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Material Characterization at Millimeter Wave Frequencies in TUBITAK UME

Erkan DANACI[1], Emre CETIN[2]

[1] TUBITAK National Metrology Institute (UME), Kocaeli, TURKIYE, erkan.danaci@tubitak.gov.tr
[2] Spark Ölçüm Teknolojileri A.Ş., Ankara, TURKIYE, emre_cetin@sparkmeasure.com

***Abstract* – The frequency response of the materials which are used in milimetre wave communication system has gained increasing importance nowadays. Frequency response measurement of materials in laboratory environments do not contain sufficient information about real working environment conditions. Free space, known as one of the most frequently used material characterization method at high frequencies, is used to give more accurate results under real operating conditions. In this study, using the TUBITAK UME's infrastructure, the measurement results in free space and the uncertainty calculations of the measurements are given for some materials such as teflon, fr4, air, komacel. Measurements were performed at 67 GHz to 115 GHz and 110 GHz to 170 GHz frequency bands by using KMMS software which is known run up to 50 GHz frequency . Measurement results of materials were compared with known low frequency response of the materials in this study.**

I. INTRODUCTION

Many insulators and semiconductor materials are used in circuits and systems that are designed in high frequency regions. While the designed electronic circuits are being realized, copper-clad fibre reinforced bases are used for standing platform. Moreover teflon insulators are used for the coating or protection of the circuits, and teflon-derived radoms are also used for the housing of the antennas. Information on the frequency responses of these type of materials at the operating frequencies helps to ensure reliable designs by having prior knowledge of the situations that will be encountered in the realization of the designed circuits with simulations.

In order to determine the frequency response of a material, it will be sufficient to measure the dielectric permitivity (ε) and magnetic permeability (μ) coefficients.

Relative permittivity (ε_r) of a material is defined in (1) [1].

$$\kappa = \varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r' + j\varepsilon_r'' \qquad (1)$$

Where, ε_o is vacuum permittivity, and ε is the complex frequency-dependent permittivity of the material. Relative permittivity is a dimensionless number that is in general complex-valued; its real (ε_r') and imaginary (ε_r'') parts are denoted in (1).

Relative permittivity of a medium is related to its electrical susceptibility. There are so many publications and studies on the relative permittivity measurements in literature [2-12].

By the development of vector measuring devices such as Vector Network Analysers (VNA), vector measurements of the relative dielectric coefficient have been made possible.

The real component (ε_r') of the relative dielectric coefficient of the material gives information about the energy it can store at the operating frequency, while the imaginary component (ε_r") gives information about the energy it will absorb.

Relative dielectric coefficients measurement methods such as open-ended coaxial probes, transmission lines, resonator cavities, free space method (for lower and higher frequencies), parallel plates and inductance (up to 1 GHz) are commonly used at high frequencies.

Transmission line [2] and free space measurement systems [3, 4] are used to measure the complex dielectric permittivity and magnetic permeability coefficients of materials, whereas open-ended coaxial probe kits [5] are used to measure the complex dielectric permittivity only. Although the reflection coefficients of materials are generally measured with arch measurement systems, studies are continuing for its use in electromagnetic material characterization [6].

The transmission line method is a useful technique for determining the dielectric and magnetic properties of the rectangular prism-shaped material, sized in the waveguide cross-section, in the frequency range of the waveguide used [7].

All other methods are operated under laboratory conditions and under special ambient conditions, except for the free space method [8].

The free space method also allows for measurements using special heating or cooling systems or special ambient conditioning systems such as clamshell furnace.

We can list the advantages and disadvantages of the free space measurement system as follows.

Advantages;

- Preferred for high frequency measurement.
- Allows non-destructive measurement.

- Measure material under test (MUT) in harsh environment.
- The magnetic and electric properties can be evaluated.

Disadvantages;

- As the frequency decreases, a wide and flat material surface is needed.
- Multiple reflections between antenna and surface of material.
- Diffraction effects at the edge of material.

