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A NEW METHOD FOR EVALUATION OF THICKNESS AND MONITORING ITS VARATION OF MEDIUM- AND LOW-LOSS MATERIALS

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Abstract—In this research paper, we propose an amplitude-only method for unique thickness evaluation of medium- and low-loss materials. The method is based on using amplitude-only measurements at different frequencies to evaluate the unique thickness. Main advantages of the method are a) it eliminates the necessity of repetitive measurements of different-length materials to evaluate the unknown thickness of the same type material and b) it determines the thickness at any desired frequency in the band. Because the method uses amplitude-only measurements and enables the thickness evaluation at any frequency, it can be a good candidate for thickness evaluation of materials in industrial-based applications.

1. INTRODUCTION

Practical applications of microwaves for nondestructive testing (NDT) of various materials are given in [1–8]. Microwaves possess certain properties that make their use for certain NDT applications more attractive than for certain NDT applications and other established techniques (ultrasonic, eddy currents, and etc.) [1, 9]. Some of these properties are 1) the ability of microwaves to penetrate through a dielectric medium, 2) the facility to conduct the measurements in a contact and a non-contact matter, and 3) the feasibility of using reflection-only measurements or transmission-only measurements or both [1–44].

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The microwave methods generally applied to materials testing and evaluation are free-space [10–24], waveguide transmission line [25–33], and open-ended waveguide coaxial methods [34–43]. While open-ended waveguide or coaxial (or parallel plate) methods are very sensitive to materials' (and composite structures') properties (thickness, disbonding, delamination, and etc.), they are also sensitive to the distance between materials and the waveguide aperture. For example, it was shown that undesired higher-order modes, which drastically affect the measurements, can appear as a result of any minuscule air gap between the waveguide aperture and materials [41]. Although waveguide aperture can be located away from materials by a distance (standoff distance), measurements must be carefully conducted by these methods since they are incoherent and highly dependent on standoff distance (in millimeter range). To eliminate the adverse effects of this distance on measurements, a method which uses orthogonally dual-polarized microwave signals can be employed [40]. However, this method is applicable to only anisotropic materials such as carbon fiber reinforced polymers.

Waveguide transmission-line methods are one of the most accurate non-resonant methods [25–33]. Besides, measurements by these methods are highly repetitive. However, they require elaborate sample preparation. In addition, they are destructive methods since they necessitate sample machining and cutting. Therefore, they are not applicable to and suitable for microwave NDT applications.

Free-space methods are nondestructive and noncontacting methods. In addition, they do not require that the sample thickness be moderate and can effectively be used in different environmental conditions (i.e., at high temperatures or chemically poisonous regions) [17]. However, free-space measurements are affected by diffractions from materials' edges. To eliminate these diffractions, spot-focusing antennas can be employed [16, 17]. Nonetheless, these antennas are band-limited, and for a broad band analysis a few sets of these antennas are required. As another solution, a calibration procedure which takes into account the diffraction effects can be incorporated to the measurement system [22–24].

Complex scattering (S-) parameters are generally measured for materials testing and evaluation. Nevertheless, there are three main problems of these measurements. First, the measured phase may differ an integral multiple of 2π from the actual value [18]. Second, any small shift from the calibration plane of materials results in enormous phase shift errors as a result of the application of inaccurate calibration [28]. Third, the phase uncertainty of reflection S-parameters for low-loss materials increases considerably when the sample length is of integer multiples of one-half wavelength [28]. Methods which use amplitude-only S-parameters can be employed to resolve all these problems. In addition, systems measuring amplitude-only information of the material under test are relatively inexpensive and require less microwave components and thus are desirable for industrial based applications when compared to those measuring amplitude and phase information [44].

In the literature, to evaluate the thickness of materials by amplitude-only measurements at any given frequency, repetitive reflection or transmission measurements of some test materials, which have the same internal (homogeneity) and electrical (permittivity) properties but different lengths as of the material under investigation, were measured [12, 25]. In this research paper, we propose another amplitude-only method, which eliminates the requirement of repetitive measurements of test samples, for evaluating the material thickness and monitoring its variation at any frequency of interest.

2. THEORETICAL BACKGROUND

A typical problem for thickness evaluation of a dielectric slab with length L by using free-space measurements is shown in Fig. 1. In the analysis, it is assumed that the slab is a isotropic, symmetric, homogenous and planar material. We also assume that it is placed at far-zone and its transverse dimensions are infinite in length.

