Nondestructive Measurement of a Dielectric Layer Using Surface Electromagnetic Waves

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Abstract —**In this investigation, the possibility of nondestructively measuring the thickness and dielectric constant of a layer of dielectric material on a conducting substrate by surface electromagnetic waves (SEW) has been demonstrated. The theoretical approximate dispersion relations near cutoff were derived for both the TE and TM modes and found to be linear functions of frequency. The thickness and dielectric constant were then calculated as simple algebraic functions of the slope and intercept of the dispersion curve. An experimental apparatus utilizing a prism-coupler was constructed to excite surface electromagnetic waves in a dielectric layer whose characteristics were known. By suitable measurements of the frequency and the coupling angle of the source, the dispersion curve was determined experimentally and the resulting dielectric constant and thickness of the layer calculated.**

I. INTRODUCTION

SURFACE electromagnetic waves (SEW) have been used in the past in the field of nondestructive evaluation. Previously, Alexander and Bell [1] used this technique to study planar optical waveguides in which a thin film of optically transparent material was coated on a conductive or semiconductive substrate. Later, Ulrich and Torge [2] published a paper which discussed measuring the thickness and refractive index of a light-guiding film using a prism-coupling technique. There are unfortunately, a number of disadvantages in using their method: 1) the film must be thick enough so that at least two modes can propagate; 2) the method is most often destructive in nature since the film must be mechanically pressed against the prism; 3) computer processing was required to fit the experimental data to the theoretical curves; 4) the method employs a laser as a source so only light-transparent materials can be measured. Later, Walter [3] used both TE and TM modes synchronously, resulting in a pair of transcendental equations for the thickness and refraction index of the layer. This method was based on the previous theory, so the same basic disadvantages were still present. Chung [4] then discussed using a single-mode, multiwavelength method, but required knowledge of the dispersion curve of the layer in advance.

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For our work, we are interested in layers of dielectric material on conductive substrates. These layers are relatively thick compared to the thin films, and are not usually optically transparent. Therefore, microwaves or millimeter waves are more appropriate for our study. Thus, it would seemingly be desirable to develop a single-mode technique which could calculate the dielectric constant and thickness of the layer independently without the use of lengthy computer analysis. The microwave system also allows optically nontransparent materials to be measured and does not require recording film as a detector, making it more suitable for real-time applications.

Our study shows that a multifrequency method of measuring both the cutoff frequency and the slope of the dispersion curve near cutoff allows a pair of simple simultaneous equations to be found which can then be solved for both the dielectric constant and the thickness of the layer. This method is seen to be suitable for any TE mode and all TM modes, except the TM_0 which has a zero cutoff frequency.

A prism coupling method developed by Ioganse [5]–[7] was then applied to an experimental test setup consisting of layers of plastic over a large sheet of aluminum. Results were then compared with direct measurements made of the thickness and dielectric constant.

Several potential applications of this method can be readily visualized. Thin protective coatings on components of jet engines, magnetohydrodynamic generators, or coal combustion chambers could be evaluated. Similarly, one might examine polymeric coatings for environmental protection or the surfaces of metals prepared for adhesive bonding, where the strength attained by the bond is known to be sensitive to the condition of the adherent surfaces. Since the measurements must be taken at frequencies above cutoff for the lowest order mode, the thickness of the dielectric layer must be greater than some minimum value which is determined by the frequency of operation and the dielectric constant of the material (e.g., for a frequency of 100 GHz and $\epsilon_r = 10$, a minimum thickness of 80 μm is required). Thus, for thin coatings, frequencies well into the millimeter-wave region may be required. The experimental measurements carried out in this work were made in the 8–12-GHz band with dielectric constants near 2 and, therefore, the thickness of the resultant layers was in the centimeter range.

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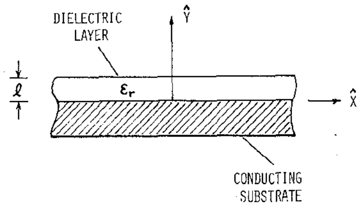

Fig. 1. Geometry and coordinate system for dielectric layer over a conducting substrate.

