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UNIQUE PERMITTIVITY DETERMINATION OF LOW-LOSS DIELECTRIC MATERIALS FROM TRANSMISSION MEASUREMENTS AT MICROWAVE FREQUENCIES

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Abstract—A non-resonant microwave method has been proposed for accurate complex permittivity determination of low-loss materials. The method uses two measurement data of the magnitude of transmission properties of the sample. While the first datum must correspond to a frequency point resulting in a maximum magnitude of transmission properties, the other can be any datum at a frequency different than the first datum and not far distant from the first datum. Two closed-from expressions are derived for a good initial guess using the above data. The limitations of each expression are discussed. 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

Various microwave techniques 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. [1–54].

Transmission-reflection non-resonant methods have extensively been employed for relative complex permittivity (ε_r) measurements of completely-loaded low-, medium-, and high-loss (solid, liquid, or granular) dielectric materials using calibration-dependent measurements [4–

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54]. These methods, when compared to resonant methods, are relatively simple to apply, give accurate information of ε_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 [30–34]; b) it undergoes less deterioration from surface roughness at high frequencies [30]; c) it is more sensitive to the dielectric properties of high-loss samples [49]; and d) it offers a wide dynamic range for measurements [49].

In the literature, various methods based on solely S_{21} measurements have been proposed for stable ε_r measurement of low-loss dielectric materials [40, 44, 45, 49–53]. While the method in [51] assumes that the sample is low-loss and thin, the method in [52] 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 [44]. In order to measure general electrical properties of magnetic materials, the method in [45] can be employed. However, these methods [44, 45, 51, 52] require a good initial guess for electrical properties of samples since complex exponential term in the expression of S_{21} yields multiple solutions [44, 47]. Measurements of two identical samples with different lengths can be utilized for unique ε_r measurement of samples [54]. 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.

Swept-frequency measurements of S_{21} of low-loss or high-loss samples over a broadband can be directly utilized to obtain unique ε_r [40, 49, 50, 53]. These methods utilize either magnitude measurements [40, 53] or phase measurements [49, 50] of S_{21} at different frequencies for assigning the correct ε_r. It is well-known that magnitude-only measurements are advantageous to complex (or phase) measurements in that the systems measuring amplitude-only information are relatively inexpensive, require less microwave components, and thus are desirable for industrial-based applications [30–35]. The method in [40] utilizes magnitude-only measurements at slightly different frequencies for unique ε_r extraction.

However, it is not applicable to low-loss materials. Besides, the method in [53] exploits the oscillatory behavior of the magnitude of S_{21} measurements over a frequency band and determines unique ε_r using measurements at frequencies resulting in extreme values of the magnitude of S_{21}. Although this technique is attractive and applicable to low-loss samples, it is not appropriate for thin samples with lower dielectric constants, which will be discussed in Section 2.2.1 of the manuscript. In this research paper, we propose a simple method for unique ε_r measurement of low-loss thin or thick samples with lower or higher dielectric constants using magnitude measurements of S_{21} at two frequencies.

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. Between calibration planes, CP1 and CP2 in Fig. 1, S_{21} can be expressed as [55]

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

where L is the sample length; $|S_{21}|$ and θ_{21} are the magnitude and phase of 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 (assumed as the wave number of light in vacuum) and cut-off and

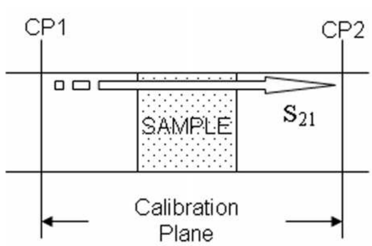

Figure 1. Measurement of complex permittivity of a sample completely filling a waveguide section between calibration planes (CP1 and CP2).

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 [44, 47, 48]. In this paper, our aim is to find a good and accurate initial guess for ε_r determination using two measurements of $|S_{21}|$ at two different frequencies.

