Two New Measurement Methods for Explicit Determination of Complex Permittivity

Changhua Wan, *Member, IEEE*, Bart Nauwelaers, *Member, IEEE*, Walter De Raedt, and Marc Van Rossum

***Abstract*—This paper presents two new measurement methods for explicit determination of complex permittivity. For the first time, these methods combine the explicit algorithm with a simplified yet accurate error-correction technique. The combination is made possible by the use of one sample of single length and another of double length. For low-loss materials, one of the methods is valid for any sample length and independent of sample positions, but needs a prior estimate of the permittivity, while the other requires no such estimate, but avoidance of the single length being multiples of half-wavelength in the sample. For high-loss materials, both methods may need the estimate. Advantages of each method can be taken if both methods are used simultaneously. Experimental results from the proposed methods show excellent agreement with those from a recent iterative method. Errors arising from small deviations from the double length are also analyzed and presented. The validity, explicitness, and simple error-correction capability make the new methods very useful.**

***Index Terms*—Calibration, permittivity measurement, scattering parameters measurement.**

I. Introduction

MANY applications require the knowledge of the complex permittivity and permeability of materials. Measurement is the only reliable means for this purpose. The broad-band method based on S-parameter measurement was introduced in the 1970's [1], [2], which has been called the transmission/reflection (TR) method. Due to its simplicity, the TR method is most widely used.[1] Several modified versions can be found in the literature [3]–[6]. Methods using open or shorted transmission lines also exist [7]–[9]. However, the accuracy of the aforementioned methods is limited by the requirement of a full two- or one-port calibration using a set of standards that inevitably cause errors due to their imperfection. In contrast, two recent methods are capable of removing systematic errors with only one sample at three positions [10] or the asymmetry of the sample loaded holder [11]. The advantage of these two methods is that they use no additional standards, except the sample and its holder, while the disadvantage is that they require an iterative procedure for determining the complex permittivity. Without an accurate estimate of the unknown, the iterative procedure will not give a correct solution.

The goal of this paper is to present two new explicit methods which still use the simple error-correction scheme in [10] and [11] for complex permittivity measurement. The theory and the measurement results are given in Section II and III, respectively. Error analysis is presented in Section IV, and conclusions are drawn in Section V.

II. Theory

A. Simple Procedure for Removing Systematic Errors

Calibration/error correction of a two-port measurement system are conveniently analyzed in terms of a wave cascading matrix (WCM) [12], which is related to the S-parameters of a two-port by the relationship

$$\mathbf{R} = \frac{1}{s_{21}}\begin{pmatrix} s_{12}s_{21} - s_{11}s_{22} & s_{11} \\ -s_{22} & 1 \end{pmatrix}. \tag{1}$$

The eight-term error model of the measurement system uses two error two-ports to represent removable errors. With this model and the WCM description, the measurement of a one-parameter device i embedded between error two-port x and y corresponds to

$$\mathbf{R}_1 = \mathbf{R}_x \mathbf{R}_i(z) \mathbf{R}_y \tag{2}$$

where z is the parameter to be determined. If another device ii with the same unknown parameter is measured, the following equation, which is similar to (2), results:

$$\mathbf{R}_2 = \mathbf{R}_x \mathbf{R}_{ii}(z) \mathbf{R}_y. \tag{3}$$

To determine the unknown z with (2) and (3), a simple procedure based on the calculation of the determinant of a matrix product is employed. The mathematical basis for the calculation is that the determinant of a matrix product is equal to the product of the individual determinants. The procedure is as follows. First, take the determinant of $\mathbf{R}_1 - \mathbf{R}_2$ using (2) and (3) and that of $\mathbf{R}_1$, and then take the ratio of the two determinants. After completing the procedure, we can express the unknown in terms of the measured information as follows:

$$\frac{\det[\mathbf{R}_i(z) - \mathbf{R}_{ii}(z)]}{\det[\mathbf{R}_i(z)]} = \frac{\det(\mathbf{R}_1 - \mathbf{R}_2)}{\det(\mathbf{R}_1)} \tag{4}$$

where $\det$ means "taking the determinant of."

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C. Wan was with the Department of Electrical Engineering, Katholieke Universiteit Leuven, 3001 Heverlee, Belgium. He is now with the Department of Physics, University of Tromsø, 9037 Tromsø, Norway.

