Using a 16 GHz Interferential Reflecto-Ellipso-Polarimeter to Study Magnetic Composite Media

RENÉ SARDOS, JEAN-FRANÇOIS ESCARMANT, YOUCEF RAMDANI, ARTHUR BALANA, AND WILLIAM J. ELLISON

Abstract —**A 16 GHz interferential reflecto-ellipso-polarimeter is described. This apparatus is a combination of a lossv turnstile junction and a three-wave interferometer. One can use it to measure very small variations in the rotation and ellipticity of reflected waves. The device has been used to study waves reflected from a magnetic composite material, formed by compression of PVC and ferrite particles, and under the influence of a magnetic field perpendicular to the direction of wave propagation. For ferrite concentrations exceeding 30 percent, several resonances were observed: they seem to be related to the average distance between the magnetic particles. This "contact" between the magnetic particles could be called magnetic percolation by analogy with electric percolation.**

I. Introduction

IN CENTIMETER-wavelength polarimetry one measures the rotation and ellipticity of a wave after it has passed through an anisotropic medium. From these measurements one can deduce certain properties of the medium related to its anisotropy. For example, with a gyromagnetic medium one can calculate its permeability tensor. For such studies to be possible, it is essential that the waves pass through the medium; i.e., the medium cannot have high losses. The measurements are also very difficult to make if the medium is very depolarizing [1].

In reflecto-polarimetry one measures the rotation and ellipticity of waves reflected from an anisotropic medium. With this technique the medium can be lossy and if it is not lossy one places a short circuit behind the sample to reflect the wave back through the medium. Thus, a reflecto-polarimeter has more applications than a traditional polarimeter. However it is much more difficult to construct. At the moment only one type of reflecto-ellipso-polarimeter can measure small changes in the reflected electromagnetic field. We shall describe the principle of the apparatus, which does not seem to be well known, and give a brief account of an application to the measurement of an anisotropic PVC–Fe_3O_4 composite in a magnetic field. Detailed experimental results will be given elsewhere.

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II. Theory of the Interferential Reflecto-Ellipso-Polarimeter

The apparatus interferential reflecto-ellipso-polarimeter (IREP) has two essential components: a lossy turnstile junction [2] and a three-wave interferometer [3]. The lossy turnstile junction (Fig. 1) consists of a modified classical turnstile junction [4]–[6] in which one of the three metallic tuning plungers has been replaced by a lossy medium.

The principal scattering matrices of this junction can be found in [7]. One of them is suitable for a reflecto-polarimeter; it is the nonunitary matrix:

$$S_1'' = \frac{1}{4}\begin{bmatrix} 1 & -1 & 1 & -1 & 2\sqrt{2} & 0 \\ -1 & 1 & -1 & 1 & 0 & 2\sqrt{2} \\ 1 & -1 & 1 & -1 & -2\sqrt{2} & 0 \\ -1 & 1 & -1 & 1 & 0 & -2\sqrt{2} \\ 2\sqrt{2} & 0 & -2\sqrt{2} & 0 & 0 & 0 \\ 0 & 2\sqrt{2} & 0 & -2\sqrt{2} & 0 & 0 \end{bmatrix}. \tag{1}$$

A diagram of the apparatus is shown in Fig. 2. It is a simplified version of a device described in [1]. The turnstile junction is adjusted to give the matrix $[S_1'']$. The waves E_3 and E_4 are sent into the rectangular arms 3 and 4 of the lossy turnstile junction. The waves E_3 and E_4, coming from the same source, have the form $D\cdot\exp(j\omega t)$; i.e., they have the same amplitude and they are in phase. Let $[v]$ be the matrix of the waves which arrive at the turnstile, then

$$[v] = \left(\begin{bmatrix} 0 \\ 0 \\ D \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ D \\ 0 \\ 0 \end{bmatrix}\right) e^{j\omega t}. \tag{2}$$

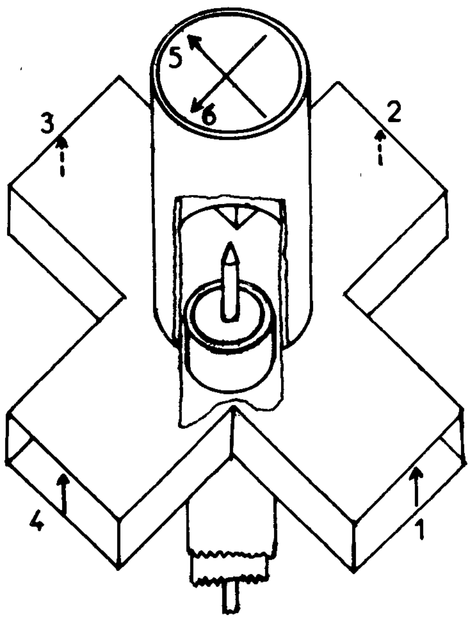

Fig. 1. The lossy turnstile junction.

