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# Measurement of Complex Permittivity in Free Space

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**Abstract**

The paper describes the measurement of complex permittivity in free space. It is an advanced non-contact method which is used to find the electromagnetic properties of materials. In this case it involves the materials which are used in aviation technology, especially for hardening the avionics against electromagnetic interference. A specialized laboratory workplace equipped with the vector network analyzer ZVA 67 from Rohde and Schwarz was built for the measurement. Initial measurements were performed at high frequencies from 220 to 325 GHz on a Teflon sample because of the ease of verifying the results. The high frequency range was achieved by using ZVA-Z325 converters from the same company and the respective antenna systems. This measuring system was used for determining the transmission coefficients. The complex permittivity which characterizes the electromagnetic properties of the material for the above frequency range was found by iterative method programmed in Matlab environment.

## 1. Introduction

Measurement of the complex permittivity in free space is based on placing a sample of unknown material in space between the transmitting and receiving antennas and let a plane electromagnetic wave pass through it [6]. The measurement principle depends on the fact that phase and attenuation of the passing or reflecting wave vary according to the material properties which are defined by the relative complex permittivity $\tilde{\varepsilon}_r$ which can be expressed as [1]

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$$\widetilde{\varepsilon}_r = \frac{\widetilde{\varepsilon}}{\varepsilon_0} = \varepsilon_r + i\frac{\sigma}{\omega\varepsilon_0} \tag{1}$$

where $\varepsilon_r$ is the relative permittivity or the relative dielectric constant, $\sigma$ is the conductivity of the sample, $\varepsilon_0 = 8,85.10^{-12}$ F/m is the dielectric constant of free space, $\omega = 2\pi f$ is the angular frequency of the electromagnetic wave.

A loss tangent tan $\delta$ is often introduced and is defined as a ratio of the imaginary to the real component of the complex permittivity [1]

$$\tan\delta = \frac{\mathrm{Im}(\widetilde{\varepsilon}_r)}{\mathrm{Re}(\widetilde{\varepsilon}_r)} \tag{2}$$

In this case equation 1 can be expressed in the form [1]:

$$\widetilde{\varepsilon}_r = \varepsilon_r(1 + i\tan\delta) \tag{3}$$

The phase and attenuation of the plane electromagnetic wave which passed through or is reflected from the sample depends on the complex permittivity of the dielectric. For the calculation it is assumed that the sample is a plane-parallel plate because the microwave method in free space uses plate-shaped samples for determining the electromagnetic properties of the materials.

## 2. Calculation of relative permittivity from measured data

Transversal electromagnetic wave, the sample of unknown material with permittivity $\varepsilon = \varepsilon_0.\varepsilon_r$ and permeability $\mu = \mu_0.\mu_r$ can be described as [2]:

$$T = e^{-jkd} \tag{4}$$

Only one pass of the wave through the material is considered. The parameter $k$ is the propagation constant and $d$ is the thickness of the material. The complex relative permittivity is expected in the form $\varepsilon_r = \varepsilon_r' - \varepsilon_r''$ [4] and the complex relative permeability $\mu_r = \mu_r' - \mu_r''$ [2]. Because the nonmagnetic material with $\mu_r = 1$ is measured the propagation constant can be simplified in the form [3]:

$$k = 2\pi f \sqrt{\varepsilon_0.\varepsilon_r\left(\varepsilon_r' - j\varepsilon_r''\right)} \tag{5}$$

and for small losses

$$\sqrt{1 - j\frac{\varepsilon_r''}{\varepsilon_r'}} \cong 1 - j\frac{\varepsilon_r''}{2\varepsilon_r'} \qquad pro \quad \frac{\varepsilon_r''}{\varepsilon_r'} << 1 \tag{6}$$

Transmission coefficient can be written as multiplication of two exponential functions representing the module and phase [3]:

$$T = e^{-j\frac{2\pi f d}{c_0}\sqrt{\varepsilon_r'}}.e^{-\frac{\varepsilon_r''}{\sqrt{\varepsilon_r'}}\frac{\pi f d}{c_0}} \tag{7}$$

For the imaginary part of the permittivity the following equation apply [3]:

$$\varepsilon_r'' = -\frac{c_0 \ln|T|\sqrt{\varepsilon_r'}}{\pi f d} \tag{8}$$

where $c_0$ is speed of light.

Without considering multiple reflections inside the material the measured transmission coefficient $S_{12}$ and the ideal one is bound with the relation [3]:

$$T = S_{12}\frac{1-\Gamma^2 T^2}{1-\Gamma^2} \quad \Rightarrow \quad S_{12} = \frac{\left(1-\Gamma^2\right)T}{1-\Gamma^2 T^2} \tag{9}$$

where

$$\Gamma = \frac{\sqrt{\varepsilon_r'}-1}{\sqrt{\varepsilon_r'}+1} \tag{10}$$

and the initial estimation of the parameter $\varepsilon_r'$ is derived from the phase of $S_{12}$.

