Noniterative Stable Transmission/Reflection Method for Low-Loss Material Complex Permittivity Determination

Abdel-Hakim Boughriet, *Student Member, IEEE,* Christian Legrand, and Alain Chapoton

***Abstract*— This paper describes a new noniterative transmission/reflection method applicable to permittivity measurements using arbitrary sample lengths in wide-band frequencies. This method is based on a simplified version of the well-known Nicolson–Ross–Weir (NRW) method. For low-loss materials, this method is stable over the whole frequency range: no divergence is observed at frequencies corresponding to integer multiples of one half wavelength in the sample. The accuracy on the dielectric permittivity is similar to that obtained with a more recently proposed iterative technique. A general equation for complex permittivity determination including the Stuchly, NRW, and new noniterative methods, is also proposed.**

I. Introduction

PERMITTIVITY and permeability measurements are required in numerous applications for a large variety of materials. The most widely used techniques in the microwave region are: cavity resonators, free space, open-ended coaxial probe, and transmission-line [1]–[4]. High Q resonant methods are accurate, but can be used narrow band. Free-space and open-ended coaxial probe methods are not destructive for the samples, but are less accurate. Transmission-line techniques are the simplest methods for electromagnetic characterization in wideband frequencies. They include short and open lines (one-port measurement) and transmission/reflection lines (two-port measurements).

For the transmission/reflection method (TR), the measuring cell is made up of a section of coaxial line or rectangular wave guide filled with the sample to be characterized. The sample electromagnetic parameters (ε^*, μ^*) are deduced from the scattering matrix defined between the sample planes and are usually measured with an automatic network analyzer. The Nicolson–Ross–Weir (NRW) procedure [5], [6] is the most commonly used method for performing this calculation. This method has the advantage of being noniterative and applicable to coaxial line and rectangular waveguide cells.

It is well known that this method diverges for low-loss materials at frequencies corresponding to integer multiples of one half wavelength in the sample. Many authors have proposed different solutions to eliminate these instabilities 1) either by decreasing the sample length to less than one half wavelength but to the detriment of the accuracy or 2) by using a recently proposed iterative procedure applicable to permittivity measurements [7]. Because of its iterative character, before starting the calculation the former procedure requires a correct estimate of permittivity in order to reach a mathematical solution.

In this paper, we identify the origin of the various forms of instability associated with the NRW method in case of low-loss materials. To suppress these instabilities, we present a different formulation and a simplified version of this method applicable for dielectric materials. Finally, we undertake an accuracy analysis.

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A.-H. Boughriet and C. Legrand are with the Département Hyperfréquences et Semiconducteurs, Institut d'Electronique et de Microélectronique du Nord, Université des Sciences et Technologies, 59652 Villeneuve d'Ascq cedex, France. They are also with the Laboratoire d'Etudes des Matériaux et des, Composants pour l'Electronique du Littoral, Université du Littoral, 62228 Calais cedex, France.

A. Chapoton is with the Institut d'Electronique et de Microélectronique du Nord, Département Hyperfréquences et Semiconducteurs, Université des Sciences et Technologies, 59652 Villeneuve d'Ascq cedex, France.

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II. Instabilities for the NRW Method in Case of Low-Loss Materials

The procedure initially proposed by Nicolson and Ross [5] and Weir [6] is deduced from the following equations, which are applicable for the coaxial line cell (TEM propagation mode) and the rectangular waveguide cell with TE_{01} propagation mode [8]–[11]:

$$S_{11} = \frac{\Gamma(1-T^2)}{1-\Gamma^2 T^2} \tag{1}$$

$$S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2} \tag{2}$$

$$\Gamma = \frac{Z-Z_0}{Z+Z_0} = \frac{\gamma_0\mu^* - \gamma}{\gamma_0\mu^* + \gamma} \tag{3}$$

$$T = \exp(-\gamma d) \tag{4}$$

$$\gamma = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon^*\mu^* - \left(\frac{\lambda^0}{\lambda_c}\right)^2} \tag{5}$$

