Measurement of Dielectric Properties at 75 - 325 GHz using a Vector Network Analyzer and Full Wave Simulator

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Abstract. *This paper presents a fast and easy to use method to determine permittivity and loss tangent in the frequency range of 75 to 325 GHz. To obtain the permittivity and the loss tangent of the test material, the reflection and transmission S-parameters of a waveguide section filled with the test material are measured using a vector network analyzer and then compared with the simulated plots from a full wave simulator (HFSS), or alternatively the measurement results are used in mathematical formulas. The results are coherent over multiple waveguide bands.*

Keywords

Dielectric constant, permittivity, loss tangent, S-parameters, material measurement.

1. Introduction

Accurate measurement of the material's electromagnetic properties provides critical information for design parameters of a circuit in any radio frequency applications. In the past years different materials have been characterized at lower frequencies but accurate measurement of dielectric materials at millimeter wavelengths remains still difficult [1]. The extraction of material parameters at millimeter wavelengths is therefore an interesting and important topic of investigation.

Various methods are available for the evaluation and determination of the material dielectric properties [2]. The results presented in this paper are based on transmission-line method where the material sample is placed inside a short section of an enclosed transmission line. The line is a section of the rectangular waveguide connected to two ports of a vector network analyzer. The reflection and transmission S-parameters are measured in the frequency band of 75 to 325 GHz to estimate the permittivity and loss tangent of the material under test. Similar situation is also simulated with a commercial full-wave simulator (HFSS) and comparison is then made between the measured and simulated results. As a reference case this is done first for Teflon (PTFE), and after that for a sample of unknown polymer. Alternatively, the S-parameter measurement results are used in mathematical formulas to obtain the permittivity and loss tangent.

2. Specimen Preparation

Steel holders of thickness 0.5 mm are used as the portion of transmission line between the waveguide test heads. The waveguide opening dimensions vary with the frequency band. These steel holders are denoted as WR-X holders where X represents the waveguide standard and has standard value 03, 05, 06, or 10 according to the frequency band. Careful preparation of the specimens is essential for accurate extraction of the material parameters. The measured value of dielectric constant depends significantly on the quality of the specimen. Small scratches and cracks in sample specimen may lead to error in the extracted material parameters. To minimize any unnecessary wear and tear on the specimen, it is placed in a secure area between measurement sessions. The material sample is measured carefully with a precision micrometer and then cut in the size such that it fits to the dimension of the waveguide opening in the steel holder. Fig. 1 shows three WR-05 waveguide steel holders with and without material inside. Similar specimens are also prepared for other frequency band steel holders. Tab. 1 presents the four waveguide standards with their cross-sectional dimensions (*a,b*), cut-off frequency (f_c) and frequency range of operation (*Range*).

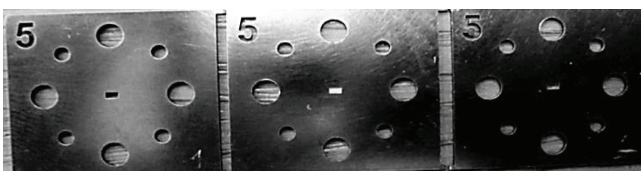

Fig. 1. Sample specimens prepared for empty, Teflon and unknown polymer using WR-05 waveguide steel holders.

	a (mm)	b (mm)	f_c (GHz)	Range (GHz)
WR-10	2.54	1.27	59.00	75-110
WR-06	1.65	0.83	90.80	110-170
WR-05	1.30	0.65	115.70	140-220
WR-03	0.86	0.43	173.6	220-325

Tab. 1. Waveguide standards.

3. Measurement Setup

The measurement system consists of a network analyzer (Agilent E8361C), a millimeter wave head controller (Agilent N5260A), two Agilent E8257D PSG analog signal generators as external synthesizers and two waveguide test head modules. The waveguide test heads are available for different bands of frequency. Each frequency band has its own standard calibration kit. TRL (thru-reflect-line) calibration is performed before each measurement in similar fashion for all four frequency bands but using corresponding standard calibration kit and waveguide test head modules. Measurement of the material is carried out in one frequency band and then the network analyzer configuration is changed along with the test heads and sample specimens when the measurement is performed in other frequency bands. From Tab. 1 it can be seen that the waveguide cross-section varies with the frequency bands. Hence samples are prepared for each waveguide standard measured. The sample specimen is then placed in between the waveguide test heads and are screwed together (Fig. 2) and the full two port S parameter measurement is carried out. To ensure that the steel holder loss is negligible, the empty holder is measured first. Measurement of the material is then carried out in four frequency bands that altogether cover the band from 75 to 325 GHz.

