Measurement Dielectric Constant of new transformer oil at frequency 18 to 26 GHz (K Band)

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Abstract—**Nondestructive, noncontact and real time evaluation of dielectric properties of low-loss liquids is important for applications such as service-aged transformer oil, biomedical, remote sensing and design of radar absorbing material. In this paper, present a method for measurement of dielectric properties of transformer oil using metal-backed method. Complex reflection coefficient (S_{11}) is measured for Plexiglas container backed by metal plate. Dielectric constants and loss factor were measured for new and used transformer oil in the frequency range 18 to 26GHz (K-Band).The thru,reflect and line (TRL) calibration technique were used to eliminate the effect of undesirable multiple reflection. The dielectric constant foe new and used transformer oil sample is 2.1± 0.1.The loss tangent (tan δ) foe new transformer oilis 0.02 to 0.06 and for used transformer oil is 0.03 to 0.07.Loss tangent for new transformer oil is lower than used transformer oil.The slight differences could be due terrors in the magnitude and phase of S_{11}, Surface of transformer oil and the air-gap effect of the sample assembly.The result for loss tangent are directly proportional to the oil deterioration.**

Keywords— Free space Measurement System (FSSM), Gaussian Optic Lens (GOA) antenna, Thru, Reflect, Line (TRL), Vector Network Analyzer (VNA), Microwave Nondestructive Testing (MNDT).

I. Introduction

Microwave techniques have been used in a large number of applications that can be classified as nondestructive testing applications [1]. The increasing use of microwave for industrial testing as reported by K. A. Jose [2] is generating a growing requirement for accurate permittivity measurement as a function of frequency. It is reported that many technique such as cavity resonant technique, coaxial line and waveguide were employed to evaluate dielectric properties of liquids. MNDT techniques have advantages over other NDT methods regarding low cost, good penetration in nonmetallic materials, good resolution and contactless feature of the microwave sensor (antenna) [3].Nondestructive testing (also called NDT, nondestructive evaluation, NDE, and nondestructive inspection, NDI) is testing that does not destroy the test object. The use of microwave method provides unique nondestructive approaches to material testing. The cost, complexity and technical expertise required to apply microwave testing method constrain the acceptable and widespread use of microwave for material flaw detection.

Some microwave material analysis techniques are becoming accepted and useful. Moisture measurement and thickness gauging are two example of widely utilize applications [4].

Transformer oil provides the required dielectric strength and insulation and also cools the transformer by circulating itself through the core and the coil structure. The transformer oil should be in the liquid state over the complete operating range of temperatures between -40°C and +50°C.

In this paper, present a method for measurement of dielectric properties of transformer oil using metal back method. Complex reflection coefficient (S_{11}) is measured for Plexiglas container backed by metal plate. Dielectric constants and loss factors were measured for new transformer oil in the frequency range of 18 to 26 GHz.

Errors in free-space microwave measurement system [6] are due to diffraction from the sample which is minimized by using spot focusing horn lens antennas. Also, errors due to multiple reflections between antennas were minimized by using free-space TRL calibration technique and time domain gating which is a feature of VNA.

II. Theory

For metal back method, complex permittivity (ε*) of the sample can be computed from measured reflection coefficient (S_{11}). Figure 1 show the schematic diagram for metal back technique for liquid sample. *d* is the thickness of Plexiglas layer and L is thickness of sample. Reflection coefficient (S_{11}) was measured by inserting a metal plate behind of Plexiglas container which is facing transmit antenna [1, 11].

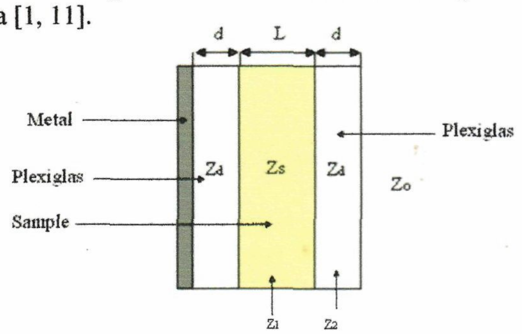

Figure 1: Schemetic diagram for metal back methods. Metal - Plexiglas – sample-Plexiglas.