Using vector potentials for electromagnetic fields and applying boundary conditions at end surfaces of the sample, free-space reflection and transmission coefficients (r and t) at slabs surfaces can be

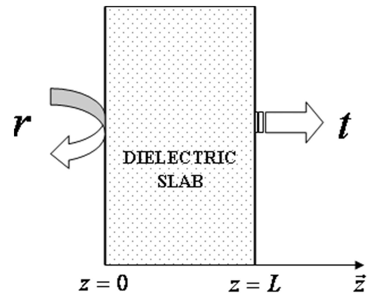


Figure 1. Free-space reflection and transmission of incident plane waves on a dielectric slab.

obtained [45] as

$$r = \frac{\Gamma\left(1 - T^2\right)}{1 - \Gamma^2 T^2}, \quad t = \frac{T\left(1 - \Gamma^2\right)}{1 - \Gamma^2 T^2}, \tag{1}$$

where Γ and T are, respectively, the reflection coefficient when the slab is semi-infinite in length and the propagation factor. Their corresponding equations are

$$\Gamma = -\frac{\gamma - \gamma_0}{\gamma + \gamma_0}, \quad T = \exp\left(-\gamma L\right), \tag{2}$$

$$\gamma = jk_0\sqrt{\varepsilon_r}, \quad \gamma_0 = jk_0, \quad k_0 = 2\pi/\lambda_0, \tag{3}$$

Here, γ_0 and γ represent, respectively, the wavenumbers of free-space and the slab; ε_r $(= \varepsilon_r' - j\varepsilon_r'')$ is the relative complex permittivity of the slab; $\lambda_0 = c/f$ corresponds to the free-space wavelength and f is the operating frequency.

3. THE METHOD

3.1. Amplitudes of Free-space Reflection and Transmission Coefficients

Because, from (1)–(3), for a given ε_r and known frequency, only T is unknown for thickness determination, we define new variables to demonstrate the dependency of L on $|r|$ and $|t|$ as

$$\Lambda_1 - j\Lambda_2 = \gamma = jk_0\sqrt{\varepsilon_r}, \quad \Lambda_3 - j\Lambda_4 = \Gamma = \frac{1 - \sqrt{\varepsilon_r}}{1 + \sqrt{\varepsilon_r}}. \tag{4}$$

It is seen from (4) that Λ_1, Λ_2, Λ_3, and Λ_4 are known quantities for a given ε_r. Then, $|r|$ and $|t|$ will be

$$|r| = \sqrt{\frac{\left(\Lambda_3^2 + \Lambda_4^2\right)\left(1 + e^{-4\Lambda_1 L} - 2e^{-2\Lambda_1 L}\cos\left(2\Lambda_2 L\right)\right)}{\Phi}}, \tag{5}$$

$$|t| = e^{-\Lambda_1 L}\sqrt{\frac{\left[\left(1 - \Lambda_3^2 + \Lambda_4^2\right)^2 + \left(2\Lambda_3\Lambda_4\right)^2\right]}{\Phi}}, \tag{6}$$

where

$$\begin{aligned}\Phi \;=\; & 1 - 2e^{-2\Lambda_1 L}\left[\left(\Lambda_3^2 - \Lambda_4^2\right)\cos\left(2\Lambda_2 L\right) + 2\Lambda_3\Lambda_4\sin\left(2\Lambda_2 L\right)\right] \\ & + e^{-4\Lambda_1 L}\left(\Lambda_3^2 + \Lambda_4^2\right)^2.\end{aligned} \tag{7}$$

3.2. Non-unique Solutions

It will be shown that there are multiple solutions for L evaluation from measured $|r|$ and $|t|$ at one frequency. This is because of the trigonometric terms present in (5)–(7) [30]. These terms appear in $|r|$ and $|t|$ as a result of $1 - T^2$ and $1 - \Gamma^2 T^2$. To demonstrate the non-unique solutions, we monitor intersections of the dependencies of the difference between measured $|r|$ and $|t|$ and computed $|r|_c$ and $|t|_c$ over L on the same graph. The subscript 'c' denotes the computed expressions. For instance, Fig. 2 illustrates these dependencies for