II. Theory

The geometry of the problem is shown in Fig. 1 and consists of a dielectric layer with relative permittivity ϵ_r and thickness l over an infinitely conducting plane.

For modes TM to $\hat{x}$, the fields in the air region $y \geqslant l$ are of the form

$$E_x, E_y, H_z \sim e^{-j(k_{0x}x+k_{0y}y)}, \; y \geqslant l;$$

$$\text{with } k_0^2 = k_{0x}^2 + k_{0y}^2 = \omega^2\mu_0\epsilon_0 \quad (1)$$

and in the dielectric material

$$E_x, E_y, H_z \sim e^{-j(k_{1x}x+k_{1y}y)}, \qquad 0 < y < l \quad (2)$$

where

$$k_1^2 = k_{1x}^2 + k_{1y}^2 = \omega^2\mu_0\epsilon_1 = \epsilon_r k_0^2.$$

Using the appropriate boundary conditions at $y = l$ and $y = 0$, the following equations can be derived in the manner of Harrington [8]:

$$k_{1y}l\tan(k_{1y}l) = \epsilon_r\beta l \quad (3)$$

and

$$(k_{1y}l)^2 + (\beta l)^2 = (\epsilon_r - 1)(k_0 l)^2 \quad (4)$$

where k_{1y} is the wavenumber in the dielectric in the $\hat{y}$ direction, and $\beta = jk_{0y}$ accounts for the decay in air normal to the surface for the pure surface wave. This pair of equations cannot be solved exactly. The usual graphical solution is shown in Fig. 2 in the $k_{1y}l-\beta l$ plane. Equation (4) is a circle of radius $(\epsilon_r - 1)^{1/2}k_0 l$, and (3) is represented by the tangent-like curves. The points of intersection between these two curves determines the solution for k_{1y} and β as a function of thickness l and dielectric constant ϵ_r. It can be seen from the figure that the TM_0 mode will be able to propagate for any frequency, but all higher order modes have a finite cutoff frequency. The cutoff wavenumber of each mode is given by

$$k_c = \frac{n\pi}{l(\epsilon_r - 1)^{1/2}}, \qquad n = 0, 1, 2, \cdots. \quad (5)$$

This one relation between ϵ_r and l can be determined (for all but the TM_0 mode) by simply measuring the cutoff frequency.

If another measurable parameter can be found that is a different function of ϵ_r and l, then both ϵ_r and l could be found independently from the two resulting equations. To this end, the dispersion relation of these TM modes can be examined more closely near cutoff. Expansion of the dispersion relation about the cutoff point and neglecting all but first-order terms, the relationship between k_{0x} and k_0 can be shown to be

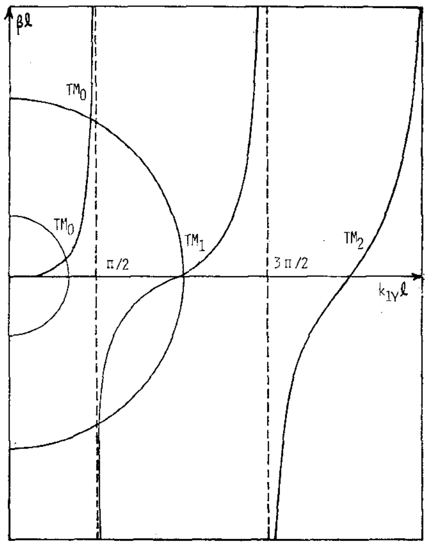

Fig. 2. Graphical solution of dispersion relation.

$$\left[\left(\frac{k_{0x}}{k_0}\right)^2 - 1\right]^{1/2} \doteq \left[\frac{\epsilon_r - 1}{\epsilon_r}l\right][k_0 - k_c] \quad (6)$$

with k_c given by (5).

