Determination of Uncertainty for Dielectric Properties Determination of Printed Circuit Board Material

Marko Kettunen, Kare-Petri Lätti, Janne-Matti Heinola, Juha-Pekka Ström and Pertti Silventoinen

Lappeenranta University Of Technology, Laboratory of Applied Electronics, P.O.Box 20,
Lappeenranta, FIN 53851.

***Abstract* — The determination of measurement uncertainty for printed circuit board material measurement has been introduced. The determination includes errors due to the network analyzer and the measurement setup. The errors due to the measurement setup consist of calibration repeatability, connector interface repeatability, effects of cable flexure and ambient condition. The uncertainty has been determined to the HP 8720D network analyzer with option 400 and TRL calibration kit, which was designed for the frequency range from 0.3 GHz to 12 GHz.**

Depending on attenuation and frequency, the total uncertainty in magnitude for the printed circuit board material measurement has been evaluated to be at the range of 0.0385 - 0.658 dB. The uncertainty in frequency was determined to be mainly due to the limited sampling points. In the measurement of FR-4 type laminate material, the frequency uncertainty was 1.1 MHz.

The effect of the measurement uncertainty in determination of dielectric properties of FR-4 type laminate material has been evaluated. The evaluation also consists of the effects of dimension variations of the measurement structures. The evaluated uncertainty with the confidence level of 95 % for dielectric constant is 0.05 and for dissipation factor 0.005 that are also used as uncertainty limits in the results of dielectric properties measurements in FR-4 EPSILON-R Modeling Project.

***Index Terms* — Uncertainty, Linearity, Mismatch, Isolation, TRL calibration.**

I. INTRODUCTION

Due to widespread use of network analyzer in the field of microwave measurements, the characteristics of the network analyzer are well known. This feature makes the network analyzer suitable for precision measurements like the determination of electrical properties of printed circuit board materials. Despite the well-established characteristics, network analyzer provides limited accuracy due to noise, mismatch or linearity distorting results without valid error correction. Some of the limitations are due to systematic errors and can be measured and eliminated by calibration. The calibration has great impact to the uncertainty of measurement performed by the network analyzer.

A lot of work has been done to find the suitable and convenient calibration procedure. Due to the investigations, several different calibration techniques have been introduced. These calibration techniques can be roughly divided into two groups, direct calibration procedures and self-calibration procedures [1]. The conventional SOLT (Short-Open-Load-Thru) calibration is a procedure included to the first group in which the well-defined calibration standards are required. The second group comprises methods allowing for partly unknown standards. One of the techniques included to the second group is the TRL (Thru-Reflect-Line) calibration introduced by Engen and Hoer [2]. Some work has been made to compare the different calibration procedures. In the work of Zhu [3], the TRL calibration has found to be the most accurate method for the calibration of the network analyzer. Zhu has also stated that the TRL calibration suffers from phase uncertainty that has to be taken into account in the phase measurements.

Despite the valid calibration method, the residual error will always arise due to imprecision in the calibration standards. These errors have to be defined in order to evaluate the total uncertainty of the measurement. The measurement uncertainty introduced in this paper applies to HP 8720D (option 400) and the TRL calibration kit, which was designed for the frequency range from 0.3 GHz to 12 GHz. The value of measurement uncertainty is included to the uncertainty determination of dielectric properties of FR-4 type laminate materials.

II. TRL CALIBRATION

Despite the accurate calibration standards, the conventional SOLT calibration method is not suited for all applications. In the microstrip measurements, the SOLT calibration usually produces additional losses that have to be eliminated afterward by calculation. With the SOLT calibration, the reference plane is difficult to set because the SOLT standards are not easy to design to the microstrip structure. This makes more convenient to use alternative calibration procedure to calibrate a measurement setup manufactured in microstrip structure.

The advantages of the TRL calibration method in the dielectric properties measurements are the better applicability for microstrip climate chamber measurement and also support of the HP 8720D network analyzer.

