DETERMINATION MAGNETIC CHARACTERISTICS OF MATERIALS USING SHORT COAXIAL LINE REFLECTION METHOD

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Abstract: *In this paper, the possibility of complex permeability measurement of ferrite materials is shown using short coaxial sample holder in frequency range between 300 kHz and 1 GHz. The design of coaxial high frequency sample holder is presented and the principle of measurement and calibration are explained in details. The measuring of complex permeability is managed based on accomplished formulas, and results that are obtained are explained in detail. For computer control and measurement, the user-friendly program has been developed. In order to verify proposed method, the results of measurement of NiZn ferrite samples are compared with catalog characteristics.*

Key Words: Complex permeability, coaxial sample holder, sintered ferrites.

1 .INTRODUCTION

Magnetic permeability measurements are reviewed from the viewpoint of radio and communications applications. Knowledge of this parameter may be applied in circuit design and wave transmission calculations. The important radio and microwave magnetic materials are mainly thin films and nonconductor forms powdered-iron suspensions and ferrites. The NiZn ferrites have wide applications in the industry. These materials have many useful properties, are versatile, and require many measurements for their characterization. The intrinsic complex permeability is the critical parameter for the optimization design, especially in the high-frequency applications.

Magnetic permeability is the ratio of magnetic flux density *B* to the applied magnetizing field *H* and it describes the interaction of a material with a magnetic field. Relative complex permeability $\tilde{\mu}_r = \mu_r' - j\mu_r''$ consists of the real part μ_r' that presents the energy storage term and imaginary part μ_r'' that presents the power dissipation term. A number of review papers [1-3] that present many different techniques, have been published on measurements of magnetic materials at RF and microwave frequencies. In order to determine the complex permeability of toroidal-shape samples, in this paper, measured of *s*-parameters have been performed using the *Agilent Technology* vector network analyzer, that work in the frequency range between 300 kHz and 8.5 GHz. Generalized network analyzer block diagram and measurement principle is depicted in Fig. 1.

The complex reflection coefficient $\tilde{\Gamma} = \Gamma' + j\Gamma''$ is obtained by measuring the ratio of a reflected signal to the incident signal. Supplies stimulus system and can sweep frequency or power. Traditionally network analyzers had one signal source while modern have option for two internal sources. Signal separation block separate incident and reflected signals. Couplers are commonly used to separate signals, that moving in opposite directions. The directional bridge circuit or varactors is used to detect the reflected signal, and the analyzer equipped with the bridge is used to supply and measure the signals. Directional bridge is good for measuring frequency-translating devices and improves dynamic range by increasing power, but have high level of noise. Narrowband detection that uses varactor has better dynamic range and harmonic immunity and provides trade off noise floor and measurement speed. Since this method makes it possible to measure reflection at the design under test (DUT), it is usable in RF and microwave band. The measured values of reflection coefficient are automatically converted into the corresponding values of the impedance in the frequency range concerned. The other measurement parameter values such as resistance *R*, inductance *L*, and permeability are calculated from the values of the measured components (Γ', Γ''). The permeability of test sample can be obtained by measuring the input differences between the short coaxial sample holder loaded with and without a toroidal sample.

