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MICROWAVE METHOD FOR THICKNESS-INDEPENDENT PERMITTIVITY EXTRACTION OF LOW-LOSS DIELECTRIC MATERIALS FROM TRANSMISSION MEASUREMENTS

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Abstract—A non-resonant microwave method has been proposed for complex permittivity determination of low-loss materials with no prior information of sample thickness. The method uses two measurement data of maximum/minimum value of the magnitude of transmission properties of the sample to determine an initial guess for permittivity and find the sample thickness. An explicit expression for sample thickness and two expressions for inversion of the complex permittivity of the sample are derived. The method has been validated by transmission measurements at X-band (8.2–12.4 GHz) of a low-loss sample located into a waveguide sample holder.

1. INTRODUCTION

Material characterization is an important issue in many material production, processing, and management applications in agriculture, food engineering, medical treatments, bioengineering, and the concrete industry [1]. For these reasons, various microwave techniques, each with its unique advantages and constraints, have been proposed to characterize the electrical properties of materials with consideration of the frequency range, required measurement accuracy, sample size, state of the material (liquid, solid, powder and so forth), destructiveness and non-destructiveness, contacting and non-contacting, etc. [1–38].

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Transmission-reflection non-resonant methods have extensively been employed for broadband relative complex permittivity (ε_r) and/or relative complex permeability (μ_r) measurements of low-, medium-, and high-loss (solid, liquid, or granular) conventional and engineered fabricated electromagnetic materials [4–38]. These methods, when compared to resonant methods, are relatively simple to apply, give accurate information of ε_r and/or μ_r over a wide frequency range, require relatively less sample preparation, and allow frequency- and time-domain analyses [1].

Measured reflection or transmission scattering (S-) parameters can be utilized for broadband ε_r extraction. However, measured transmission S-parameter (S_{21}) has several superior advantages over measured reflection S-parameter (S_{11}) as: a) it provides longitudinal averaging of variations in sample properties, which is particularly important for relatively high-loss heterogeneous materials such as moist coal and cement-based materials [21]; b) it undergoes less deterioration from surface roughness at high frequencies [14]; and c) it offers a wide dynamic range for measurements [34].

In the literature, various methods based on complex S_{21} measurements have been proposed for stable ε_r measurement of high-loss and low-loss dielectric materials [30–38]. While the method in [30] assumes that the sample is low-loss and thin, the method in [31] uses a second-order approximation to derive a one-variable objective function for fast ε_r measurements. We also derived a one-variable objective function for rapid and broadband ε_r extraction of thin or thick low-to-high-loss materials [32]. In order to measure general electrical properties of magnetic materials, the method in [33] can be employed. However, these methods [30–33] require a good initial guess for electrical properties of samples since complex exponential term in the expression of S_{21} yields multiple solutions [26, 32]. Measurements of two identical samples with different lengths can be utilized for unique ε_r measurement of samples [10]. Nonetheless, the accuracy of ε_r measurement by this approach may decrease as a consequence of increased uncertainty in sample thickness. In addition, any inhomogeneity or irregularity present in the second sample also lowers the measurement accuracy. Besides, swept-frequency phase measurements [34, 35] or magnitude measurements [36–38] of S_{21} over a broadband can be directly utilized to obtain unique ε_r. While the formulation in [34], sometimes, requires at least three measurements at different frequencies for a correct initial guess of ε_r, those in [35] are complex in nature. The method in [36] is not applicable to low-loss materials. Although the technique in [37] is attractive and applicable to low-loss samples, it is not appropriate for thin samples with lower dielectric constants. To eliminate this drawback, the method in our recently published paper [38] can be employed. However, the discussed methods in [34–38] need precise knowledge of the sample thickness. Elimination this necessity is very crucial in the extraction of electrical properties of low-loss materials, as will be discussed in Results Section of the paper. In this research paper, we propose a simple microwave method for unique ε_r measurement of low-loss samples with no prior information of sample thickness using measurements of S_{21}.