Z_s is characteristic impedance for sample which is defines as [1]:

$$Z_s = \frac{Z_o}{\sqrt{\varepsilon_s^*}} \quad (1)$$

The characteristic impedance for Plexiglas can be defined as:

$$Z_d = \frac{Z_o}{\sqrt{\varepsilon_d^*}} \quad (2)$$

Zo is characteristic impedance for free-space:

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377 \text{ Ohms} \quad (3)$$

Complex phase constant for sample and Plexiglas define as:

$$\beta_s = \frac{2\pi}{\lambda_o}\sqrt{\varepsilon_s^*} \quad (4)$$

$$\beta_d = \frac{2\pi}{\lambda_o}\sqrt{\varepsilon_d^*} \quad (5)$$

Xd and Xs are defines as given below.

$$X_d = \tan(\beta_d d) \quad (6)$$

$$X_s = \tan(\beta_s L) \quad (7)$$

Then, by using transmission line theory, it can be shown that input impedance Z1 for metal backed Plexiglas and the sample layer (as shown in figure 3) is given by

$$Z_1 = \frac{j(X_d Z_d + Z_s X_s)}{\left[1 - \left(\frac{X_s}{Z_s}\right) Z_d X_d\right]} \quad (8)$$

We denoted this Z_1 as some function $f_1(\varepsilon_s^*)$.

Z_2 is input impedance of the Metal - Plexiglas –sample-Plexiglas assembly as shown in figure 3 .The ,Z_2 is related to the measured S_{11} by the following relationship.

$$Z_2 = Z_o\left[\frac{1+S_{11}}{1-S_{11}}\right] \quad (9)$$

Also, it can be shown from transmission line theory that the input impedance Z_1 is related to Z_2 by the following relationship.

$$Z_1 = Z_d\left[\frac{Z_2 - jX_d Z_d}{Z_d - jZ_2 X_d}\right] \quad (10)$$

We denote this Z_1 as $f_2(\varepsilon_s^*)$.

Then, we define error function E as given below.

$$E = f_1(\varepsilon_s^*) - f_2(\varepsilon_s^*) \quad (11)$$

It is necessary to find ε_s^* iteratively by finding zeros of the error function .The Muller method will deflection is used for calculation of zeros of the error function [7].

III. CALIBRATION AND MEASUREMENT SET UP

GOA antennas are available in waveguide bands from 18 to 220 GHz. For these antennas, the ratio of focal distance to antenna diameter (F/D) of the lens is equal to one and D is approximately 30.5 cm. In Gaussian optics transmission, the propagating signal is not confined by metal or by dielectric walls, but travels in free space, resulting in a very low loss system. The series GOA is available in single or dual polarization. A specially fabricated sample holder is mounted at the common focal plane for holding planar samples. The sample is sandwiched between two perspex plates (one plate is fixed and the other is moveable). The transformer oil is located at the middle between two plates. Network Analyzer measures the two-port scattering parameters of a device under test (DUT). In this project, Plexiglas used to contain transformer oil to measure dielectric constant. Network Analyzer measures the two-port scattering parameters of a device under test (DUT).

Because of multiple reflections between coaxial-to-rectangular waveguide adapters, rectangular-to-circular waveguide transitions and the antennas, there is a need to calibrate the measurement system in free space for S-parameter measurements. We have implemented free-space TRL calibration technique. This calibration technique along with smoothing or time domain gating feature of the network analyzer can eliminate effects of multiple reflections. It is known that LRL calibration technique can produce the highest quality calibration available. Also, it is easier to realize LRL calibration standards in free-space as compared with open, short and matched termination standards used in coaxial and waveguide media. Free-space LRL calibration is implemented by establishing three standards, namely, a through connection, a short circuit connected to each port and a transmission line connected between the test ports. Figure 4 show below is represented the complete schematic diagram of the free-space microwave measurement system.