B. Nauwelaers is with the Department of Electrical Engineering, Katholieke Universiteit Leuven, 3001 Heverlee, Belgium.

W. De Raedt and M. Van Rossum are with the Interuniversitair Micro-Electronika Centrum, 3001 Heverlee, Belgium.

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B. Propagation Constant Determination Using Two Lines

As an application of the procedure presented above, the propagation constant from two line measurements is derived here. For two nonreflecting lines of length l_1 and l_2, we have

$$\mathbf{R}_i(\gamma) = \begin{pmatrix} e^{-\gamma l_1} & 0 \\ 0 & e^{\gamma l_1} \end{pmatrix} \quad \mathbf{R}_{ii}(\gamma) = \begin{pmatrix} e^{-\gamma l_2} & 0 \\ 0 & e^{\gamma l_2} \end{pmatrix} \tag{5}$$

where γ is the complex propagation constant. Substituting (5) into (4) yields

$$\gamma = \frac{\cosh^{-1}\left[1 - \dfrac{\det(\mathbf{R}_1 - \mathbf{R}_2)}{2\det(\mathbf{R}_1)}\right]}{l_2 - l_1}. \tag{6}$$

This expression is exactly equivalent to [13, eq. (4)] and is more general than [14, eq. (1)], which is only valid for a reciprocal system where $\det(\mathbf{R}_1) = 1$.

C. Explicit Determination of Complex Permittivity Using One Sample of Length l and Another of $2l$

Let us define ε_0 as the permittivity in air and ε_r as the relative permittivity in nonmagnetic samples under test. To derive explicit equations for determining ε_r, we consider one sample of length l and another of $2l$ and five measurements, as shown in Fig. 1. Either of the two methods described below uses four of the five measurements. The sample holder can be a section of coaxial line or waveguide.

For the convenience of derivation, the measured WCM's corresponding to the measurements shown in Fig. 1(a)–(e) are denoted by $\mathbf{R}_a$, $\mathbf{R}_b$, $\mathbf{R}_c$, $\mathbf{R}_d$, and $\mathbf{R}_e$ in order. The WCM of the first sample filled portion of the holder, which will be used in the following subsections, takes the form of (7), shown at the bottom of the page [15], where $j = \sqrt{-1}$, β_0, and β are, respectively, the phase constant in the air-filled and sample filled portions of the holder. Replacing l by $2l$ immediately gives the WCM of the second sample filled portion.

1) Method 1: This method uses the measurements in Fig. 1(b)–(e). To generate a basic equation, we first use the measurements shown in Fig. 1(b) and (c). The procedure is: replace $\mathbf{R}_i(z)$ in (4) with $\mathbf{R}_l(\beta)$ in (7) and $\mathbf{R}_{ii}(z)$ in (4) with

$$\mathbf{R}'_l(\beta) = \begin{pmatrix} e^{-j\beta_0 d_1} & 0 \\ 0 & e^{j\beta_0 d_1} \end{pmatrix} \mathbf{R}_l(\beta) \begin{pmatrix} e^{j\beta_0 d_1} & 0 \\ 0 & e^{-j\beta_0 d_1} \end{pmatrix}. \tag{8}$$

On the right-hand side of (8), the first matrix is the WCM of an air-filled portion with positive length d_1, while the last is that with negative length $-d_1$, both due to the movement of