$$\gamma_0 = j\frac{2\pi}{\lambda_0}\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{6}$$

$$Z = \frac{j\omega\mu_0\mu^*}{\gamma} \tag{7}$$

$$Z_0 = \frac{j\omega\mu_0}{\gamma_0} \tag{8}$$

where S_{11} and S_{21} are the reflection and transmission scattering parameters; Γ and T are the first reflection and the transmission coefficients; γ_0, Z_0, and γ, Z represent. respectively, the propagation constants and the impedances of the empty and filled cells; λ_0 and λ_c correspond to the free-space and the cutoff wavelength; d is the sample length; and ε^* and μ^* are the sample electromagnetic parameters.

The NRW procedure includes two steps, shown in (9)–(14)

$$S_{11}, S_{21}$$

$$\Downarrow$$

$$K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{9}$$

$$\Gamma = K \pm \sqrt{K^2 - 1} \tag{10}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{11}$$

$$\frac{1}{\Lambda^2} = \left[\frac{j}{2\pi d}\ln(T)\right]^2 \tag{12}$$

$$\Downarrow$$

$$\mu^* = \frac{\lambda_{0g}}{\Lambda}\left(\frac{1+\Gamma}{1-\Gamma}\right) \tag{13}$$

$$\varepsilon^* = \frac{\lambda_0^2\left(\frac{1}{\Lambda^2} + \frac{1}{\lambda_c^2}\right)}{\mu^*}. \tag{14}$$

First, Γ, T, and the $1/\Lambda$ term are calculated from the measured scattering parameters using (9)–(12). These are determined from (1) and (2). The equality $1/\Lambda = j(\gamma/2\pi)$ is similar to the expression $\Re e(1/\Lambda) = 1/\lambda_g$, where λ_g is the wavelength in the sample. Secondly, both complex permittivity and permeability are calculated using (13) and (14). These latter equations are deduced from (3) to (8). Equation (13) is dependent upon the parameter:

$$\lambda_{0g} = \frac{1}{\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}}$$

which represents the wavelength in the empty cell.

It is well known that for low-loss materials, the NRW procedure presents divergence at frequencies corresponding to integer multiples of one half wavelength in the sample. This is illustrated in Fig. 1, where the real permittivity and permeability of a polytetrafluoroethylene (PTFE) sample is plotted against of frequency in 8.2–12.4 GHz band waveguide. At these particular frequencies, the magnitude of the measured S_{11} parameter is particularly small (thickness resonance) and the S_{11} phase uncertainty becomes large. This leads to the appearance of inaccuracy peaks on the permittivity and permeability curves.

Equations (13) and (14) reveal that the two terms $1 - \Gamma/1 + \Gamma$ and λ_{0g}/Λ occur in the calculation of the complex permittivity and permeability. In Figs. 2 and 3, we have represented the variation of these two terms (magnitude and phase) corresponding to the previous PTFE sample versus the frequency. We can notice that the inaccuracy peaks are visible only on the term $1 - \Gamma/1 + \Gamma$ and not on λ_{0g}/Λ, although these two terms depend on the S_{11} parameter. Hence, the term $1 - \Gamma/1 + \Gamma$ is only responsible for the inaccuracy peaks observed on the electromagnetic parameters. The opposite divergence observed on real permittivity and permeability (as shown in Fig. 1) can be explained as follows: the term $1 + \Gamma/1 - \Gamma$ and its inverse $1 - \Gamma/1 + \Gamma$ occur, respectively, in (13) and (14).