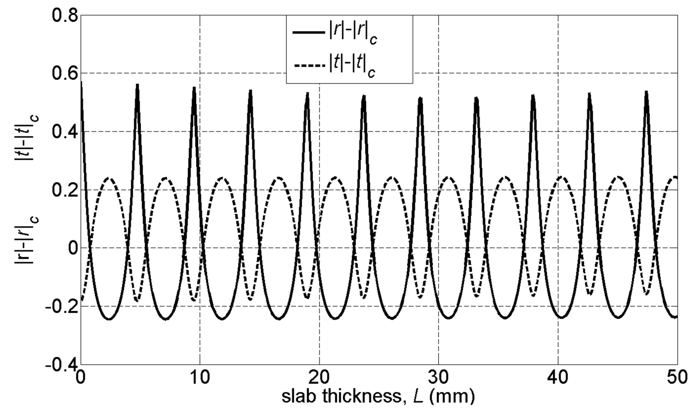


Figure 2. Dependencies of $|r| - |r|_c$ and $|t| - |t|_c$ over slab thickness, L, for $\varepsilon_r = 10 - j0.01$, $L = 15\,\text{mm}$ and $f = 10\,\text{GHz}$.

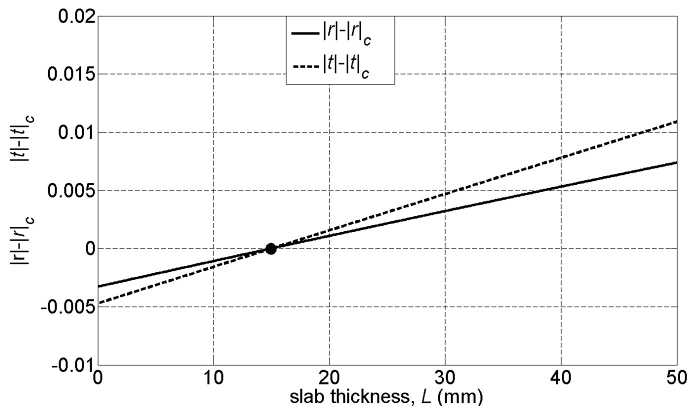


Figure 3. Dependencies of $|r| - |r|_c$ and $|t| - |t|_c$ over slab thickness, L, in Fig. 2 when values of trigonometric terms are assumed known.

measured $|r| \cong 0.492$ and $|t| \cong 0.861$ which are computed from $\varepsilon_r = 10 - j0.01$, $L = 15\,\text{mm}$ and $f = 10\,\text{GHz}$.

To determine unique L, $|r| - |r|_c$ and $|t| - |t|_c$ must simultaneously diminish at one L. However, it is seen from Fig. 2 that there are multiple common intersections of $|r| - |r|_c = 0$ and $|t| - |t|_c = 0$. This means that unique solution is not possible for a given $|r|$ and $|t|$ at one frequency. It is obvious that the dependencies in Fig. 2 show some periodicity over L. One can suspect that this can be because of the trigonometric terms in (5)–(7) since $\exp(2\Lambda_1 L)$ and $\exp(-2\Lambda_1 L)$ are unique functions for a known Λ_1. As a result, we re-draw the dependencies in Fig. 2 when values of trigonometric terms, which are functions of unknown L, are assumed known for the sake of analysis. They are shown in Fig. 3.

It is obvious from Fig. 3 that the there is no oscillatory behavior of both dependencies when values of trigonometric terms are assumed known. This is clearly the evidence that the trigonometric terms in (5)–(7) are multi-valued terms.

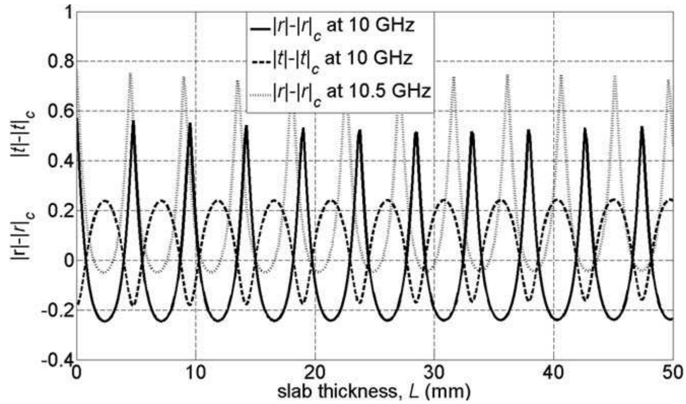
3.3. Unique Thickness Evaluation

In this subsection, we will present two remedies to determine unique L. As of these remedies, firstly we will employ a numerical technique and then derive explicit expressions.