Fig. 2. WR-05 sample specimen placed in between the waveguide test heads.

4. Simulation Setup

Full wave simulator software is used to simulate the transmission-line measurement structure and obtain the reflection and transmission coefficient magnitude and phase. In this task, Ansoft HFSS (High Frequency Structure Simulator) version 13 is used where two conditions of the measurement are simulated. First, the empty space between the waveguide sections which represents the empty holder situation in real measurement and the second is the sample material between the waveguide sections representing the holder with Teflon or unknown polymer. The wave port excitation is de-embedded by the distance of 3 mm to remove the effects of the fixture (Fig. 3). The boundaries are assigned for the waveguide section as perfect electric boundary and for the steel walls of the holder surrounding the material as finite conductivity boundary (Fig. 4). The structure is simulated in the frequency range of 75 to 325 GHz, and the reflection and transmission parameters are extracted from the simulation. The simulation model is scaled accordingly for different waveguide frequency bands. Parametric sweep is performed for the different values of dielectric constant, loss tangent and the sample thickness. From the simulation, various set of curves are obtained that are compared with the measurement data to estimate the material parameters.

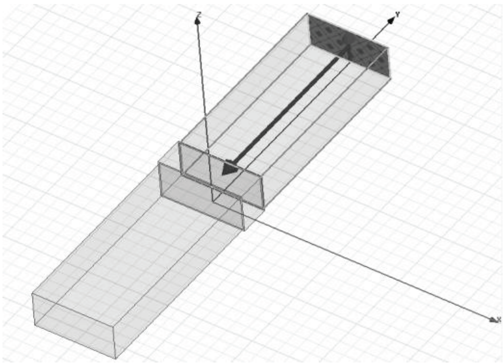

Fig. 3. Simulation structure in HFSS with de-embedded wave-port excitation.

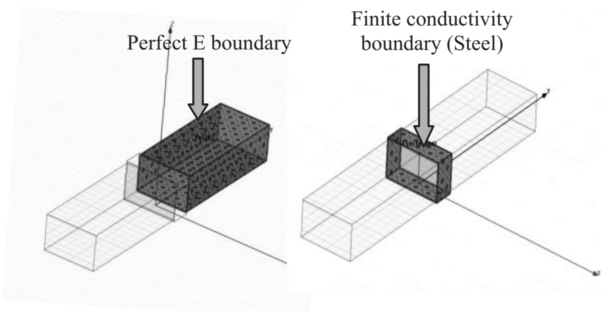

Fig. 4. Boundary condition assignment for the waveguide sections and the sample holder.

5. Results

The simulation and the measurement results for an empty holder, a holder with Teflon and a holder with unknown polymer are used to extract the dielectric constant and loss tangent. Measurement of the empty holder is an important part in material measurement task as holder without sample has air inside. Since the dielectric constant of air is known ($\varepsilon_r = 1$), it is easier to compare the method being used to measure the permittivity. Empty holder measurement does not only assure the correctness of the method but can also be used for loss extraction of the material under test. The measurement result of the empty steel holder in frequency range of 75-325 GHz is presented in Fig. 5 and 11. The transmission coefficient (S_{21}) is close to 0 dB and the reflection coefficient (S_{11}) is fairly below –20 dB across the frequency band (Fig. 5). Hence these steel holders can be used as a portion of transmission line in our method of extraction as the losses are negligible.

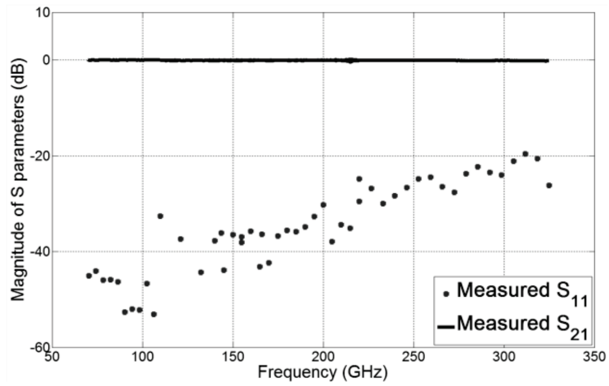

Fig. 5. Empty holder measurement in the frequency range of 75-325 GHz.