It should be noted that a linear relation will result if the quantity

$$\left[\left(\frac{k_{0x}}{k_0}\right)^2 - 1\right]^{1/2}$$

is plotted versus k_0. Its intercept will be

$$k_c = \frac{n\pi}{l(\epsilon_r - 1)^{1/2}}$$

and its slope will be

$$\frac{(\epsilon_r - 1)l}{\epsilon_r}.$$

Thus, if the value of k_{0x} is found for several frequencies just above f_c, the slope and intercept of the above curve can be found, and the quantities ϵ_r and l can be determined from k_c and the slope S

$$\epsilon_r = \frac{1 \pm \left[1 - 4\left(\frac{Sk_c}{n\pi}\right)^2\right]^{1/2}}{2\left(\frac{Sk_c}{n\pi}\right)^2} \quad (7)$$

$$l = \frac{\epsilon_r S}{\epsilon_r - 1}. \quad (8)$$

(The equation for ϵ_r is a double valued function and thus some approximate value of ϵ_r must be known from another source.)

It should be noted that for the TM_0 mode, (5) does not provide one of the required relationships between ϵ_r and l, and thus (7) and (8) cannot be used. Equation (6) can still be utilized, however, and if either ϵ_r or l is known, the measured slope can be used to predict the remaining unknown parameter.

Similar expressions for TE to $\hat{x}$ modal fields can be found for H_x, H_y, and E_z components. Again, from Harrington [8], the following relations can be found:

$$-k_{1y}l \cot k_{1y}l = \beta l \tag{9}$$

$$(k_{1y}l)^2 + (\beta l)^2 = (\epsilon_r - 1)(k_0 l)^2 \tag{10}$$

with cutoff defined by

$$k_c = \frac{(2n+1)\pi}{2l(\epsilon_r - 1)^{1/2}}. \tag{11}$$

For the TE modes, even the lowest TE_0 mode has a nonzero cutoff frequency, and thus any TE mode can be used to find both ϵ_r and l. Following a similar procedure as was previously done for TM modes, the following relation is found:

$$\left[\left(\frac{k_{0x}}{k_0}\right)^2 - 1\right]^{1/2} \doteq (\epsilon_r - 1)l\left(\frac{k_c}{k_0}\right)^{1/2}(k_0 - k_c). \tag{12}$$

Since we are near cutoff

$$(k_c/k_0)^{1/2} \doteq 1$$

and

$$\left[\left(\frac{k_{0x}}{k_0}\right)^2 - 1\right]^{1/2} \doteq (\epsilon_r - 1)l(k_0 - k_c). \tag{13}$$

Thus, near cutoff, a graph of

$$\left[\left(\frac{k_{0x}}{k_0}\right)^2 - 1\right]^{1/2}$$

versus k_0 will produce a straight line with intercept k_c and slope $S = (\epsilon_r - 1)l$. This results again in being able to calculate ϵ_r and l from the experimental measurement of several values of k_{0x} near cutoff. For the lowest order TE_0 mode, substituting $n = 0$ in (11) yields

$$\epsilon_r = \left(\frac{2k_c S}{\pi}\right)^2 + 1 \tag{14}$$

and

$$l = \frac{S}{\epsilon_r - 1}. \tag{15}$$

An alternative procedure would be to measure k_c directly and then find k_{0x} at a slightly greater frequency than k_0. Then, calculating the slope from the two points and the knowledge of k_c, one could find both ϵ_r and l. This method has the additional advantage in that the more accurate dispersion relation given by (12) rather than (13) can be used to find ϵ_r and l.

It is necessary to establish exactly which mode is being propagated (value of n) to be able to use either method for the TE modes or to use a higher order TM mode in the previous derivation. The slope of all modes near cutoff is constant ($S = [(\epsilon_r - 1)l]/\epsilon_r$ for TM modes and $(\epsilon_r - 1)l$ for TE modes), but the value of k_c, of course, depends on the mode number n. Experimentally, if one knows the approximate values of ϵ_r and l, it is normally relatively simple to ascertain which mode is propagating. If absolutely nothing is known, one must begin at a very low frequency and scan upwards in frequency until the lowest mode is excited.