## 3. The measuring equipment

Number of different methods exist for the measurement of the complex relative permittivity, e.g. in dielectric waveguide [5]. Unfortunately, this method is inappropriate for measuring of small examples of the material because of the difficulty in ensuring the contact conditions because unwanted signal wrapping may occur. Further, this measurement must be conducted for high frequencies in the order of tens or hundreds of gigahertz. Because of this drawback a new laboratory for measuring the complex permittivity in free space was assembled.
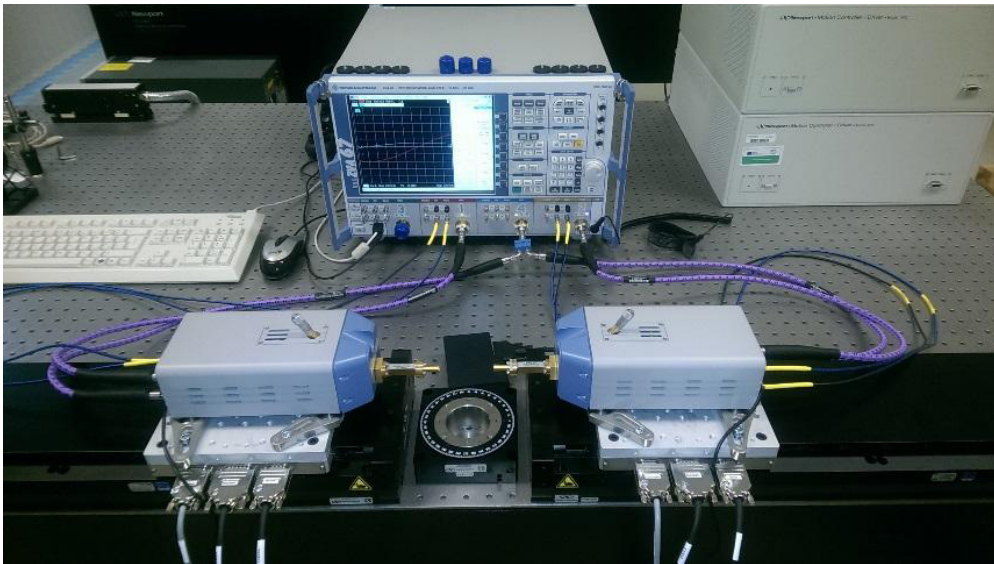


Fig. 1. Equipment for measuring in laboratory environment.

This laboratory is equipped with the Rohde and Schwarz's vector network analyser ZVA 67. The frequency range is from 10 MHz to 67 GHz. These limits were expanded by four sets of frequency converters to the final 325 GHz. These converters are ZVA-Z90E (60 to 90 GHz), ZVA-Z140 (90 to 140 GHz), ZVA-Z220 (140 to 220 GHz) a ZVA-Z325 (220 to 325 GHz). Every frequency range must have its own antenna system which are custom made. The circular horn antennas are chosen for better achievement of the Gauss shape of the beam. The movement of the converters with attached antennas is supported by motion drivers through the motion controller from the Newport company. The whole measuring equipment can be seen in Fig. 1.

## 4. Example of the measurement

As an example of the measurement of the complex relative permittivity in free space a sample of Teflon plate is chosen because of its known parameters. The thickness of the sample is 2 mm and is placed between the transmitting and receiving antenna. The main goal of the measurement is to verify the accuracy of the measurement and following calculation of the permittivity value. The measurement is performed in the range from 220 to 325 GHz. Collected data from the analyser were processed in the Matlab environment. Neither the lens system nor mirrors were used to transform the beam to the plane electromagnetic wave.
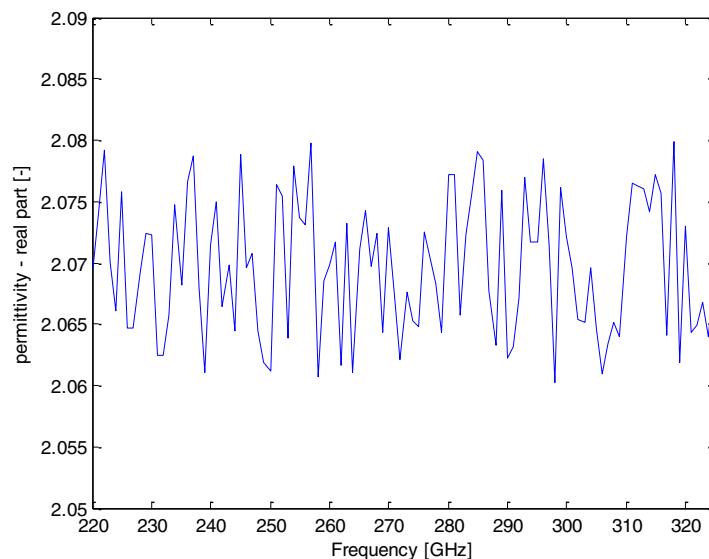


Fig. 2. Calculated real part of the permittivity.

As can be seen in Fig. 2 the real part of the Teflon sample permittivity in measured frequency range is approximately 2.07 which corresponds to the 2.1, which is the theoretical value.

## Conclusion

In this contribution a free space method was used for determine the complex permittivity of the material. A sample of nonmagnetic Teflon was used for the measurement due to its known parameters. This material also serves as a reference to prove correctness of the chosen method and calculation of the permittivity from the measured data. An iterative program in Matlab environment was used for determine the permittivity. According to the data the method seemed to be suitable for dielectric parameter estimation of materials. These materials can be used for example in avionics. In the future an extension of the measuring equipment is planned. A set of lenses will be added to transform the beam to a plane electromagnetic wave. Also the iterative method should be improved or replaced by a more precise one. The effect of vertical rotation of the material sample towards the emitting antenna will be studied in future research.

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