For Teflon and unknown polymer, the simulated reflection and transmission coefficients for different values of the dielectric constant and loss tangent are compared with the measured coefficients using least square error fitting method. Fig. 6 and 7 show the transmission coefficient (S_{21}) phase results obtained from the measurement and simulation. The best fit with measured data is obtained for the curve with dielectric constant 2.0 and loss tangent 0.003 for Teflon whereas for unknown polymer the dielectric constant is 2.4 and the loss tangent 0.06. A change of ± 10 percent in the dielectric constant of Teflon is illustrated in Fig. 8. Similarly, for unknown polymer, ± 12.5 percent change in dielectric constant is shown in Fig. 9. The measured data stays clearly within the indicated limits. From these two figures it can be seen that in the cases studied here an accuracy of ± 12.5 percent can be estimated for this method. The loss tangent for the sample can be extracted by comparing the simulated and measured losses due to the material in the holder. The loss is computed using S-parameters as

$$Loss\ \text{dB} = -10\log_{10}[\ S_{11}{}^{2} + \ S_{21}{}^{2}]\ . \qquad (1)$$

Fig. 10 presents the measured loss compared with the simulated loss for tanδ 0.05, 0.06 and 0.07 for the unknown polymer. Here the average loss tangent of 0.06 seems to be a good estimate in W-band frequencies. For Teflon, which is very low-loss material, the loss tangent of 0.003 is estimated with uncertainty of ± 100 percent.

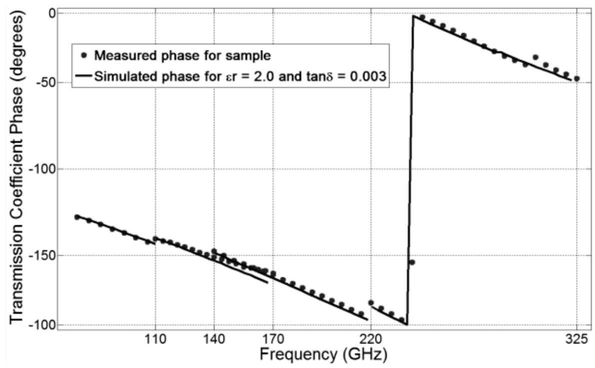

Fig. 6. Measured and simulated transmission coefficient phase for Teflon.

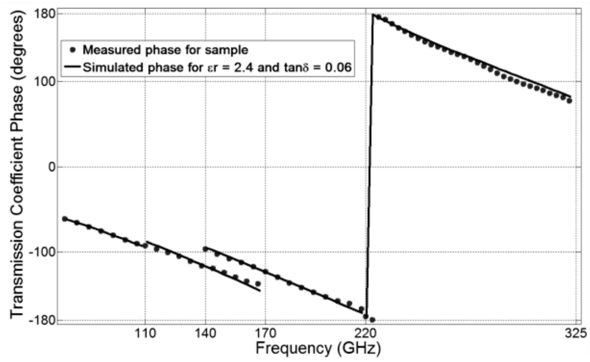

Fig. 7. Measured and simulated transmission coefficient phase for unknown polymer.

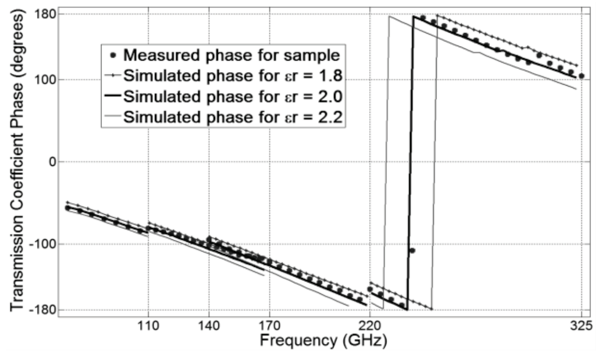

Fig. 8. Transmission coefficient phase for Teflon with ± 10 percent change in dielectric constant.

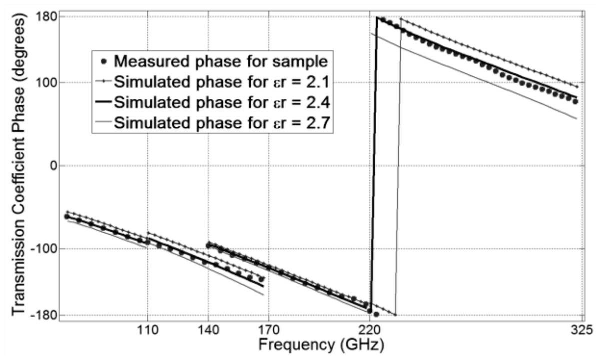

Fig. 9. Transmission coefficient phase for unknown polymer with ± 12.5 percent change in dielectric constant.