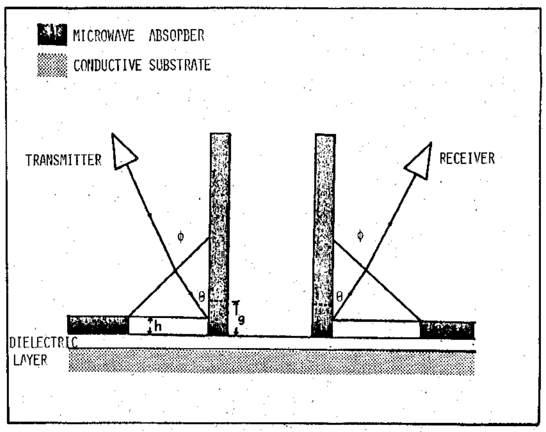

Fig. 3. Experimental apparatus for launching surface electromagnetic waves.

III. Experimental Procedures

To indirectly measure the thickness and dielectric constant, the relationship between k_{0x}, the surface electromagnetic wavenumber, and the free space wavenumber k_0 must be obtained. To determine this dependence, and to launch the surface waves themselves, a prism-layer coupler was constructed and utilized. Such a device was first discussed by Tien, Ulrich, and Martin [9], and later by Midwinter *et al.* [10]. A diagram of the experimental apparatus is shown in Fig. 3. The operation of the prism-layer coupler depends on the incident wave inside the prism striking the lower edge of the prism at an angle θ greater than the critical angle. An evanescent wave is then set up in the air gap of height h along the bottom edge of the right-angle prism. The coupling is then strongest when the x-component of the SEW-wave vector is equal to the x-component of the wave vector in the prism

$$k_0\sqrt{\epsilon_{rp}} \sin\theta = k_{0x} \tag{16}$$

where ϵ_{rp} is the relative dielectric constant of the prism material. If the wave inside the prism, which is incident on the prism-air interface, were an ideal plane wave, there would be a single internal angle of incidence at which the SEW could be launched. In practice, the illuminating source horn antenna produces a set of plane waves varying slightly in direction about the central ray. Hence, as θ is varied, the TM_n SEW-mode amplitude also varies but is a maximum for the proper value of θ. Thus, by measuring this optimum θ as a function of frequency, the functional dependence of k_{0x}/k_0 on k_0 can be obtained. The magnitude of the SEW is measured by a second identical prism-layer coupler to convert the SEW back to a plane wave to be detected by a receiving horn. Either of the two types of modes, TE_n or TM_n, can be excited by the choice of polarization of the feed and receiver horns. A vertically polarized horn produces the TM SEW modes, while a horizontally polarized one results in TE modes. For precise measurements of the angles, the lateral position of the prism must be adjusted so that the central ray of the beam passes through the right-angle corner of the prism. This procedure was followed in all measurements, and is discussed in detail in Ou's previous work [11]. Also shown in the diagram of Fig. 3 are several pieces of microwave absorbing material to prevent the receiving horn from receiving direct and reflected radiated fields from the source other than the desired SEW mode. To insure a plane-wave approximation for the incident fields, the horns were mounted on 80-cm radius divided circles. A minimum distance ($2D^2/\lambda$) of about 40 cm would be needed for the usual far field requirement. The two horns were each 13 cm long with a 7.7 by 7.7-cm aperture providing a gain in the 8–12-GHz band of approximately 20 dB, and a 3-dB beamwidth of 30°. The vertical absorbers were each 50 cm high and had a gap of $g = 9$ cm between their lower edge and the dielectric layer. The base of the prism was 20 by 20 cm, and its height was 20 cm and was made of commercial paraffin ($\epsilon_{rp} = 2.22$). To couple the wave in the prism into the desired SEW mode there must be an air gap between the prism and the dielectric layer. Experimentally, it was found that best coupling occurred for separations near one-half wavelength ($h \doteq 1.5$ cm).

The sample to be measured consisted of a 250 by 20-cm sheet of aluminum as the conductive substrate and similar size layers of dielectric material stacked on top to provide the desired thickness. Two kinds of materials were used for the dielectric layer: polypropylene with a nominal relative dielectric constant of 2.25 at 10 GHz; and polyvinyl chloride with a value of 2.64 at the same frequency. The dielectric sheets and the aluminum plane were mechanically clamped together to minimize any air gaps.