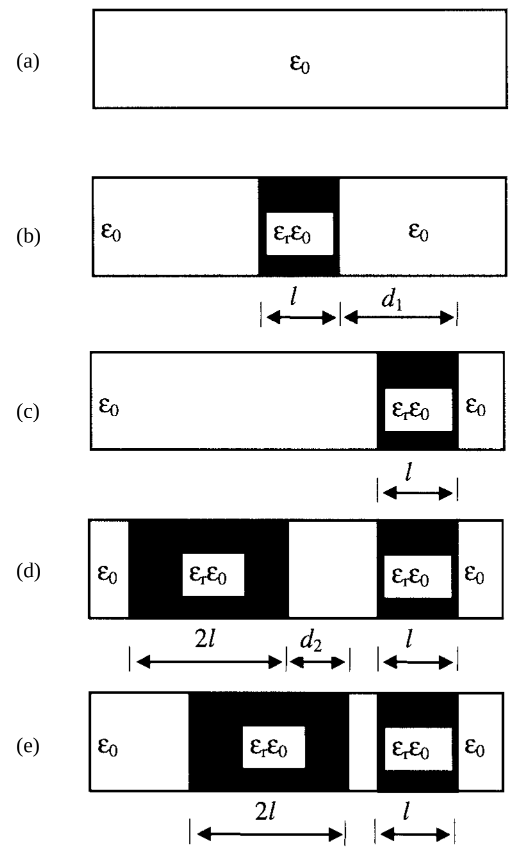

Fig. 1. Measurements for permittivity determination using (a) an empty holder, (b) the same holder loaded with a sample of length l, (c) the same as (b), except that the sample is moved a distance d_1, (d) the same as (c), except that another sample of length $2l$ is inserted, and (e) the same as (d), except that the second sample is moved a distance d_2.

the sample. After some manipulations, we obtain

$$\left[\left(\frac{\beta_0}{\beta} - \frac{\beta}{\beta_0}\right)\sin(\beta l)\sin(\beta_0 d_1)\right]^2 = -\frac{\det(\mathbf{R}_b - \mathbf{R}_c)}{\det(\mathbf{R}_b)}. \tag{9}$$

This equation is completely equivalent to [10, eq. (8)] as well as [11, eq. (6)]. For explicit determination of the complex permittivity, the measurements shown in Fig. 1(d) and (e) are then used to produce another similar equation, namely,

$$\left[\left(\frac{\beta_0}{\beta} - \frac{\beta}{\beta_0}\right)\sin(\beta 2l)\sin(\beta_0 d_2)\right]^2 = -\frac{\det(\mathbf{R}_d - \mathbf{R}_e)}{\det(\mathbf{R}_d)}. \tag{10}$$

Solving (9) and (10) simultaneously for β leads to

$$\beta^2 = \beta_0^2\left[1 + \frac{C}{2} \pm \sqrt{\left(\frac{C}{2}\right)^2 + C}\right] \tag{11}$$

$$\mathbf{R}_l(\beta) = \begin{pmatrix} \cos(\beta l) - \frac{j}{2}\left(\dfrac{\beta_0}{\beta} + \dfrac{\beta}{\beta_0}\right)\sin(\beta l) & \dfrac{j}{2}\left(\dfrac{\beta_0}{\beta} - \dfrac{\beta}{\beta_0}\right)\sin(\beta l) \\ -\dfrac{j}{2}\left(\dfrac{\beta_0}{\beta} - \dfrac{\beta}{\beta_0}\right)\sin(\beta l) & \cos(\beta l) + \dfrac{j}{2}\left(\dfrac{\beta_0}{\beta} + \dfrac{\beta}{\beta_0}\right)\sin(\beta l) \end{pmatrix} \tag{7}$$

where

$$C = \frac{4A^2 \sin^2(\beta_0 d_2)}{\sin^2(\beta_0 d_1)[4A \sin^2(\beta_0 d_2) - B \sin^2(\beta_0 d_1)]} \tag{12}$$

$$A = -\frac{\det(\mathbf{R}_b - \mathbf{R}_c)}{\det(\mathbf{R}_b)} \tag{13}$$

$$B = -\frac{\det(\mathbf{R}_d - \mathbf{R}_e)}{\det(\mathbf{R}_d)}. \tag{14}$$

For a general transmission-line sample holder,

$$\beta_0 = \frac{2\pi}{\lambda}\sqrt{1 - \left(\frac{\lambda}{\lambda_c}\right)^2} \tag{15}$$

$$\beta = \frac{2\pi}{\lambda}\sqrt{\varepsilon_r - \left(\frac{\lambda}{\lambda_c}\right)^2}. \tag{16}$$

In (15) and (16), λ and λ_c are the operating wavelength in free space and the cutoff wavelength of the holder, respectively. For a coaxial line $\lambda_c = +\infty$, and for a rectangular waveguide with only the dominant mode propagating, $\lambda_c = 2a$, where a is the waveguide width. Inserting (15) and (16) in (11) results in

$$\varepsilon_r = 1 + \left[1 - \left(\frac{\lambda}{\lambda_c}\right)^2\right]\left[\frac{C}{2} \pm \sqrt{\left(\frac{C}{2}\right)^2 + C}\right]. \tag{17}$$

