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MICROWAVE BRIDGE WITH FERRITE SAMPLE

FRANEK, J.[1]), KABOŠ, P.[1]), Bratislava

A microwave bridge system with transmission line model of the longitudinally magnetized ferrite slab is pressented and analysed. The analysis of the microwave bridge with regard to the ferrite parameters (ΔH, M_s, ε_r) represents an inverse problem. The results should prove useful in the prediction of the system behaviour for different magnetic fields or frequencies.

I. INTRODUCTION

Transmission line model of a semiconductor slab has been presented in [1, 2]. The model allowed to analyse experiments with the excitation of helicon waves in semiconductor plasma. The experimental setup presented in [1, 2] can be used for the investigation of the properties of ferrite materials too (Fig. 1). In spite of the identical setup configuration the description of the propagation of helicon waves in semiconductor plasma and of electromagnetic waves in ferrite is different. Due to the strong damping of the helicon waves it has been possible to take into account only the propagation of the ordinary helicon wave, while the propagation of the extraordinary wave could be neglected. The situation in the case of ferrites is different. The losses in ferrite are much lower and so it is necessary to take into account both propagating circulary polarized electromagnetic waves, which shows in the change of the transmission line model used.

II. THEORY

We assume that the source (antenna) excites in sample a linearly polarized plane electromagnetic wave. Let the electric field intensity be oriented along the x axis and the direction of propagation be along the z axis. Let the electric field intensity of the wave on the surface of the sample be

$$\mathscr{E}_1 = \begin{vmatrix} E_1 \\ 0 \end{vmatrix}, \qquad (1)$$

[1]) Department of electrical engineering Slovak Technical University, BRATISLAVA, CSFR

where the matrix vector description has been used. The time dependence is expected in the form $\exp(j\omega t)$, so the vector components are complex numbers. Let the phase of the E_1 be zero for simplicity. A linearly polarized electromagnetic wave in ferrite can be decomposed (see e.g. [3]) into two circulary polarized waves. We denote the electrical intensity of the first by the subscript A and of the second by B. The polarizations of the waves are expressed through the matrices $\begin{vmatrix} 1 \\ j \end{vmatrix}$ and $\begin{vmatrix} 1 \\ -j \end{vmatrix}$, where j is the imaginary unit. The corresponding wave vectors and wave impedances are denoted k_A, k_B, Z_A, Z_B. Expressing electromagnetic fields in the slab as a superposition of the forward and backward waves one can obtain the resulting electric field intensity of the electromagnetic wave at the beginning of the sample in the form

$$\mathscr{E} = \mathscr{E}_1^+ + \mathscr{E}_1^- = A_1(\bar{\bar{I}} + \bar{\bar{\varrho}}_2 e^{-j2k_A l})\begin{vmatrix} 1 \\ j \end{vmatrix} + B_1(\bar{\bar{I}} + \bar{\bar{\varrho}}_2 e^{-j2k_B l})\begin{vmatrix} 1 \\ -j \end{vmatrix}, \tag{2}$$

where $\bar{\bar{I}}$ is the unit tensor, l the length of the sample, $\bar{\bar{\varrho}}_2$ the reflection matrix

$$\bar{\bar{\varrho}}_2 = \begin{vmatrix} \frac{1}{2}(\varrho_A + \varrho_B) & \frac{\varrho_A - \varrho_B}{2j} \\ -\frac{\varrho_A - \varrho_B}{2j} & \frac{1}{2}(\varrho_A + \varrho_B) \end{vmatrix} \tag{3}$$

with ϱ_A, ϱ_B reflection coefficients of the corresponding waves. An analogical approach can be used for calculation of the magnetic field intensities. The resulting magnetic field intensity at the beginning of the sample then will be

$$\mathscr{H}_1 = \mathscr{H}_1^+ + \mathscr{H}_1^- = \frac{A_1}{jZ_A}(\bar{\bar{I}} - e^{-j2k_A l}\bar{\bar{\varrho}}_2)\cdot\begin{vmatrix} 1 \\ j \end{vmatrix} + \frac{B_1}{-jZ_B}(\bar{\bar{I}} - e^{-j2k_B l}\bar{\bar{\varrho}}_2)\cdot\begin{vmatrix} 1 \\ -j \end{vmatrix}. \tag{4}$$

The equations (3), (4) allow to introduce input impedance in the form

$$\bar{\bar{Z}}_{11} \cdot \mathscr{H}_1 = \mathscr{E}_1$$

form which after some algebra for the input impedance of the A type wave there follows that

$$Z_{11A} = jZ_A \frac{Z_0 \cosh(jk_A l) + Z_A \sinh(jk_A l)}{Z_0 \sinh(jk_A l) + Z_A \cosh(jk_A l)} \tag{5}$$

and analogically for the second input impedance (B wave)

$$Z_{11B} = -jZ_B \frac{Z_0 \cosh(jk_B l) + Z_B \sinh(jk_B l)}{Z_0 \sinh(jk_B l) + Z_B \cosh(jk_B l)} \tag{6}$$