The two principal experimental parameters to measure are the operating frequency and the external angle of incidence ϕ. Once these quantities are known accurately, the internal angle of incidence θ, and thus k_{0x}, can be calculated directly as a function of frequency (or equivalently k_0). In actuality the incident angle can be scanned over the 0°–90° range to determine the number of modes propagating on the structure, and the desired mode can be identified. Then the position of the two horns are synchronously varied in small increments (keeping the transmitting and receiving angles equal) to locate the exact position of the peak signal. This procedure is then repeated for several other frequencies so that the slope and intercept of the curve may be accurately measured.

For the TE_0 mode, the alternate procedure previously mentioned may be utilized by first obtaining the cutoff frequency directly. The cutoff frequency occurs when $k_{0x} = k_0$, which from (16) gives

$$\theta = \sin^{-1}\sqrt{\frac{1}{\epsilon_{rp}}}.$$

For the case of 45° paraffin prisms with $\epsilon_{rp} = 2.22$, this will always occur at $\phi = 40.76°$. Thus, if both horns are set at $\phi = 40.76°$ and the frequency is varied, the maximum of the signal at the receiver will identify the cutoff frequency for the TE_0 mode. Then the frequency can be increased slightly and the new optimum angle measured. These two points can then be used to calculate k_{0x}/k_0 and ultimately to find ϵ_r and l of the dielectric layer.

IV. Experimental Results

Several objectives were selected for experimental investigation: 1) verification that the predicted modes are present for particular frequencies and sample geometries; 2) demonstration that the cutoff frequency for the TM_0 mode is zero; 3) determination of whether the cutoff frequency for the TE_0 mode is sharply defined; and 4) comparison of the predicted values of dielectric constant and thickness from the SEW measurements with those found by direct independent means.

To check the experimental apparatus, TM polarized waves were excited in different thicknesses of polypropylene layers, and the detected signal amplitude as a function of external incidence angle ϕ is shown in Fig. 4. At the selected frequency for the thinner of the layers ($l = 0.5$ cm), theory would predict only the TM_0 mode would be able to propagate. Experimental measurements confirm this behavior as only a single peak is detected near $\phi = 52°$. When the thickness is increased to $l = 1.5$ cm, the TM_1 mode can also propagate, and an experimental peak is found near $\phi = 40°$ for this mode, along with another near $\phi = 72°$ for the TM_0 mode.

Two distinct experimental procedures were developed to measure the thickness and dielectric constant of the layer. The first is called "Initial Slope Determination" (ISD method) and consists of measuring the external incidence angle ϕ for maximum signal response from the desired mode as a function of frequency. The internal incidence angle θ (see Fig. 2) can then be calculated as follows:

$$\theta = \frac{\pi}{4} - \sin^{-1}\left[\frac{\sin\left(\frac{\pi}{4} - \phi\right)}{\sqrt{\epsilon_{rp}}}\right], \qquad \text{for } \phi \leqslant \frac{\pi}{4} \tag{17}$$

$$\theta = \frac{\pi}{4} + \sin^{-1}\left[\frac{\sin\left(\phi - \frac{\pi}{4}\right)}{\sqrt{\epsilon_{rp}}}\right], \qquad \text{for } \phi > \frac{\pi}{4} \tag{18}$$

where ϵ_{rp} is the relative dielectric constant of the prism.

From the previous work on prism coupling, the incidence angle is determined by

$$k_{0x} = k_0\sqrt{\epsilon_{rp}}\sin\theta \tag{19}$$

and thus knowing k_0 from the measured frequency, and θ from the measured angle ϕ, the ratio k_{0x}/k_0 can be found and the quantity $[(k_{0x}/k_0)^2 - 1]^{1/2}$ plotted versus k_0. From the several data points for different frequencies, a curve can be fit and its slope S and intercept k_c can be found. Then using S and k_c, experimentally determined