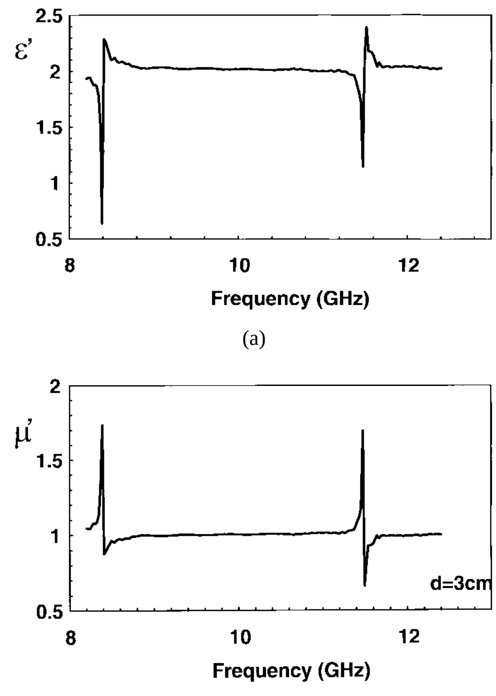


Fig. 1. Real permittivity (a) and permeability (b) of a PTFE sample characterized in X band waveguide (NRW procedure).

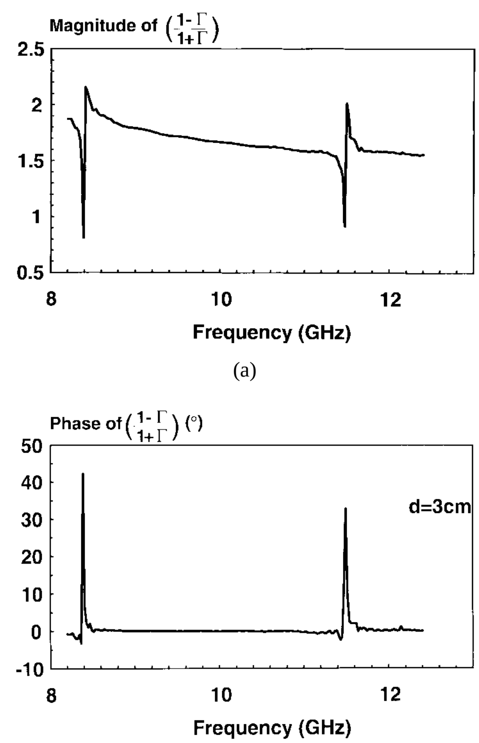
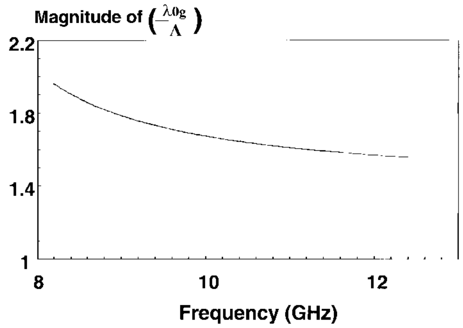
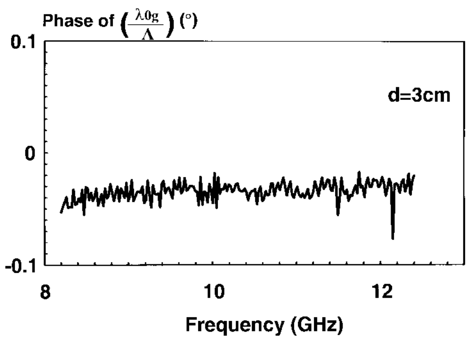


Fig. 2. The evolution of magnitude (a) and phase (b) of the term $1-\Gamma/1+\Gamma$ for PTFE sample versus frequency.



(a)



(b)

Fig. 3. The evolution of magnitude (a) and phase (b) of the term λ_{0g}/Λ for PTFE sample versus frequency.

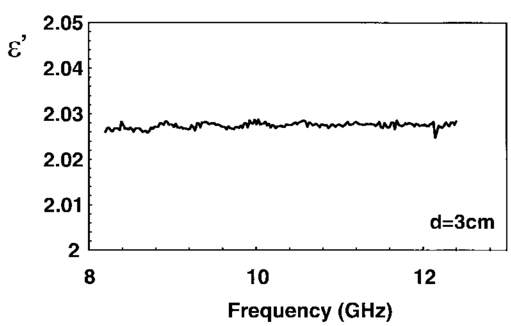


Fig. 4. Real permittivity obtained from the noniterative method for PTFE sample.

