Dielectric Permittivity and Permeability Measurement System

Nikolay S. Knyazev, Alexander I. Malkin

Ural Federal University, Yekaterinburg, Russia,
alexander.malkin@urfu.ru

Abstract. The article describes a measurement system, which is used for determining the dielectric permittivity and permeability. The applied methods and algorithms of recalculation allow one to measure the parameters of materials in wide frequency bandwidth with high accuracy. Calibration during the measurements and the practical results are also presented in the article. Choice of the Through - Reflect - Load (TRL) calibration method is explained and the standards that were used during the calibration procedure are described. The theory of material parameters measurement and recalculation methods are described and the main advantage and disadvantage of considered methods are explained. A sample of teflon (PTFE) was measured and errors, which had influenced the measurement results, were discussed. The methods of increasing accuracy of material parameters measurement are presented in the article as well.

Keywords: Permittivity, permeability, measurement system

1 Introduction

Nowadays we use a huge number of different radio devices. Commonly, various types of dielectrics are used in design of these devices, for example, in printed circuit board (PCB). It is very important to know the real parameters of the used material at a stage of the devices elements development; otherwise, we should make additional steps to determine correct size of the designed element. The capacitance (parallel plate) method is used very often for the permittivity determination. But this method has a lot of restrictions, especially, in frequency above some hundred megahertz. Another method, which we can use for determination of permittivity, is a measurement with an open coaxial probe. But this method is suitable to measure liquid not solid materials because we cannot consider the air gap between probe and sample; and it adds additional errors in our measurement result, which is unwanted. Another frequently applied method is to use resonator for measurement. This method allows one to determine permittivity of dielectric materials with the lowest possible errors. This happens because we use a resonance effect for determining the parameters of materials. We can measure only thin and low loss sample, because in other case if we use thick or losses material, it will be impossible to find and measure the parameters of resonance. In addition, this method has a restriction in frequency resolution because we have a discrete frequency grid and a frequency step will be defined by the parameters of resonator. The most suitable method, which allows one to measure permittivity of various material, is a transmission line method.

2 Transmission line method

This method allows one to measure permittivity and permeability of various materials using transmission lines (waveguide, airline, free space). In Figure 1, a sample is placed in a waveguide or an airline. Parameters of a scattering matrix of a measured sample, which we need to know to calculate parameters of material sample, are found during analysis of distribution of the electromagnetic field in using transmission line. During calculation, we need to take into account the boundary conditions. We devided space into three areas and parameters were measured separately in different areas.

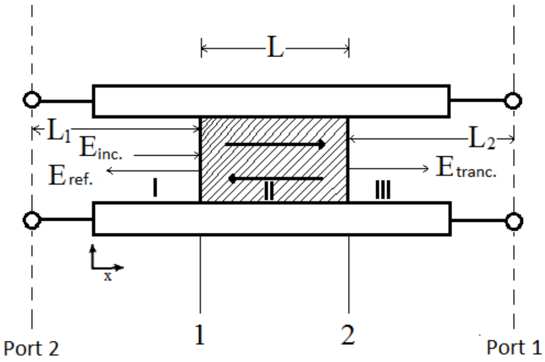


Fig. 1. Measurement sample in the transmission line.

If we assume that the electric field in I, II, and III areas takes the value accordingly E_{I}, E_{II} and E_{III}, we can write a distribution of the electric field as follows:

$$E_{\mathrm{I}} = e^{(-y_0 \cdot x)} + C_1 \cdot e^{(y_0 \cdot x)}, \tag{1}$$

$$E_{\mathrm{II}} = C_2 \cdot e^{(-y \cdot x)} + C_3 \cdot e^{(y \cdot x)}, \tag{2}$$

$$E_{\mathrm{III}} = C_4 \cdot e^{(-y_0 \cdot x)} + C_5 \cdot e^{(y_0 \cdot x)}. \tag{3}$$

The propagation constant in the used transmission line with measured sample and without it is described:

$$y = j \cdot \sqrt{\frac{\omega^2 \mu_r \varepsilon_r}{c_{vac}^2} - (\frac{2\pi}{\lambda_c})^2}, \tag{4}$$

$$y = j \cdot \sqrt{(\frac{\omega}{c_{lab}^2})^2 - (\frac{2\pi}{\lambda_c})^2}. \tag{5}$$

Here, c_{vac} is the speed of light in vacuum, c_{lab} is the speed of light in the transmission line, ω is the angular frequency, λ_c is a cutoff wavelength of using waveguide, μ_r and ε_r are complex permeability and permittivity. The main advantages of this method are the following: possibility to measure a sample with arbitrary form and different aggregate state, possibility to measure losses materials, possibility to make measurements in wide frequency bandwidth and with arbitrary frequency step size. The method is based on measuring of the samples S-parameters by using a vector network analyzer (VNA) [1]. Then, measured parameters are recalculated in value of permittivity and permeability. Accuracy of the permeability and permittivity measurement will depend on many different factors such as:

- the error of an amplitude and phase measurement of S-parameters;
- the air gap between sample and sample holder;
- the error of sample length measurement;
- high order waves excitation;
- calibration errors.