In recent years, many studies can be seen in the scientific literature on the measurements of dielectric coefficients when millimeter wave frequencies are achievable [9, 10, 11]. In addition, these measurements can be made by using some special measurement kits (SWISSto12) [12] and some special software (Keysight Material Measurement Suits – KMMS etc.).

In this study, the KMMS software in the TUBITAK UME infrastructure was operated for free space method at millimeter frequencies and the dielectric coefficients of materials (MUT) such as Teflon, Fr4, Komacel, and Air were measured. Measured values were compared with low frequency values of materials. Type A uncertainties of relative permittivity measurement of MUT was given in this study either.

II. FREE SPACE MEASUREMENT TECHNIQUES

Free space measurement method uses the S-Parameters to determine relative permittivity. A basic free space measurement setup is given in Fig. 1 by VNA at millimetre wave frequencies.

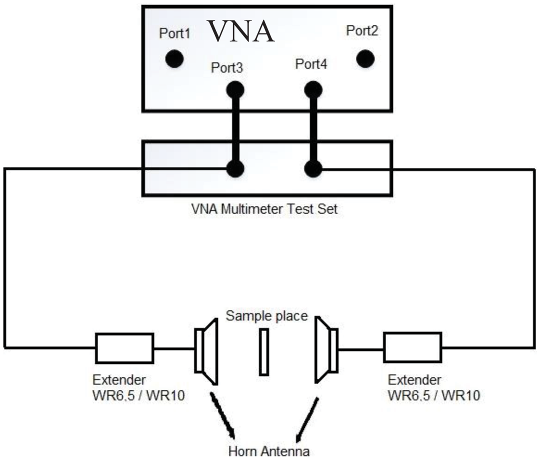

Fig. 1. Basic free space measurement setup.

MUT is fixed between the antennas with a proper distance in this method. This distance should be more than the far field region of antennas. Far-field (Fraunhofer) region is defined as that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. Far-field region is commonly taken to exist at distances greater than $2D^2/\lambda$ from the antenna, where λ is wavelength and D is maximum aperture of antenna [13, 14]. The far-field patterns of some antennas, such as multibeam reflector antennas, are sensivite to variations in phase over their apertures. For these antennas far field distance might be inadequate.

Before starting the permittivity measurement, VNA should be calibrated first. At the VNA calibration, through-reflect-line (TRL), the through-reflect-match (TRM) and the line-reflect-line (LRL) can be preferred.

In free space measurement process, TRL calibration is firstly performed done at frequency extender's waveguide ports. Then S-parameters of an empty sample holder are measured by placing the sample holder in the middle between the two antennas. As a reflect standard, a metal plate is also placed at sample holder. The MUT is then placed on the sample holder and the S-parameter measurement is performed again. The influence of the sample holder can be cancelled out by using the de-embedding function of the VNA. So only the S-parameter of the MUT can be obtained.

In order to get correct S-parameters in free space method, MUT surface should be larger than the antennas beam pattern. Also time domain gating should be applied to prevent multiple reflection from material. Time domain gating also eliminates the diffraction of energy from the edge of the antennas. The dielectric properties can be determined by post processing in a dedicated software.

There are various approaches for obtaining the permittivity and permeability from S-parameters. Commonly used permittivity measurement method which uses the S-parameters are listed in Table 1 [15].

Table 1. Permittivity measurement method by using S-parameters

Method Name	Used parameters	Properties
Nicholson-Ross-Weir	S_{11}, S_{21}, S_{12}, S_{22} or S_{11}, S_{21}	ε_r, μ_r
NIST Iterative	S_{11}, S_{21}, S_{12}, S_{22} or S_{11}, S_{21}	ε_r, $\mu_r=1$
New non-iterative	S_{11}, S_{21}, S_{12}, S_{22} or S_{11}, S_{21}	ε_r, $\mu_r=1$
Short circuit line (SCL)	S_{11}	ε_r

Nicholson-Ross-Weir (NRW) is the most commonly used method for performing direct calculation of both the permittivity and permeability from the S-parameters [16]. This method requires all reflection coefficients and transmission coefficients (S_{11}, S_{21}, S_{12}, S_{22}) or a pair (S_{11}, S_{21}) of S-parameters of the material under test to be measured.