The TRL method is based on the fact that using unterminating and de-embedding, introduced by Bauer and Penfield [4], the device under test can be measured at the reference plane. The reference plane is usually established in the detector interface of network analyzer while the actual measurement plane can be established to the end of measurement cables or inside microstrip structures. In the calibration, the effects of a fixture between the reference plane and the measurement plane are determined by measuring several calibration standards, which are connected to the measurement plane. The effects of the fixture can be eliminated by calculation after the calibration. The used calibration standards define the calibration method, for example the TRL calibration consists of three standards; thru, line and reflect.

A calibration kit was designed for the dielectric properties measurements. The designed calibration kit consisted of the thru standard that was used to set the measurement plane. The measurement plane was set 30 mm from the edge of the microstrip structure to eliminate the attenuation of the connector interface. The impedance reference of calibration kit was set to 50 ohms with line standards and the reflect standard was carried out with open circuit.

III. UNCERTAINTY OF THE FREQUENCY MEASUREMENT

The frequency accuracy of the HP 8720D network analyzer is defined to be ±10 ppm (at 23 °C ±3 °C) [5]. In addition, the aging and the temperature drifting cause ±3 ppm and ±7.5 ppm errors respectively. In the worst case, the maximum error due to the frequency characteristics of the network analyzer is ±20.5 ppm that means about 250 Hz at 12 GHz. Minimum frequency resolution is therefore defined by the relation between the maximum sampling points of the network analyzer and the used bandwidth. Using the HP 8720D network analyzer, the maximum sampling points are 1601. The measurement was performed in frequency range from 0.3 GHz to 10.8 GHZ that was divided in three equal 3.5 GHz frequency bands. The frequency resolution was 2.2 MHz due to the maximum sampling points and the used bandwidth. Due to the frequency resolution, the maximum frequency error was 1.1 MHz.

IV. UNCERTAINTY IN MAGNITUDE

The determination of uncertainty of magnitude is based on the EA publication, EA-10/12 [6]. In determination of the uncertainty, data of the Agilent's TRL calibration kits have been used [5] to get some indication of the order of typical magnitude uncertainties.

The determined magnitude error model consists of imprecision of calibration standards, connector interfaces and the effects of cables and ambient conditions. Three last mentioned error components are due to the measurement setup and are combined as random errors of the measurement.

According to the EA publication, the error model of transmission measurement can be presented using only the major error terms as follows [6]:

$$U_{\mathrm{TM}} = L + M_{\mathrm{TM}} + I + R_{\mathrm{dB}} \qquad (1)$$

where L is the estimated system deviation from linearity
M_{TM} is the calculated error term due to mismatch
I is the estimated cross talk, (dA in eg. (3))
R_{dB} is combined random errors of the measurement.

A. The Estimated Linearity

The value of linearity defines how much the magnitude accuracy of the network analyzer fluctuates in function of frequency. It can be defined by measuring the step attenuators whose traceability to national standards has been established.

In this work, the traceable step attenuators could not be used, so the linearity was estimated with the value of 0.002 dB/dB defined by the EA publication. The value is not considered to be too optimistic value.

B. Mismatch

There will be uncertainty due to the imprecision of the network analyzer and the calibration standards. The uncertainty will be consisted of the residual reflections from the source of the network analyzer and the input and the output ports of the device under test. Therefore all scattering parameters of device under test will be influenced by mismatch.

According to [7] the mismatch M_{TM} is

$$M_{TM} = 20\log_{10} \frac{1+\left(|MS_{11}| + |\Gamma_L S_{22}| + |M\Gamma_L S_{11} S_{22}| + |M\Gamma_L S_{21} S_{12}|\right)}{1-|M||\Gamma_L|} \tag{2}$$

where M is the effective test port match
Γ_L is the effective load match
S_{ij} are the scattering parameters of device being measured

Mismatch increases usually in function of frequency and attenuation and will be the dominant component in magnitude uncertainty of high attenuation devices.

C. Effective test port match

According to EA publication [6], the effective test port match can be measured using the beadless airline and matched load. After calibration, one end of the beadless airline is connected to measurement plane and another end is terminated with the short circuit. In the EA publication, the definition of effective test port match is defined to SOLT calibration.