The equations (5) and (6) are identical with the equations for the input impedance of a transmission line of length l, loaded with the impedance Z_0, the impedance of the medium behind the ferrite slab. Following further the standard procedure the electric field intensity at the end of the slab for the A wave can be expressed in the form

$$\mathscr{E}_{2A} = \mathscr{E}_{1A}\left[\cosh(jk_A l) - \frac{jZ_A}{Z_{11A}}\sinh(jk_A l)\right] \tag{7}$$

and in a simmilar way for a B type wave in the form

$$\mathscr{E}_{2B} = \mathscr{E}_{1B}\left[\cosh(jk_B l) + \frac{jZ_B}{Z_{11B}}\sinh(jk_B l)\right] \tag{8}$$

The vectors E_{1A}, E_{1B} represent the resulting intensity of the electromagnetic wave at the beginning of the sample. Therefore there holds

$$\mathscr{E}_1 = \mathscr{E}_{1A} + \mathscr{E}_{1B} = E_1\begin{vmatrix} 1 \\ 0 \end{vmatrix} = E_{1A}\begin{vmatrix} 1 \\ j \end{vmatrix} + E_{1B}\begin{vmatrix} 1 \\ -j \end{vmatrix} \tag{9}$$

From (9) it follows that

$$E_{1A} = E_{1B}. \tag{10}$$

The resulting intensity of the electromagnetic wave at the end of the sample can be obtained by a superposition of the waves of both types. Therefore, the field gained by the measuring antenna at he end of the sample will be

$$\mathscr{E}_2 = \mathscr{E}_{2A} + \mathscr{E}_{2B} = \begin{vmatrix} E_{2A} + E_{2B} \\ j(E_{2A} - E_{2B}) \end{vmatrix}. \tag{11}$$

We further expect that the receiving antenna is sensitive to the linearly polarized electromagnetic field, and that the angle between the antenna and the x axis is δ. The field at the antenna can be therefore expressed as

$$E_{ant.} = (E_{2A} + E_{2B})\cos\delta + j(E_{2A} - E_{2B})\sin\delta. \tag{12}$$

This signal represents the expected field in one arm of the analysed microwave bridge schematically shown in Fig. 1. The resulting intensity at the detector will be

$$E_g = E_{ant.} - E_{22}, \tag{13}$$

where E_{22} is the electric field intensity at the detector from the reference arm of the bridge.

III. EXPERIMENT

The experimental setup is schematically shown in Fig. 1 [1]. The microwave signal in the reference arm passes the attenuator and the phase shifter and is incident at one part of the magic T. The signal arm consists of the measured sample (ferrite slab with the exciting and receiving antenna) and is connected with the second arm of the magic T.

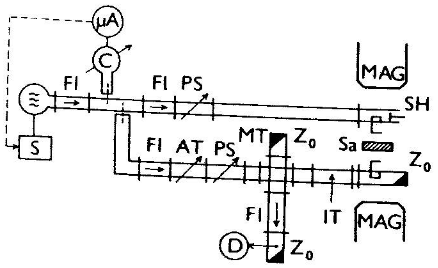

Fig. 1. Microwave bridge. S — source, FI — ferrite isolator, PS — phase shifter, AT — attenuator, MT — magic T, Z_0 — characteristic impedance, D — detector, IT — impedance transformer, SH — moving short, Sa — sample, MAG — magnet, C — microwave cavity.

The sample is placed in the holder between the between the exciting and the receiving antenna. The antenna shown in Fig. 2a represents an open loop transvering the microwave power from the waveguide to the sample and ensuring the linear polarization of the incident power. The mutual orientation of both antennae is perpendicular, as it is possible to see from Fig. 2b. The coupling between the antennae without or with but unmagnetized sample was below the measuring sensitivity of our setup (i.e. less than 40 dB).

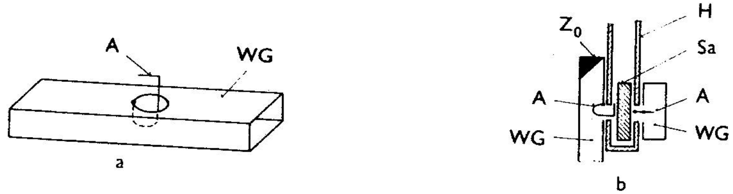

Fig. 2. a) Detail of the antenna. A — antenna, WG — waweguide, b) Position of the Sample, Sa — Ferrit Sample, H — Holder.

Usually, the output voltage at the detector arm of the magic T, as a function of the applied external magnetic field, is recorded. The standard measuring procedure starts with balancing the bridge, at a certain value of the external field B_{0i}, by a proper choice of the attenuation and the phase shift in the reference arm, and proceeds with the changing of the external magnetic field with a simultaneous recording of the detector voltage. A typical experimental dependence is in Fig. 3a, b indicated by dots.