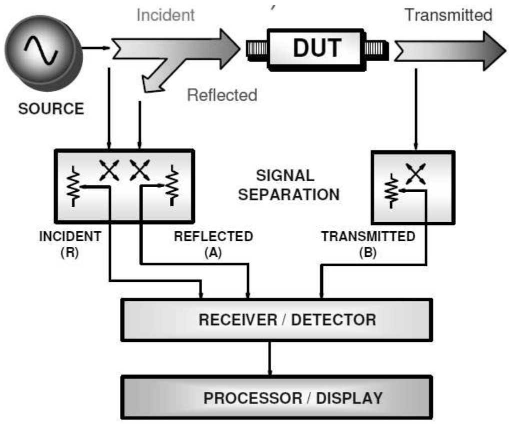


Fig. 1. *Measurement principle of Agilent Technology network analyzer.*

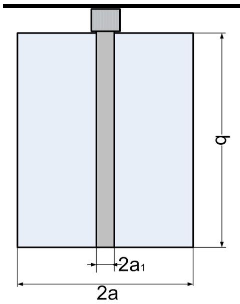
This paper presents the experimental technique for measuring the complex permeability of toroidal sample, based on short coaxial line method in the frequency range between 300 kHz and 1 GHz. Two original coaxial line holders were used from *Agilent*, one for small and the other for large samples. In comparison with the some other coaxial techniques that are widely used [4], elimination of undesirable influences such as optimization and phase compensation are eliminated. A simple holder method for high frequency measurement of *s*-parameter of toroidal magnetic samples has been designed and verified. In order to verify the proposed method, the result of measurements of NiZn ferrite samples are compared with catalog results and discussed. Two NiZn samples from Fair-Rate Corp. (F14 and F19 ferrite) were used to verify the relevance of proposed method. In order to simplify the evaluation of obtained results and calculation process a user-friendly program is written for computer control.

2. MEASURED PRINCIPLE

High frequency measurement of complex permeability is almost based the coaxial line method [4]. For this purpose two different coaxial line cells have been used, Fig. 2. The first one was for large core (up to 10mm) and the other one was an original 50Ω for small cores (up to 7mm). The both connector are terminated with the APC-7 connector. Main characteristics of given holders are summarized in Table I. The vector analyzer has a test port equipped with a fixed APC-7 connector. Sample holders have conductive shield surrounding the central conductor, which terminates in short circuit. The short circuit produced a maximum magnetic field and a minimum electric field near the sample, thus making the short circuit technique particularly suited for the measurement of the magnetic properties, such as permeability of the test sample. The medium between the inner and outer conductors of cell is air. The inner length *b* is 20mm for both holder, obeys the condition b<λ/4 for maximal frequency (f=1GHz) in order to avoid the λ/4 resonant effect, where λ is signal wavelenght.

Fig. 2. *APC-7 conector and standard coaxial line cells.*

Table 1. *Main characteristics of given holders*

	Type	Impedance	Dimensions
	04191-85302	Z_0=50Ω	2a=7mm $2a_1$=3mm b=20mm
	16091-60012	Z_0=66Ω	2a=10mm $2a_1$=3mm b=20mm

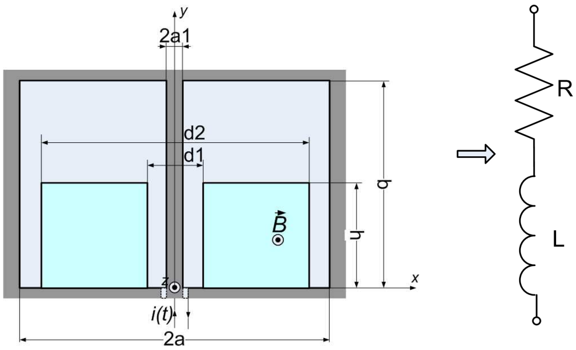


Fig. 3. *Cross section of sample holder with toroidal sample and adequate electrical model.*

When the sample is inserted into the holder, the whole system is completely closed and then connected thought the APC-7 to the previously calibrated impedance analyzer. The analyzer supplies an electromagnetic wave propagating in a TEM mode. The reflection coefficient is measured, permitting the determination of the input impedance of the cell with sample. Equation for the determination of complex permeability of the holder equipped with the test sample is derived in this section. Since the construction of this holder creates one turn around the toroid, Fig. 3 the complex magnetic flux of the measurement circuit including the ring core is given by the equation:

$$\tilde{\Phi} = \iint_S \vec{B} \cdot d\vec{S} = \int_0^a \int_0^b \frac{\mu_0 \mu_r I}{2\pi x} dxdy \,. \tag{1}$$