It is helpful to consider a lossless material for a sign choice in (17). Since ε_r is now real, (9), (10), and (12) become real expressions. To make ε_r larger than 1, "+" must be chosen in (17) if C is positive. Actually, whatever sign is chosen in (17), a zero or negative value of C will make an impossible ε_r. As a result, "+" is the correct choice. This choice is also correct for low-loss materials where the 'lossless' approximation can be applied to resolve the sign ambiguity. For high-loss materials, the sign choice is to be made with the help of a prior estimate of the permittivity. It should be pointed out that the dimension of l (d_1 and d_2) should differ from multiples of half-wavelength in the sample (air)-filled portion of the holder.

2) Method 2: This method uses the measurements shown in Fig. 1(a)–(d). Using an air-filled portion [with the same length as the first sample in the measurement shown in Fig. 1(b)] of the empty holder in the measurement shown in Fig. 1(a) as device i, we simply have

$$\mathbf{R}_i = \begin{pmatrix} e^{-j\beta_0 l} & 0 \\ 0 & e^{j\beta_0 l} \end{pmatrix}. \tag{18}$$

As a result, the use of the measurements shown in Fig. 1(a) and (b) in (4) generates

$$\cos(\beta l)\cos(\beta_0 l) + \frac{1}{2}\left(\frac{\beta_0}{\beta} + \frac{\beta}{\beta_0}\right)\sin(\beta l)\sin(\beta_0 l) = 1 - \frac{\det(\mathbf{R}_a - \mathbf{R}_b)}{2\det(\mathbf{R}_a)}. \tag{19}$$

In deriving (19), (7) has been used in place of $\mathbf{R}_{ii}$ in (4). Incorporating the first sample filled portion into an error two-port and using the measurement shown in Fig. 1(d) (with the second sample) in association with the measurement shown in Fig. 1(c) produces the following similar equation:

$$\cos(\beta 2l)\cos(\beta_0 2l) + \frac{1}{2}\left(\frac{\beta_0}{\beta} + \frac{\beta}{\beta_0}\right)\sin(\beta 2l)\sin(\beta_0 2l) = 1 - \frac{\det(\mathbf{R}_c - \mathbf{R}_d)}{2\det(\mathbf{R}_c)}. \tag{20}$$

Solving (19) and (20) simultaneously for β yields

$$\beta = \frac{1}{l}\cos^{-1}\left[D\cos(\beta_0 l) \pm \sqrt{(D^2 - 1)\cos^2(\beta_0 l) + \frac{1}{2}(1 - E)}\right] \tag{21}$$

where

$$D = 1 - \frac{\det(\mathbf{R}_a - \mathbf{R}_b)}{2\det(\mathbf{R}_a)} \tag{22}$$

$$E = 1 - \frac{\det(\mathbf{R}_c - \mathbf{R}_d)}{2\det(\mathbf{R}_c)}. \tag{23}$$

Once β is found from (21), ε_r can be calculated by (16). This method is independent of sample positions and involves no singularities related to sample lengths. However, it requires a choice of sign in (21) as well as a choice of period for the $\cos^{-1}$ function. Such choices are best made with the help of an estimate of ε_r. Note that if this method is implemented alone, it only requires three measurements.

III. Measurement Results

In order to validate the proposed methods, we prepared one PVC sample of length 5.74 mm and another of length 11.48 mm. The samples were measured with a rectangular waveguide holder along with a vector network analyzer in the frequency range of 8–12 GHz. Five raw S-matrices were obtained following the sequence in Fig. 1 to allow disconnection/connection to occur only at one end of the holder. Finally, the measured raw S-parameters were processed to give the relative permittivity using the new explicit methods and an existing iterative method [10]. The results are shown in Fig. 2 for comparison. Note that two measurements corresponding to each sample at two positions have been used in the implementation of the iterative method because the three-position approach [10] may easily involve singularities though the information about sample positions can be eliminated. The comparison indicates the following.