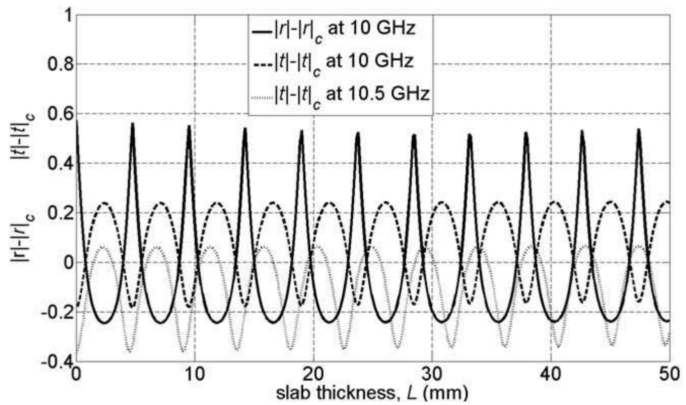
3.3.1. A Numerical Technique for Unique Thickness Evaluation

The proposed numerical technique monitors common intersections of the dependencies of the difference between measured $|r|$ and $|t|$ and computed $|r|_c$ and $|t|_c$ over L on the same graph at two different frequencies. For demonstration of the technique, in Fig. 4, we plot these dependencies at two different frequencies, $f = 10\,\text{GHz}$ and $f = 10.5\,\text{GHz}$, for the same parameters used for the dependencies in Fig. 2. The measured values at $f = 10.5\,\text{GHz}$ are computed as $|r| \cong 0.767$ and $|t| \cong 0.635$.

It is clearly seen from Figs. 4(a) and (b) that there is only one common intersection of the dependencies of measured $|r|$ and $|t|$ at two different frequencies. This means that three amplitude-only measurements of $|r|$ and $|t|$ at different frequencies will help us determine unique L.



(a)



(b)

Figure 4. Dependencies of $|r| - |r|_c$ and $|t| - |t|_c$ over slab thickness, L, for $\varepsilon = 10 - j0.01$, $L = 15\,\mathrm{mm}$, $f = 10\,\mathrm{GHz}$ and $f = 10.5\,\mathrm{GHz}$.

3.3.2. Derivation of Explicit Formulae for Unique Thickness Evaluation

It was shown in Fig. 3 that trigonometric terms are responsible for multiple solutions. Therefore, these multi-valued terms should be eliminated while performing L evaluation. In this section, we will derive explicit expressions for L evaluation, which is very useful since the evaluation does not necessitate any numerical computation. To this end, we expressed $\cos(2\Lambda_2 L)$ by dividing (5) over (6) as

$$\cos\left(2\Lambda_2 L\right) = \frac{e^{2\Lambda_1 L} + e^{-2\Lambda_1 L} - \Lambda_5}{2}, \tag{8}$$

where

$$\Lambda_5 = \left(\frac{|S_{11}|}{|S_{21}|}\right)^2 \frac{\left[\left(1-\Lambda_3^2+\Lambda_4^2\right)^2+\left(2\Lambda_3\Lambda_4\right)^2\right]}{\left(\Lambda_3^2+\Lambda_4^2\right)}. \tag{9}$$

Next, we substitute (9) into (5) and find $\sin(2\Lambda_2 L)$ as

$$\begin{aligned}\sin\left(2\Lambda_2 L\right) \;=\; & \frac{\left(1-\Lambda_3^2+\Lambda_4^2\right)}{2\Lambda_3\Lambda_4}e^{2\Lambda_1 L}+\frac{\left(\Lambda_3^2+\Lambda_4^2\right)^2-\left(\Lambda_3^2-\Lambda_4^2\right)}{2\Lambda_3\Lambda_4}e^{-2\Lambda_1 L}\\ & -\left[\frac{\left(1-|r|^2\right)\Lambda_3^2+\left(1+|r|^2\right)\Lambda_4^2}{2\Lambda_3\Lambda_4|r|^2}\right]\Lambda_5.\end{aligned} \tag{10}$$