By dividing the surfaces of cross section into the holder, equation (1) for complex flux density is given by equation (2), where $\vec{B}$ present complex phasor-vector of magnetic density, μ_0 is permeability of free space, μ_r is relative permeability of sample, and *I* is a complex phasor of harmonic time-dependent electrical current *i(t)*:

$$\tilde{\Phi} = \int_{\frac{d_2}{2}}^{a} \int_{0}^{b} \frac{\mu_0 I}{2\pi x} dxdy + \int_{\frac{d_1}{2}}^{\frac{d_2}{2}} \int_{0}^{h} \frac{\mu_0 \tilde{\mu}_r I}{2\pi x} dxdy + \int_{\frac{d_1}{2}}^{\frac{d_2}{2}} \int_{h}^{b} \frac{\mu_0 I}{2\pi x} dxdy + \int_{0}^{\frac{d_1}{2}} \int_{0}^{b} \frac{\mu_0 I}{2\pi x} dxdy + \int_{0}^{a_1} \int_{0}^{b} \frac{\mu_0 I}{2\pi x} dxdy \cdot \tag{2}$$

The magnetic flux of measured circuit is then:

$$\tilde{\Phi} = \frac{\mu_0 I}{2\pi} \left\{ (\tilde{\mu}_r - 1) h \cdot \ln\left(\frac{d_2}{d_1}\right) + b \cdot \ln\left(\frac{a}{a_1}\right) \right\} \tag{3}$$

and the complex susceptibility of a sample under test is given by equation:

$$\tilde{\chi} = \frac{2\pi\left(\tilde{\Phi} - \tilde{\Phi}_{air}\right)}{hI\mu_0 \cdot \ln\left(\frac{d_2}{d_1}\right)}, \tag{4}$$

where $\tilde{\Phi}_{air}$ is a magnetic flux when ferrite cores is not mounted in the holder:

$$\tilde{\Phi}_{air} = \frac{b\mu_0 I}{2\pi} \ln\left(\frac{a}{a_1}\right). \tag{5}$$

The measured complex impedance *Z* of an equivalent electric circuit of the cell loaded with the ferrite core shown in Fig. 3 can be defined as $\tilde{Z} = R + j\omega L = j\omega\tilde{\Phi} / I$. Instead of fluxes $\tilde{\Phi}$ i $\tilde{\Phi}_{air}$ in equation (4) we can use corresponding complex impedance *Z* and Z_{air}, measured with and without magnetic core, respectively:

$$\tilde{\mu}_r = 1 + \tilde{\chi} = 1 + \frac{\left(\tilde{Z} - \tilde{Z}_{air}\right)}{jh \cdot \mu_0 \cdot f \cdot \ln\left(\frac{d_2}{d_1}\right)}, \tag{6}$$

where d_1 and d_2 denotes the inner and outer diameters of the toroid, respectively, *h* is the height of the toroid and *f* is the frequency of applied *ac* electromagnetic field. Complex permeability is therefore calculated from difference between the impedance of cell loaded with and without toroidal sample. The vector analyzer measures the complex reflection coefficient, which is recalculated to the input impedance of the cell (with or without sample) according to the following equation:

$$\tilde{Z}_{in} = Z_0 \frac{1 + \tilde{\Gamma}}{1 - \tilde{\Gamma}}, \tag{7}$$

with Z_0=50Ω characteristic impedance of the 7mm test port. Resistance R_{in} and reactance X_{in} values of the input impedance of the cell $\tilde{Z}_{in} = R_{in} + jX_{in}$ can then be calculated using the following relations:

$$R_{in} = Z_0 \frac{1-\Gamma'^2 - \Gamma''^2}{(1-\Gamma')^2 + \Gamma''^2},$$

$$X_{in} = Z_0 \frac{2\Gamma''}{(1-\Gamma')^2 + \Gamma''^2}. \tag{8}$$

Once Z_{in} of the holder with and without toroidal sample is known and the complex (relative) permeability $\tilde{\mu}_r$ is obtained by equation (6).