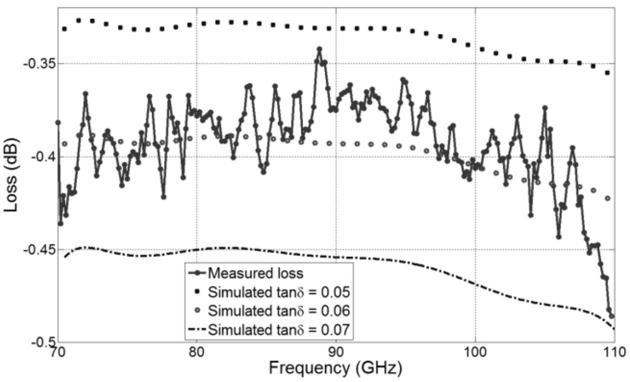

Fig. 10. Measured loss for unknown polymer compared with the simulated losses for different values of loss tangent.

6. Material Parameter Extraction using Mathematical Equations

Mathematical calculation of the dielectric constant and loss tangent is performed using Modified Nicolson-Ross-Weir (MNRW) extraction technique [3]. The phase factor and the wave impedance are calculated from the reflection and transmission measurement and simulation data.

Refractive index is

$$n_N = \frac{1}{k_0 d}\left[-j\ln\left(\left|e^{j\omega_N\sqrt{\mu\varepsilon}d}\right|\right) + \varphi_0 + \sum_{i=1}^{N}\arg\left(\frac{e^{j\omega_i\sqrt{\mu\varepsilon}d}}{e^{j\omega_{i=1}\sqrt{\mu\varepsilon}d}}\right)\right] \quad (2)$$

where N is the number of sample point, ω_N is the angular frequency, d is the thickness of the sample, k_0 is the wave number in free space, and φ_0 is the argument of the phase factor at the first sample frequency ω_0.

The phase factor can be calculated from the S-parameters as

$$e^{j\omega\sqrt{\mu\varepsilon}d} = \frac{1-S_{11}^2+S_{21}^2}{2S_{21}} + \frac{2S_{11}}{\left(z-\frac{1}{z}\right)S_{21}} \quad (3)$$

and the wave impedance Z is obtained from the following equation

$$z = \sqrt{\frac{\mu_r}{\varepsilon_r}} = \sqrt{\frac{(1+S_{11})^2-S_{21}^2}{(1-S_{11})^2-S_{21}^2}}\ . \quad (4)$$

The dielectric constant of the material can now be calculated from the refractive index

$$n_N = \sqrt{\varepsilon_r\mu_r} \quad (5)$$

and the loss tangent is obtained from

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}\ . \quad (6)$$

The calculated ε_r' and the loss tangent are plotted in MATLAB as the function of frequency from 75 to 325 GHz for all three measurement procedures (empty holder, Teflon and unknown polymer). The real and the imaginary part of the permittivity are calculated for both the simulated and measured results. Fig. 11-13 show the calculated dielectric constant and loss tangent plots for air (empty holder), Teflon and unknown polymer respectively.

There is data overlap from 140 GHz to 170 GHz (Fig. 11) because the extraction is performed for full waveguide band and the frequency bands WR-06 and WR-05 overlap at these frequencies (Tab. 1). The dielectric parameters extracted within the overlapping frequencies from two different waveguides have approximately the same values as seen in Fig. 11-13.

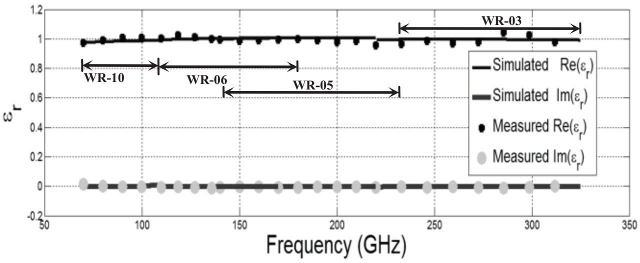

Fig. 11. Calculated dielectric constant for air (empty holder) using MNRW extraction technique.

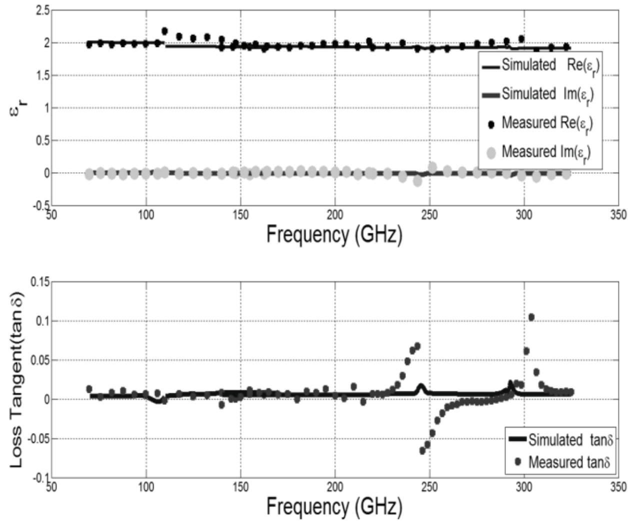

Fig. 12. Calculated dielectric constant and loss tangent for Teflon using MNRW extraction technique.