In this work, the length of the thru standard was defined to be 60 mm when the measurement plane was set to be 30 mm from the edge of the microstrip structure. The calibration kit was embedded on printed circuit board. Due to the construction of the calibration kit, the beadless airline could not be connected between the measurement plane and short circuit as in the EA publication.

Due to the limitation of the calibration kit, the effective test port match value was estimated with 0.02 (-34 dB) defined by the EA publication [6]. In the EA publication, the value is upper limit of the range where the effective test port match should be varying. The value is also bigger than the reference value provided for Agilent's TRL calibration kits [5]. Thus, the estimated value cannot be considered to be too optimistic for the effective test port match.

D. Effective load match

During the TRL calibration, the reflection from the other test port is determined by measuring the thru and line standards. Due to the imperfections of these calibration standards, the errors in the load match will arise. After the calibration, the effective load match uncertainty can be represented by combining uncertainties due to the effective directivity, the test port match and the transmission medium used in definition of test port match.

The measurement of the effective directivity is not obvious when the calibration kit is embedded on printed circuit board. Due to the difficulties on the determination of the effective directivity, the effective load match was estimated with 0.02 defined by the EA publication [5]. The value is not considered to be too optimistic value.

E. Estimated Cross Talk

Due to the cross talk, the part of the measurement signal is coupled directly between the measurement ports. The result of the cross talk is a leakage signal. The phenomenon will increase in function of attenuation of the device under test. According to the manufacturer of the network analyzer, the cross talk has to be taken into account in calibration when the attenuation will be over 90 dB.

The isolation between test ports can be determined when the cross talk is evaluated. The value of isolation defines how well test ports are isolated from each other. In any case, there will always be uncertainty due to effects of imperfect isolation after calibration. The uncertainty arising due to imperfect isolation can be calculated as follows [8]

$$dA = \pm 20 \cdot \log\left[1 + 10^{-\frac{(I-A)}{20}}\right], \tag{3}$$

where dA is an isolation uncertainty
I is a cross talk defined by the manufacturer
A is an attenuation of device under test

The effects of the isolation uncertainty are not linear and should be measured with attenuation over 50 dB. In the printed circuit board material measurements, devices having attenuation over 50 dB were not used, so the check measurement was not carried out and the cross talk was estimated with the equation (3).

F. System Repeatability

The evaluation of the system repeatability should be carried out by determining the standard deviation of series of measurements using the different calibration without reconnecting the measured device. The test establishes a value of the system repeatability and should be performed over the operation frequency range and for several values of attenuation.

The system repeatability definition was performed by measuring eight attenuator circuits having nominal attenuation of 0, 3, 5, 8, 15, 30, 45 and 60 dB. Each circuit was measured using eight different calibrations over frequency range from 0.3 GHz to 12 GHz. In every measured frequency point, each sample was normalized by the average of the eight different samples. The normalized standard deviation was evaluated from the normalized samples for each frequency point. The standard deviation was calculated by multiplying the normalized standard deviation with the nominal attenuation. The calculated system repeatability is shown in Fig. 1.

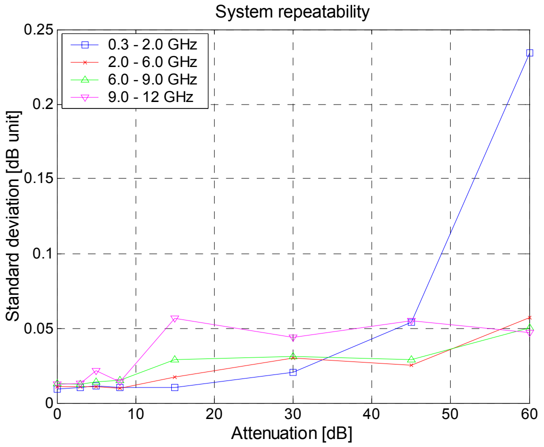

Fig. 1. The system repeatability in function of attenuation and frequency. In the calculation of the final standard deviation, the normalized samples and multiplication by nominal attenuation value were used.