III. Methods Developed to Suppress Instabilities for Dielectric Materials

A. Baker-Jarvis Iterative Method

Baker-Jarvis *et al*. [7] proposed an iterative procedure to bypass the inaccuracy peaks applicable to dielectric materials. The permittivity is calculated numerically using (3)–(6) and (16)

$$S_{21}+\beta S_{11}=\frac{T(1-\Gamma^2)}{1-\Gamma^2T^2}+\beta\frac{\Gamma(1-T^2)}{1-\Gamma^2T^2}. \qquad (16)$$

This equation is obtained by considering (1) and (2) of the scattering parameters as a function of the first reflection and the transmission coefficient. This iterative method, applicable to coaxial line and rectangular waveguide cells, is stable for low-loss materials if parameter β is set to zero. In this case, permittivity can be calculated on the basis of the S_{21} scattering parameter.

B. New Noniterative Method for Dielectric Materials

1) Different Formulation of the NRW Method: In the following equations, a different formulation of the NRW method is proposed:

$$S_{11}, S_{21}$$

$$\Downarrow$$

$$K, \Gamma, T \text{ and } \frac{1}{\Lambda^2} \text{ with (9) to (12)}$$

$$\Downarrow$$

$$\mu^*_{\text{eff}}=\frac{\lambda_{0g}}{\Lambda}\left(\frac{1+\Gamma}{1-\Gamma}\right) \qquad (17)$$

$$\varepsilon^*_{\text{eff}}=\frac{\lambda_{0g}}{\Lambda}\left(\frac{1-\Gamma}{1+\Gamma}\right) \qquad (18)$$

$$\Downarrow$$

$$\mu^*=\mu^*_{\text{eff}} \qquad (19)$$

$$\varepsilon^*=\left(1-\frac{\lambda_0^2}{\lambda_c^2}\right)\varepsilon^*_{\text{eff}}+\frac{\lambda_0^2}{\lambda_c^2}\frac{1}{\mu^*_{\text{eff}}}. \qquad (20)$$

Equations (9)–(12) are unchanged, and an intermediate step is added by introducing the effective electromagnetic parameters $(\varepsilon^*_{\text{eff}}, \mu^*_{\text{eff}})$. These parameters presuppose a TEM propagation mode in the cell. These effective electromagnetic parameters are deduced using mathematical expressions (17) and (18), which are determined from the first reflection Γ and the transmission coefficient T:

$$\Gamma=\frac{\sqrt{\frac{\mu^*_{\text{eff}}}{\varepsilon^*_{\text{eff}}}}-1}{\sqrt{\frac{\mu^*_{\text{eff}}}{\varepsilon^*_{\text{eff}}}}+1} \qquad (21)$$

$$T=\exp\left(-j\frac{2\pi}{\lambda_{og}}\sqrt{\mu^*_{\text{eff}}\varepsilon^*_{\text{eff}}}\,d\right). \qquad (22)$$

The sample electromagnetic parameters (ε^*, μ^*) are then deduced from the effective ones using (19) and (20), obtained by equating (5) and (7) of the propagation constant and the impedance with (23) and (24) [13]:

$$\gamma=\gamma_0\sqrt{\varepsilon^*_{\text{eff}}\mu^*_{\text{eff}}} \qquad (23)$$

$$Z=Z_0\sqrt{\frac{\mu^*_{\text{eff}}}{\varepsilon^*_{\text{eff}}}}. \qquad (24)$$

This new formulation has two advantages: 1) it is easily extended to other measuring cells like, for example, microstrip or coplanar lines [14] or rectangular waveguide with TM_{01} propagation mode and 2) the two terms introduced in the previous section appear in the expressions of the effective electromagnetic parameters [i.e, (17) and (18)].