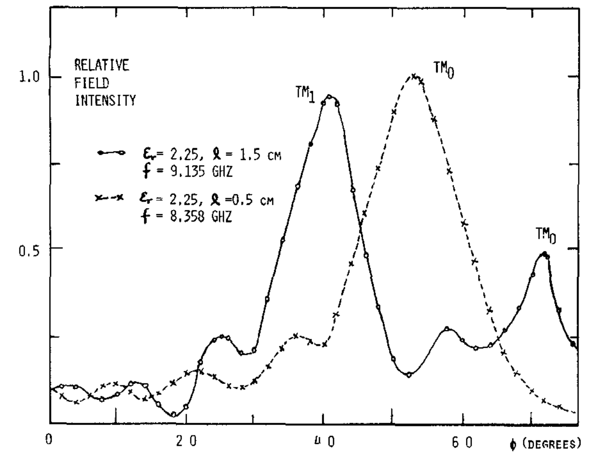

Fig. 4. Relative received signal versus ϕ for TM modes.

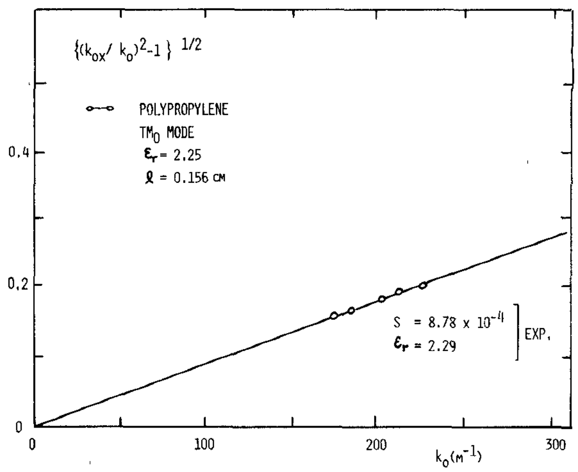

Fig. 5. Dispersion curve for TM_0 mode in polypropylene.

values for ϵ_r and l can be ascertained for the TM_1 mode from (7) and (8).

The second procedure is called "Cutoff Frequency Determination" (CFD method), and can only be used for modes with nonzero cutoff frequencies. It consists of setting the external incidence angle to $\phi = 40.76°$ (corresponding to cutoff for our prisms) and varying the frequency until a peak reading is obtained. This measured value of f_c then determines $k_c = 2\pi f_c/c$, the intercept, directly. The frequency is then varied upward slightly and the new angle ϕ measured. The value of $[(k_{0x}/k_0)^2 - 1]^{1/2}$ can then be found from (21) and the slope calculated. This measurement may be repeated several times for differing frequencies to enable an average slope to be calculated.

To check the ISD method and to confirm the zero cutoff frequency for the TM_0 mode, measurements were made on a layer of polypropylene with $l = 0.156$ cm over the 8–11 GHz range. The experimentally determined points are shown in Fig. 5 along with a least-square fit curve for the data. The intercept is seen to be quite near $k_0 = 0$ and when the known thickness of $l = 0.156$ cm is used, an experimentally calculated value of $\epsilon_r = 2.29$ is obtained. (Both ϵ_r and l cannot be calculated independently for the TM_0 mode since it has zero cutoff frequency.)

It is necessary to utilize the TM_1 mode on a thicker layer to measure both material properties independently. Another polypropylene sample ($\epsilon_r \doteq 2.25$) with $l = 1.65$ cm was measured using the ISD method. Data was again taken over the X-band frequency range (8.4–12 GHz) with the results shown in Fig. 6. One can observe the very nearly linear behavior near the cutoff frequency, and the departure from linearity for $k_0 > 220$ m^{-1}. Since the theory assumed frequencies near cutoff, this variation should be expected. Only the first eight data points were used in the least-square fit curve which produced a slope of 9.19×10^{-3} m and an intercept of $k_c = 169$ m^{-1}. When these parameters are used to find the properties of the dielectric, the results are $\epsilon_r = 2.31$ and $l = 1.62$ cm, which correspond well with the known values. Similar data was taken for a layer of polyvinyl chloride ($\epsilon_r = 2.64$) with $l = 1.51$ cm. Those