However, material thickness is important for this measurement method. This method diverges for low loss materials at frequencies corresponding to integer multiples of one-half wavelength in the sample which is due to the phase ambiguity. So, optimum sample thickness should be times of $\lambda/4$.

Nicholson-Ross-Weir (NRW) method uses the following formula for determining the relative permittivity.

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

$$S_{21} = \frac{T(1-\Gamma^2)}{(1-\Gamma^2 T^2)} \tag{3}$$

Where;

$$\Gamma = X \pm \sqrt{X^2 - 1} \tag{4}$$

And by solving of (4), (5) can be obtained.

$$X = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{5}$$

$$T = \frac{S_{11}^2 + S_{21}^2 - \Gamma}{1-(S_{11}+S_{21})\Gamma} \tag{6}$$

Relative permittivity and relative permeability can be calculated in (7) and (8).

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda^2} - \left[\frac{1}{2\pi L} ln\left(\frac{1}{T}\right)\right]^2\right) \tag{7}$$

Where;

$$\mu_r = \frac{1+\Gamma}{\Lambda(1-\Gamma)\sqrt{\frac{1}{\lambda_0^2}-\frac{1}{\lambda_c^2}}} \tag{8}$$

$$\frac{1}{\Lambda^2} = \left(\frac{\varepsilon_r.\mu_r}{\lambda_0^2} - \frac{1}{\lambda_C^2}\right) = -\left(\frac{1}{2\pi L} ln\left(\frac{1}{T}\right)\right) \tag{9}$$

III. KMMS APPLICATION AND CAPABILITIES

Keysight Material Measurement Suite (KMMS) is a commercial software [17, 18]. It has so many special tools for permittivity and permeability measurement. By using KMMS, measurements can be performed from 200 MHz to 50 GHz frequency ranges and from -40 ºC to 200 ºC temperature ranges with the different probes such as high temperature and different type of open-ended coaxial probes. With KMMS tools, paramagnetic materials, flat, isotropic and homogeny materials can be measured. KMMS has also NRW calculation method for permittivity and permeability.

KMMS can run with multiport VNA also and it calculates permittivity and permeability coefficients by using the S-parameter measurement with VNA. The permittivity and permeability model obtained with KMMS is valid for higher frequencies.

In this study, KMMS software was also used at millimeter wave frequencies with NRW method, assuming with the dielectric calculation model would be the same at millimeter wave frequencies. During the measurements discontinuities appered where thickness is not an integer multiplier of λ/4. For that reason, “Reflection/Transmission Epsilon Fast Model” was choosen in KMMS software. All measurement were performed using “Reflection/Transmission Epsilon Fast Model”.

IV. MEASUREMENT RESULTS WITH FREE SPACE METHOD AT MILLIMETER WAVE FREQUENCIES

Relative dielectric coefficient measurements were performed in TUBITAK UME RF and Microwave laboratory at two different millimeter wave frequencies. These frequency ranges were selected as 67 GHz to 115 GHz and from 110 GHz to170 GHz. VNA calibration for error term calculation was performed with two different calibration kits (WR 10 and WR6.5). Measurements and calculated uncertainties are given in this study at two different frequency ranges.

TUBITAK UME free space dielectric measurement setup functional block diagram is similar as Fig. 1 and setup picture is given in Fig. 2.

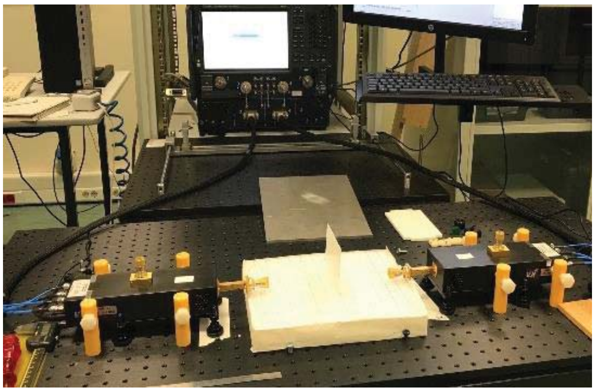

Fig. 2. Free Space measurement setup at TUBITAK UME.

