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AUTOMATED MEASUREMENT OF COMPLEX PERMEABILITY AND PERMITTIVITY AT HIGH FREQUENCIES

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The paper reports here on the reflection frequency-domain measurements to determine the selected electromagnetic properties of materials using an Agilent 8714ET Network analyzer. The measurement process as well as results evaluation are performed by means of computer control. For this purpose, a VEE program (Agilent technology) has been developed. The discussion concerning the optimisation of measurement process and the reduction of unwanted effects is covered in detail. Some ferrite and ferrite-based polymer composite materials were used in experiments and obtained frequency dependences of electromagnetic parameters are analyzed.

Keywords: measurement, permeability, permittivity, network analyzer, ferrite, composite material

1 INTRODUCTION

The high-frequency measurement of electromagnetic properties of materials such as complex permeability $\mu^* = \mu' - j\mu''$ and permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$ is important not only for scientific but also for industrial applications. For example, areas in which knowledge of the properties of materials at high frequencies (as described by μ^* and ε^*) is useful are applications of microwave heating, biological effects of microwaves, non-destructive testing, suppression of electromagnetic interference in communication systems, etc.

Various methods for the measurement of μ^* and ε^* of the non-metallic materials have been reported [1, 2]. Among them, a short-circuited coaxial transmission line method is frequently used [3, 4]. In this case it is possible to make automatic measurements over the wide frequency range with a convenient vector based analyzer. Therefore we enhanced the automated measurement system described in [4] with a computer-controlled network analyzer (Agilent 8714ET).

Using the method described in this work, the complex values of μ^* and ε^* are determined from reflection coefficient measurements made directly in the frequency domain. The relevance of the used measurement method was verified on some MnZn ferrite and MnZn/PVC polymer composite materials.

2 MEASUREMENT SET-UP AND SOFTWARE

A computer-controlled instrument (Agilent 8714ET) is used to measure the complex reflection coefficient $\Gamma^* = \Gamma' + j\Gamma''$ by means of a network analysis method in the frequency range of 300 kHz – 3 GHz, Fig.1. The instrument hardware consists of an internal sweeping signal source, a test set to separate forward and reverse test signals, and a multi-channel phase-coherent highly sensitive receiver (detector). The signal source launches a signal at a single frequency to the sample (ie material under test – MUT).

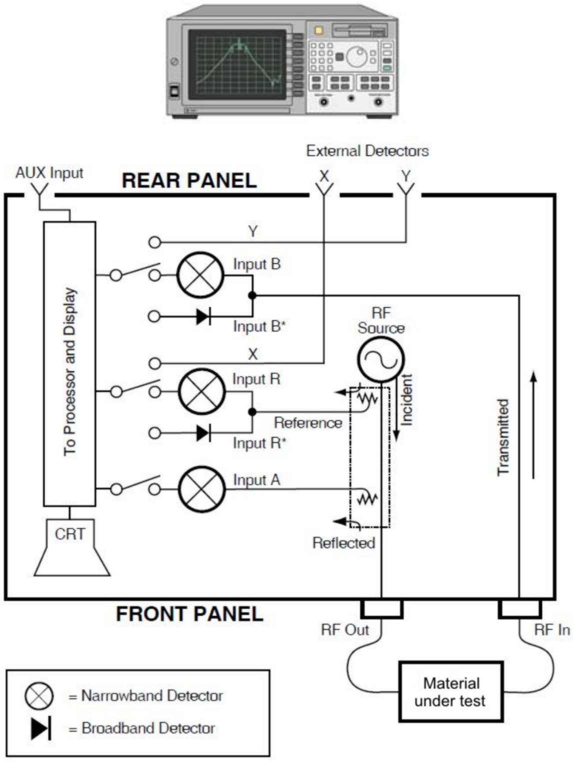

Fig. 1. The operation principle of 8714ET.

The receiver is tuned to that frequency to detect the reflected and transmitted signals from the sample, [5]. The measured response produces the magnitude and phase data at that frequency.

The source is then stepped to the next frequency and the measurement is repeated to display the reflection (and/or transmission) measurement response as a function of frequency. The internal processor is able to recalculate the measured complex reflection (or transmission) coefficient to corresponding complex impedance *Z*.