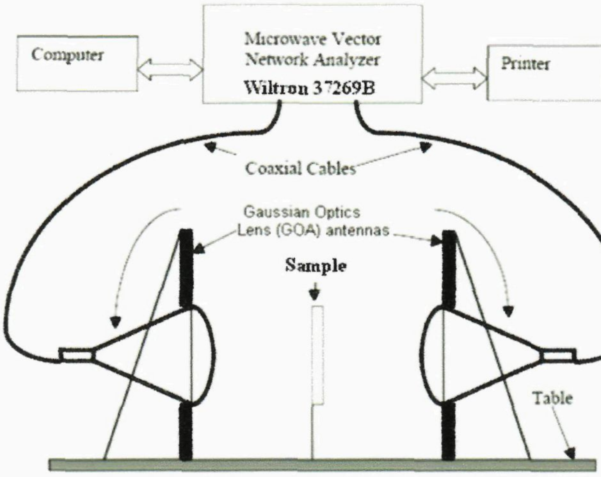

Figure 2: Schematic diagram for Nondestructive Testing (NDT) techniques in free-space measurement

Figure 3: Vector Network Analyzer (VNA)

The first devices are set to 0.00mm because of calibration technique testing for thru concept. That means at the middle of two plates no device is located. This project is presented in half-wave at mid-band and the mid-band for the K-band frequency is 22GHz. The distance at the micrometer for the measurement must be moved behind for 3.409mm from the center of middle reference plates. These processes are designed for the line concept of calibration technique. For the reflection concept of the calibration technique is the distance must be moved behind depending on the thickness of the metal plate used (3.18mm). All the process that are used for calibration technique must ensure that the focal distance to antenna diameter (F/D) of the lens is equal to one and D is approximately 30.5 cm. S-parameter measurements in free-space were measured by Wiltron 37269B vector network analyzer system. Wiltron 37269B network analyzers utilize synthesized-frequency sources to provide a known test stimulus that can sweep across a range of frequencies or power levels. Vector network analyzer measures amplitude and phase of reflected or transmitted signal in transmission media such as coaxial line, rectangular waveguide, microstrip line and free-space. Wiltron 37269B network analyzers also can perform rationed measurements (including phase), which require multiple receivers. The Wiltron 37269B can provide a wealth of knowledge about a device under test (DUT), including its magnitude, phase, and group-delay response. After TRL calibration, the thru connection was measured. The amplitude and phase of S_{11} were 0.0 ± 0.2 dB and 180° ± 1°, while the amplitude and phase of S_{21} were 0.0 ± 0.1 dB and 0° ± 1° respectively.

Figure 3 shows the Vector Network Analyzer Wiltron 37269B used for the calibration and measurement system. A complete VNA system consists of a fast sweeping synthesized signal source, auto-reversing S-parameter test set, display unit and a controlling computer. This network analyzer is used to make accurate reflection and transmission (S-parameters) measurements in free-space using line-reflect-line calibration model.

After LRL calibration, for the verification purpose, we measured dielectric properties at 22GHZ for Teflon and Plexiglas materials. Measured dielectric constants of Plexiglas and Teflon sample are 2.64 and 2.02, respectively. In the literature [8], Plexiglas and Teflon value are reported as 2.59 and 2.08, respectively.There is a good match in dielectric constant values.

IV RESULTS

For measurement of complex transmission coefficient (S_{21}) and complex reflection coefficient (S_{11}) of composite material sample, the reference planes corresponding to transmit and receive antennas were located at the front and back face of the sample which is Plexiglas. The residual post calibration errors can be further reduced by using time domain gating or smoothing function of VNA. It is observed that magnitude and phase of S11 are within ± 0.2 dB and ± 1° of the theoretical value of 0 dB and 180° for the metal plate. For the through connection, the measured magnitude and phase of S_{21} are within ± 0.05 dB and ± 0.2° of the theoretical values of 0 dB and 0°.

The measured value of the complex permittivity of Teflon and Plexiglas is 2.00 and 2.64. The standard value of Teflon and Plexiglas is 2.08 and 2.65 based on reported data from Von Hippel [5]. The Plexiglas quarter wavelength was 3.409mm.

By using the computer simulation based on the equations (1) to (11), the result of the complex permittivity of transformer oil samples can be calculated. The dielectric constant (ε'), loss tangent for new transformer oil samples at frequency 22GHz are shown in the table 1.

Table 1
The dielectric constant and loss tangent for new transformer oil

Number Of Sample	Dielectric Constant (ε)	Loss Tangent (tan δ)
1	2.139	0.029
2	2.119	0.037
3	2.130	0.034
4	2.090	0.033

Table 2
The dielectric constant and loss tangent for used transformer oil.

Number Of Sample	Dielectric Constant (ε')	Loss Tangent (tan δ)
1	2.115	0.040
2	2.096	0.040
3	2.008	0.038
4	2.307	0.061

Used transformer oil was taken from high voltage power transformer (22kV/275kV, 590MVA) of different usage ages.