In order to reach the millimeter wave frequencies with VNA, some suitable special frequency extenders were used for these frequency ranges. In this study, two compatible frequency extenders were used to reach for each millimeter wave frequency bands.

List of the equipment used at the measurement setup is given as below;

- Keysight N5247B PNA-X Network Analyser
- Keysight N5292A VNA Multimeter Test Set
- VDI Extender WR6.5 110-170 GHz Model VNAX
- VDI Extender WR10 67-115 GHz Model VNAX
- VDI 6.5 VNAX Calibration Kit N5262AC06
- VDI 10.0 VNAX Calibration Kit N5262AC10
- Horn antennas for 65-115 GHz frequency band
- Horn antennas for 110-170 GHz frequency band

Below parameters were applied before measurements.

- Thickness of the reflector metal which is used for KMMS calibration is 5.0 mm at 67-115 GHz frequency band and 1.0 mm at 110-170 GHz frequency band.
- 10 measurements for each frequency step with 2 second wait.

- Number of points were selected 1201 at 110-170 GHz band and 961 at 67-115 GHz band.
- Nominal power was arranged less than 10 dBm for both frequency bands.
- Distances between antennas were arranged as 76.6 mm for 67-115 GHz frequency band.
- Distances between antennas were arranged as 35 mm for 110-170 GHz frequency band.
- Teflon thickness was 1 mm and 6 mm, Fr4 thickness was 1.2 mm, Komacel thickness was 19 mm.

Measurement results were given in Table 2 as magnitude, real and imaginary components of relative dielectric coefficient for Air, Fr4, Teflon, and Komacel in two different millimeter frequency bands. At the measurements, relative permittivity were measured. Permeability were not measured.

From the measurement results, we can list the parameters that affect the measurement accuracy as follows;

- Antennas alignment (faced each other in mm)
- Perpendicular of the measured material to the antennas
- The roughness of the surface of MUT
- The accuracy of the VNA calibration for calculating the error terms
- Determining the distance of the material to be measured from the antenna with the time domain.

Table 2. Relative dielectric constant values for Air, FR4, Teflon and Komacel from 67 to 115 GHz and 115 to 170 GHz frequency bands