The VEE environment (Agilent technology) was used to develop an object-oriented program for the computer control of measurement process. To achieve this purpose, the

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8714ET instrument was connected with a host PC via a GPIB interface (USB/GPIB Interface 82357B), Fig. 2. The developed program allows to:

- define the measuring conditions (test frequency, output signal level, number of measured points, etc.)
- perform the full one-port calibration (OPEN, SHORT and LOAD calibrations)
- provide both the electrical length and residual/stray impedance (or admittance) compensations
- measure the complex reflection Γ^* (or transmission T^*) coefficient
- recalculate the obtained measured quantity (Γ^* or T^*) to corresponding values of complex impedance
- calculate the complex permeability μ^* and permittivity ε^*
- display the response of μ^* and ε^*

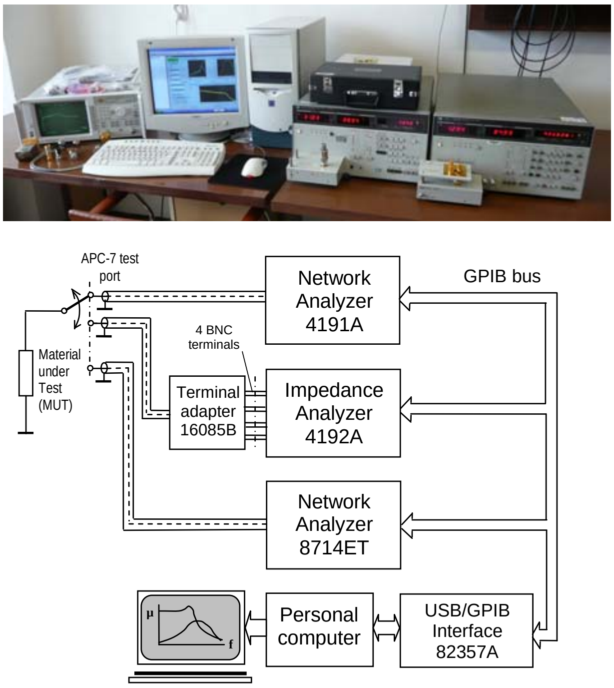

Fig. 2. The photograph and block diagram of experimental set-up.

3 DESCRIPTION OF SAMPLE HOLDERS

Each of parameters (μ^* and ε^*) requires different type of a sample holder. For the determination of complex permeability $\mu^* = \mu' - j\mu''$ of a material, a piece of an enclosed coaxial transmission line (Agilent 16454A, [6]) as a sample holder was used, Fig. 3. The magnetic holder is a conductive shield surrounding the central conductor, which terminates in a short circuit. The length of the holder should be less than the wavelength λ of incident ac electromagnetic wave to avoid the λ/4–dimensional resonance effect. Since the construction of the holder creates one turn around the toroidal sample (with no magnetic flux leakage), the (complex) magnetic flux of the measurement circuit including the ring core is given by $\Phi^* = \iint_S \vec{\mathcal{B}} \cdot d\vec{S}$ with $\vec{\mathcal{B}}$ the magnetic flux density phasor-vector and S the cross section of the ring sample.

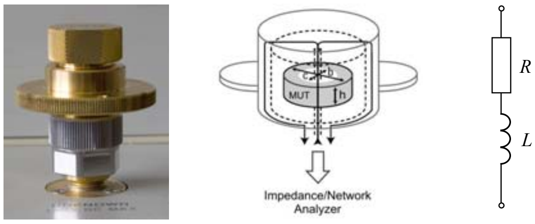

Fig. 3. View of the 16454A magnetic holder and its structure.

If $Z = R + j\omega L = j\omega\Phi^*/\mathrm{I}$ is the equivalent series impedance of the holder loaded with the magnetic core (I is the phasor of sinusoid electric current), we can derive the equation for the complex (relative) permeability μ^* and its real μ' and imaginary μ'' parts, [3]:

$$\mu^* = \mu' - j\mu'' = 1 + \frac{Z - Z_{\mathrm{air}}}{jh \cdot f \cdot \mu_{\mathrm{o}} \cdot \ln(b/c)} \tag{1}$$

$$\mu' = 1 + \frac{X - X_{\mathrm{air}}}{h \cdot f \cdot \mu_{\mathrm{o}} \ln(b/c)} \qquad \mu'' = \frac{R - R_{\mathrm{air}}}{h \cdot f \cdot \mu_{\mathrm{o}} \ln(b/c)} \tag{2,3}$$

