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An Improved NRW procedure for Dielectric Characterization for solids and Uncertainty Estimation

Asheesh Kumar Sharma(1),(2), Satya Kesh Dubey*(1),(2)
(1)Academy of Science & Innovative Research (AcSIR), Ghaziabad, India;
(2)CSIR-National Physical Laboratory, New Delhi, India

Abstract

We present a modified approach for extraction of dielectric properties of low-loss dielectric materials using two port T/R measurement. The procedure utilizes NRW method, but without the need for shifting the reference planes. This is done by employing full two-port (TOSM) calibration at the waveguide ports and specially designed sample holders along with precisely machined MUT samples. This approach enables repeatable and precise placement of MUTs in sample holder, during repetitive measurements and reduces the errors due to improper placing of MUT in the sample holder/guide. This also makes the uncertainty evaluation less complex compared to the traditional NRW approach. Sample holders of different lengths have been fabricated for WR90 waveguide (X-band; 8.2 GHz to 12.4 GHz). Experimental measurements are carried out for multiple samples of two of most commonly used low-loss dielectric materials in RF & microwave domain i.e. Poly-Tetra-Fluro-Ethylene (PTFE or Teflon) and Poly-Propylene (PP). Different lengths of same materials are used and the results are compared with traditional NRW method as well. Combined uncertainty budgets for the proposed procedure have been presented, using the experimentally obtained sensitivity coefficients for the modified dielectric property extraction procedure along with other system uncertainty contributors.

Keywords: Dielectric Property Extraction, NRW method, Two-port Transmission-Reflection method, Uncertainty budget

1. Introduction

In 1970, Nicolson and Ross [1, 2] introduced a method to extract complex dielectric properties for linear materials in frequency domain using time-domain measurement in a coaxial transmission line (cylindrical). Soon after, in 1974, Weir [3] proposed the automatic complex dielectric measurement method for TEM transmission line using similar approach. Since then, this method is continued to be referred as Nicolson-Ross-Weir (NRW) algorithm and is most utilized method for extraction of material parameters, despite its inherent limitations and ambiguities. Multiple authors have contributed to provide modified NRW procedures [4,5,6] by suggesting improvements to this routine in terms of addressing its ambiguities and limitations. The NRW method essentially requires measurement of S-parameters at end of transmission line ports and later mathematical transformation of reference planes for calculating S-parameters at the air-material interface. The detailed expressions and plane transformations have been discussed in detail in literature [7, 8].

Apart from the inherent limitations and ambiguities at specific sample lengths, an important limitation to this method is the requirement for measurement of empty space in the transmission line/waveguide (length L1 shown in figure 1). The procedure also requires precision, while placing the material under test (MUT) inside the line, as the material cross section needs to be perpendicular to the direction of wave propagation in the line. It becomes tougher, while removing and placing the material inside again for repeating the measurement. Any inaccuracy in these, results in large errors in estimated dielectric properties. Also, if the MUT is not snuggly fit in the line, it may result in errors due to air gaps. Also, it is difficult to accurately place a “snuggly-fitting” sample properly in the line, while performing repetitive measurements. In this study, we address these issues and present a way to eliminate these.

We have fabricated specialized sample holders and precisely machined MUT samples for this and modified the NRW algorithm for countering these issues. Also, different lengths of same MUT have been used to verify the applicability and ruggedness of the procedure. A thorough comparison of our modified procedure with traditional NRW method is also carried out and presented. In last, a detailed uncertainty analysis for the proposed method is carried out, with evaluation of sensitivity coefficients using mathematical analysis and uncertainty budget for relative permittivity has been prepared.

2. Theory

The basic arrangement required to carry out Transmission-Reflection (T/R) measurement using a transmission line/waveguide is shown in figure 1. Here, a MUT of length “L” is placed inside a section of transmission line, connected to VNA ports (i.e. Port 1-Port 2). Port 1’-Port 2’ represent the plane with MUT's face i.e. air-material interface. Considering the line to be a rectangular waveguide of cross section dimension "a x b", (a>b) and assuming the MUT to be isotropic and homogenous, the dielectric parameters of the MUT can be obtained using the measured S-parameters at the Port 1-Port 2, using either traditional Nicholson-Ross-Weir (NRW) method [1, 3] or improved NRW routines [4, 5, 6].