2.2. Derivation of Two Expressions for a Good Estimation of Permittivity

In this subsection, we present closed-form expressions for a good initial guess for ε_r of low-loss dielectric materials using $|S_{21}|$ measurements at two different frequencies. To this end, for simplifying the analysis, we introduce the following new variables into (1)

$$\chi - j\xi = \sqrt{\varepsilon_r - (f_c/f)^2}, \quad B = \exp\left(-4\pi\xi L/\lambda_0\right), \tag{3}$$

$$A = 4\pi\chi L/\lambda_0, \quad \kappa = \sqrt{1 - (f_c/f)^2}. \tag{4}$$

We, then, obtain $|S_{21}|$ as [47, 48]

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

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, it was not yet possible to measure a unique ε_r using two independent $|S_{21}|$ measurements at one frequency as a consequence of the presence of periodic functions (trigonometric terms in (6)) [44, 48]. In this research paper, we demonstrate that it is possible to obtain a unique ε_r using measurements of one thicker low-loss sample at two different frequencies if one of which corresponds to a Fabry-Pérot frequency (integer multiples of one-half wavelength in the sample).

We, next, consider any simplification of the expressions in (6)–(8) at Fabry-Pérot frequencies. We illustrated that, at those frequencies and assuming a passive low-loss sample, $|S_{21}|$ attains its maximum value (minimum value of the magnitude of S_{11}) and $\cos(A)$ and $\sin(A)$ in (6) can be approximated as

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

Substituting these expressions into (6) and rearranging (5), we find

$$|S_{21}|^2_{\max} = \frac{16B\left(\chi^2+\xi^2\right)\kappa^2}{B^2\Lambda_3^2+\Lambda_4^2-2B\left(\Lambda_1^2-\Lambda_2\right)}, \tag{10}$$

where $|S_{21}|_{\max}$ denotes the value (maximum) of $|S_{21}|$ at any Fabry-Pérot frequency. We note that, using the approximate expressions for $\cos(A)$ and $\sin(A)$, we avoid multiple-solutions arising as a consequence of periodicity. This circumstance is very similar to those at which trigonometric functions are linearized for thinner low-loss samples [51] or for thicker (or thinner) lossy samples [43].

It is obvious from (10) that, at any Fabry-Pérot frequency, it is possible to express χ in terms of ξ. In a similar manner, for low-loss samples where $\varepsilon_r'' \ll \varepsilon_r'$, we can consider $\xi^2 \ll 1$ and obtain B in terms of χ. Using these two approaches, in the following subsection, we present closed-form expressions for a good initial guess of ε_r using another $|S_{21}|$ measurement at a frequency different than the Fabry-Pérot frequency.

2.2.1. Derivation of First Expression for Initial Guess

Here, we will give a closed-form expression for the estimate of ε_r by obtaining χ in terms of ξ from (10). Doing this leads to

$$\Lambda_1\chi^4+\Lambda_2\chi^3+\Lambda_3\chi^2+\Lambda_4\chi+\Lambda_5=0, \tag{11}$$

where

$$\Lambda_1=|S_{21}|^2_{\max}(1-B)^2, \quad \Lambda_2=4\kappa|S_{21}|^2_{\max}\left(1-B^2\right), \tag{12}$$

$$\Lambda_3=2\left[|S_{21}|^2_{\max}\left(3\kappa^2+\xi^2\right)\left(1+B^2\right)-2B|S_{21}|^2_{\max}\left(\xi^2-\kappa^2\right)-8B\kappa^2\right], \tag{13}$$

$$\Lambda_4=4\kappa|S_{21}|^2_{\max}\left(1-B^2\right)\left(\xi^2+\kappa^2\right), \tag{14}$$

$$\Lambda_5=2\kappa^2\left[|S_{21}|^2_{\max}\left(1+B^2\right)+2B\left(3|S_{21}|^2_{\max}-4\right)\right]\xi^2 +|S_{21}|^2_{\max}(1-B)^2\kappa^4+|S_{21}|^2_{\max}(1-B)^2\xi^4. \tag{15}$$

The four roots of χ in (11) can be found using either closed-form formulae [40] or "roots" function of MATLAB, which simply finds the eigen values of a matrix consisting of Λ_1, Λ_2, Λ_3, Λ_4, and Λ_5. After some trial and error, we note that only one of the roots of χ is a valid result provided that χ is real [44] and $\chi > \kappa$ for $\varepsilon_r' > 1$. The latter condition can be directly seen from (3) and (4), if one lets $\varepsilon_r' > 1$.