Table 1 and table 2 show the results that both dielectric constant and loss tangent collected from measurement at 22GHz. Four samples were used for this measurement in order to get an accurate result. The averages of four samples are shown in one graph.

Figure 4 shows the measured dielectric constant for new and used transformer oil, respectively. Measured dielectric constant for new and used transformer oil is 2.1± 0.1 as reported by Wadhawa [16] at 50Hz. So, the result is the same with published data.

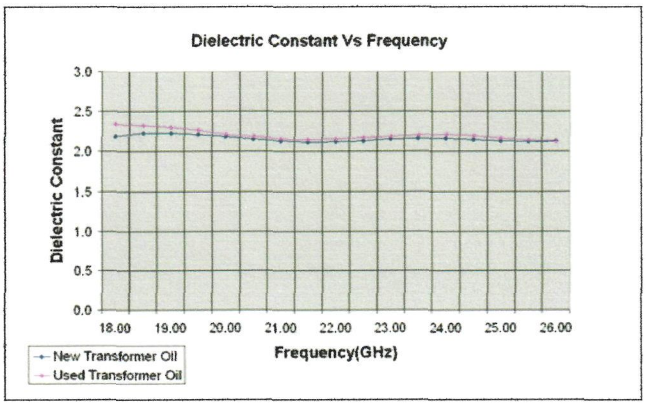

Figure 4: Dielectric constant Vs Frequency

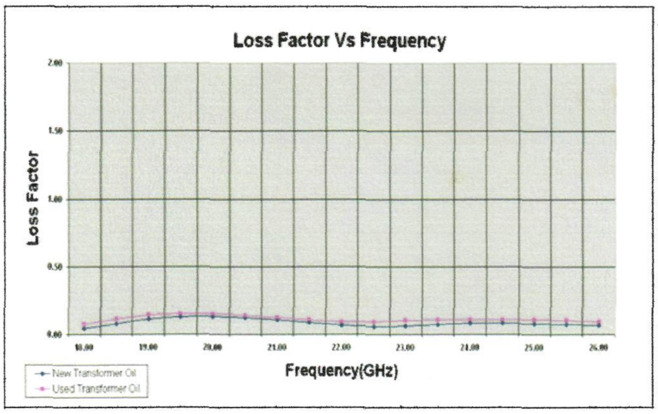

Figure 5: Loss Factor Vs Frequency

Figure 5 gives loss factor values which correspond to loss tangent in the range of 0.045 to 0.089 for new transformer oil and 0.074 to 0.157 for used transformer oil. Loss factor refers to the imaginary part of the complex permittivity and denoted by ε". It is measure of how dissipative or lossy a material is to an external electric field.

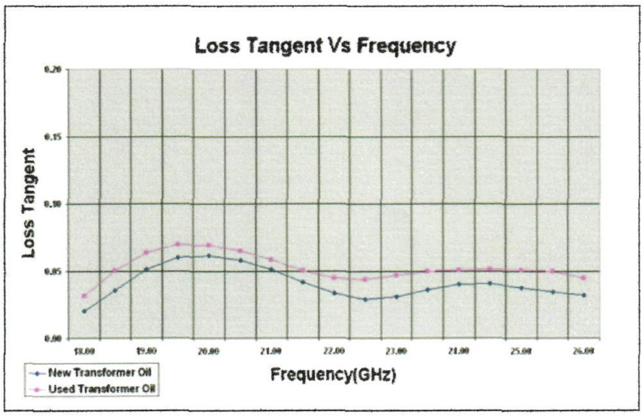

Figure 6: Loss Tangent Vs Frequency

Figure 6 gives values loss tangent for new and used transformer oil. Range for new transformer oil is 0.02 to 0.06 and for used transformer oil is 0.03 to 0.07.Loss tangent for new transformer oil is lower than used transformer oil. Result for loss tangent is depending on dielectric constant and loss factor of the samples.

V. Discussion

From the result obtained, the dielectric constant for new and used transformer oil is close 2.2 that reported by Wadhawa [10] at 50Hz. The results show that the loss tangent is directly proportional to the oil deterioration. Calibration is very important before make a measurement.