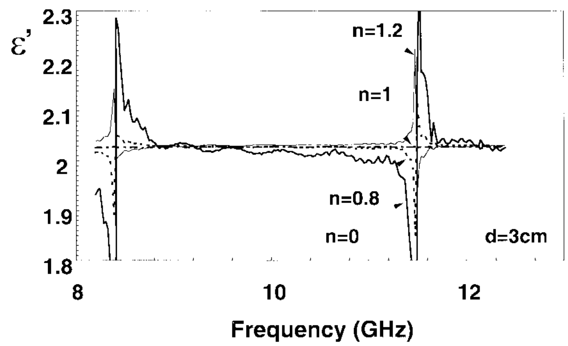


Fig. 5. Influence of the n parameter on the calculated real permittivity ε' for PTFE sample (observed for $n = 0$ and, respectively, $n = 1 + x, n = 1 - x$ with $x = 0.2$).

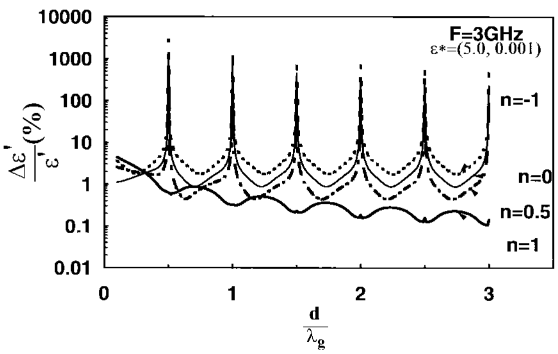


Fig. 6. Real permittivity accuracy for low-loss material as a function of normalized length and influence of the n parameter.

2) New Noniterative Method for Dielectric Materials: For dielectric materials, assuming that $\mu^* = \mu^*_{\rm eff} = 1$, it is possible to establish a new expression of the effective complex permittivity from (17) and (18):

$$\varepsilon^*_{\rm eff} = \varepsilon^*_{\rm eff}\mu^*_{\rm eff} = \frac{\lambda^2_{0g}}{\Lambda^2}. \tag{25}$$

This relationship can also be obtained from (22). This equation is still valid to calculate the material permittivity, in particular as far as the rectangular waveguide cell is concerned. To our knowledge, (25) has not been reported in the literature. In this equation, the term $1-\Gamma/1+\Gamma$ has been eliminated and, taking into account the conclusion of Section II, we can expect the suppression of the inaccuracy peaks on the permittivity. This is confirmed in Fig. 4 and points out the interest of this new procedure of calculus, called the "new noniterative method."

C. General Equation

For dielectric materials ($\mu^* = \mu^*_{\rm eff} = 1$), a more general equation can be written by combining (17) and (18)

$$\varepsilon^*_{\rm eff} = \varepsilon^*_{\rm eff}(\mu^*_{\rm eff})^n = \left(\frac{1-\Gamma}{1+\Gamma}\right)^{n-1}\left(\frac{\lambda_{0g}}{\Lambda}\right)^{n+1}. \tag{26}$$

The exponent n is a positive or negative real. This general equation includes the Stuchly method [12] (with $n = -1$), the NRW method (with $n = 0$), and the new noniterative method (with $n = 1$). In Fig. 5, we have represented the calculated permittivity ε' for PTFE versus frequency at various

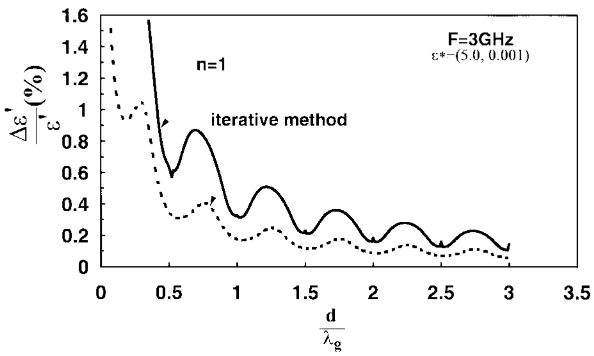


Fig. 7. Comparison of real permittivity accuracy obtained using the new noniterative method and with that determined from the Baker–Jarvis iterative procedure for a low-loss material.

values of the n parameter. We can notice that inaccuracy peaks amplitudes decrease as n approaches the value of one, and completely disappear when $n = 1$. Fig. 5 also shows a symmetry in the inaccuracy peaks for cases $n = 1 + x$ and $n = 1-x$ (for example, $n = 1.2$ and $n = 0.8$). This is easily explained by the intervention of the $(1 - \Gamma/1 + \Gamma)^{n-1}$ term in (26).