After obtaining χ in terms of ξ from (11), we can find a good initial estimate for ε_r using another $|S_{21}|$ measurement at a frequency different than the Fabry-Pérot frequency already employed in the derivation of χ from (11). Assuming that ε_r does not much change (or slightly change) with frequency, we are at liberty choosing the second frequency. This frequency can even be another Fabry-Pérot frequency [53]. However, the rate of change of A in (4) with frequency sets an upper limit for selecting the second frequency, since, at the second frequency it may not be possible anymore to utilize zero-order approximation [$\varepsilon_r(f_1) \cong \varepsilon_r(f_2)$ where f_1 corresponds to Fabry-Pérot frequency, while f_2 denotes another frequency]. For example, Fig. 2 demonstrates the dependence of $|S_{21}|$ of two thin polytetrafluoro-ethylene (PTFE) samples (1 mm and 2 mm in length) over a broadband (for simplicity, it is assumed that $f_c \to 0$). The ε_r of the PTFE sample is assumed $\varepsilon_r = 2.05 - j10^{-4}$ [56]. It is seen form Fig. 2 that the frequency range for the validity of the assumption used in [53] that the ε_r of the sample does not change over two subsequent frequency points that yield extreme values of $|S_{21}|$ is too wide. For those circumstances, higher-order approximations should be employed [43, 48]. The degree of approximation largely depends on electrical properties of materials. In this research paper, instead, we will choose the second frequency close to the Fabry-Pérot frequency to apply the zero-order approximation [43, 48]. In this way, there is no need to consider the degree of approximation for ε_r for a possible change with frequency, and the expressions for the initial estimate for

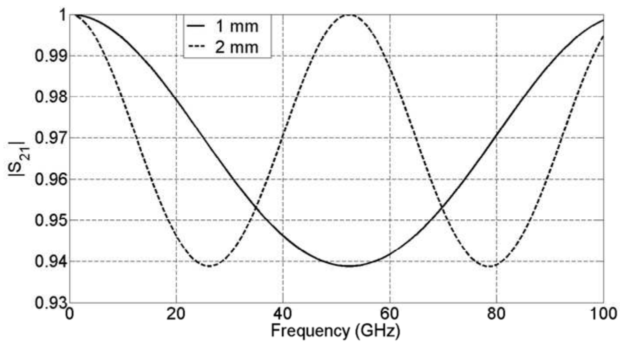

Figure 2. Dependence of the magnitude of transmission scattering parameter of two thin PTFE samples over a broad frequency band.

ε_r become simpler.

Assuming ε_r (and, in turn χ and ξ) does not much change over the selected two frequencies (one is Fabry-Pérot frequency) provided that we measure two distinct values of S_{21} at those frequencies, we can substitute the found χ from (11) at Fabry-Pérot frequency into (5), use $|S_{21}|$ datum at the second frequency, and finally determine ξ. It seems that, using this procedure, it is possible to obtain one ξ. However, our analysis demonstrates that this is not the case. This circumstance arises since we still need to use trigonometric functions ($\cos(A)$ and $\sin(A)$) in (5) at the second frequency. Nonetheless, we succeed in obtaining a unique solution for ξ (and thus χ) using the expression in (9). It is apparent from (9) that

$$\chi \cong n\pi/(k_0 L), \quad n = 1, 2, 3, \ldots \tag{16}$$

since $\chi > 0$. Enforcing the constrain condition in (16) along with the previous ones, a unique estimate for ξ and χ (and ε_r) is possible. For example, Fig. 3 demonstrates the dependence of $F_1(\xi^{cal}) = |S_{21}^{sim}| - |S_{21}^{cal}| = 0$ and $F_2(\xi^{cal}) = |\chi - \chi^{cal}| = 0$, where χ is given in (16), over ξ^{cal} for $n = 5$. From here after, the superscripts $'sim'$ and $'cal'$ denote the simulated and calculated quantities, respectively. For simulated data, we used $\varepsilon_r = 3.5 - j0.001$, $L = 40\,\text{mm}$ and $f_c = 6.555\,\text{GHz}$, and assigned $f_1 = 10.61\,\text{GHz}$ and $f_2 = 10.7\,\text{GHz}$ as the Fabry-Pérot frequency and the second frequency, and $|S_{21}^{sim}| \cong 0.997$ and $|S_{21}^{sim}| \cong 0.988$ as the simulated data at the Fabry-Pérot frequency and the second frequency, respectively.