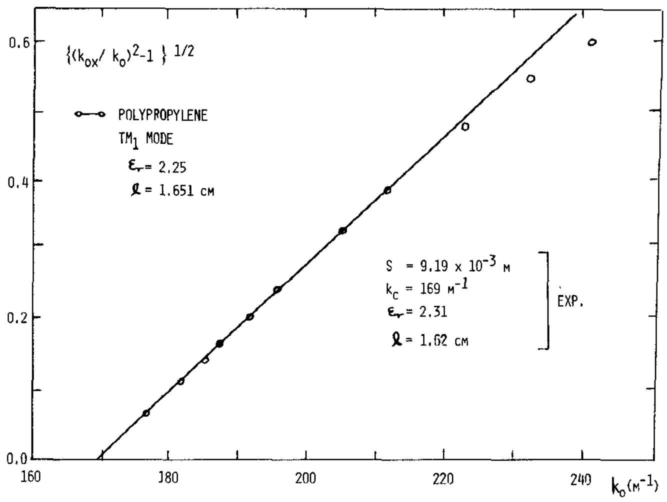

Fig. 6. Dispersion curve for TM_1 mode in polypropylene.

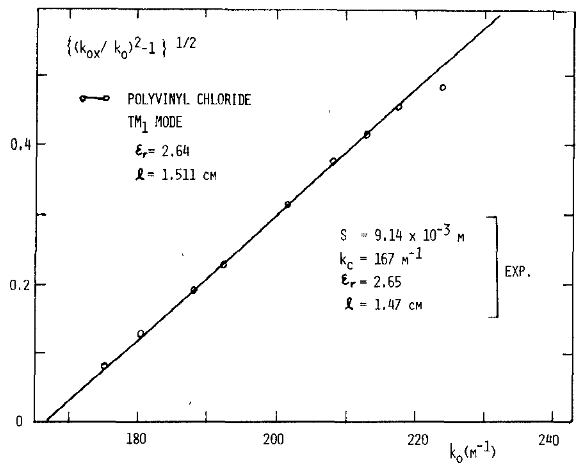

Fig. 7. Dispersion curve for TM_1 mode in polyvinyl chloride.

measurements are shown in Fig. 7, which result in experimental values of $\epsilon_r = 2.65$ and $l = 1.47$ cm.

The first transverse electric mode, the TE_0, can also be excited by rotating the transmitting and receiving horns by 90°. Better results are obtained for the TE_0 mode using the

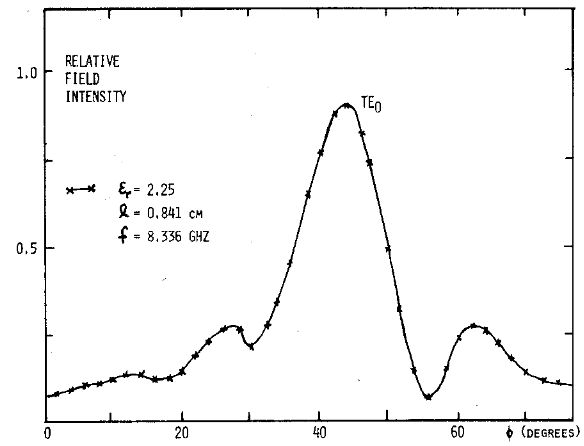

Fig. 8. Relative received signal versus ϕ for TE_0 mode.

TABLE I
EXPERIMENTAL RESULTS

Mode Used	Dielectric Material	ISD Method ϵ_r	ISD Method ℓ(cm)	CFD Method ϵ_r	CFD Method ℓ(cm)	Direct Measurements ϵ_r	Direct Measurements ℓ(cm)	Difference (%) ϵ_r	Difference (%) ℓ(cm)
TM_0	polypropylene	2.29	-			2.25	-	1.8	-
TM_1	polypropylene	2.31	1.62			2.25	1.651	2.7	1.8
TM_1	polyvinyl chloride	2.65	1.47			2.64	1.511	0.4	2.5
TE_0	polypropylene			2.27	0.712	2.25	0.714	0.9	0.3
TE_0	polyvinyl chloride			2.63	0.641	2.64	0.645	0.4	0.6

CFD method. The dispersion relation of (21) contains the term $(k/k_c)^{1/2}$, and while the ISD method uses the approximate relation of (22) which assumes this term to be unity, the CFD method does not. Thus, better results are obtained using the CFD procedure for this mode. A plot of the received signal is shown in Fig. 8 for a polypropylene sample of thickness $l = 0.841$ cm. The peak for the TE_0 mode is seen near $\phi = 42°$. Other smaller peaks are also seen near $\phi = 28°$ and $62°$. These do not represent other modes but instead are the results of the side lobes of the horn antenna.