IV. Uncertainty Analysis

A. Calculus Method

From the effective permittivity accuracies and by using (20), it is possible to determine the material permittivity ones as follows:

$$\frac{\Delta\varepsilon'}{\varepsilon'} = \left(1 - \frac{\lambda_0^2}{\lambda_c^2}\right)\frac{\Delta\varepsilon'_{\rm eff}}{\varepsilon'} \tag{27}$$

$$\frac{\Delta\varepsilon''}{\varepsilon''} = \left(1 - \frac{\lambda_0^2}{\lambda_c^2}\right)\frac{\Delta\varepsilon''_{\rm eff}}{\varepsilon''}. \tag{28}$$

The effective permittivity uncertainties are calculated from the following formulas [7]:

$$\Delta\varepsilon'_{\rm eff} = \sqrt{\left(\frac{\partial\varepsilon'_{\rm eff}}{\partial|S_\alpha|}\Delta|S_\alpha|\right)^2 + \left(\frac{\partial\varepsilon'_{\rm eff}}{\partial\theta_\alpha}\Delta\theta_\alpha\right)^2 + \left(\frac{\partial\varepsilon'_{\rm eff}}{\partial d}\Delta d\right)} \tag{29}$$

$$\Delta\varepsilon''_{\rm eff} = \sqrt{\left(\frac{\partial\varepsilon''_{\rm eff}}{\partial|S_\alpha|}\Delta|S_\alpha|\right)^2 + \left(\frac{\partial\varepsilon''_{\rm eff}}{\partial\theta_\alpha}\Delta\theta_\alpha\right)^2 + \left(\frac{\partial\varepsilon''_{\rm eff}}{\partial d}\Delta d\right)} \tag{30}$$

where $\alpha = 11$ and 21 and $\Delta|S_\alpha|\Delta\theta_\alpha$, and Δd are, respectively, the uncertainties on the magnitude, the phase of scattering parameters, and the sample length. The $\Delta|S_\alpha|$ and $\Delta\theta_\alpha$ uncertainties are those given by the automatic network analyzer specifications [15]. The derivatives in (29) and (30) can be calculated from the following equations:

$$\frac{\partial\varepsilon^*_{\rm eff}}{\partial|S_\alpha|} = \left(\frac{\partial\varepsilon^*_{\rm eff}}{\partial\Gamma}\frac{\partial\Gamma}{\partial S_\alpha} + \frac{\partial\varepsilon^*_{\rm eff}}{\partial T}\frac{\partial T}{\partial S_\alpha}\right)\exp{(j\theta_\alpha)} \tag{31}$$

$$\frac{\partial\varepsilon^*_{\rm eff}}{\partial\theta_\alpha} = j|S_\alpha|\frac{\partial\varepsilon^*_{\rm eff}}{\partial|S_\alpha|} \tag{32}$$

$$\frac{\partial\varepsilon^*_{\rm eff}}{\partial d} = \frac{\partial\varepsilon^*_{\rm eff}}{\partial T}\frac{\partial T}{\partial d}. \tag{33}$$

By using (9) to (11)

$$\frac{\partial \Gamma}{\partial S_{11}} = \left(1 \pm \frac{K}{\sqrt{K^2-1)}}\right)\left(\frac{2S_{11}^2 - 2S_{21}^2 + 1}{2S_{11}^2}\right) \tag{34}$$

$$\frac{\partial \Gamma}{\partial S_{21}} = \left(1 \pm \frac{K}{\sqrt{K^2-1)}}\right)\left(-\frac{S_{21}}{S_{11}}\right) \tag{35}$$

$$\frac{\partial T}{\partial S_\alpha} = \frac{1 - \Gamma^2 + \frac{\partial \Gamma}{\partial S_\alpha}((S_{11}+S_{21})^2 - 1)}{(1-(S_{11}+S_{21})\Gamma)^2} \tag{36}$$

and general equation (26)

$$\frac{\partial \varepsilon_{\text{eff}}^*}{\partial \Gamma} = (1-n)\left(\frac{j\lambda_{0g}}{2\pi d}\ln(T)\right)^{(1+n)}\left(\frac{1-\Gamma}{1+\Gamma}\right)^{(-n)} \tag{37}$$