It is seen from Fig. 3 that $F_1(\xi^{cal})$ intersects the zero abscissa at multiple points (multiple-solutions) which shows that unique ξ solution is not possible using just $F_1(\xi^{cal})$. On the other hand,

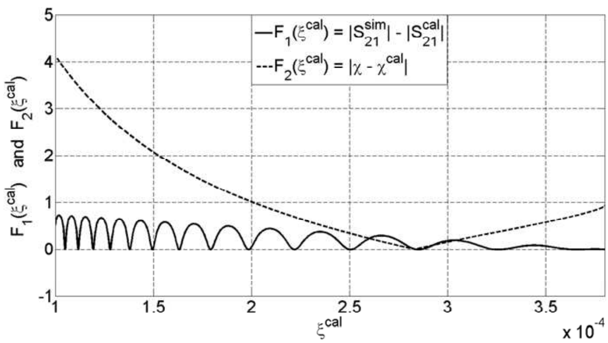

Figure 3. The dependence of $F_1(\xi^{cal}) = |S_{21}^{sim}| - |S_{21}^{cal}| = 0$ and $F_2(\xi^{cal}) = |\chi - \chi^{cal}| = 0$ over ξ^{cal} for $n = 5$.

$F_2(\xi^{cal})$ intersects the zero abscissa at one point for a given n. Using the common (or very close) intersections of $F_1(\xi^{cal})$ and $F_2(\xi^{cal})$, we determine $\xi^{cal} \cong 2.831 \times 10^{-3}$ and then $\varepsilon_r \cong 3.508 - j0.001$, which is very close to the simulated datum ($\varepsilon_r = 3.5 - j0.001$). It is noted that, for various n values, $F_2(\xi^{cal})$ intersects the zero abscissa at different unique points. However, n values different than $n = 5$ do not yield common intersections for $F_1(\xi^{cal}) = 0$ and $F_2(\xi^{cal}) = 0$. To verify our closed-form expressions for a good initial estimate for ε_r, we also performed other numerical simulations and noted that our closed-form expressions output a good and unique initial guess for ε_r.

2.2.2. Derivation of Second Expression for Initial Guess

Although we have validated our first closed-form expressions using the simulated data, we noted that $F_1(\xi^{cal})$ significantly changes with ξ^{cal}, which is extremely a small value as can be seen from Fig. 3. Consequently, a misleading initial estimate may occur if there is some noise in measurements. To eliminate this drawback, in this paper, we propose another closed-form expression for an initial guess for ε_r based on χ. To demonstrate this, we first presume that $\xi \ll 1$ (which is a very good approximation for low-loss samples, since the imaginary part of $\sqrt{j[\varepsilon_r - (f_c/f)^2]}$ is taken as ξ) and simplify the expressions in (5)–(8) assuming that $|S_{21}|$ corresponds to its maximum value ($|S_{21}|$ datum at any Fabry-Pérot frequency). Then, we find an expression for B as

$$B_{(1,2)} \cong \frac{\Omega_2 \mp \sqrt{\Omega_2^2 - 4\Omega_1\Omega_3}}{2\Omega_1}, \quad \xi_{(1,2)} \cong \frac{\ln\left(B_{(1,2)}\right)}{-2k_0L}, \tag{17}$$

where $\cos(A) \cong 1$, $\sin(A) \cong 0$, and

$$\Omega_1 = |S_{21}|^2_{\max}(\chi - \kappa)^4, \quad \Omega_3 = |S_{21}|^2_{\max}(\chi + \kappa)^4, \tag{18}$$

$$\Omega_2 = 2\left[|S_{21}|^2_{\max}\left(\chi^2 - \kappa^2\right)^2 + 8\kappa^2\chi^2\right]. \tag{19}$$

It is noted that only the negative sign before the square root in (17) is valid for B, since $\Omega_1 > 0$ and $\Omega_3 > 0$ and $0 < B < 1$ for $\xi \ll 1$.