2. THE METHOD

2.1. Background

The problem for ε_r determination of a dielectric low-loss sample using waveguide measurements is shown in Fig. 1. Assuming $e^{j\omega t}$ time convention, between calibration planes in Fig. 1, the normalized S_{21} can be expressed as [24, 38]

$$S_{21} = \frac{S_{21}^m e^{-\gamma_0 L}}{S_{21}^0} = |S_{21}| e^{j\theta_{21}} = \frac{4\gamma\gamma_0 e^{-\gamma L}}{(\gamma+\gamma_0)^2 - (\gamma-\gamma_0)^2 e^{-2\gamma L}}, \qquad (1)$$

where S_{21}^m and S_{21}^0 are, respectively, the measured transmission S-parameters when sample is present and when there is only air (empty line) between calibration planes; l_1, l_2, and L are, respectively, the distances between the sample and terminals of the sample holder and the length of the sample; $|S_{21}|$ and θ_{21} are the magnitude and phase of normalized S_{21}; and γ and γ_0 are, respectively, propagation constants of the sample- and air-filled sections, which are given as

$$\gamma = jk_0\sqrt{\varepsilon_r - (f_c/f)^2}, \quad \gamma_0 = jk_0\sqrt{1-(f_c/f)^2}, \quad \varepsilon_r = \varepsilon_r' - j\varepsilon_r''. \qquad (2)$$

In (2), k_0, f_c, and f are, respectively, the free-space wave number and cut-off and operating frequencies. It is assumed that the length between the calibration planes is known (transmission measurements are not dependent on the position inside the calibration planes for a uniform and non-dispersive sample holder).

The presence of exponential terms in (1) simply produces multiple ε_r solutions for a measured S_{21} at one frequency [26, 27, 32]. In this paper, our aim is to first determine the thickness of the sample and then obtain an initial guess for the ε_r using two measurements at two frequencies corresponding to extreme values of $|S_{21}|$, and finally extract the ε_r of the sample using complex S_{21} measurements.

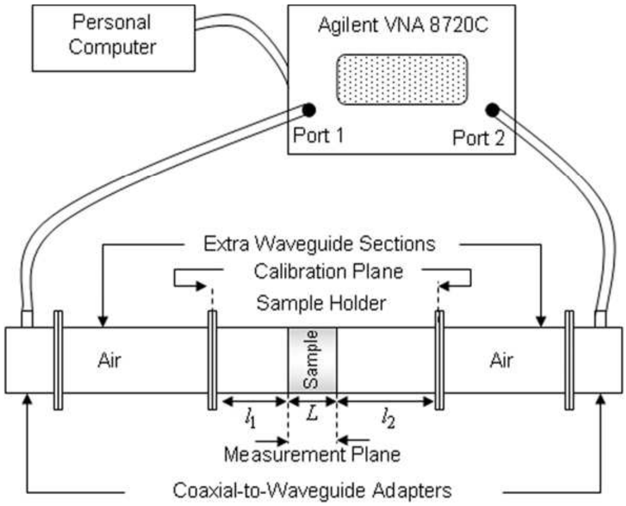

Figure 1. Measurement setup (adapted from [9], ©IEEE).

2.2. Analysis of the Problem

To demonstrate the problem of ε_r determination with no knowledge of L, we define

$$\chi - j\xi = \sqrt{\varepsilon_r - (f_c/f)^2}, \quad B = \exp(-2k_0\xi L), \tag{3}$$

$$A = 2k_0\chi L, \quad \kappa = \sqrt{1 - (f_c/f)^2}. \tag{4}$$

Incorporating these variables into (1), we find $|S_{21}|$ as [26, 27, 38]

$$|S_{21}| = \sqrt{16B(\chi^2 + \xi^2)\kappa^2/\psi}, \tag{5}$$

where

$$\psi = B^2\Lambda_3^2 + \Lambda_4^2 + 8\kappa\xi B\sin(A)\Lambda_1 - 2B\cos(A)\left(\Lambda_1^2 - \Lambda_2\right), \tag{6}$$

$$\Lambda_1 = \chi^2 + \xi^2 - \kappa^2, \quad \Lambda_2 = 4\kappa^2\xi^2, \tag{7}$$

$$\Lambda_3 = (\chi - \kappa)^2 + \xi^2, \quad \Lambda_4 = (\chi + \kappa)^2 + \xi^2. \tag{8}$$