1) The results from the two explicit methods agree very well with each other over the whole frequency band and with the normal data from the iterative one.
2) The abrupt peak near 8.7 GHz on the curve from the iterative method for Sample 2 is apparently due to a singularity since $\beta 2l \approx \pi$ around that frequency.
3) The abnormal large oscillations in the range of 10.8–12.0 GHz with the iterative solution for Sample 1 are probably caused by divergence in the iterative process because in that range $\beta l \approx 0.7\pi$ and no singularities are involved.

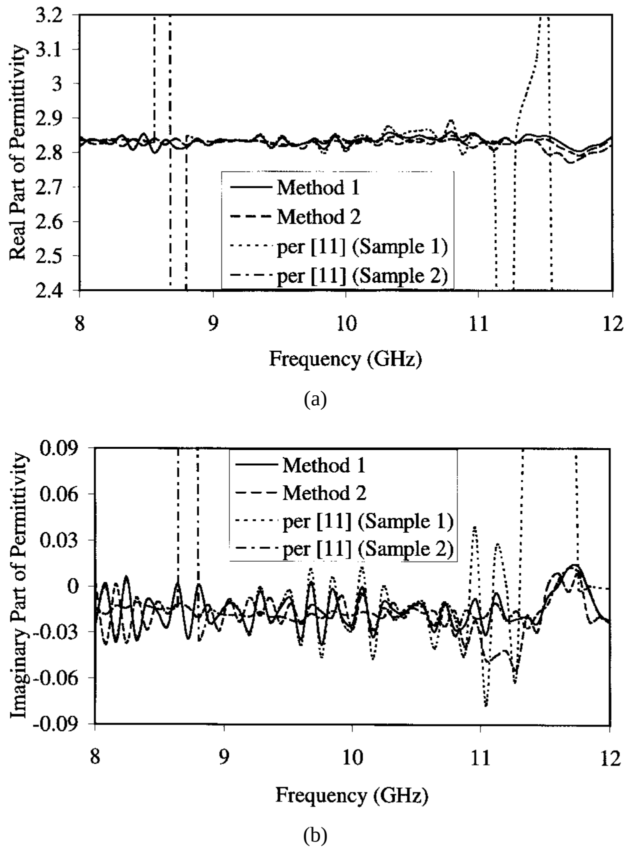

Fig. 2. Measured relative permittivity using proposed explicit methods and an existing iterative method [10]. (a) Real part. (b) Imaginary part.

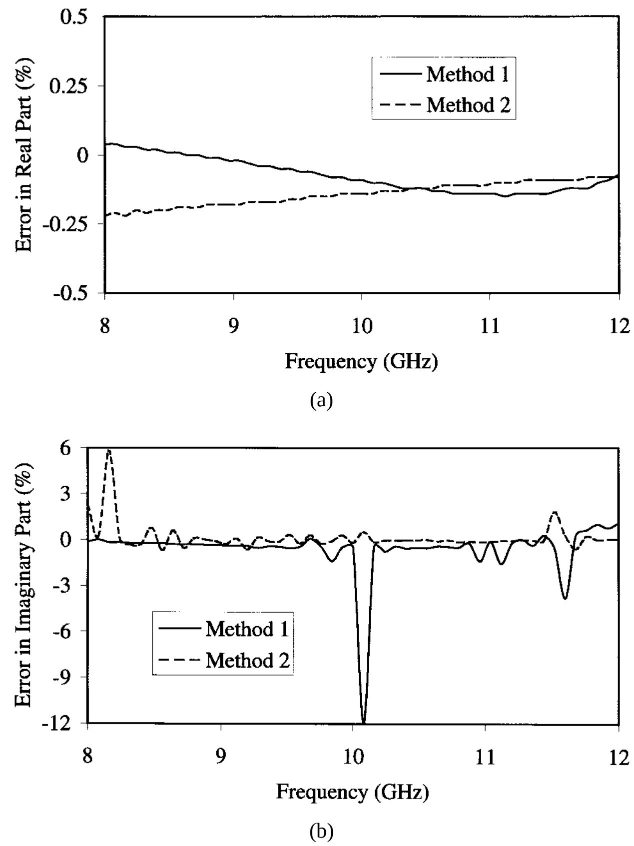

Fig. 3. Measurement errors in the (a) real and (b) imaginary parts of the permittivity of PVC samples with $\delta l = 0.02$ mm.