After obtaining a unique B and ξ in terms of χ from (17), we can substitute them into (5) and determine χ using $|S_{21}|$ at a second frequency by considering the frequency selection criterion discussed above. For example, Fig. 4 demonstrates the dependence of $F_3(\chi^{cal}) = |S_{21}^{sim}| - |S_{21}^{cal}| = 0$ over χ^{cal} for various values of n using the same simulated data used in validation of the first expression for the initial estimate of ε_r in previous subsection. It is seen from Fig. 4 that there is only one point that $F_3(\chi^{cal}) = |S_{21}^{sim}| - |S_{21}^{cal}|$ intersects the zero abscissa, which in turn validates that unique ε_r solution can be

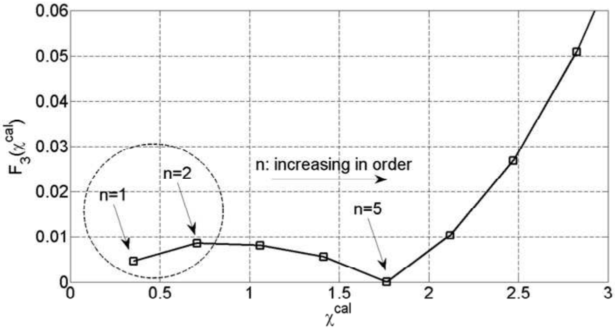

Figure 4. The dependence of $F_3(\chi^{cal}) = |S_{21}^{sim}| - |S_{21}^{cal}|$ over χ^{cal} for various n values.

possible for the second closed-form expressions. It is noted that, for the dependence in Fig. 4, we already used the constrain in (16) in (17)–(19) and (5). We also note that χ^{cal} values corresponding to $n = 1$ and $n = 2$ values cannot be valid since, for these values, $\chi^{cal} < \kappa$.

3. MEASUREMENTS

A general purpose X-band waveguide measurement set-up is used for validation of the proposed method ($f_c \cong 6.555\,\text{GHz}$) [48]. An HP8720C VNA connected as a source and measurement equipment. For validation of the proposed method, we use the measurement data of an 76.28 mm long PTFE sample [48]. We note that we used the measurements of this long PTFE sample because we need to observe either maximum (or minimum) values of $|S_{21}|$ over a short frequency band (9.7–11.7 GHz). To apply our method, first the maximum of $|S_{21}|$ is found. Using our measured data, we recorded two maximum S_{21} values at $f_{1(1)} \cong 10.118\,\text{GHz}$ and $f_{1(2)} \cong 11.355\,\text{GHz}$ over 9.7–11.7 GHz range. Then, using the measurement datum at $f_{1(1)}$ (or $f_{1(2)}$) and that at another frequency ($f_2 = 11.5\,\text{GHz}$), we determined the initial guess for the PTFE sample using our two closed-form expressions. By applying our first expression in Section 2.2.1, we found $\varepsilon_r \cong 2.064 - j0.049$, while using our second expression in Section 2.2.2, we obtained $\varepsilon_r \cong 2.072$. Both of these initial guesses are very close to the reference data for the PTFE sample in the literature [56] (at 10 GHz, the ε_r of the PTFE sample given by von Hippel is $2.08 - j0.00076$). To compare the accuracy of our closed-form expressions with that in [53], we also obtained an initial guess for the PTFE sample using $f_{1(1)}$ and $f_{1(2)}$. We found $\varepsilon_r \cong 2.064 - j0.270$ as

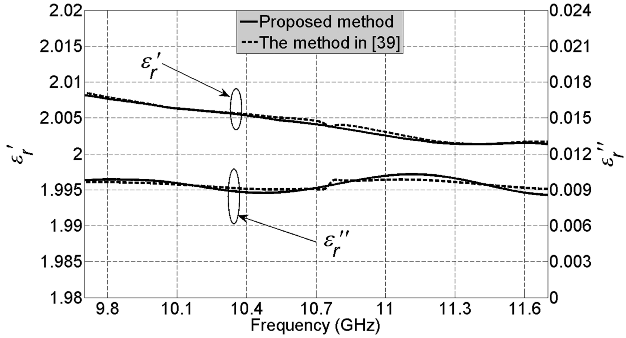

Figure 5. Measured complex permittivity of a PTFE sample using our method and that in [39].

an initial guess from the procedure in [53]. It is seen from these results that our first closed-form expression is much better in estimating the loss tangent of low-loss samples than that in [53], while the second closed-form expression assures the correctness of the first initial guess and is in charge as a feedback.

Using our estimated $\varepsilon_r \cong 2.064 - j0.049$ at $f_{1(1)}$ as an initial guess throughout the frequency band, we measured the ε_r of the PTFE sample over 9.7–11.7 GHz, as shown in Fig. 5. In order to compare the result of the proposed method, we also measured the ε_r of the PTFE sample by the method in [39]. It is seen from Fig. 5 that the results obtained from both methods are in good agreement with each other and the data available in the literature [56].