At this point, it is instructive to discuss any possible solution of ε_r using (5)–(8). It is seen from (5) that it seems possible to determine a unique ε_r using two independent $|S_{21}|$ measurements [either using measurements of one thicker (greater than one-quarter wavelength) low-loss sample at two independent frequencies or using two identical thicker low-loss samples with different lengths at one frequency], since we have two degrees of freedom as ε_r' and ε_r''. However, inversion a unique ε_r from (5)–(8) using two independent measurements is not an easy task. This is mainly because of the oscillatory behavior of trigonometric terms $\cos(A)$ and $\sin(A)$ over f [27]. We observed that approximating these terms to some values is one of the key steps to extract unique ε_r using two independent measurements [27, 37, 38].

With the above information at hand, we consider any simplification of the expressions in (6)–(8) at frequencies resulting in extreme values of $|S_{21}|$. We illustrated that when $|S_{21}|$ attains its maximum value, $\cos(A)$ and $\sin(A)$ in (6) could be approximated as [27]

$$\cos(A) \cong 1, \quad \sin(A) \cong 0. \tag{9}$$

We also observed that at frequencies resulting in minimum of $|S_{21}|$, it is found [27]

$$\cos(A) \cong -1, \quad \sin(A) \cong 0. \tag{10}$$

It is obvious from (9) and (10) that unique A cannot be extracted because of periodicity of $\cos(A)$ and $\sin(A)$. However, utilizing successive maximum and/or minimum $|S_{21}|$ measurements, we can write

$$\cos\left(A_{\max}^{(1)}\right) \cong 1 \to A_{\max}^{(1)} = 2k_{0,\max}^{(1)}\chi_{\max}^{(1)}L = 2\,(n+1)\,\pi, \tag{11}$$

$$\cos(A_{\min}^{(1)}) \cong -1 \to A_{\min}^{(1)} = 2k_{0,\min}^{(1)}\chi_{\min}^{(1)}L = 2\,(n+3/2)\,\pi, \tag{12}$$

$$\cos(A_{\max}^{(2)}) \cong 1 \to A_{\max}^{(2)} = 2k_{0,\max}^{(2)}\chi_{\max}^{(2)}L = 2\,(n+2)\,\pi. \tag{13}$$

In (11)–(13), $A_{\max}^{(1)}$, $A_{\min}^{(1)}$, $A_{\max}^{(2)}$ $k_{0,\max}^{(1)}$, $k_{0,\min}^{(1)}$, $k_{0,\max}^{(2)}$, $\chi_{\max}^{(1)}$, $\chi_{\min}^{(1)}$, and $\chi_{\max}^{(2)}$, respectively, denote the A, k_0, and χ values in (4) at frequencies corresponding to the first maximum, the first minimum, and the second maximum values of $|S_{21}|$ at frequencies $f_{\max}^{(1)}$, $f_{\min}^{(1)}$, and $f_{\max}^{(2)}$, and n is any integer value. It is straightforward from (11)–(13) that the unknown n value can be eliminated using measurements at $f_{\max}^{(1)}$, $f_{\min}^{(1)}$, and $f_{\max}^{(2)}$.