Freq. (GHz)	Air				Fr4				Teflon				Komacel			
	e_r’	e_r”	Mag	u_A	e_r’	e_r”	Mag.	u_F	e_r’	e_r”	Mag.	u_T	e_r’	e_r”	Mag.	u_K
67	1.00	0.00	1.00	4E-05	4.02	0.38	4.50	6E-03	2.05	0.00	2.10	6E-05	1.22	0.01	1.20	6E-05
70	1.00	0.00	1.00	2E-05	4.03	0.30	4.51	7E-03	2.07	-0.01	2.09	2E-04	1.24	0.00	1.24	6E-05
75	1.00	0.00	1.00	2E-05	3.88	-0.06	4.38	2E-03	2.04	0.00	2.09	3E-04	1.29	0.00	1.29	7E-05
80	1.00	0.00	1.00	8E-06	3.86	0.09	4.33	2E-03	2.10	0.00	2.07	3E-04	1.31	0.01	1.31	5E-05
85	1.00	0.00	1.00	2E-05	3.94	0.07	4.42	1E-03	2.08	0.00	2.06	2E-04	1.34	0.01	1.34	5E-05
90	1.00	0.00	1.00	1E-05	4.02	0.22	4.50	1E-03	2.07	-0.01	2.09	6E-04	1.37	0.01	1.37	6E-05
95	1.00	0.00	1.00	1E-05	3.90	0.13	4.37	1E-03	2.08	-0.01	2.08	3E-04	1.39	0.01	1.39	6E-05
100	1.00	0.00	1.00	9E-06	3.90	0.13	4.38	1E-03	2.08	0.01	2.08	2E-04	1.41	0.01	1.41	6E-05
105	1.00	0.00	1.00	9E-06	3.83	0.21	4.29	2E-03	2.08	-0.01	2.08	1E-04	1.43	0.01	1.43	6E-05
110	1.00	0.00	1.00	8E-06	3.76	0.09	4.22	3E-03	2.07	0.01	2.09	2E-04	1.44	0.01	1.45	6E-05
115	1.00	0.00	1.00	1E-05	3.75	0.13	4.20	4E-03	2.08	-0.01	2.09	3E-04	1.15	0.01	1.15	2E-04
120	1.00	0.00	1.00	1E-05	4.56	0.15	4.56	2E-03	2.07	-0.01	2.07	2E-04	1.17	0.01	1.17	2E-05
125	1.00	0.00	1.00	9E-06	4.56	-0.11	4.56	4E-03	2.07	-0.01	2.07	2E-04	1.19	0.01	1.19	2E-05
130	1.00	0.00	1.00	8E-06	4.66	0.13	4.66	3E-03	2.06	0.00	2.06	8E-05	1.21	0.02	1.21	2E-05
135	1.00	0.00	1.00	8E-06	4.73	-0.02	4.73	1E-03	2.07	0.00	2.07	1E-04	1.23	0.02	1.23	2E-05
140	1.00	0.00	1.00	9E-06	4.77	0.06	4.77	7E-04	2.07	0.00	2.07	7E-05	1.25	0.02	1.25	2E-05
145	1.00	0.00	1.00	8E-06	4.68	0.10	4.69	4E-04	2.06	-0.01	2.06	1E-04	1.27	0.02	1.27	1E-05
150	1.00	0.00	1.00	7E-06	4.76	0.11	4.76	2E-04	2.07	-0.01	2.06	7E-05	1.29	0.02	1.29	2E-05
155	1.00	0.00	1.00	6E-06	4.74	0.14	4.74	1E-03	2.07	0.00	2.07	2E-04	1.30	0.02	1.30	1E-05
160	1.00	0.00	1.00	7E-06	4.63	0.18	4.63	2E-03	2.07	0.00	2.07	1E-04	1.32	0.02	1.32	9E-06
165	1.00	0.00	1.00	4E-06	4.76	0.11	4.76	2E-03	2.06	0.00	2.06	1E-04	1.33	0.02	1.33	2E-05
170	1.00	0.00	1.00	8E-06	4.65	0.24	4.65	7E-03	2.07	-0.03	2.07	8E-05	1.34	0.02	1.34	2E-05

Relative dielectric coefficient was calculated from real and imaginary component of the measurements for each materials in this study. Relative dielectric coefficient were given in Fig. 4 in two frequency bands with reference magnitude values. Ref_A is air, Ref_F is Fr4, Ref_T is Teflon, Ref_K is Komacel reference values in Fig. 4. These reference values were obtained out from older studies performed at lower frequencies.

Imaginary component values of relative permittivity of the material are less than zero in some frequencies in Table 2. Values below zero are assumed as numerical calculation error of the calculation of the model.

Due to the measurements performed using two different cal kits, differences in the relative permittivities were observed at the adjacent frequencies of the two different frequency bands.

V. TYPE A UNCERTAINTY CALCULATION OF RELATIVE DIELECTRIC MEASUREMENTS AT MILLIMETER WAVE FREQUENCIES

While calibration services are provided, the calculated value from repeated measurements made with reference devices during the devices are in the laboratory is one of the inputs of the measurement uncertainty calculation. The uncertainty component (u_x), called Type A, from the repeatable measurements, is calculated as in (10) [19].