4. CONCLUSION

A non-resonant microwave method has been proposed for accurate complex permittivity determination of low-loss materials from measured magnitude of transmission S-parameter over a broadband. In the derivation of the expressions for a unique initial guess for the permittivity, we use less approximation for increasing the accuracy of the guess. The method eliminates the drawbacks of another similar method in the literature by using two measurement data at frequencies not very distant.

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REFERENCES

1. Kaatze, U., "Techniques for measuring the microwave dielectric properties of materials," *Metrologia*, Vol. 47, No. 2, S91–S113, 2010.
2. Zhang, H., S. Y. Tan, and H. S. Tan, "An improved method for microwave nondestructive dielectric measurement of layered media," *Progress In Electromagnetics Research B*, Vol. 10, 145–161, 2008.
3. Zhang, H., S. Y. Tan, and H. S. Tan, "A novel method for microwave breast cancer detection," *Progress In Electromagnetics Research*, Vol. 83, 413–434, 2008.
4. Le Floch, J. M., F. Houndonougbo, V. Madrangeas, D. Cros, M. Guilloux-Viry, and W. Peng, "Thin film materials characterization using TE modes," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 4, 549–559, 2009.
5. Jin, H., S. R. Dong, and D. M. Wang, "Measurement of dielectric constant of thin film materials at microwave frequencies," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 5–6, 809–817, 2009.
6. Wu, Y. Q., Z. X. Tang, Y. H. Xu, and B. Zhang, "Measuring complex permeability of ferromagnetic thin films using microstrip transmission method," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 10, 1303–1311, 2009.
7. Hasar, U. C., O. Simsek, and M. Gulnahar, "A simple procedure to simultaneously evaluate the thickness of and resistive losses in transmission lines from uncalibrated scattering parameter measurements," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 8-9, 999–1010, 2009.
8. Hasar, U. C., "Accurate complex permittivity inversion from measurements of a sample partially filling a waveguide aperture," *IEEE Trans. Microw. Theory Tech.*, Vol. 58, No. 2, 451–457, 2010.
9. Hasar, U. C. and A. Cansiz, "Simultaneous complex permittivity

and thickness evaluation of liquid materials from scattering parameter measurements," *Microw. Opt. Technol. Lett.*, Vol. 52, No. 1, 75–78, 2010.

10. Hasar, U. C., O. Simsek, M. K. Zateroglu, and A. E. Ekinci, "A microwave method for unique and non-ambiguous permittivity determination of liquid materials from measured uncalibrated scattering parameters," *Progress In Electromagnetics Research*, Vol. 95, 73–85, 2009.
11. Hasar, U. C., G. Akkaya, M. Aktan, C. Gozu, and A. C. Aydin, "Water-to-cement ratio prediction using ANNs from non-destructive and contactless microwave measurements," *Progress In Electromagnetics Research*, Vol. 94, 311–325, 2009.
12. Hasar, U. C., "A new method for evaluation of thickness and monitoring its variation of medium- and low-loss materials," *Progress In Electromagnetics Research*, Vol. 94, 403–418, 2009.
13. Hasar, U. C., "A new microwave method for electrical characterization of low-loss materials," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 12, 801–803, 2009.
14. Hasar, U. C., "A microwave method for noniterative constitutive parameters determination of thin low-loss of lossy materials," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 6, 1595–1601, 2009.
15. Hasar, U. C., "Thickness-independent complex permittivity determination of partially filled thin dielectric materials into rectangular waveguides," *Progress In Electromagnetics Research*, Vol. 93, 183–203, 2009.
16. Hasar, U. C., "Thickness-independent automated constitutive parameters extraction of thin solid and liquid materials from waveguide measurements," *Progress In Electromagnetics Research*, Vol. 92, 17–32, 2009.
17. Hasar, U. C. and O. Simsek, "On the application of microwave calibration-independent measurements for noninvasive thickness evaluation of medium- and low-loss solid materials," *Progress In Electromagnetics Research*, Vol. 91, 377–392, 2009.
18. Hasar, U. C. and O. E. Inan, "A position-invariant calibration-independent method for permittivity measurements," *Microw. Opt. Technol. Lett.*, Vol. 51, No. 6, 1406–1408, 2009.
19. Hasar, U. C. and O. Simsek, "A calibration-independent microwave method for positioninsensitive and nonsingular dielectric measurements of solid materials," *J. Phys. D: Appl. Phys.*, Vol. 42, No. 7, 10, 075403, 2009.