2.3. Closed-form Expressions for Determination of Thickness and an Initial Guess for Complex Permittivity

In the following derivations, we assume that electrical properties of the sample under investigation do not much change with frequency. That is, $\varepsilon_r(f) \approx \varepsilon_r(f_2)$ where $f_2 = f + \Delta f$ and $\Delta f \ll f$. We note that this assumption does not mean that $\chi(f) \approx \chi(f_2)$ and $\xi(f) \approx \xi(f_2)$ because of the dispersive nature of waveguides, $f_c \neq 0$. Using (3) and assuming $\varepsilon_r(f) \approx \varepsilon_r(f_2)$, we find

$$\begin{aligned} \chi(f_2) &= \left[0.5\left(\Lambda_5 + \sqrt{\Lambda_5^2 + [2\chi(f)\,\xi(f)]^2}\right)\right]^{1/2}, \\ \xi(f_2) &= \chi(f)\,\xi(f)/\chi(f_2), \end{aligned} \tag{14}$$

where

$$\Lambda_5 = \chi^2(f) - \xi^2(f) + (f_c/f)^2 - (f_c/f_2)^2. \tag{15}$$

The correct root of $\chi(f_2)$ in (14) is assigned as follows. First, from (3), we obtain $\chi(f)$ in terms of $\xi(f)$ as

$$\chi(f)\xi(f) = \varepsilon''_{rs}/2, \quad \chi(f) = \left[\left(\varepsilon'_{rs} - 1\right) + \xi^2(f) + 1 - (f_c/f)^2\right]^{1/2}. \tag{16}$$

Then, substituting $\chi(f)$ and $\xi(f)$ in (16) into Λ_5 in (15), we find that $\Lambda_5 > 0$, which proves (14). We note that f and f_2 can be replaced with $f_{\max}^{(1)}$ and $f_{\min}^{(1)}$ (or $f_{\max}^{(1)}$ and $f_{\max}^{(2)}$, or $f_{\min}^{(1)}$ and $f_{\max}^{(2)}$) in (11)–(13).

On the other hand, from (11)–(13), we can determine the sample thickness as

$$\begin{aligned} L &= \frac{1}{2\pi\left(k_{0,\min}^{(1)}\chi_{\min}^{(1)} - k_{0,\max}^{(1)}\chi_{\max}^{(1)}\right)}, \text{ or} \\ L &= \frac{1}{\pi\left(k_{0,\max}^{(2)}\chi_{\max}^{(2)} - k_{0,\max}^{(1)}\chi_{\max}^{(1)}\right)}. \end{aligned} \tag{17}$$

The key factor for determining the explicit expression for L in (17) comes from that the sample thickness is a physical parameter (not changing with f). It is also evident that, using (14), (15), and (17) one can find L in terms of $\chi_{\max}^{(1)}$, $f_{\max}^{(1)}$, and $f_{\min}^{(1)}$ (or $f_{\max}^{(2)}$).

Therefore, incorporating (14)–(17) and utilizing measured extreme values of $|S_{21}|$, we can determine L in addition to an initial guess for ε_r. To demonstrate the application of our method, in particular, we consider that we have measurements of $|S_{21}|$ at frequencies $f_{\max}^{(1)}$ and $f_{\min}^{(1)}$, corresponding, respectively, to subsequent maximum and minimum values of $|S_{21}|$. From (9) and (10) and using (5)–(8), we obtain

$$\begin{aligned} &F_1\left(\chi_{\max}^{(1)}, \xi_{\max}^{(1)}, f_{\max}^{(1)}, L\right) \\ &= \frac{16B_{(1)}\left(\chi_{\max}^{2(1)} + \xi_{\max}^{2(1)}\right)\kappa_{(1)}^2}{B_{(1)}^2\Lambda_{3(1)}^2 + \Lambda_{4(1)}^2 - 2B_{(1)}\left(\Lambda_{1(1)}^2 - \Lambda_{2(1)}\right)} - |S_{21}|_{\max}^2 = 0, \end{aligned} \tag{18}$$

and

$$F_2\left(\chi_{\min}(1),\xi_{\min}^{(1)},f_{\min}^{(1)},L\right) = \frac{16B_{(2)}\left(\chi_{\min}^{2(1)}+\xi_{\min}^{2(1)}\right)\kappa_{(2)}^2}{B_{(2)}^2\Lambda_{3(2)}^2+\Lambda_{4(2)}^2+2B_{(2)}\left(\Lambda_{1(2)}^2-\Lambda_{2(2)}\right)}-|S_{21}|_{\min}^2=0, \quad (19)$$