Calibration result should be same as theoretical which as S_{11} almost magnitude equal 0 dB and phase equal 180°. S_{21} magnitude is 0dB and phase equal 0°.Another factor that can influence the measurement result is environment of measurement. It is very important because microwave is very sensitive. Thickness of container is another factor that affects the results. Thickness container must be same at both end (right and left).

Loss tangent is comparison between loss factor and dielectric constant. Loss tangent can be referring to a measure of the energy loss in the form of heat.

The formula for loss tangent is

$$\text{Loss tangent } (\tan\delta) = \left|\frac{\varepsilon''}{\varepsilon'}\right| \qquad (12)$$

ε" is refer for loss factor and ε' is dielectric constant. Loss tangent are directly proportional to the breakdown voltage and directly proportional to the oil deterioration.

VI CONCLUSION

In this paper, FSMM systems have been employed for MNDT of new transformer oil and used transformer oil. From the samples that we have measured, we can obtain the dielectric constant, loss factor and loss tangent for new and used transformer oil.

The dielectric constant for new transformer oil is (2.13 to 2.26) and for used transformer oil is (2.21 to 2.47).At 22GHz the result for both samples is slightly same but at another frequency is different. Loss tangent for new transformer oil is low compare with used transformer oil. We found that the measured complex permittivity for new transformer oil in this research are closed to expected values published by the Wadhawa[10]. The microwave measurement result showed that the values of both values of both dielectric constant and loss tangent are directly proportional to the oil deterioration [12].

Free space nondestructive material and contactless method is developed at microwave frequency which gives accurate values of dielectric properties of transformer oil samples. Although the primary results show some promising, other factors should be included to improve the accuracy. In the future development, we have to include the process of adding density factor to help the accuracy. In the future development, we have to include process of adding density factor to help the accuracy. Beside that, NDT method can provide fast response and it is cheap with respect to the other NDE methods regarding low cost, good penetration in nonmetallic materials, good resolution and contactless feature of the microwave sensor (antenna).

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REFERENCES

[1] Mohd Aziz b Aris, D. K. Ghodgaonkar and Norasimah Khadri ,"Nondestructive and non contact dielectric measurement method for low-loss liquids using free space microwave measurement system in 8-12.5vGHZ frequency range"2004

[2] K. A. Jose, V. K. Varadan and V. V. Varadan, "Wideband and Noncontact Characterization of The Complex Permittivity of Liquids," Microwave and Optical Technology Letters, Vol. 30, No 2,July 20,2001, pp. 75 – 79

[3] Alfred J.Bahr, Microwave Non-Destructive Testing Methods SRI, International pp 1-3

[4] Don E.Bray,Don Mc Bride, " Nondestuctive testing techniques",A Wiley-interscience Publication,1992.

[5] M S Naidu, V Kamaraju," *High Voltage Engineering*", Tata McGraw-Hill Publishing Company Limited

[6] D. K. Ghodgaonkar. V. V. Varadan., "Free- Space Measurement of Complex Permittivity of Magnetic Materials at Microwave Frequencies," IEEE Transactions on Instrumentation and Measurement, Vol. 19, No. **2,** April 199O.pp. 387 – 394.

[7] Muller, D. E., "A Method for Solving Algebraic equations using an automated Computer", *Malh. Tables and Ai& IO Compufofion.* Vol. IO, pp. 208-215, 1956

[8] Arthur Von Hipple,"Dielectric Materials and Applications,"Artech House Boston London, P.18-19, 1995.

[9] N.H.Baba, Z.Awang, and D.K. Ghodgaonkar, "Accuracy Consideration for Dielectric Measurements of Semiconductor Wafers Using Free nSpace Microwave System in 8-13Ghz Range", pp.177-181, October, 5-6, 2004, Subang selangor, Malaysia

[10] C.L.Wadhawa,"High Voltage Engineering," New Age International (p) LTD, Publisher, 1994.p.20

[11] Aris Aziz , D.K Ghodgaonkar," Nondestructive and Noncontact Dielectric Measurement Methods for High-Loss Liquids Using Free Space Microwave Measurements Systems in 8-12.5GHz Frequency Range"pp.169-176, October, 5-6, 2004, Subang selangor, Malaysia

[12]Salah I, Al-Mously, Member, IEEE, and Y. Ahmad," An Alternative Test For Evaluating Transformer-oil Deterioration Using Microwaves", IEEE Xplore Journal, pp 884-887,1999