20. Hasar, U. C. and O. Simsek, "A simple approach for evaluating the reciprocity of materials using calibration-independent measurements," *Progress In Electromagnetics Research*, Vol. 91, 139–152, 2009.
21. Hasar, U. C. and O. Simsek, "An accurate complex permittivity method for thin dielectric materials," *Progress In Electromagnetics Research*, Vol. 91, 123–138, 2009.
22. Hasar, U. C., "A self-checking technique for materials characterization using calibrationindependent measurements of reflecting lines," *Microw. Opt. Technol. Lett.*, Vol. 51, No. 1, 129–132, 2009.
23. Hasar, U. C., "A new calibration-independent method for complex permittivity extraction of solid dielectric materials," *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, No. 12, 788–790, 2008.
24. Wu, Y., Z. Tang, Y. Yu, and X. He, "A new method to avoid crowding phenomenon in extracting the permittivity of ferroelectric thin films," *Progress In Electromagnetics Research Letters*, Vol. 4, 159–166, 2008.
25. Challa, R. K., D. Kajfez, J. R. Gladden, et al., "Permittivity measurement with a non-standard waveguide by using TRL calibration and fractional linear data fitting," *Progress In Electromagnetics Research B*, Vol. 2, 1–13, 2008.
26. Zainud-Deen, S. H., M. E. S. Badr, E. El-Deen, and K. H. Awadalla, "Microstrip antenna with corrugated ground plane surface as a sensor for landmines detection," *Progress In Electromagnetics Research B*, Vol. 2, 259–278, 2008.
27. He, X., Z. X. Tang, B. Zhang, and Y. Q. Wu, "A new deembedding method in permittivity measurement of ferroelectric thin film material," *Progress In Electromagnetics Research Letters*, Vol. 3, 1–8, 2008.
28. Wu, Y. Q., Z. X. Tang, Y. H. Xu, X. He, and B. Zhang, "Permittivity measurement of ferroelectric thin film based on CPW transmission line," *Journal of Electromagnetic Waves and Applications*, Vol. 22, No. 4, 555–562, 2008.
29. Kharkovsky, S. N. and U. C. Hasar, "Measurement of mode patterns in a high power microwave cavity," *IEEE Trans. Instrum. Meas.*, Vol. 52, No. 6, 1815–1819, 2003.
30. Kharkovsky, S. N., M. F. Akay, U. C. Hasar, and C. D. Atis, "Measurement and monitoring of microwave reflection and transmission properties of cement-based materials," *IEEE Trans. Instrum. Meas.*, Vol. 51, No. 6, 1210–1218, 2002.

31. Hasar, U. C., "Permittivity determination of fresh cement-based materials by an open-ended waveguide probe using amplitude-only measurements," *Progress In Electromagnetics Research*, Vol. 97, 27–43, 2009.
32. Hasar, U. C., O. Simsek, and A. C. Aydin, "Application of varying-frequency amplitude-only technique for electrical characterization of hardened cement-based materials," *Microw. Opt. Tehcnol. Lett.*, Vol. 52, No. 4, 801–805, 2010.
33. Hasar, U. C., "Non-destructive testing of hardened cement specimens at microwave frequencies using a simple free-space method," *NDT & E Int.*, Vol. 42, No. 6, 550–557, 2009.
34. Hasar, U. C., "Nondestructive and noncontacting testing of hardened mortar specimens using a free-space method," *J. Mater. Civ. Engn.*, Vol. 21, No. 9, 484–493, 2009.
35. Hasar, U. C., "A microcontroller-based microwave free-space measurement system for permittivity determination of lossy liquid materials," *Rev. Sci. Instrum.*, Vol. 80, No. 5, 056103(3), 2009.
36. Nicolson, A. M. and G. Ross, "Measurement of the intrinsic properties of materials by time–domain techniques," *IEEE Trans. Instrum. Meas.*, Vol. 19, No. 4, 377–382, 1970.
37. Weir, W. B., "Automatic measurement of complex dielectric constant and permeability at microwave frequencies," *Proc. IEEE*, Vol. 62, No. 1, 33–36, 1974.
38. Baker-Jarvis, J., E. J. Vanzura, and W. A. Kissick, "Improved technique for determining complex permittivity with the transmission/reflection method," *IEEE Trans. Microw. Theory Tech.*, Vol. 38, No. 8, 1096–1103, 1990.
39. Boughriet, A. H., C. Legrand, and A. Chapoton, "Noniterative stable transmission/reflection method for low–loss material complex permittivity determination," *IEEE Trans. Microw. Theory Tech.*, Vol. 45, No.1, 52–57, 1997.
40. Hasar, U. C., "Elimination of the multiple-solutions ambiguity in permittivity extraction from transmission-only measurements of lossy materials," *Microw. Opt. Technol. Lett.*, Vol. 51, No. 2, 337–341, 2009.
41. Hasar, U. C., "A fast and accurate amplitude-only transmission-reflection method for complex permittivity determination of lossy materials," *IEEE Trans. Microw. Theory Tech.*, Vol. 56, No. 9, 2129–2135, 2008.
42. Hasar, U. C., C. R. Westgate, and M. Ertugrul, "Noniterative permittivity extraction of lossy liquid materials from reflection