where subscripts '(1)' and '(2)' denote the corresponding expressions in (4)–(8) for $f_{\max}^{(1)}$ and $f_{\min}^{(1)}$. It is obvious from (3) that $B_{(1)}$ and $B_{(2)}$ are functions of L. Therefore, we utilize the left equation for L in (17) and substitute it into (18) and (19) for determination of $B_{(1)}$ and $B_{(2)}$. Then, using (14) and (15), we express $\chi_{\min}^{(1)}$ and $\xi_{\min}^{(1)}$ in terms of $\chi_{\max}^{(1)}$, $\xi_{\max}^{(1)}$, $f_{\max}^{(1)}$, and $f_{\min}^{(1)}$. As a result, utilizing a constrain expression comprising of (18) and (19) (i.e., sum of the absolutes of F_1 and F_2), one can compute first $\chi_{\max}^{(1)}$ and $\xi_{\max}^{(1)}$, and then $\chi_{\min}^{(1)}$, $\xi_{\min}^{(1)}$ and L. As a result, employing the foregoing steps, one not only determines an initial guess for ε_r with no information of L, but also finds the sample thickness as a by-product of the process.

3. VALIDATION OF THE PROPOSED METHOD

3.1. Numerical Verification

To assess the accuracy of the proposed method, we performed a numerical analysis. In the analysis, we first assume some test parameters as representative of low-loss samples ($\varepsilon_r'' \ll \varepsilon_r'$) and then substitute them into the expressions of S_{21} in (1). Next, we compute $|S_{21}|$ and f values corresponding to extreme values of $|S_{21}|$ using fminsearch function of MATLAB. Finally, we extract the ε_r and L by our method. For example, Table 1 demonstrates the test and extracted parameters along with used quantities in the process, where it is assumed that $f_c \cong 6.555\,\text{GHz}$. We note that there is not any a specific reason in selecting the test parameters except that they either represent low-loss samples (Table 1) or medium-loss samples (Table 2).

It is seen from Table 1 that extracted ε_r and L values from two frequencies corresponding to maximum values of $|S_{21}|$ are much better than those obtained from maximum and minimum values of $|S_{21}|$. We think that the main reason of this is the accuracy of approximation for $\cos(A)$ for $|S_{21}|_{\max}$ and $|S_{21}|_{\min}$, as given in (9) and (10). For example, for the test $\varepsilon_r = 7.3-j0.002$ and $L = 20\,\text{mm}$ values, we found the values of $\cos(A)$ corresponding to $f_{\max}^{(1)} \cong 8.668\,\text{GHz}$, $f_{\min}^{(1)} \cong 9.946\,\text{GHz}$, and $f_{\max}^{(2)} \cong 11.36\,\text{GHz}$ as $\cos(A) = 0.9999$, $\cos(A) = -0.9898$, and

$\cos(A) = 0.9999$, respectively. Besides, we also conclude from Table 1 that, for a given ε_r and a selected combination of $|S_{21}|_{\max}$ and/or $|S_{21}|_{\min}$, the relative errors in the extracted ε_r and L decrease with L. This is because the relative percentage error in the extraction of L descends if L increases. The same parallelism is also true for ε_r since, for low-loss samples, ε_r' and L are multiplied in A in (4). In other words, if the period of oscillatory behavior in $|S_{21}|$ increases, the percentage errors in the extraction of ε_r and L should decrease.

For low-loss samples, the approximations used in (9) and (10) are very accurate. Because our proposed method is based on these approximations, it is instructive to evaluate the accuracy of our method for medium-loss samples. Toward this end, we performed another numerical analysis. This time, assumed ε_r values are representatives of medium-loss samples. Table 2 exhibits the results of such an analysis.