There exist several methods of recalculating S-parameters of the sample into permittivity [2]. A short overview of some of them is shown in Table 1. We choose the Nicholson-Ross-Weir (NRW) method as the main one for the reason that it is the most widely used. We calculate complex values of permittivity and permeability from propagation constant using (4) and (5). According to the NRW method, the formulas for calculating permittivity and permeability will be the following ones [3]:

$$\mu_r = \frac{1 + \Gamma}{\Lambda(1 - \Gamma)\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}}, \tag{6}$$

and

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

For a new non-iterative method, formula for calculating permittivity will be:

$$\varepsilon_r = (1 - \frac{\lambda_0^2}{\lambda_c^2})\varepsilon_{eff} + \frac{\lambda_0^2}{\lambda_c^2}\frac{1}{\mu_{eff}}. \tag{8}$$

There are several methods of recalculating S-parameters of the sample into permittivity. A short overview of some of them is shown in Table 1

Table 1. Overview of recalculating methods.

Sample	Calc. method	Speed	Accuracy
Thin losses non-magnetic materials	NRW	fast	medium
Thin losses magnetic materials	NRW	fast	medium
Thick low losses non-magnetic materials	NIST Iterative	slow	good
Thick low losses non-magnetic materials	New non-iterative	fast	good

3 Measuring system description

3.1 Hardware and Software

In our measurement system shown in Figure.2, we used the transmission line method described above as well as two algorithms of recalculation - the NRW and New Non-Iterative (NNI) were applied. NNI allows one to measure with high speed and good accuracy, while the NRW method helps us to calculate permeability.

For S-parameters measurement, we used the Rohde and Schwarz ZVA vector network analyzer because it provides good accuracy. For calculating permittivity from measured S-parameters, we decided to use external software because it allowed us to make remote control of the equipment and to change parameters of calculations method easily. Given in fact that the ZVA had already got the LabVIEW driver for the remote control for programming, we just used it. The graphical user interface for the LabVIEW program is shown in Figure.3.

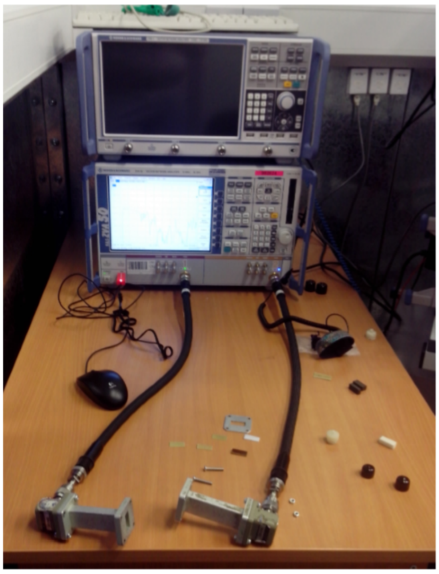
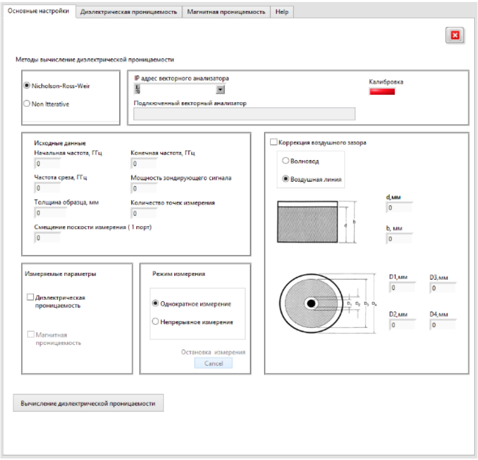


Fig. 2. General view of the measurement system.



Методы вычисление диэлектрической проницаемости

● Nicholson-Ross-Weir
○ Non Itterative

IP адрес векторного анализатора

Подключенный векторный анализатор

Исходные данные

Начальная частота, ГГц
0

Конечная частота, ГГц
0

Частота среза, ГГц
0

Мощность зондирующего сигнала
0

Толщина образца, мм
0

Количество точек измерения
0

Смещение поскости измерения (1 порт)
0

☐ Коррекция воздушного зазора

○ Волновод
● Воздушная линия

d,мм
0

b, мм
0

D1,мм
0

D3,мм
0

D2,мм
0

D4,мм
0

Измеряемые параметры

☐ Диэлектрическая проницаемость
☐ Магнитная проницаемость

Режим измерения

● Однократное измерение
○ Непрерывное измерение

Fig. 3. View of the user interface.