IV. Error Analysis

In actual permittivity measurement, errors due to S-parameter uncertainty, gaps between the sample and sample holder, and uncertainty in sample lengths and positions may arise. Here, we are only interested in the uncertainty resulting from the assumption that one sample is twice as long as the other since other uncertainties have been treated in the literature [5]. In the following, a simple, yet reasonable, error analysis is presented. To analyze the uncertainty under study, we assume that the length of the long sample is $2l + \delta l$ where δl is small when compared with $2l$. For example, δl is within 0.02 mm for the sample used in our measurement. In order to determine the conditions for applying approximations, we define

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{24}$$

and

$$\beta = \beta' - j\beta''. \tag{25}$$

Inserting (24) and (25) into (16) gives

$$\varepsilon_r' = \left(\frac{\lambda}{\lambda_c}\right)^2 + (\beta'^2 - \beta''^2)\left(\frac{\lambda}{2\pi}\right)^2 \tag{26}$$

$$\varepsilon_r'' = 2\beta'\beta''\left(\frac{\lambda}{2\pi}\right)^2. \tag{27}$$

Consider the highest frequency (12 GHz) in our measurement and set $\beta'\delta l \leq 1^\circ$ and $\beta''\delta l \leq 0.1^\circ$. From (26) and (27), we immediately obtain $\varepsilon_r' \leq 12.23$ and $\varepsilon_r'' \leq 2.41$. Under these conditions, we can use the following first-order approximation:

$$\sin\beta(2l + \delta l) \approx \sin\beta 2l + \beta\delta l \cos\beta 2l \tag{28}$$

$$\sin^2\beta(2l + \delta l) \approx \sin^2\beta 2l + \beta\delta l \sin\beta 4l \tag{29}$$

$$\cos\beta(2l + \delta l) \approx \cos\beta 2l - \beta\delta l \sin\beta 2l \tag{30}$$

in the error analysis. Actually, (17) and (21) can be considered as zeroth-order solutions. It is reasonable that we use these zeroth-order solutions in the correcting term with δl in (28)–(30) to calculate first-order corrections.

With the above consideration, we easily obtain the first-order corrections to the zeroth-order solutions in Section II. For the first method, (14) should be replaced by

$$B = -\frac{\det(\mathbf{R}_d - \mathbf{R}_e)}{\det(\mathbf{R}_d)} - \left(\frac{\beta_0}{\beta} - \frac{\beta}{\beta_0}\right)^2 \beta\delta l \sin\beta 4l \sin^2\beta_0 d_2 \tag{31}$$

where β is the zeroth-order solution from (11) with $\delta l = 0$.

Similarly, the second method requires replacing (23) with

$$E = 1 - \frac{\det(\mathbf{R}_c - \mathbf{R}_d)}{2\det(\mathbf{R}_c)} + \frac{\beta^2 - \beta_0^2}{2\beta\beta_0}\delta l \cdot(\beta_0 \sin\beta 2l \cos\beta_0 2l - \beta\cos\beta 2l \sin\beta_0 2l) \tag{32}$$

where again, β is the corresponding zeroth-order solution from (21) with $\delta l = 0$. Errors in the determination of the real and imaginary parts of the permittivity are calculated using the above theory, and are shown in Fig. 3. It is found that the error in the real part is rather small (within 0.25%), while that in the imaginary part may be as large as 11.9% at some frequencies in the measurement. This confirms that the measurement uncertainty of loss factor for low-loss materials is usually high when S-parameter-based methods are used.

