Measurement 46 (2013) 3796–3801

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Complex permittivity measurement using capacitance method from 300 kHz to 50 MHz

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ARTICLE INFO

Article history:
Received 6 September 2012
Accepted 25 June 2013
Available online 4 July 2013

Keywords:
Component
Complex permittivity
Parallel plate capacitor
Vector network analyzer
VNA
Dielectric constant
Measurement

ABSTRACT

Complex permittivity measurement has been performed using a parallel plate capacitor and a vector network analyzer (VNA) from 300 kHz to 50 MHz. The material under test (MUT) is a flat and thin sample clamped between the capacitor plates and connected to the VNA to obtain its two port *S* parameters. The *S* parameter is converted into impedance to calculate the complex permittivity using Matlab program. Techniques used to overcome the air gap and stray capacitance was described. Measurement obtained using the proposed method was compared with the free space method to validate its accuracy. The percent difference is less than 5%.

1. Introduction

Complex permittivity ($\varepsilon_r' + j\varepsilon_r''$) is a very useful parameter where the quality factor ($\varepsilon_r'/\varepsilon_r''$) and tangent delta ($\varepsilon_r''/\varepsilon_r'$) can be derived from the complex permittivity. These parameters are useful in power industry because they can be used as an indication of the power cable's insulation quality [1,2]. Therefore there is a strong demand for complex permittivity measurement related research.

There are a lot of methods developed for measuring the complex permittivity but these techniques are limited to specific frequencies, materials, and applications [3]. A list of currently known complex permittivity measurement has been described by Jarvis et al. in NIST technical note [4]. Two widely used measurement methods are resonant method and transmission/reflection method [5]. Resonant methods [6] have many variants such as split cylinder resonator, cavity resonator [7], Courtney technique, whispering gallery resonator and Farbry Perot resonators. Although resonant methods are highly accurate, measurements can only be done at one frequency which is the resonant frequency. Transmission/reflection method is able to measure the complex permittivity in a frequency range but requires the usage of waveguides [8–11]. Waveguides has two disadvantages. First, it is necessary to machine the sample to precisely fit the waveguide cross section with negligible air gaps. This requirement will limit the accuracy of measurements for materials which cannot be machined precisely [12]. The second disadvantage is the size limitation. Smaller sample size requires smaller waveguides which forces measurement to take place at a much higher frequency.

There are plenty of research and implementation of resonant methods and transmission/reflection methods at GHz frequency range. Therefore this paper will focus on the less developed capacitance method in the MHz range.

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0263-2241/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.measurement.2013.06.039

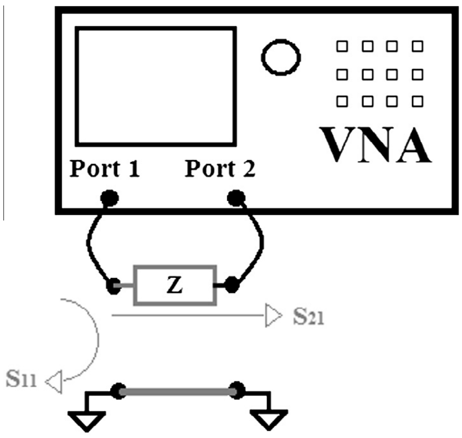

Fig. 1. Fixture and VNA connection.

The capacitance method involves sandwiching a thin material between two electrodes to form a capacitor. The typical capacitance method frequency range is from DC to 100 MHz [13]. This limitation is due to the fact that the capacitor will start to behave like an inductor above its resonance frequency which may vary for different materials. Capacitance method has several benefits which are the relatively low cost, easier sample preparation, easy to built fixture, and ability to measure at a frequency range.

In this work, two round copper plates with diameter of 2.5 cm were used as the electrodes. The techniques to overcome the two main weaknesses of capacitance method i.e. stray capacitance and air gap will be discussed. The measured samples are thin, flat and has a surface area larger than the capacitor conducting plate [14]. The uniqueness of this work is the usage of VNA to measure impedance instead of LCR meter. Impedance is obtained through conversion of measured *S* parameter. VNA is preferred because it is more commonly available in research labs.

2. Measurement theory

2.1. Converting S parameters to impedance

In this work, the *S* parameters were measured using Agilent's E5070 vector network analyzer (VNA). Full two port calibration was performed using the Agilent 85032B calibration kit before the measurement. The test fixture was connected to the VNA as shown in Fig. 1. SMA cables were used as coaxial cables to connect the fixture to the VNA.

Once the test fixture is connected as shown in Fig. 1, its *S* parameters can be converted to impedance using Eq. (1) [15].

$$Z = 100(1 - S_{21})/S_{21} \tag{1}$$

The impedance measured by this method is the combinations of MUT impedance and fixture impedance. The fixture impedance must be removed to prevent systematic error in future calculations. The fixture impedance consists of residual impedance and stray admittance as depicted in Fig. 2 [16].

To determine the stray admittance, an open circuit was created at the MUT. This will cause the stray admittance to be huge and the residual impedance to be negligible. Hence the impedance measured when MUT is open will be the stray admittance. The residual impedance was measured when the test fixture was shorted. This will cause the stray admittance to be shorted and the measured impedance value will be the residual impedance. The MUT impedance Z_{mut} can be determined once the residual impedance and stray admittance is known using the following equation.

$$Z_{mut} = (Z_{measured} - Z_s)/(1 - Y_o(Z_{measured} - Z_s)) \tag{2}$$

2.2. Converting impedance to complex permittivity

The test fixture sandwiching the MUT can be modeled as a capacitor that has an equivalent circuit shown in Fig. 3. The equivalent circuit can be modeled as a series model or parallel model. Impedance to permittivity conversion requires the parallel model. Conversion between parallel and series model can be done using Eqs. (4) and (5).

$$\mathrm{Tan}\,\delta = \omega R_s C_s = 1/(\omega R_p C_p) \tag{3}$$

$$C_p = C_s/(1 + (\mathrm{Tan}\,\delta)^2) \tag{4}$$

$$R_p/R_s = 1 + 1/(\mathrm{Tan}\,\delta)^2 \tag{5}$$

$$Y = G + j\omega C_p \tag{6}$$

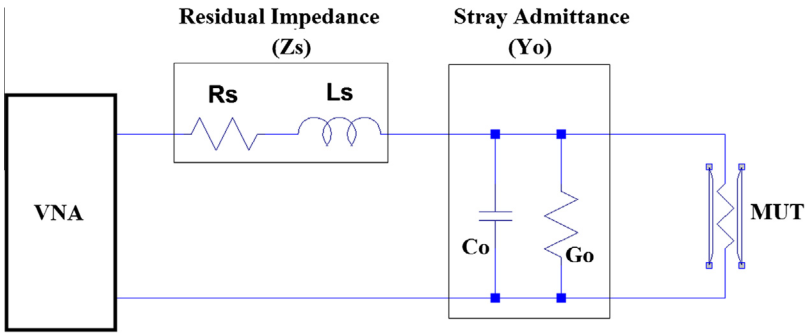

Fig. 2. Test fixture's impedance model.