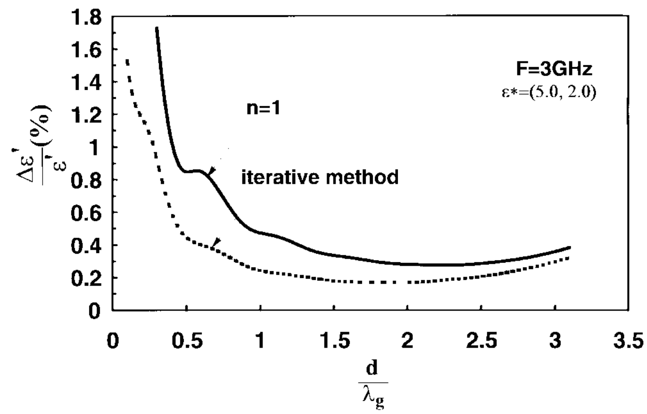
$$\frac{\partial \varepsilon_{\text{eff}}^*}{\partial T} = (1+n)\left(\frac{j\lambda_{0g}}{2\pi d}\ln(T)\right)^{(n)}\left(\frac{1-\Gamma}{1+\Gamma}\right)^{(1-n)} \cdot \left(\frac{j}{2\pi d}\frac{\lambda_{0g}}{T}\right). \tag{38}$$

The data processing was made automatic by writing an HP Basic program that accepts as input the simulated materials together with scattering parameters uncertainties and gives as output the permittivity accuracies.

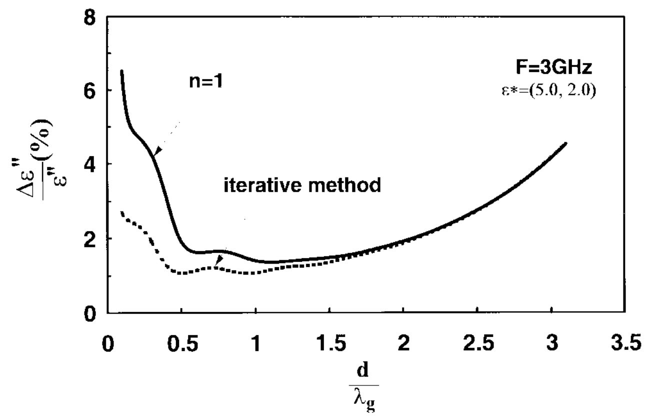
B. Discussion

The method described in the previous section is used to study permittivity accuracies in the general case from the influence of the n parameter. For these simulations, we have chosen the same materials as those used by Baker–Jarvis *et al*. [7]. In Fig. 6, we see the influence of the n parameter in case of a low-loss material $[\varepsilon^* = (5.0, 0.001)]$. The accuracy on ε' is plotted against the normalized sample length at 3 GHz for a coaxial line. The data obtained confirm the previous results, i.e, the best accuracy on the permittivity is obtained for the new noniterative method $(n = 1)$. This result can be explained by the influence of the n parameter in (37) and (38) for $n = 1, \partial\varepsilon_{\text{eff}}^*/\partial\Gamma = 0$.

It is possible to compare the Baker-Jarvis accuracies with those found using the new noniterative method. From the Baker–Jarvis iterative method, we have calculated the accuracy from all the expressions given in their paper [7]. These results are given in Figs. 7 and 8 for materials of different losses. We conclude that the permittivity accuracies found from these two methods are similar.