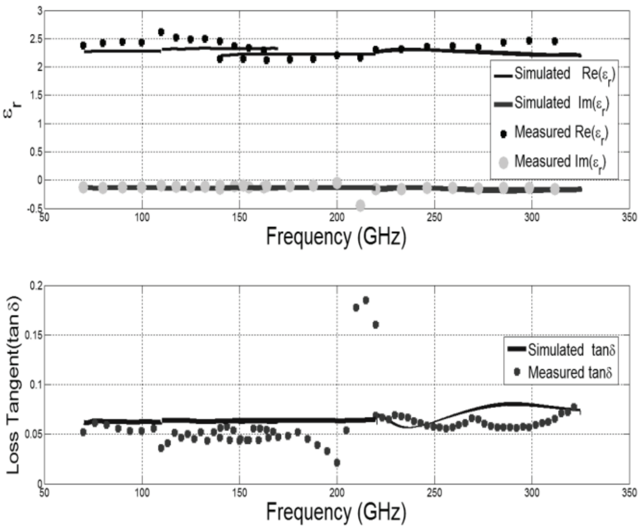

Fig. 13. Calculated dielectric constant and loss tangent for unknown polymer using MNRW extraction technique.

7. Discussion

Using the least square error fitting method, the best fit is obtained for permittivity of 2.0 and loss tangent 0.003 for Teflon (Fig. 6). Dielectric constant of Teflon measured at 1000 GHz at room temperature is 2.09 and the loss tangent around 0.007 [5]. The permittivity of the unknown polymer is obtained to be 2.4 and loss tangent 0.06 (Fig. 7). These values are approximately the same as those calculated from the mathematical equations. The simulated and measured values for permittivity and loss tangent are in good resemblance with some ambiguities in frequency range of 200 GHz to 250 GHz as presented in Fig. 12 and 13.

The sources of uncertainty in the results include errors in scattering parameter magnitude and phase measurements, errors in sample thickness, gaps between the sample and the steel holder, and sample holder dimensional variations. The uncertainty in the extracted parameters is higher near the half wavelength resonance frequency (around 230 GHz) where the thickness of the material sample is one half of the guided wavelength. At half wavelength frequency the scattering parameter S_{11} gets very small and the uncertainty in measured phase is higher [4]. The sample and the steel holder thickness are measured with a precision micrometer. An air gap between the sample and the holder affects also the measured value of permittivity [2]. This effect is significant along the wide side of the waveguide as it has high electric field. To minimize this effect the material samples are prepared with care such that the sample fits the dimension of the waveguide steel holder. Careful sample selection, specimen preparation and handling are practiced throughout the measurement process to minimize the deterioration of the specimen.

Calibration is performed for each frequency band prior to the measurement to eliminate the systematic measurement errors caused by the imperfections of the system. All the measurements are performed in the controlled environment such that the temperature variations between the time of calibration and the time of measurement are limited to $\pm 0.5\ ^{o}C$ which minimizes the random errors due to measurement environment variations.

8. Conclusion

Different methods are available for the evaluation and determination of the dielectric parameters of materials. Selection of the appropriate method is determined by accuracy, convenience, and shape and form of the sample material. Transmission-line method is suitable in terms of broadband, convenience and economic point of view but suffers from half wavelength resonance problem. An inhomogeneous and asymmetric sample also adds uncertainty to the measurement. Hence sample selection and preparation should be performed carefully with precision. Two approaches for material measurement in frequency band of 75 to 325 GHz were performed. In the first approach, the dielectric parameters of the material were estimated based on the reflection and transmission scattering parameter measurement using a vector network analyzer and performing the curve fitting with the simulated results. In the second approach, the analytical method was used where the parameters were calculated from the measured and simulated data using numerical formulae and implemented MATLAB code.

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About Authors

Subash KHANAL was born in Kavrepalanchok, Nepal. He received his Bachelor degree in electrical and electronics engineering from Kathmandu University, Nepal, in 2008, and is currently working towards the M.Sc degree in radio science and engineering at the Department of Radio Science and Engineering, Aalto University. His research interests include material measurement at terahertz frequencies and characterization of Schottky diodes.

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