3. EXPERIMENT AND RESULTS

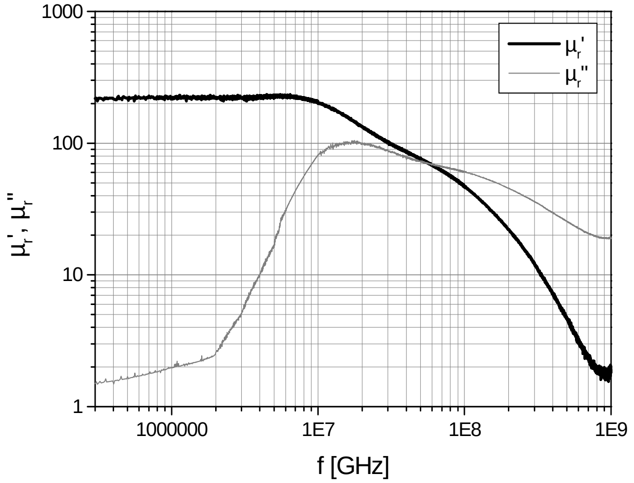
In order to the verification of proposed method that use short coaxial line holder, two test sample of Fair-Rite company are used, base on NiZn material called F14 and F19. The basic characteristics of used samples are shown in Table II, where B_s denote saturation flux density, B_r is remanent flux density, H_c is coercitivity. Dimensions of both samples are also shown in Table II. The thickness of samples satisfies the condition b<λ/4, at witch dimensional resonance effect cannot occur in the measured results.

Table 2. *Characteristics parameters of Fair-rate samples: F14 and F19*

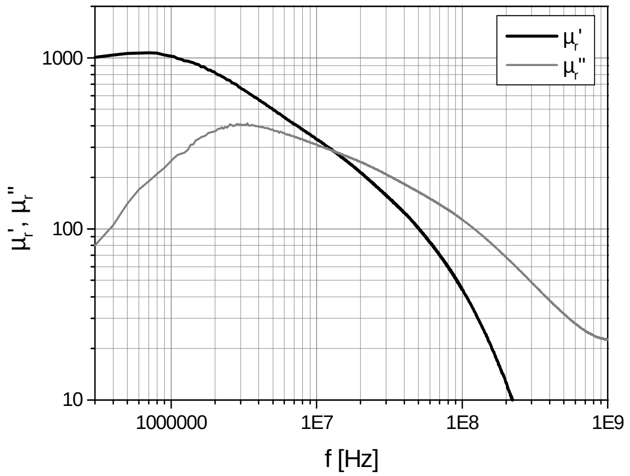
	F14	**F19**
Dimensions	6.35x3.18x1.52	9.52x4.75x3.18
Initial permeability	220 B<0.1mT/10kHz	1000 B<0.1mT/10kHz
B_s **[mT]**	350	260
B_r **[mT]**	217	165
H_c **[A/m]**	172	53

Calculated results obtained using proposed equation for real and imaginary part of compel permeability for F14 and F19 samples in function of frequency are shown in Fig. 4. All measurements are done in ideal condition on the temperature of 25°C.

The change of real part of complex permeability with frequency close the critical frequency f_c is called the dispersion of permeability and the change of imaginary part with frequency is known as absorption. Sintered NiZn ferrites showed a resonant type of frequency dispersion. At low frequency NiZn samples have high values of real part of complex permeability (at about 200 for F14 and about 1000 for F19). Critical resonant frequency is the value at which the imaginary part has a maximum and for F14 and F19 they are: 25MHz and 3MHz, respectively. It is proportional to the saturation magnetization of ferrite filler and with arising demagnetization fields of ferrite particles incorporated into the polymer matrix.