V. Conclusion

Two new explicit methods for determining complex permittivity have been presented. Besides their explicit nature, they are capable of removing systematic errors using only two measurements, one of which may be considered as calibration measurement and the other as device measurement. The error-correction procedure is simple, in that no additional calibration standards are needed and high measurement accuracy can be expected. The proposed methods only require disconnection/connection at one end of the sample holder during system calibration/device measurement. This ensures better connection repeatability. Experimental data have shown that the results from the new explicit methods are in excellent agreement with the normal data from an existing iterative method that may also generate abnormal data in a frequency band without singularities, probably due to divergence in the iterative process. The above features and validity make the developed methods more attractive than existing ones. In practical applications, both methods can be implemented jointly so that their advantages can be combined since the first method is simple and accurate and requires no prior estimate, while the second one is valid for any sample length and independent of sample positions. Errors due to deviations from the ideal sample length have been analyzed, and calculations based on the measured information have indicated that the error in the real part is very small, but that in the imaginary part can be large for the used low-loss material at some frequencies. This is a common phenomenon among S-parameter-based methods. There should be no upper limits for complex permittivity measurement using the proposed methods with a coaxial-line sample holder. However, a waveguide sample holder does have such limits that are determined by the well-known cutoff phenomenon. Like any other S-parameter-based methods, the new methods will also present high uncertainties in measuring $\mathrm{Re}(\varepsilon_r)$ near 1.0 or small $\mathrm{Im}(\varepsilon_r)$.

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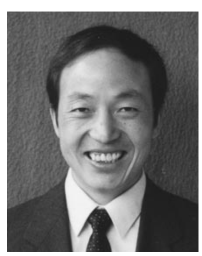

Changhua Wan (M'97) was born in Jiangxi, China, in 1963. He received the B.E., M.E., and Ph.D. degrees from the University of Electronic Science and Technology of China (UESTC) (formerly Chengdu Institute of Radio Engineering), Chengdu, China, in 1983, 1986, and 1991, respectively.

From 1986 to 1988, he was a Research Engineer at the Shanghai Research Institute of Microwave Technology, working on microstrip circuit design for harmonic radar applications. In 1991, he joined the Microwave Center, UESTC, performing research related to computer-aided analysis (CAA) and computer-aided design (CAD) of microwaves and supervising B.E. and M.E. theses. From 1993 to 1995, he was a Post-Doctoral Fellow at the Polytechnic University of Madrid, Madrid, Spain, where he developed a technique for analysis of frequency-selective surfaces. From June 1995 to June 1997, he was a Human Capital and Mobility (HCM) Fellow at the Catholieke Universiteit Leuven, Belgium, and the Interuniversitair Micro-Electronika Centrum, Belgium, where he developed new methods for monolithic-microwave integrated-circuit (MMIC) measurements. In July 1997, he joined the Department of Physics, University of Tromsø, Tromsø, Norway, as an Associate Professor, where he teaches electrical engineering courses and conducts research on microwave techniques, antennas, and electromagnetic compatibility. He has authored or co-authored over 40 technical journal and conference papers. His research interests include microwave measurement techniques, investigation of new microwave and millimeter-wave structures, design of microwave planar circuits and waveguide components, and analytical and numerical techniques for applied electromagnetics.

Dr. Wan was the recipient of the Second Award for Advances in Science and Technology presented by the Chinese Ministry of Machinery and Electronics in 1991.

Bart Nauwelaers (S'80–M'86) was born in Niel, Belgium, on July 7, 1958. He received the M.S. and Ph.D. degrees in electrical engineering from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1981 and 1988, respectively. He also received a Mastère degree from ENST, Paris, France.

Since 1981, he has been with the Department of Electrical Engineering, Katholieke Universiteit Leuven, where he has been involved in research on microwave antennas, microwave integrated circuits and MMIC's, and wireless communications. He also teaches courses on microwave engineering and analog and digital communications.

Walter De Raedt received the M.Sc. degree in electrical engineering from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1981.

He subsequently joined the ESAT Laboratory, as a Research Assistant, where he worked on electron-beam lithography. In 1984, he joined the Interuniversitair Micro-Electronika Centrum (IMEC), Heverlee, Belgium, where he began work on advanced submicrometer III–V devices and MMIC's. His current research activities are oriented toward microwave MCM systems.

Marc Van Rossum received the Ph.D. degrees in physics and habilitation from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1976 and 1981, respectively.

Following a post-doctoral period at the California Institute of Technology, he joined the Interuniversitair Micro-Electronika Centrum (IMEC), Heverlee, Belgium, in 1985, as Head of compound semiconductor processing, and became Head of VLSI materials and technologies in 1989. Since 1997, he has been Head of advanced materials research and nanoelectronics. He is also an Associate Professor at the University of Leuven. His main interests are in the physics and technology of advanced semiconductor devices. Since 1992, he has been the Manager of PHANTOMS, the European Network of Excellence in the field of mesoscopic physics and technology.