where $Z = R + jX$ and $Z_{\mathrm{air}} = R_{\mathrm{air}} + jX_{\mathrm{air}}$ are the input complex impedances of the holder with and without ring core, respectively, h is the height of the sample, f the frequency, μ_{o} is the permeability of free space, and b and c the outer and inner diameters of the ring core. The dimensions b, c and h must satisfy the following conditions: $b \le 8$ mm, $c \ge 3.05$ mm and $h \le 3$ mm. The electrical length between the holder and a measuring port (APC–7) of the network analyzer must be compensated. Therefore, after the calibration of the analyzer, the electrical length (N connector and N to APC–7 adapter) is set to zero. Without this compensation, spurious geometrical resonances might be present in the experimental data. When the sample is inserted into the holder, the whole system is completely closed and then connected to the previously calibrated network analyzer, which supplies an electromagnetic wave propagating in a TEM mode. The reflection coefficient Γ^* is measured, permitting the determination of the input impedance Z of the holder with the sample. Once the input impedance of the holder with (Z) and without (Z_{air}) the toroidal sample is known, the complex (relative) permeability μ^* is obtained by the equations (1-3).

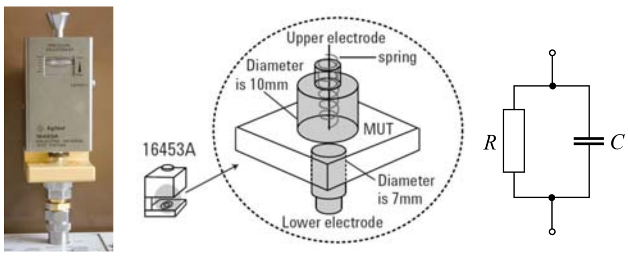

Fig. 4. View of the 16453A dielectric holder and its structure.

For the determination of complex permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$ of a material, a dielectric holder (Agilent 16453A, [7]) has been used, Fig. 4. The applicable sample should be a solid sheet that is smooth, and has equal thickness from one end to the other. The diameter D and thickness t of the MUT must satisfy the following conditions: $D \ge 15$ mm and $0.3 \le t \le 3$ mm. The structure of the dielectric holder is similar to the "parallel plate capacitor" and consists of an upper electrode (with a diameter of 10 mm) and a bottom electrode (with a diameter of 7 mm). The upper electrode has an internal spring, which allows the MUT to be fastened between the electrodes. Applied pressure can be adjusted as well. It should be noted that the dielectric holder is not equipped with any "guard electrode" because this type of electrode at high frequency (typically over 30 MHz) only causes greater residual impedance and poor overall frequency characteristics. The effect of edge capacitance due to the missing guard electrode can be eliminated using a special correction function (based on simulation results). Also residual impedance, which is a major cause for measurement error at high frequencies, cannot be entirely removed by only OPEN and SHORT compensations. Therefore also the LOAD compensation (with a calibrated Teflon sheet) must be provided. The equivalent electric circuit of the "parallel plate capacitor" formed using the 16453A dielectric holder, is considered to comprise an equivalent parallel conductance G and an equivalent parallel capacitance C, as shown in Fig. 4. The complex impedance $Z_{\mathrm{sample}} = R_{\mathrm{s}} + \mathrm{j}X_{\mathrm{s}}$ of the equivalent electric circuit is given by

$$Z_{\mathrm{sample}} = \frac{1}{G + j\omega C} = \frac{1}{j\omega C_{\mathrm{o}}\left(\dfrac{C}{C_{\mathrm{o}}} - j\dfrac{1}{\omega R C_{\mathrm{o}}}\right)} = \frac{1}{j\omega C_{\mathrm{o}}\varepsilon^{*}} \tag{4}$$

where $C_{\mathrm{o}} = \varepsilon_{\mathrm{o}} S/t$ is the capacitance when between the electrodes is air, S is the area of bottom electrode, ω is the angular frequency and ε^{*} is the complex (relative) permittivity of MUT. Therefore, the ε^{*} and its real ε' and imaginary ε'' parts can be calculated by

$$\varepsilon^{*} = \varepsilon' - j\varepsilon'' = -j\frac{1}{Z_{\mathrm{sample}} C_{\mathrm{o}} 2\pi f} \tag{5}$$

$$\varepsilon' = -\frac{t \cdot X_{\mathrm{s}}}{2\pi f (R_{\mathrm{s}}^2 + X_{\mathrm{s}}^2)\varepsilon_{\mathrm{o}} S} \qquad \varepsilon'' = \frac{t \cdot R_{\mathrm{s}}}{2\pi f (R_{\mathrm{s}}^2 + X_{\mathrm{s}}^2)\varepsilon_{\mathrm{o}} S} \tag{6}$$