It is seen from Table 2 that as the loss tangent of the sample increases (the sample becomes lossier), the accuracy of our method lowers. In addition, we note that, for medium-loss samples, while the accuracy of L determination using maximum values of $|S_{21}|$ is superior to other combinations, that of ε_r becomes poorer. We expect that this happens as a consequence of the approximations given in (9) and (10) [27].

Table 1. Extracted ε_r and L (mm) values from assumed test parameters for low-loss samples. f values are given in GHz.

Test Parameters				Extracted Parameters	
ε_r	Assumed measurement data		L	ε_r	L
$7.3-j0.002$	$\|S_{21}\|^{(1)}_{\max} \cong 0.997$; $f^{(1)}_{\max} \cong 8.668$	$\|S_{21}\|^{(1)}_{\min} \cong 0.531$; $f^{(1)}_{\min} \cong 9.946$	20	$7.27-j0.0019$	19.92
	$\|S_{21}\|^{(1)}_{\max} \cong 0.997$; $f^{(1)}_{\max} \cong 8.668$	$\|S_{21}\|^{(2)}_{\max} \cong 0.997$; $f^{(2)}_{\max} \cong 11.36$	20	$7.30-j0.0020$	19.89
	$\|S_{21}\|^{(1)}_{\min} \cong 0.531$; $f^{(1)}_{\min} \cong 9.946$	$\|S_{21}\|^{(2)}_{\max} \cong 0.997$; $f^{(2)}_{\max} \cong 11.36$	20	$7.41-j0.0021$	19.77
$7.3-j0.002$	$\|S_{21}\|^{(1)}_{\max} \cong 0.996$; $f^{(1)}_{\max} \cong 9.559$	$\|S_{21}\|^{(1)}_{\min} \cong 0.544$; $f^{(1)}_{\min} \cong 10.43$	30	$7.29-j0.0019$	29.31
	$\|S_{21}\|^{(1)}_{\max} \cong 0.996$; $f^{(1)}_{\max} \cong 9.559$	$\|S_{21}\|^{(2)}_{\max} \cong 0.995$; $f^{(2)}_{\max} \cong 11.36$	30	$7.30-j0.0020$	29.29
	$\|S_{21}\|^{(1)}_{\min} \cong 0.544$; $f^{(1)}_{\min} \cong 10.43$	$\|S_{21}\|^{(2)}_{\max} \cong 0.995$; $f^{(2)}_{\max} \cong 11.36$	30	$7.37-j0.0020$	29.18
$3.8-j0.002$	$\|S_{21}\|^{(1)}_{\max} \cong 0.997$; $f^{(1)}_{\max} \cong 8.392$	$\|S_{21}\|^{(1)}_{\min} \cong 0.706$; $f^{(1)}_{\min} \cong 10.07$	20	$3.78-j0.0019$	19.48
	$\|S_{21}\|^{(1)}_{\max} \cong 0.997$; $f^{(1)}_{\max} \cong 8.392$	$\|S_{21}\|^{(2)}_{\max} \cong 0.996$; $f^{(2)}_{\max} \cong 12.01$	20	$3.80-j0.0020$	19.44
	$\|S_{21}\|^{(1)}_{\min} \cong 0.706$; $f^{(1)}_{\min} \cong 10.07$	$\|S_{21}\|^{(2)}_{\max} \cong 0.996$; $f^{(2)}_{\max} \cong 12.01$	20	$3.96-j0.0021$	19.17

Table 2. Extracted ε_r and L (mm) values from assumed test parameters for medium-loss samples. f values are given in GHz.