The system repeatability shown in Fig. 1 is worse at attenuation over 10 dB than the reference values presented in other documents [6,9,10]. The difference to the reference values is mostly due to imprecision of calibration kit and connector interfaces of the measured attenuation circuit used in this work.

According to Hoer's work [10], the system repeatability can be measured at 3 GHz and use the value at whole frequency range because it is essentially same in the frequency range from 2 GHz to 12 GHz. The Fig. 1 proves that the statement of Hoer is not valid and the system repeatability is varying in function of frequency. The variation of system repeatability has been taken into account in the calculation of total magnitude uncertainty.

G. Connector Repeatability

The test described above applies to connector repeatability, when a recalibration is performed. The test of system repeatability includes also uncertainty due to connector repeatability and it is difficult to separate these two tests. The reliability of the tests will be increased when the several devices will be used to estimate the uncertainty.

The test was performed for the same circuit as in the test of the system repeatability. Each circuit was measured ten times reconnecting the circuit after each measurement. The bending of measurement cables was kept same that the errors due to the position of cables did not affect to the result. The normalization and calculation of the final standard deviation were evaluated as in the test of system repeatability. The connector repeatability is shown in Fig. 2.

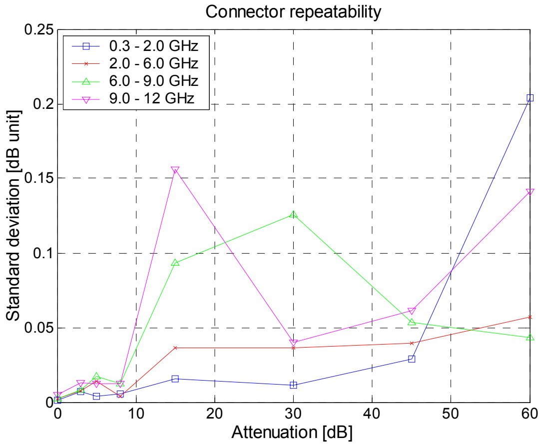

Fig. 2. The connector repeatability in function of attenuation and frequency. In the calculation of the final standard deviation, the normalized samples and multiplication by nominal attenuation value were used.

In Fig 2., the standard deviation of connector repeatability includes some points that are not expected comparing to the other points in the curves. The phenomenon is mostly occurred at frequencies above 6 GHz and due to the imprecision in measured attenuation circuits. When these points are ignored, the result of connector repeatability is reasonable comparing to value provided by EA publication [6]. The results are little higher than the value in EA publication that is mostly due to the standard SMA connectors used in this work.

H. Effects of Cable Flexure and Ambient Conditions

In the measurement of printed circuit board laminate, several cables were used to connect the calibration kit and measurement structures to the network analyzer. In the measurements of the dielectric properties, the cables were always moved and bend after the calibration. This cause a error component. Effect of the error component to the total magnitude uncertainty was minor and it was estimated with the typical value of 0.004 dB presented in EA publication [6].

The measurement of the FR-4 type laminate material was performed at the typical laboratory conditions. During the measurements, the conditions of laboratory were stable (23± 1ºC). Due to the stability of laboratory conditions, the effects of ambient condition were minor and were neglected.

V. CALCULATION OF TOTAL MAGNITUDE UNCERTAINTY

The estimates of contributions were divided by the value depending on the contribution's distribution. The divider of Gaussian distribution was 2 and it was used for the measured estimates. The divider of $\sqrt{2}$ and $\sqrt{3}$ was used in U-shaped and rectangular distribution, respectively. While the U-shaped distribution was used to contributions that were dependent on the other contributions, the rectangular distribution was used to contributions that were not established by authors.

The combined standard uncertainty was calculated by adding the individual contributions in the way of root sum of squares. The way of root sum of squares was used because the contributions were assumed to be independent for each other. The final uncertainty in magnitude was performed by expanded uncertainty based on the coverage factor of 2. Using the expanded uncertainty, the uncertainty implements a level of confidence of approximately 95% at normal distribution.