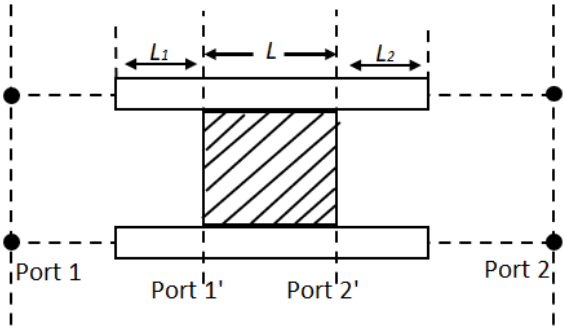

Figure 1. A dielectric MUT (length L) in a section of Transmission Line/Waveguide

2.1 The reference plane transformation problem

It can be noted that the NRW method only requires the transmission and reflected coefficients through the MUT sample length L in a guide. If the S-parameters can be directly measured at the air-MUT interface, the method should work same as before. But the procedure requires following additional steps before actual dielectric property measurement:

(a) S-parameters measurement at line/waveguide ends
(b) Measurement of empty length of waveguide before the MUT position
(c) Reference plane transformation and correction to measured S-parameters

These steps introduce additional errors to the measurement because it requires accurate estimation of sample/MUT in the partially filled guide. Also, the procedure requires the MUT sample to be snuggly fitting the guide with no air gaps. But it may not be easy to precisely place a tight-fitting sample vertically in the guide, if guide length (L+L1+L2) is large. Additionally, while performing multiple measurements, it is very challenging to remove and re-place the MUT sample in the guide repeatedly, precisely at the same position. This adds to complexity of the measurement routine. As a result, the approach becomes needlessly complicated without any genuine requirements in the dielectric property extraction, leaving the user with the choice to either repeat whole measurement or applying complex error corrections at a later stage. When making precision measurements, particularly for metrology purposes, the issue becomes more complicated and is way too complex to be dealt with, during uncertainty estimation.
In this study, we evaluate present our modified approach of measuring the T/R S-parameters (S11 & S21) directly at the air-MUT interface. We have fabricated precise sample holders and machined MUT samples for properly fitting in the sample holders to ensure no air gaps. We evaluate the dielectric properties using modified approach and compare our results with original NRW procedure. A thorough uncertainty estimation has been carried out for the proposed method, based on mathematical analysis for evaluation of each uncertainty parameter along with their sensitivity coefficient. Sample uncertainty budget have also been presented for 10 GHz frequency for one MUT sample of each material.

We attempt to come out with an improved NRW based procedure to enable faster, less complex and reliable dielectric measurement for solids, along with detailed uncertainty estimation.

3. Experimental

We have fabricated precise sample holders (for X-Band waveguide WR90) and machined MUT samples for snuggly fitting in the sample holders, so that no air gaps are present. Due care has been taken to ensure the surface flatness and evenness in the sample holders and the MUT samples.

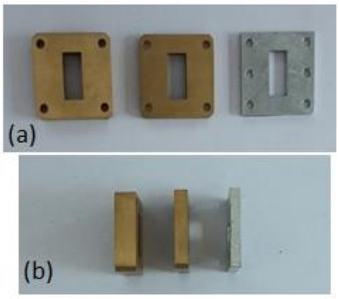

Figure 2. Fabricated Sample Holders (from left SH1, SH2, SH3) (a) Cross section (Tip view) (b) side view

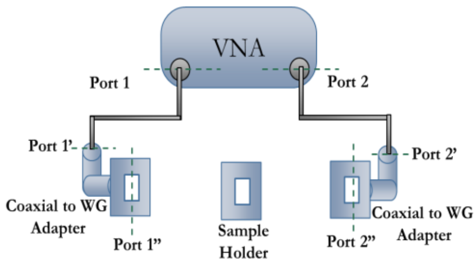

Figure 3. Schematic of measurement system showing measurement ports and calibration planes

The schematic of the measurement system has been shown in figure 3. The sample holder is placed in between two coaxial to waveguide adapters (WR90), which are connected to Port 1-Port 2 of the VNA by cables. The *Port1"-Port2"* are located at the waveguide ends of the coaxial to waveguide adaptors and can be calibrated by appropriate waveguide calibration kit.

An algorithm based on presented improved NRW procedure, without the reference plane transformation step, has been developed for this work. The MATLAB® based program utilizes the measured S-parameters at air- MUT interface (Port 1”-Port 2”) and calculates dielectric properties (ε* & μ*) directly from raw S-parameters. No other smoothening or data fitting has been used in this work.