Test Parameters				Extracted Parameters	
ε_r	Assumed measurement data		L	ε_r	L
$7.3 - j0.2$	$\lvert S_{21}\rvert^{(1)}_{\max} \cong 0.766$; $f^{(1)}_{\max} \cong 8.662$	$\lvert S_{21}\rvert^{(1)}_{\min} \cong 0.484$; $f^{(1)}_{\min} \cong 9.942$	20	$7.26 - j0.1909$	19.88
	$\lvert S_{21}\rvert^{(1)}_{\max} \cong 0.766$; $f^{(1)}_{\max} \cong 8.662$	$\lvert S_{21}\rvert^{(2)}_{\max} \cong 0.748$; $f^{(2)}_{\max} \cong 11.34$	20	$7.24 - j0.1982$	19.92
	$\lvert S_{21}\rvert^{(1)}_{\min} \cong 0.484$; $f^{(1)}_{\min} \cong 9.942$	$\lvert S_{21}\rvert^{(2)}_{\max} \cong 0.748$; $f^{(2)}_{\max} \cong 11.34$	20	$7.41 - j0.2066$	19.73
$7.3 - j0.5$	$\lvert S_{21}\rvert^{(1)}_{\max} \cong 0.551$; $f^{(1)}_{\max} \cong 8.646$	$\lvert S_{21}\rvert^{(1)}_{\min} \cong 0.409$; $f^{(1)}_{\min} \cong 9.945$	20	$7.296 - j0.485$	19.63
	$\lvert S_{21}\rvert^{(1)}_{\max} \cong 0.551$; $f^{(1)}_{\max} \cong 8.646$	$\lvert S_{21}\rvert^{(2)}_{\max} \cong 0.519$; $f^{(2)}_{\max} \cong 11.23$	20	$7.106 - j0.483$	19.84
	$\lvert S_{21}\rvert^{(1)}_{\min} \cong 0.409$; $f^{(1)}_{\min} \cong 9.945$	$\lvert S_{21}\rvert^{(2)}_{\max} \cong 0.519$; $f^{(2)}_{\max} \cong 11.23$	20	$7.425 - j0.498$	19.49

3.2. Experimental Verification

A general purpose X-band waveguide measurement set-up is used for validation of the proposed method ($f_c \cong 6.555$ GHz) [27]. The waveguide has a broader dimension of 22.86 mm and a narrower dimension of 10.16 mm. An HP8720C vector network analyzer (VNA) is connected as a source and measurement equipment. The thru-reflect-line calibration technique [39] is utilized before measurements. We used a waveguide short and the shortest waveguide spacer (44.38 mm) in our lab for reflect and line standards. The line has a $\pm 70°$ maximum offset from $90°$ over 9.7–11.7 GHz. In order to assess the accuracy of measurements, we measured the magnitude of S_{11} for waveguide through measurements and noted that it ranges from -40 dB to -75 dB.

For validation of the proposed method, we used the measurement data of an 76.28 mm long PTFE sample [27]. To apply our method, we first located the maximum and minimum values of $|S_{21}|$ over 9.7–11.7 GHz. We recorded that there are two minimum values of $|S_{21}|$ at $f \cong 10.118$ GHz and $f \cong 11.355$ GHz, and one maximum value of $|S_{21}|$ at $f \cong 10.747$ GHz (In the paper [38], we note that we mistakenly designated and took extreme values of $|S_{21}|$. However, the analysis and the presented method in that paper still work if maximum $|S_{21}|$ value is utilized in the extraction process). After, using (14)–(19), we determined the initial guess of ε_r and L using the above extreme values of $|S_{21}|$. The extracted L values by our proposed method are as: $L \cong 77.251$ mm using maximum and minimum values of $|S_{21}|$ at $f \cong 10.747$ GHz and $f \cong 11.355$ GHz, respectively; $L \cong 75.293$ mm using minimum and maximum values of $|S_{21}|$ at $f \cong 10.118$ GHz and $f \cong 10.747$ GHz, respectively; and $L \cong 78.051$ mm using two minimum values of $|S_{21}|$ at $f \cong 10.118$ GHz and $f \cong 11.355$ GHz, respectively. Figs. 2 and 3 demonstrate measured real and imaginary parts of ε_r of the sample using above extracted L values by the proposed method (PM). In those figures, we also superimpose the measured ε_r by the methods in [24] and [38] using $L = 76.28$ mm.