3.2 Calibration and placement

For calibration of the ZVA with waveguides, the TRL method was used. Advantages of the TRL method are: possibility of using sample holder as the line standard and possibility of using reflection standard with unknown S-parameters [1]. Developed measurement system allows one to verify the state of calibration of VNA and to set the main parameters (frequency bandwidth, number of measurement points, and power of signal). It is possible to make measurements in a single mode as well as in a continuous one and to choose different calculation method (NRW or NNI).

During calibration, we have to provide the same reflection coefficients for both measuring ports (for steps of calibration with reflection standard). If coefficients of reflection differ, we will see a ringing on trace of permittivity. The right placement of the reference plane in our measurement system is also has a great im-portance because samples and sample holders are not equal by size (especially concerning thickness) so, there mismatches may become a cause of the wrong value of phase. For the moving reference plane, we use offset feature of VNA; and our program has possibilities of setting an offset. Taking into account an air gap between a sample and a sample holder, we use the capacitance method in our program [2].

4 Measurement example

To make the real measurements, we decided to use the PTFE sample with thickness 2 mm. The parameters of that sample were measured in 813 GHz frequency band with using the WR90-type waveguide. We used the TRL method to do the calibration. We have got a mismatch between the sample and the sample holder of approximately 0.1 mm. The real and imaginary measured parts of complex permittivity are shown in Figure4 and 5 respectively (the straight line is without the gap correction, dash line with the gap correction). We can see that the gap correction allows one to improve the measurement accuracy because these results are much closer to the reference value of the PTFE permittivity (value is about 2.1).

On the graphics we can also see the ringing in the high frequency area and the cause of it is a nonequal reflection conditions on both measuring ports during the TRL calibration.

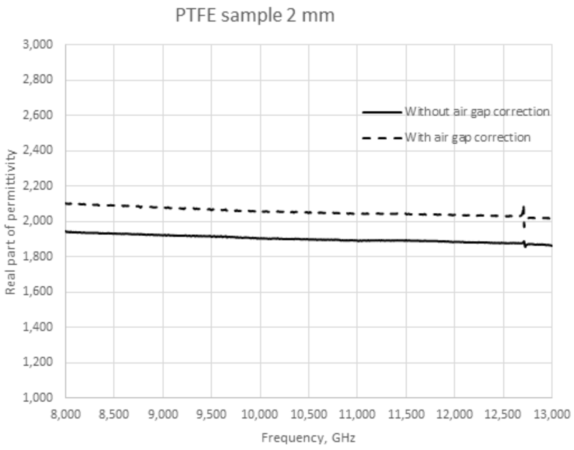


Fig. 4. Real part of complex permittivity versus frequency.

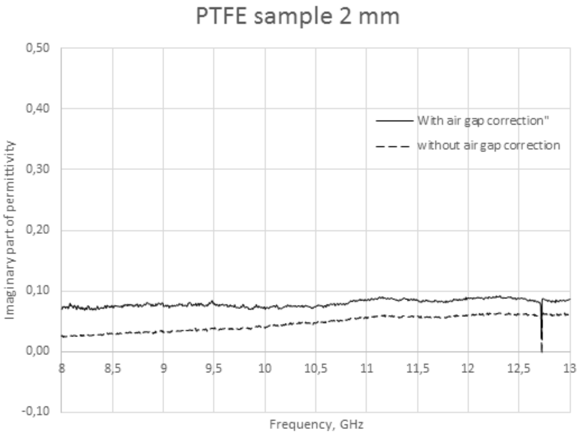


Fig. 5. Imaginary part of complex permittivity versus frequency.

5 Conclusions

We can summarize that presented system is very flexible and has a great opportunity to measure the various types of dielectrics. Also it is a high-speed system with a wide frequency bandwidth, which is limited only by the frequency range used by the VNA and the measurement transmission line. It is possible to increase the measurement accuracy by using special experimental processing data algorithms that allow one to take take into account the air gap between the sample and the sam-ple holder into account. This helps to reduce the requirements for precision of manufacturing the measured samples, which are important for the practical application of the system.

References

1. Heibel, M.: Fundamentals of Vector Network Analysis. Rohde-Schwarz, Germany (2008)
2. Kuek, C.: Measurement of Dielectric Material Properties: application note. Rohde-Schwarz, Germany (2012)
3. Barker-Jarvis, J.: Improved technique for determining complex permittivity with the transmission/reflection method. Trans Microwave Theory Tech, vol. 38(8), pp. 1096-1103. IEEE (1990)
4. Nicolson, A. M.: Measurement of the Intrinsic Properties of Materials by Time-Domain Techniques, Transactions on instrumentation and measurement, vol. 19(4), pp. 377-382. IEEE (1970)