dependence of the reflection coefficient on the dielectric constant and the geometry of the post, criteria for the uniqueness of the solution cannot be established analytically. However, using the numerical analysis it was found that the dielectric constant becomes a single-valued function of the dielectric constant when the electrical thickness of the post ($d\sqrt{|\epsilon|}$) is small relative to the wavelength (away from the resonance). Fig. 6 shows the three-dimensional and the contour map of the magnitude of the reflection coefficient as a function of both ϵ' and ϵ'' for the circular dielectric post at 10 GHz. The sensitivity of the reflection coefficient function to changes in ϵ when both ϵ' and ϵ'' are large is very low and inversion may not be very accurate. Again using the forward numerical model it was found that Γ is very sensitive to ϵ when the electrical thickness of the post is small compared to the wavelength.

To examine the accuracy of the inversion algorithm a circular Teflon post with d =0.5 cm was placed in the sample holder, and its dielectric constant was calculated from the measured reflection coefficient. Fig. 7 shows the calculated dielectric constant of the Teflon post as a function of frequency

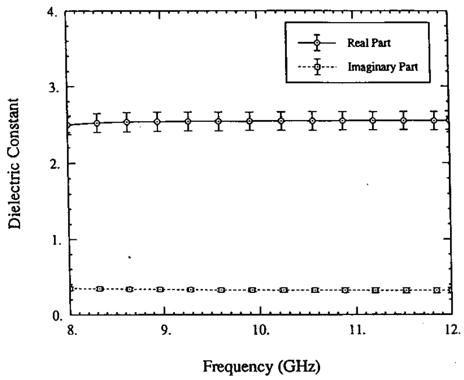

Fig. 8. Calculated real and imaginary parts of the dielectric constant from the measured reflection coefficient of circular dry wooden posts with $d = 0.32$ cm and moisture content $m_g < 0.01$.

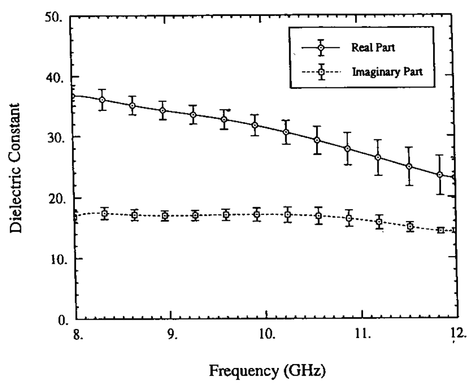

Fig. 9. Calculated real and imaginary parts of the dielectric constant from the measured reflection coefficient of circular wet wooden posts with $d = 0.32$ cm and moisture content $m_g < 0.5$.

which agrees well with the expected values of ϵ for Teflon. To show another example, the dielectric inversion algorithm was applied to wooden cylinders with different moisture contents (m_g). Ten samples of cylindrical wooden posts with $d = 0.32$ cm were prepared, and their reflection coefficients were measured. The experiment was repeated after the wooden posts were soaked in water for a day. The calculated average dielectric constants of the dry wood with $m_g < 0.01$ and wet wood with $m_g = 0.5$ are shown in Figs. 8 and 9, respectively. The bars on the measured real and imaginary parts of the dielectric constant indicate the standard deviation of the measured quantity derived from ten samples.

V. Conclusion

An accurate method for measurement of the dielectric constant of cylindrical objects with arbitrary cross section is presented. In this technique the dielectric constant of the cylinder with known cross section is calculated from the measured complex reflection coefficient of a matched rectangular waveguide containing the dielectric object. A novel and efficient inversion algorithm based on the method of moments and eigen analysis is introduced. The validity and accuracy of the method are examined from the measurement of dielectric posts with known dielectric constant. It is found that the accuracy in dielectric measurement decreases as the electrical thickness of the cylindrical post is increased. The choice of sample holder in this technique is suited for *in situ* and *in vivo* dielectric measurement of pine needles.

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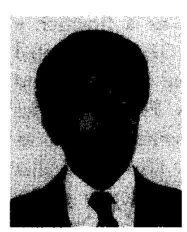

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