It is seen from Figs. 2 and 3 that measured ε_r by methods in [24] and [38] and our proposed method with various L values are in good agreement with the reference data (At 10 GHz, the ε_r of the PTFE sample given by von Hippel is approximately $2.08 - j0.00076$) in [40], except for the frequency range $f = 10.7$–10.8 GHz. This range corresponds to maximum value of $|S_{21}|$. We note that the ripple observed around $f \cong 10.74$ GHz in the measured ε_r (whereas the ripple of ε_r'' near that frequency is easily noticable in Fig. 3, that of ε_r' seems low-level in Fig. 2 although it is also prevalent) using the method in [24] decreases considerably with a decrease in the parameter β. This is completely in agreement with the results given in [24]. Therefore, our proposed method eliminates this ripple without selecting any proper value of β.

In addition, it is seen from Fig. 2 that better results for both ε_r and L measurement by our method can be achieved if one utilizes measurements corresponding to two maximum values of $|S_{21}|$. This is in complete agreement with the results of numerical analysis in Section 3.2 for low-loss samples. Furthermore, extracted ε_r'' values in Fig. 3 by our method and those in [24, 38] demonstrate an oscillatory

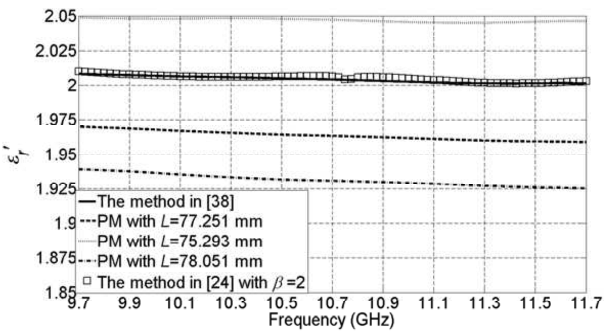

Figure 2. Measured real part of ε_r of the PTFE sample ($L = 76.28$ mm) using our proposed method and the methods in [24] and [38]. In the figure, PM refers to the abbreviation of the proposed method.

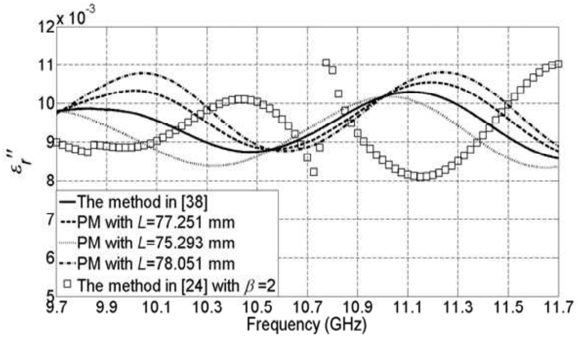

Figure 3. Measured imaginary part of ε_r of the PTFE sample ($L = 76.28\,\text{mm}$) using our proposed method and the methods in [24] and [38]. In the figure, PM refers to the abbreviation of the proposed method.

behavior within a small region (2 in a 1000 value), which can be due to the fact that non-resonant methods are not so accurate for measurement of ε_r'' less than approximately 0.001 [27].

Finally, we note that our method is attractive in eliminating the need for accurate knowledge of L in ε_r measurement of low-loss samples, because non-resonant methods are seriously affected by any inaccuracy in L [24]. Although our method is accurate for this specific problem, it requires a broadband measurement S_{21} data of a sample with substantial length.

4. CONCLUSION

A non-resonant microwave method has been proposed for accurate ε_r extraction of low-loss materials using measured S_{21} data. We derived a closed-form expression for sample thickness using extreme values of S_{21}. From the numerical analysis and measurements, we note that when compared to other combinations of extreme values of S_{21} better results for both L and ε_r were attained by using measurement combination of two maximum values of S_{21} for low-loss samples. On the other hand, we recommend using other combinations for simultaneous measurement of L and ε_r for medium-loss samples. We think that proposed method can be employed for ε_r measurement of low-loss samples if L is not precisely known.

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