In case of a conductive material with dc electrical conductivity σ_{dc}, the imaginary part ε'' of ε^{*} is modified

$$\varepsilon'' = \frac{t \cdot R_{\mathrm{s}}}{2\pi f (R_{\mathrm{s}}^2 + X_{\mathrm{s}}^2)\varepsilon_{\mathrm{o}} S} - \frac{\sigma_{\mathrm{dc}}}{2\pi \varepsilon_{\mathrm{o}}} \tag{7}$$

It should be noted that silver (paste) is highly recommended to use in order to minimize the errors due to air gaps.

The determination of both the electromagnetic parameters, complex permeability μ^{*} and complex permittivity ε^{*}, also requires to perform the residual impedance, stray admittance and electrical length compensations. The additional information about these compensations can be found in [3, 4].

4 EXPERIMENTAL

As example, Fig. 5 and Fig. 6 depict the frequency dependences of real (μ' and ε') and imaginary (μ'' and ε'') parts of complex (relative) permeability $\mu^{*} = \mu' - \mathrm{j}\mu''$ and permittivity $\varepsilon^{*} = \varepsilon' - \mathrm{j}\varepsilon''$ for sintered MnZn ferrite with the chemical formula $Mn_{0.52}Zn_{0.43}Fe_{2.05}O_4$ (Fig.6,a and Fig.7,a) and MnZn/PVC polymer composite material with the volume content of 60 vol% (Fig.6,b and Fig.7,b). The details about the preparation conditions and properties of samples can be found elsewhere [8].

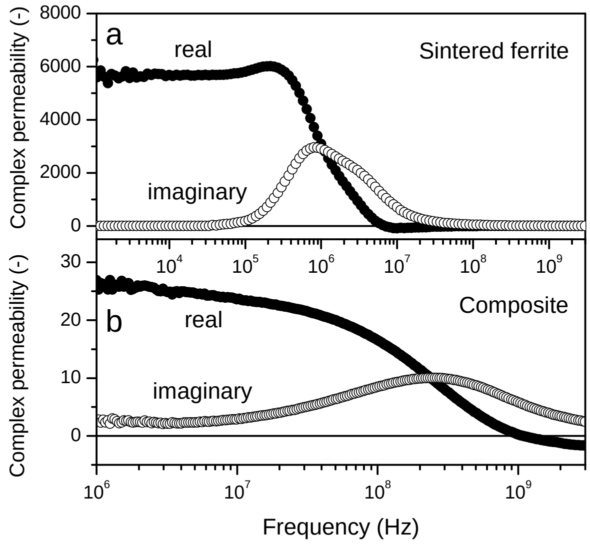

Fig. 5. The frequency dependences of real and imaginary parts of complex permeability for a) sintered MnZn ferrite and b) MnZn/PVC composite.

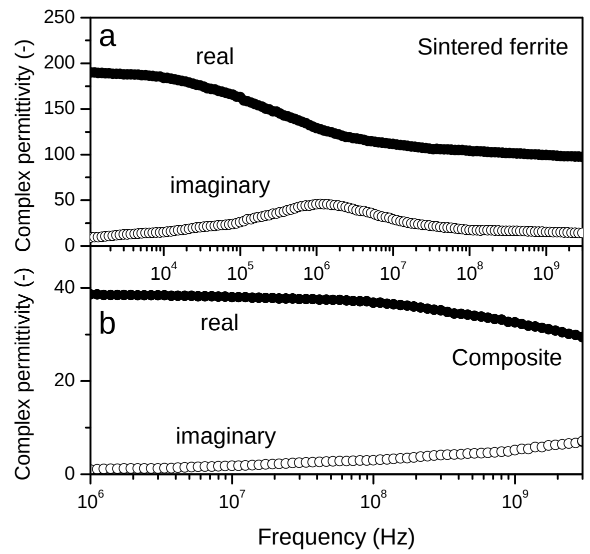

Fig. 6. The frequency dependences of real and imaginary parts of complex permittivity for a) sintered MnZn ferrite and b) MnZn/PVC composite.