4. Results

4.1 Dielectric Property retrieval for MUT

Dielectric properties for MUT obtained from measurement using SH1 are shown in figure 4 and same for measurement using SH2 are shown in figure 5. Dielectric property results for Air (for reference) are also shown in the figures.

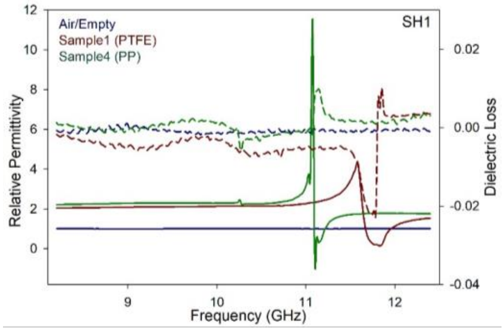

Figure 4. Dielectric properties of MUTs (PTFE (Dark red) & PP (Dark Green))) in sample holder SH1 (9.808mm) along with Air (Dark Blue) as reference

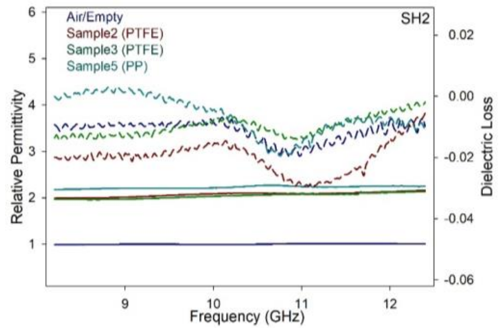

Figure 5. Dielectric properties of MUTs (PTFE (Dark red, Dark Green) & PP (Dark Cyan))) in sample holder SH2 (6.112mm) along with Air (Dark Blue) as reference

A sudden peak in dielectric properties is observed, for the proposed method as well, at frequency at which the sample length is multiple of one-half wavelength (figure 4), which is consistent with literature traditional NRW method results. However, while using a thin sample ($L< \lambda/2$) as in figure 5, the method works pretty well. These findings are similar to literature values [9] and those obtained using traditional and modified NRW routine [3, 5].

4.2 Comparison of traditional NRW method with proposed improved NRW method

Figure 13 shows the comparison of the obtained dielectric properties for PTFE (“*Sample2*”) using the traditional NRW method for both configuration1 and configuration2 and the proposed method. It can be seen that the results of proposed method are close match to traditional NRW method.

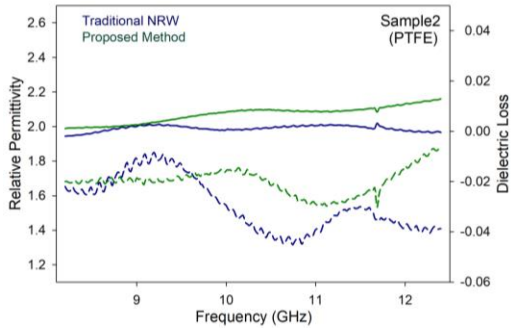

Figure 6. Comparison of Dielectric properties of PTFE “*Sample2*” using traditional NRW and proposed method for Dielectric Property retrieval

5. Uncertainty Evaluation

Uncertainty analysis for any measurement requires in-depth analysis of all the possible error sources & contributors, which are part of the measurement system including both the standards used and the methodology followed. The uncertainty estimation of dielectric property extraction from two-port T/R measurement also follows the same. It requires:

(a) Assessment and evaluation of system uncertainty contributors such as standards used, MUT samples, Sample holders, along with assessment of uncertainties due to VNA and waveguide apparatus used, etc. &
(b) Assessment and evaluation of uncertainty contributors based on the mathematical model used for dielectric property extraction from S-parameters

For this study we have utilized method provided in [10] and following are the uncertainty contributors for dielectric property measurement using two port T/R measurements:

(i) Uncertainty in S parameters (S_α & θ_α)
(ii) Gap between sample holder and sample (d)
(iii) Sample holder dimension variation (d)
(iv) Uncertainty in sample length/dimensions (L)