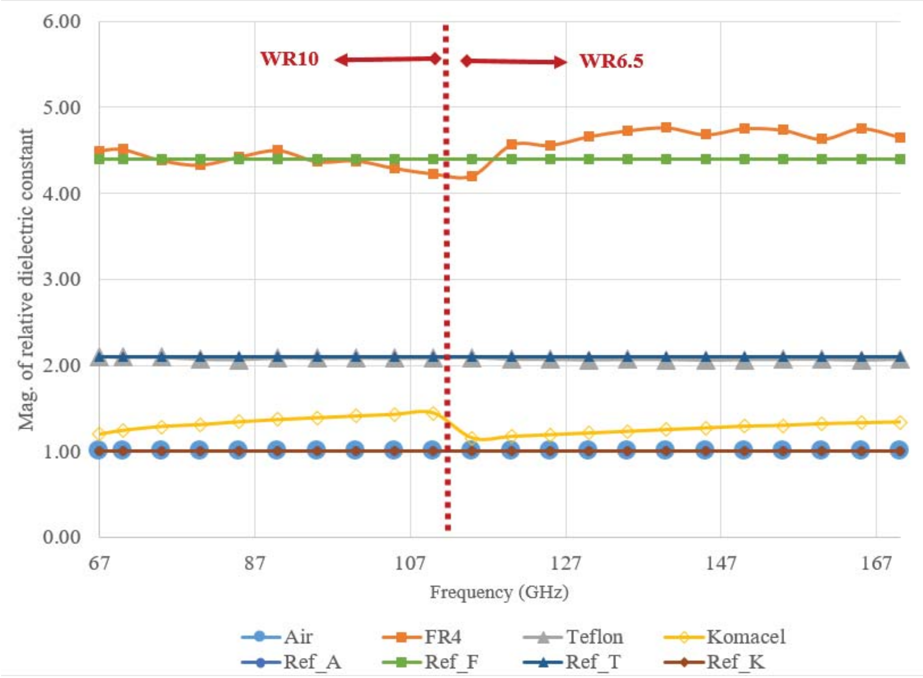

Fig. 4. Relative dielectric contants of Air, Fr4, Teflon and Komacel with known lower frequency reference values at 67 to 115 GHz frequency band and 110 to 170 GHz frequency band

$$u_X = \sqrt{\frac{\frac{1}{(N-1)} \cdot \sum_1^N \left(x_i - x_{Aveg}\right)^2}{N}} \tag{10}$$

Where x_i is the instant measurement data, x_{Aveg} is the mean of the repeated measurements, and N is the number of measurements.

Uncertainty calculated from repeatable measurements over 10 metrological is assumed to have a normal distribution.

In this study, for each material measurement, 10 repetitive measurement had been performed. Calculated Type A uncertainty of magnitude values of permittivities were given in Table 2 for two millimeter wave frequency bands as Air (u_A), Fr4 (u_F), Teflon (u_T) and Komacel (u_K).

Type A uncertainty of magnitude permittivity of Fr4 is higher than the other uncertainties. Standard deviation of Fr4 measurements were also higher than the other materials'.

VI. CONCLUSION

In this study, repeatable relative dielectric coefficient measurements were performed at millimeter wave frequencies (from 67 to 115 GHz and from 110 to 170 GHz) with KMMS software by using the infrastructure of TUBITAK UME RF and Microwave Laboratory. Although, KMMS was known a software that run up to 50 GHz with its own special probes, it is also proved with this study that KMMS can be able to use at millimeter wave frequencies.

From the measurement results, the parameters that affect the relative permittivity measurement accuracy were determined such as antennas alignment, material position in the setup, accuracy of VNA calibration, thickness of the material. Imaginary component values of relative permittivity of the material were measured less than zero in some frequencies. This kind of values were assumed as numerical calculation error of the calculation of the model.

The uncertainty component from repeatable measurements was calculated and the results of the measurements were shared in the study. Type A uncertainty were less than the compared measured values.

With performed measurements, it has been shown that the calculation model in KMMS (Reflection/Transmission Epsilon Fast Model) can also be used at millimeter wave frequencies. With this study, it has been demonstrated that dielectric coefficient measurements can be performed at millimeter wave frequencies with the free space method in future studies in the environment where the materials are used.

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