asymmetric amplitude-only microwave measurements," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 6, 419–421, 2009.

43. Hasar U. C., C. R. Westgate, and M. Ertugrul "Permittivity determination of liquid materials using waveguide measurements for industrial applications," *IET Microw. Antennas Propagat.*, Vol. 4, No. 1, 141–152, 2010.
44. Hasar, U. C., "A generalized formulation for permittivity extraction of low-to-high-loss materials from transmission measurement," *IEEE Trans. Microw. Theory Tech.*, Vol. 58, No. 2, 411–418, 2010.
45. Hasar, U. C., "A new microwave method based on transmission scattering parameter measurements for simultaneous broadband and stable permittivity and permeability determination," *Progress In Electromagnetics Research*, Vol. 93, 161–176, 2009.
46. Hasar, U. C. and O. E. Inan, "Elimination of the dependency of the calibration plane and the sample thickness from complex permittivity measurements of thin materials," *Microw. Opt. Technol. Lett.*, Vol. 51, No. 7, 1642–1646, 2009.
47. Hasar, U. C. and C. R. Westgate, "A broadband and stable method for unique complex permittivity determination of low-loss materials," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 2, 471–477, 2009.
48. Hasar, U. C., "Two novel amplitude-only methods for complex permittivity determination of medium- and low-loss materials," *Meas. Sci. Technol.*, Vol. 19, No. 5, 055706(10), 2008.
49. Ness, J., "Broad-band permittivity measurements using the semi-automatic network analyzer," *IEEE Trans. Microw. Theory Tech.*, Vol. 33, No. 11, 1222–1226, 1985.
50. Ball, J. A. R. and B. Horsfield, "Resolving ambiguity in broadband waveguide permittivity measurements on moist materials," *IEEE Trans. Instrum. Meas.*, Vol. 47, No. 2, 390–392, 1998.
51. Mahony, J. D., "Measurements to estimate the relative permittivity and loss tangent of thin, low-loss materials," *IEEE Antennas Propag. Mag.*, Vol. 47, No. 3, 83–87, 2005.
52. Muqaibel, A. H. and A. Safaai-Jazi, "A new formulation for characterization of materials based on measured insertion transfer function," *IEEE Trans. Microw. Theory Tech.*, Vol. 51, No. 8, 1946–1951, 2003.
53. Xia, S., Z. Xu, and X. Wei, "Thickness-induced resonance-based complex permittivity measurement technique for barium

strontium titanate ceramics at microwave frequency," *Rev. Sci. Instrum.*, Vol. 80, No. 11, 114703(4), 2009.

54. Hasar, U. C., "Simple calibration plane-invariant method for complex permittivity determination of dispersive and nondispersive low-loss materials," *IET Microw. Antennas Propagat.*, Vol. 3, No. 4, 630–637, 2009.
55. Constantine, A. B., *Advanced Engineering Electromagnetics*, John Wiley & Sons, 1989.
56. Von Hippel, A. R., *Dielectric Materials and Applications*, 134–135, 310–332, John Wiley & Sons, New York, NY, 1954.