Then, using the trigonometric identity $\cos^2(2\Lambda_2 L)+\sin^2(2\Lambda_2 L)=1$, we derive an equation in terms of only L as

$$e^{-8\Lambda_1 L}+\alpha_3 e^{-6\Lambda_1 L}+\alpha_2 e^{-4\Lambda_1 L}+\alpha_1 e^{-2\Lambda_1 L}+\alpha_0=0, \tag{11}$$

where

$$\begin{aligned}\alpha_3 \;=\; & -\left\{\left[\frac{\left(1-|r|^2\right)\Lambda_3^2+\left(1+|r|^2\right)\Lambda_4^2}{|r|^2}\right]\right.\\ & \left.\left[\frac{\left(\Lambda_3^2+\Lambda_4^2\right)^2-\left(\Lambda_3^2-\Lambda_4^2\right)}{4\Lambda_3^2\Lambda_4^2}\right]+\frac{1}{2}\right\}\frac{\Lambda_5}{\alpha_4},\end{aligned} \tag{12}$$

$$\alpha_2 \;=\; \left\{\begin{array}{l}\left\{\left[\frac{\left(1-|r|^2\right)\Lambda_3^2+\left(1+|r|^2\right)\Lambda_4^2}{2\Lambda_3\Lambda_4|r|^2}\right]^2+\frac{1}{4}\right\}\Lambda_5^2\\ +\left[\left(\Lambda_3^2+\Lambda_4^2\right)^2-\left(\Lambda_3^2-\Lambda_4^2\right)\right]\frac{\left(1-\Lambda_3^2+\Lambda_4^2\right)}{2\Lambda_3^2\Lambda_4^2}-\frac{1}{2}\end{array}\right\}\frac{1}{\alpha_4}, \tag{13}$$

$$\begin{aligned}\alpha_1 \;=\; & -\left\{\left[\frac{\left(1-|r|^2\right)\Lambda_3^2+\left(1+|r|^2\right)\Lambda_4^2}{|r|^2}\right]\right.\\ & \left.\left[\frac{\left(1-\Lambda_3^2+\Lambda_4^2\right)}{\Lambda_3^2\Lambda_4^2}\right]+1\right\}\frac{\Lambda_5}{2\alpha_4},\end{aligned} \tag{14}$$

$$\alpha_0 \;=\; \left\{\left[\frac{\left(1-\Lambda_3^2+\Lambda_4^2\right)}{2\Lambda_3\Lambda_4}\right]^2+\frac{1}{4}\right\}\frac{1}{\alpha_4},$$

$$\alpha_4 \;=\; \left[\frac{\left(\Lambda_3^2+\Lambda_4^2\right)^2-\left(\Lambda_3^2-\Lambda_4^2\right)}{2\Lambda_3\Lambda_4}\right]^2+\frac{1}{4}. \tag{15}$$

The four roots of (11) will be [32]

$$\exp\left(-2\Lambda_1 L\right)_{(1,2)} = -\frac{1}{4}\alpha_3 + \frac{1}{2}R \mp \frac{1}{2}D,$$
$$\exp\left(-2\Lambda_1 L\right)_{(3,4)} = -\frac{1}{4}\alpha_3 - \frac{1}{2}R \mp \frac{1}{2}E, \tag{16}$$

where

$$R = \sqrt{\frac{1}{4}\alpha_3^2 - \alpha_2 + Y},$$

$$D = \begin{cases} \sqrt{\frac{3}{4}\alpha_3^2 - R^2 - 2\alpha_2 + \frac{\left(4\alpha_3\alpha_2 - 8\alpha_1 - \alpha_3^3\right)}{4R}} \text{ for } R \neq 0 \\ \sqrt{\frac{3}{4}\alpha_3^2 - 2\alpha_2 + 2\sqrt{Y^2 - 4\alpha_0}} \text{ for } R = 0 \end{cases}, \tag{17}$$

$$E = \begin{cases} \sqrt{\frac{3}{4}\alpha_3^2 - R^2 - 2\alpha_2 - \frac{\left(4\alpha_3\alpha_2 - 8\alpha_1 - \alpha_3^3\right)}{4R}} \text{ for } R \neq 0 \\ \sqrt{\frac{3}{4}\alpha_3^2 - 2\alpha_2 - 2\sqrt{Y^2 - 4\alpha_0}} \text{ for } R = 0 \end{cases}, \tag{18}$$