At low frequencies, the real part of complex permeability, μ', is about 5630 for ferrite and about 27 for composite. As the frequency increases, the measured dependence for ferrite remains level at first and then rises to a certain peak before falling rapidly to relatively low values. The loss component, μ'', rises to a pronounced peak as μ' falls. This is the resonance type of permeability dispersion. The resonance/relaxation frequency f_{c}, at which μ'' has a maximum value, is about 850 kHz for ferrite and about 260 MHz for composite. The frequency dispersion of permeability in ferrite and composite material is principally due to the resonance of oscillating domain walls and the resonance of preceding magnetic moments in domains (natural ferromagnetic resonance). In case of composite, we observe relaxation type of permeability dispersion in contrary to sintered ferrite.

The variation of $\varepsilon^* = \varepsilon' - j\varepsilon''$ with frequency reveals the dispersion due to Maxwell-Wagner type interfacial polarization (and the presence of space charge at grain boundaries) in agreement with Koops phenomenological theory [9]. Moreover, the polarization in ferrites (and also ferrite-based materials such as ferrite-polymer composites) is through a mechanism similar to the conduction process [10]. By electron exchange between $Fe^{2+} \leftrightarrow Fe^{3+}$, one obtains local displacement of electrons in the directions of the electric field and these electrons determine the polarization. The polarization decreases with increase in frequency and then reaches almost a constant or maximum value due to the fact that, beyond a certain frequency of external ac electric field, the electronic exchange $Fe^{2+} \leftrightarrow Fe^{3+}$ cannot follow the ac field. The relatively large values of ε' at low frequencies are due to the predominance of the species like Fe^{2+} ions, interfacial dislocations, oxygen vacancies, grain boundary defects, etc. The decrease in ε' with frequency is natural because of the fact that any species contributing to the polarization will be lagging behind the applied ac field at higher frequencies.

5 CONCLUSIONS

The paper presented the one-port short-circuit transmission line method to extract constitutive material parameters such as complex permeability and permittivity from the measured complex reflection parameter in the frequency range concerned (300 kHz – 3 GHz). The VEE object-oriented software for the whole computer control, post processing and results evaluation has been developed and verified on the selected ferrite and ferrite-polymer composite materials. The relevance of described measurement method, the used relations for material parameters calculation and developed software was confirmed.

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REFERENCES

[1] BUSSEY, H.E.: Measurement of RF Properties of Materials, A Survey, Proc. of the IEEE **55** (1967), 1046-1053.

[2] LYNCH, A.C.: Precise Measurements on Dielectric and Magnetic Materials, IEEE Trans. Instrum. Meas. **IM-23** (1974), 425-431.

[3] DOSOUDIL, R. – OLAH, V.: Measurement of Complex Permeability in the RF Band, Journal of Electrical Engineering **55**, No. 10/S, (2004), 97-100.

[4] DOSOUDIL, R. – UŠÁK, E – OLAH, V.: Computer Controlled System for Complex Permeability Measurement in the Frequency Range of 5 Hz – 1 GHz, Journal of Electrical Engineering **57**, No. 8/S, (2006), 105-109.

[5] Agilent 8714ET, Vector Network Analyzer 300 kHz – 3000 MHz, Operation manual

[6] Agilent 16454A, Magnetic Material Test Fixture, Operation manual

[7] Agilent 16453A, Dielectric Material Test Fixture, Operation manual

[8] DOSOUDIL, R. – UŠÁKOVÁ, M. – SLÁMA, J. – GRUSKOVÁ, A.: Permeability Dispersion in Ni–Zn–Cu Ferrite and Its Composite Materials, Czechoslovak Journal of Physics **54**, Suppl.D (2004), D675–D678.

[9] KOOPS, C.G.: On the Dispersion of Resistivity and Dielectric Constant of Some Semiconductors at Audio Frequencies, Phys. Rev. **83** (1951), 121-124.

[10] DOSOUDIL, R. – GRUSKOVÁ, A. – ĎURMAN, V. – UŠÁKOVÁ, M. – ŠUBRT, J.: Electrical and Dielectric Properties of Ni-Zn Ferrites, Proceedings of the 15th Inter. Conf. DISEE (2004), 208-212.

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