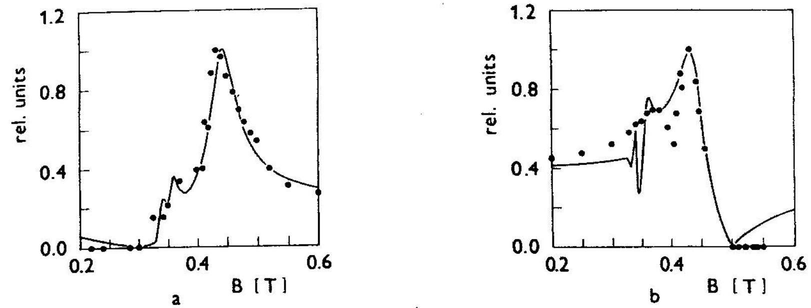

Fig. 3. a) Experimental results (dots) and computer simulation (full line). Microwave bridge is balanced at the magnetic induction $B_r = 0.3$ [T], the other parameters are the same as in Fig. 3b. b) Experiment — dots, computer simulation — full line. Bridge is balanced at $B_r = 0.5$ [T]. $f = 9.22$ [GHz], $M_0 = 0.171$ [T], $\Delta H = 7 \times 10^{-5}$ [T], $\varepsilon_r = 16$, $l = 3.78$ [mm], $\delta = 0.99$ (rad], $Z_p = 23.24$ [Ω], $\varphi_p = 2.97$ [rad], $R_0 = 40$ [Ω].

IV. ANALYSIS OF THE BRIDGE

The equivalent circuit of the bridge is shown in Fig. 4. To fulfil the condition (10) the homogeneous transmission lines A and B connected in parallel at the input. The electric field intensities in the circuit are described by the corresponding voltages. The transmission lines are loaded by the impedance Z_0, and the

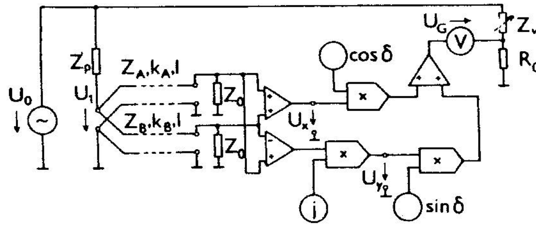

Fig. 4. Equivalent circuit.

detector has been represented by a voltmeter. The impedances R_0, Z_V, Z_p in Fig. 4 are field independent, and the expressions for k_A, k_B, Z_A, Z_B are [3]

$$k_A = k_0 \sqrt{(\varepsilon_r(\mu + \mu_a))} \tag{14}$$

$$k_B = k_0 \sqrt{(\varepsilon_r(\mu - \mu_a))} \tag{15}$$

$$Z_A = \frac{\omega(\mu + \mu_a)\mu_0}{k_A} \tag{16}$$

$$Z_B = \frac{\omega(\mu - \mu_a)\mu_0}{k_B} \tag{17}$$

with μ, μ_a diagonal resp. nondiagonal components of the high frequency permeability tensor [3], $k_0 = \omega/c$, ω is the circular frequency of the signal used. The use of the equations (5) through (13) allows (for given material parameters) the computer analysis of the microwave bridge output voltage as a function of the external magnetic field. To be able to compare the obtained experimental results with the calculations it would be necessary to know all the input parameters entering the mentioned equations. Unfortunately some of them as, e.g., the circuit impedances are not directly measurable, and therefore the problem of the determination of sample parameters such as M_0, ε_r, ΔH represents a badly formulated inverse problem. In the shown example the ferrite parameters M_s, ε_r, ΔH and the frequency ω therefore have been kept constant and the rest has been changed in order to get the least mean square value of the difference between the calculated and the measured voltage in all measured points (i.e. for both balancing fields B_{01} and B_{02}). The calculated results obtained by the mentioned fitting procedure are shown in Fig. 3a, b by full lines.

V. CONCLUSION

It has been shown that the equivalent circuit approach to the modelling of electromagnetic field problems, as shown on the example of the measuring microwave bridge with the ferrite sample, allows the computer analysis of the experiment. In spite of the bad formulating, it is useful in the prediction of the system behaviour investigated as a function of the magnetic field, frequency, temperature etc. Contary to the procedure used in [2] obtaining ferrite parameters from measurement the use to the equivalent circuit approach represents a much more complicated problem which needs a further investigation.

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МИКРОВОЛЬНЫЙ МОСТ С ФЕРИТОВЫМ ОБРАЗОМ

В работе обсуждается система микроволного моста с линией передачи в форме продольно намагниченного ферита. Анализ микроволнового моста с точки зрения параметров ферита (ΔH, M_s, ε_r) представляет обратную задачу. Результаты можно использовать при предсказании поведения системы для разных магнитных полей и частот.