Other than of the contributors mentioned, line loss, connector mismatch, cable flexing and connector, cable repeatability can be directly incorporated through uncertainty on S-parameters with appropriate coverage factor. Also, since the method proposed in this study, the transformation of reference planes is not required, hence it has been omitted from the contributors. The uncertainty contributions due to ambient condition variations and noise have been also included, as per standard values for two-port measurements [11, 12]. The uncertainty in dielectric constant (real part ε_R') is given by:

$$\frac{\Delta\varepsilon_R'}{\varepsilon_R'} = \frac{1}{\varepsilon_R'}\sqrt{\begin{array}{c}\sum_\alpha\left[\left(\frac{\partial\varepsilon_R'}{\partial|S_\alpha|}\Delta|S_\alpha|\right)^2 + \left(\frac{\partial\varepsilon_R'}{\partial\theta_\alpha}\Delta\theta_\alpha\right)^2\right] + \\ \left(\frac{\partial\varepsilon_R'}{\partial L}\Delta L\right)^2 + \left(\frac{\partial\varepsilon_R'}{\partial d}\Delta d\right)^2 + \left(\frac{\partial\varepsilon_R'}{\partial T_a}\Delta T_\alpha\right)^2\end{array}} \quad (1)$$

The sensitivity coefficients viz. $\frac{\partial \varepsilon_R'}{\partial|S_{21}|}$, $\frac{\partial \varepsilon_R''}{\partial|S_{21}|}$, $\frac{\partial \varepsilon_R'}{\partial|\theta_{21}|}$, $\frac{\partial \varepsilon_R''}{\partial \theta_{21}}$, $\frac{\partial \varepsilon_R'}{\partial|S_{11}|}$, $\frac{\partial \varepsilon_R''}{\partial|S_{11}|}$, $\frac{\partial \varepsilon_R'}{\partial \theta_{11}}$, $\frac{\partial \varepsilon_R''}{\partial \theta_{11}}$, $\frac{\partial \varepsilon_R'}{\partial L}$, $\frac{\partial \varepsilon_R''}{\partial L}$, $\frac{\partial \varepsilon_R'}{\partial d}$, & $\frac{\partial \varepsilon_R''}{\partial d}$ are calculated from the experimental data at respective frequencies and used for final uncertainty budget. The calculated uncertainties in relative permittivity ($\Delta\varepsilon_R'$) for X-band frequencies (8.2 GHz to 12.4 GHz), as per prepared uncertainty budget, is shown in figure 7 (figure 7(a) for "*Sample2*" and figure 7(b) for "*Sample5*" respectively).

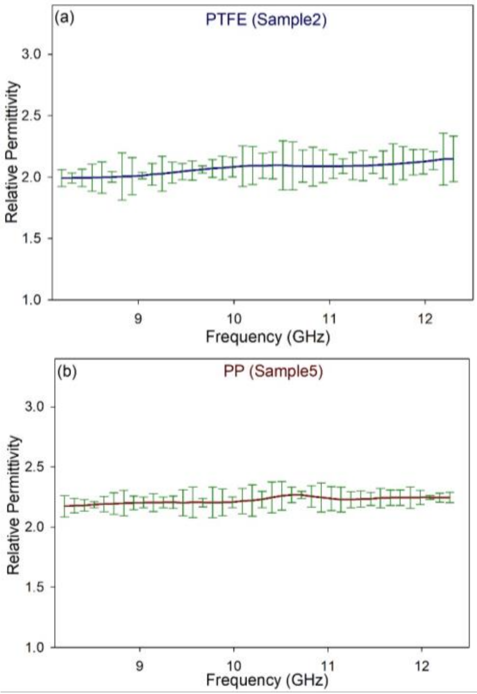

Figure 7. Relative permittivity of (a) PTFE "*Sample2*" & (b) PP "*Sample5*" along with measurement uncertainties using proposed improved method for Dielectric Property retrieval

6. Conclusion

The paper proposes a modified approach (NRW based) for extraction of dielectric properties of solids in X-band using by direct measurement of S-parameters at air-material interface. The proposed method reduces certain steps from the original NRW routine and makes it simpler to carry out multiple measurement and by allowing precise placement of MUT in sample holder. A detailed uncertainty analysis has been done with estimation of sensitivity coefficient for all the uncertainty contributors and detailed uncertainty budget has been prepared. This method can enable direct computation of uncertainty contributors, while dielectric property retrieval and can be integrated in the measurement software/algorithm. This will bring additional degree of validation to existing commercial measurements systems.

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