$$Y = \left[\frac{1}{2}Q + \sqrt{\frac{Q^2}{4} + \frac{P^3}{27}}\right]^{1/3} + \left[\frac{1}{2}Q - \sqrt{\frac{Q^2}{4} + \frac{P^3}{27}}\right]^{1/3} - S, \tag{19}$$

$$Q = \frac{2}{27}\alpha_2^3 - \frac{1}{3}\alpha_2\left(\alpha_1\alpha_3 - 4\alpha_0\right) - \left(4\alpha_0\alpha_2 - \alpha_1^2 - \alpha_0\alpha_3^2\right), \tag{20}$$

$$P = \left(\alpha_1\alpha_3 - 4\alpha_0\right) - \frac{1}{3}\alpha_2^2,\ S = -\frac{\alpha_2}{3}. \tag{21}$$

Here, Y is the real root of the cubic function [32]

$$Y^3 - \alpha_2 Y^2 + \left(\alpha_1\alpha_3 - 4\alpha_0\right)Y + \left(4\alpha_0\alpha_2 - \alpha_1^2 - \alpha_0\alpha_3^2\right) = 0. \tag{22}$$

Finally, the length of the material can be determined by taking the logarithm on both sides of equations in (16).

Although L in (16) will have four roots, we succeeded on determining unique L as follows. Since Λ_1, Λ_2, Λ_3, Λ_4, and Λ_5 are all real, then α_0, α_1, α_2, and α_3 in (12)–(15) must be real. Then, it is expected that all roots of L should be real. However, we observed that E in (16) always yields a complex number, which is definitely superfluous. Since $\exp(-2\Lambda_1 L)_{(3,4)}$ in (16) uses E for L determination, we can remove both of these roots. The correct root from the remaining roots is assigned by comparing the candidate L solutions at two frequencies, as we did in numerical technique in Section 3.3.1. Between the extracted roots at two different frequencies, identical (or similar) ones will help us determine the actual L.

4. MEASUREMENT RESULTS

For validation of thickness measurements by the proposed method, we applied the measurement apparatus in [24]. Before carrying out thickness measurements, we calibrated the apparatus using the procedure in [24]. Before finding the error terms in the calibration process, transmit and receive antennas are separated according to a) the distance between them fulfils the plane wave condition, b) the centre of the sample exactly matches the centre of horn antennas, c) the maximum amount of incident signal is received when there is no sample between antennas, and d) samples are placed at the middle distance of antennas to reduce multiple reflections between antenna and samples. Plane wave assumption was satisfied practically by $L_{rs} \gg 2D_r^2/\lambda$ where D_r, λ, and L_{rs} are the maximum lateral dimension of the radiator, the wavelength, and the distance between the radiator (antenna) and each slab specimen. According to the cross section of used horn antennas, $60.5 \times 45\,\mathrm{mm}^2$, the value of D_r is approximately 75 mm and maximum L_{rs} is calculated as 380 mm at X-band (8.2–12.4 GHz). Transmit and receive antennas were separated from each other approximately 100 cm. The maximum received signal is obtained by changing relative distance of the antennas.

In the determination of error terms, we measured reflected and transmitted signals for two cases: a) when a metal plate with cross section of 30 cm × 30 cm is located and b) when there is nothing between antennas. Then, we placed prepared slab specimens and again measured reflection and transmission properties. At each measurement step, the level of incident signal was kept constant. As a result, we obtained the calibrated reflection and transmission coefficients of slab specimens as [24]

$$|r|_{calib} = \sqrt{\frac{R^s T^f + (T^f - T^m)\, E_d - T^m R^f}{R^m T^f - (T^f - T^m)\, E_d - T^m R^f}}, \quad |t|_{calib} = \sqrt{\frac{T^s - T^m}{T^f - T^m}}, \quad (23)$$

where R^m and T^m are the reflected and transmitted signals for the metal plate; R^f and T^f are the reflected and transmitted signals in free-space; R^s and T^s are the reflected and transmitted signals for slab specimens; and E_d is the measured reflected signal when a matched waveguide load is connected to the terminal of the waveguide section where the transmit antenna is connected [24]. The square-root in (23) arises because measured signals from a square-law detector are proportional to square of the reflection (transmission) signal.