(a)



(b)

Fig. 8. Comparison of (a) real and (b) imaginary permittivity accuracy obtained from the new noniterative method with that determined from the Baker–Jarvis iterative procedure for a high-loss material.

V. Conclusion

In this paper, we have shown that the $1 - \Gamma/1 + \Gamma$ term is responsible for the NRW method instabilities observed with low-loss materials. Introducing effective electromagnetic parameters, we have proposed a different formulation of this method that has the advantage to be easily extended to other measuring cells, including TM_{01} waveguide, microstrip, and coplanar lines. For dielectric materials, setting $\mu^* = \mu_{\text{eff}}^* = 1$, we have established a general equation for permittivity determination based on a simplification of this method. This general equation includes the Stuchly method and the NRW method obtained for particular values of the real parameter n (respectively, $n = -1, n = 0$). The particular case $n = 1$ corresponds to the new noniterative method. This method presents the advantage of being stable over the whole frequency range for arbitrary sample lengths. Uncertainty analysis has been performed for different losses materials. The permittivity accuracies have been compared and found similar to those determined from the Baker-Jarvis iterative method. Other advantages of this new noniterative method have been found: 1) it maintains the analytical character of the NRW method and 2) a correct estimation of the permittivity is not necessary to converge to the solution.

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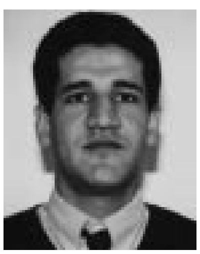
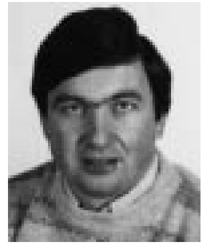


Abdel-Hakim Boughriet (S'93) was born in Oran, Algeria, on January 5, 1968. He received the B.S. degree in electrical engineering from E.N.S.E.T. of Oran. He graduated in electrical engineering "Maîtrise E.E.A" and received the M.Sc. degree "D.E.A" in electronics in 1991 and 1992, respectively, from the University of Lille, France. He joined the laboratory "Département hyperfréquences et Semi-conducteurs" at I.E.M.N (Institut d'Electronique et de Micro-électronique du Nord) at University of Lille in 1992, where he is currently working toward the Ph.D. degree in electronics.

From 1988 to 1990, he was a Physics Teacher at Oran. His main research interests are microwave techniques for dielectric measurements to develop microwave sensors applied to biological tissues and thermoplastic polymers. Currently, he is a Temporary Assistant in the "Institut Universitaire de Technologie du Littoral" (IUT), Calais, and a Graduate Research Assistant at the L.E.M.C.E.L at "Université du Littoral."



Christian Legrand was born in Mazingarbe, France, on November 8, 1958. In 1994, he received the "Docteur es Sciences" degree from the University of Lille, France, for his work on the dielectric properties of thermotropic liquid crystals.

Since 1981, he has been working in Institut d'Electronique et de Micro-électronique du Nord (I.E.M.N). In 1996, as a Professor in the Université du Littoral, he joined the Laboratoire d'Etudes des Matériaux nouveaux et des Composants pour l'Electronique (L.E.M.C.E.L), Calais. His research interests are concerned with experimental and theoretical aspects of materials dielectric and magnetic properties: large-frequency and temperature-range technics, ferroelectric liquid crystals and polymer dispersed liquid crystals for display applications, and conducting polymers for electronic devices (electroluminescent diodes and MISFET transistors).

Alain Chapoton received the Ph.D. degree from the University of Lille, France, in 1973 for his work on the dielectric properties of the water in zeolites.

In 1978, as a Professor at the University of Lille, he joined the "Institut d'Electronique et de Micro-électronique du Nord," a laboratory associated with the "Centre National de la Recherche Scientifique." His research interests various aspects of material dielectric and magnetic properties: measurement devices over a wide range of frequencies, liquid crystals characterization for display applications, humidity measurements, and conducting polymers studies for microwave absorbing materials or microelectronics devices (MISFET transistors, electroluminescent diodes).