In the Fig. 3., the expanded magnitude uncertainty in the confidence level of 95% is shown.

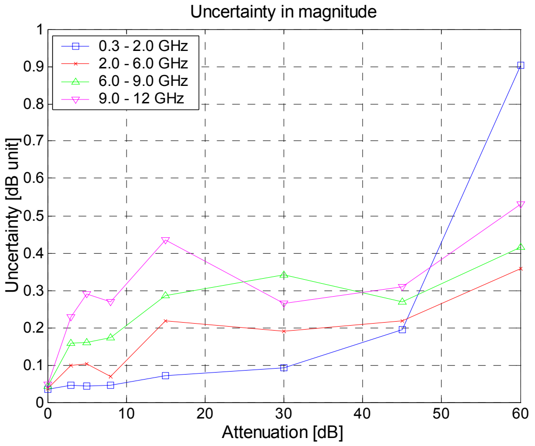

Fig. 3. Uncertainty in magnitude at the function of attenuation and frequency. In the calculation of the uncertainty, the expanded uncertainty with the coverage factor 2 has been used. The coverage factor 2 assigns the confidence level of 95 %.

The uncertainty shown in Fig. 3. is reasonable comparing to the reference value provided by the data of the network analyzer manufacturer [5]. The magnitude uncertainty determined by authors is slightly higher than the reference value, but it was expected because the embedded calibration kit and the standard SMA connector were used in this work.

VI. THE EFFECT OF UNCERTAINTY TO DETERMINED VALUES OF DIELECTRIC CONSTANT AND DISSIPATION FACTOR

In the evaluation of the total uncertainty, the effects of measurement uncertainty and dimension variation have to be taken into account. The measurement uncertainty consists of uncertainties in magnitude and frequency and is determined above while the dimension variations are depending on the variations of thickness of laminate material, thickness of conductor strip and width of conductor strip. The dimension variations were considered as a maximum variation in a measurement sample and were determined from the microsections. Depending on the dielectric characteristic being considered, the influence of uncertainty components will vary.

A. The Total Uncertainty of Dielectric Constant

The uncertainty of dielectric constant was mostly influenced by frequency uncertainty of measurement system and the dimension variations of the measurement structures while the magnitude uncertainty of the measurement system had a negligible effect. Depending on the frequency, the effects of frequency uncertainty varied at the range of 0.01 – 0.015. The effects of dimension variation were at the range of 0.01 – 0.02, when the dimensions varied 20 μm and 70 μm in line width and laminate height, respectively.

The total uncertainty of dielectric constant was calculated by adding maximum uncertainty in order to get worst-case value. The worst-case value for uncertainty was 0.05 with confidence level of 95 % at normal distribution.

B. The Total Uncertainty of Dissipation Factor

The uncertainty of dissipation factor was mostly influenced by uncertainty of magnitude while the effects of dimension variation and frequency uncertainty were minor. As can be seen from Fig. 3, the magnitude uncertainty was dependent on attenuation and frequency. With used resonator structures, the maximum uncertainty was around 0.3 dB. Due to the maximum uncertainty in magnitude uncertainty, the total uncertainty of dissipation factor was 0.005 in the worst case with confidence level of 95 % at normal distribution.

VII. SUMMARY

The effect of measurement uncertainty to evaluation of dielectric properties of FR-4 type laminate material has been determined. The determination includes the uncertainty due to the measurement system and dimensions variation of the measurement structures.

The effects of measurement system and dimension variations have been noticed to vary depending on the dielectric properties under determination. In the determination of dielectric constant, the magnitude uncertainty of system has negligible effect, while dissipation factor is mostly influenced by magnitude uncertainty of system.

The evaluated values are 0.05 for dielectric constant and 0.005 for dissipation factor with the confidence level of 95 % at normal distribution. The evaluated values give reasonable uncertainty limits for the determination methods used in the FR-4 EPSILON-R Modeling project and also in halogen free material project.

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