(a)



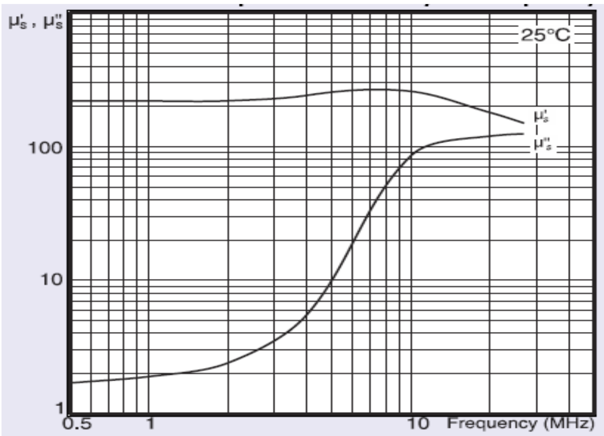
(b)

Fig. 4. *Calculated results for real and imaginary part of complex permeability for: (a) F14, (b) F19*

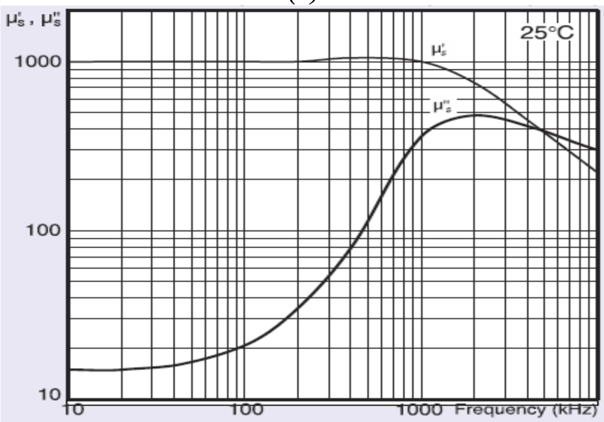
Fig. 5. Catalog characteristics of NiZn samples: (a) F14 and (b) F19 reprinted from [5].
In order to verify proposed method obtained measurement results of NiZn ferrite samples are compared with catalog characteristics. Catalog characteristics for F14 and F14 samples are shown in Fig. 5, reprinted from [5]. Good arrangement between results obtained using short coaxial line method and catalog characteristics are obtained in the frequency range between 300 kHz and 1 GHz. Small variations exist as a consequence of tolerance of sample dimensions.

4. CONCLUSION

In this paper, short circuit sample holder for measured a complex permeability of toroidal magnetic samples is described, in details. The measurement principles of system that allow measurement of complex permeability in wide frequency range are proposed. Special attention has been paid to conversion of measured values of complex reflection coefficients to the characteristic impedance. Program code for computer control processing of measuring results is developed. In order to verify proposed method, the results of measurement are compared with catalog characteristics for NiZn Fair-rate samples F14 and F19. A good arrangement with results obtained using short coaxial line method can be are obtained in the wide frequency range, expect for shift in a frequency that is consequences of sample dimensions.



(a)



(b)

5. REFERENCE

[1] W. B. Weir: "Automatic measurement of complex dielectric constant and permeability at microwave frequencies," Proc. of the IEEE, 1972, Vol. 62,

[2] Hewlett-Packard Product Note no.8510-3,

[3] V. Chukhov: "Methodic of magnetic permeability measurement," 14th International Crimean Conference on **Microwave and Telecommunication Technology, CriMico,** Sept.2004. pp:680- 681,

[4] R. Dosoudil, E. Ušak, V. Olah: "Computer controlled system for complex permeability measurement in the frequency range of 5Hz-1GHz," *Journal of Electrical Engineering*, Vol. 57, No 8/S, 2006, pp.105-109,

[5] Fair-Rate products Corp.: "Soft Ferrites-Ferrite Products for the Electronics Industry," 14th Edition, 2001, www.fair-rate.com,