We tested the calibration procedure by using low-loss dielectric slabs with different lengths and cross sections. It is noted that the accuracy of thickness measurements by the proposed method decreases for samples with cross sections less than 20 cm × 20 cm. This is because of the untolerable effect of diffractions at the sample edges on calibration procedure. Another important fact that we would like to note is that the calibration procedure does not take into account the coupling between antenna aperture and sample surface [19]. In future, we would like to incorporate this effect into the calibration process to increase the overall accuracy.

We utilized two different dielectric slabs (polytetrafluoro-ethylene (PTFE) and Plexiglas) with various lengths ($L = 10$ mm, 14 mm, and 18 mm for Plexiglas specimen; and $L = 10$ mm, 15 mm, and 20 mm for PTFE specimen) as test samples to validate the proposed method. The cross sections of these specimens are approximately 30 cm × 30 cm. Complex permittivities of these specimens are almost constant over X-band and are taken to be $\varepsilon_r \cong 2.59 - j0.018$ and $\varepsilon_r \cong 2.05 - j0.004$, respectively, for Plexiglas and PTFE specimens. We measured the $|r|_{calib}$ and $|t|_{calib}$ of each specimen 10 times at some discrete frequencies over X-band after removing and re-positioning it. In this way, the effect of any bad specimen positioning on measurements was eliminated and we ensured that the centre of the sample exactly matched the centre of horn antennas. Finally, we computed the thickness of each specimen by using both the graphical technique and explicit expressions in (11)–(22). It is realized that both techniques evaluate fairly the same thickness. In Table 1, only the results from explicit expressions are shown.

It is clearly seen from Table 1 that the proposed method estimates fairly accurate thicknesses of specimens throughout the frequency band. At some frequencies, the accuracy of thickness estimation by the proposed method increases as a result of increased accuracy in $|r|$ and $|t|$ and the calibration. It is also noted from Table 1 that the accuracy of measurements increases for thicker samples. There can be two reasons for this. First, the accuracy of physical measurements increases for thicker samples. Second, the ability of any measurement instrument to

Table 1. Estimated thicknesses of Plexiglas and PTFE specimens at some discrete frequencies.

Frequency (GHz)			10.17	10.49	11.13	11.17	11.43
Plex.	Slab Length (mm)	10	9.90	9.88	9.86	10.12	9.89
		14	14.12	14.09	14.13	13.89	13.88
		18	18.13	18.10	17.93	17.89	18.17
PTFE		10	9.80	9.82	10.13	9.86	10.15
		15	14.83	14.86	15.12	15.10	15.15
		20	19.88	19.85	20.14	20.11	19.92

resolve or detect measurements at sequentially and linearly separated frequencies for thicker samples is greater than for thinner samples [33]. In addition, we observed that the accuracy of thickness evaluation for Plexiglas slabs is better than that of PTFE slabs. This is because, from (2), an increase in dielectric constant may be interpreted as an increase in sample thickness.

It should be noted that the presented analysis assumes that the slab is homogeneous with a constant thickness and known permittivity. In industrial applications, it is difficult to have all these conditions satisfied simultaneously. In addition, at some instances, multiple dielectric plugs are attached together which results in reflection asymmetry measurements. The aim of this research paper is to demonstrate that non-ambiguous and unique thickness of low-loss dielectric slabs can be evaluated by using amplitudeonly measurements while eliminating the requirement of repetitive measurements of different-length materials which has the same internal and electrical properties of the sample under test. In the future, we would like to consider the cases in which the slab is inhomogeneous or does not have a constant thickness as well as multiple attached dielectric plugs.

5. CONCLUSION

A new method for thickness evaluation of medium- and low-loss materials is proposed. There are two attractive features of the method over those in the literature. First, it does not require repetitive measurements of specimens with different lengths to have a database, which will be used for comparison of the same type specimen with unknown sample length. Second, it evaluates the sample thickness for any frequency of interest in the band, which in that way the method could be adapted to band-limited measurement systems. Since the proposed method uses amplitude-only measurements, it is a good candidate for thickness evaluation and its monitoring using a simple and relatively inexpensive measurement system for industrial-based applications.

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