A sample of polypropylene ($\epsilon_r = 2.25$ and $l = 0.714$ cm) was used to excite the TE_0 mode, and a cutoff frequency of 9.36 GHz was measured. This corresponds to a theoretically calculated value of 9.392 GHz and represents an error of only 0.3 percent (considerably better than should be expected from the experimental setup). Measurements at three different frequencies above cutoff and subsequent averaging result in experimental values of $\epsilon_r \doteq 2.27$ and $l = 0.712$. Similar measurements on a layer of polyvinyl chloride $\epsilon_r = 2.64$ and $l = 0.645$ with a theoretical cutoff of 9.074 GHz resulted in an experimental cutoff frequency of 9.16 GHz and average figures of $\epsilon_r = 2.63$ and $l = 0.641$ cm.

In all cases, the direct measurements of the thickness were simply made using a micrometer. The dielectric constant was directly measured using the "two-point" method [12] in which a piece of the dielectric was placed in a slotted waveguide and the shift in standing wave pattern noted. From this method, a value of $\epsilon_r = 2.25$ was measured for the polypropylene, and an $\epsilon_r = 2.64$ for the polyvinyl chloride. A summary of the results is shown in Table I.

V. CONCLUSIONS

The nondestructive measurement of the dielectric constant and thickness of a dielectric layer using surface electromagnetic waves has been demonstrated. To determine both properties independently, modes with nonzero cutoff frequencies must be used (i.e., TM_1 or TE_0). For the TM cases, a quadratic equation is solved for ϵ_r and two possible solutions result: one for $\epsilon_r \geqslant 2$ and another for $\epsilon_r \leqslant 2$. Thus, if this mode is to be used, some approximate value of ϵ_r must be known. For the TE-mode case, no previous knowledge needs to be assumed. In both cases, the experimentally found values correlate very well with direct measurements made on the dielectric material.

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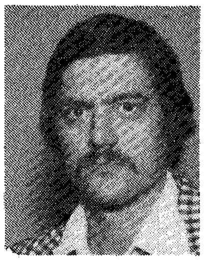

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Determination of Loaded, Unloaded, and External Quality Factors of a Dielectric Resonator Coupled to a Microstrip Line

APS KHANNA AND Y. GARAULT

Abstract—**In the case of a dielectric resonator coupled to a microstrip line, the relations for the determination of unloaded, loaded, and external quality factors, in terms of directly measurable reflection or transmission coefficient at the resonant frequency, have been derived and represented on the corresponding vectorial and scalar planes. Construction of a linear frequency scale and a graphical method to accurately determine the unloaded Q from the loaded Q measurement presented.**

I. Introduction

The advent of temperature stable, high-Q and low-loss ceramic materials has created a considerable interest in the application of dielectric resonators in the microwave integrated circuits [1]. The dielectric resonator coupled to a microstrip line has been used for realizing a number of stable oscillators [2]–[4] and filters [5]. Complete characterization of a microstrip coupled dielectric resonator (Fig. 1) is necessary for the analysis and synthesis of these integrated circuits. Ginzton [6] introduced the plotting of loci of various quality factors and the construction of a linear frequency scale in the case of a single-port

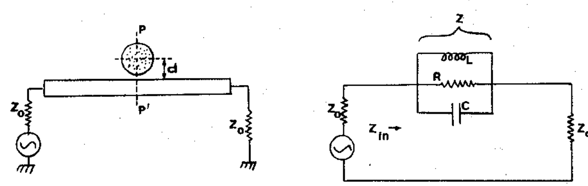

Fig. 1. Dielectric resonator coupled to a microstrip line and its equivalent circuit in symmetry plane PP'.

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