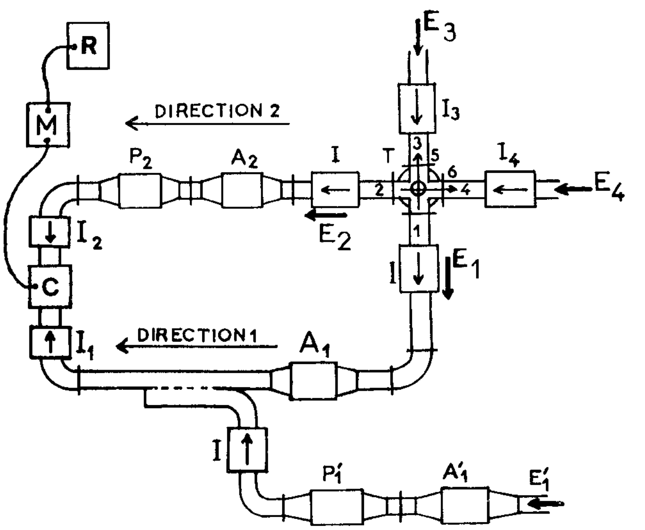

Fig. 2. Three-wave interferential reflecto-polarimeter-ellipsometer recorder. Note that ports 5 and 6 of the turnstile are two different polarizations in the same waveguide: T—lossy turnstile junction; P—phase shifter; A—attenuator; I—isolator; C—comparator; M—$VSWR$ meter; R—recorder.

The matrix of the waves which leave the turnstile junction by the circular waveguide is

$$[S_1''][v] = [V] = -D/\sqrt{2}\begin{bmatrix}0\\0\\0\\0\\1\\1\end{bmatrix}e^{j\omega t}. \qquad (3)$$

This matrix shows that there is no wave propagation in arms 1, 2, 3, and 4 which leaves the turnstile. However there are two rectilinear waves in directions 5 and 6 which propagate in the circular waveguide. These waves have the same amplitude, $D/\sqrt{2}$, and are in phase. One can regard them as the components of a vibration of amplitude D in the direction of the bisector of the directions 5 and 6 (Fig. 3).

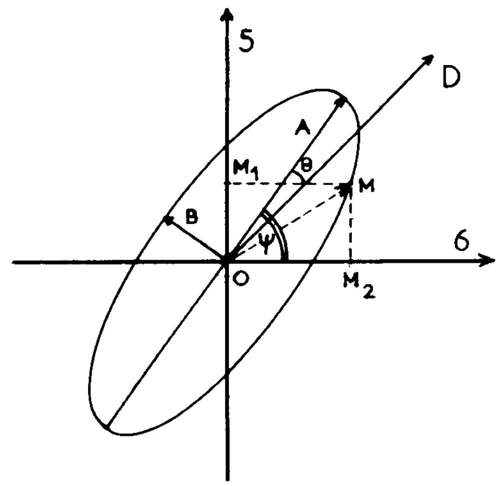

Fig. 3. Geometry of the polarization of fields. A and B are the semi-axes of the reflected elliptical vibration. This vibration is characterized by $\tan\beta = B/a$, with $0 < \beta < \pi/4$ and $\psi = \theta + \pi/4$.

If there is a reflection in the circular waveguide, the wave returns toward the lossy turnstile. Let us suppose that the returning wave is elliptically polarized (by being reflected from an anisotropic medium, for example); the major axis of the ellipse is at an angle θ (Fig. 3) with the direction of the incident wave D and at an angle $\psi = \theta + \pi/4$ with direction 6 (Fig. 1). The components OM_1 and OM_2 in the directions of the axes 5 and 6 are

$$OM_2 = a\cdot\exp\left[j(\omega t - \phi_2)\right]$$
$$OM_1 = b\cdot\exp\left[j(\omega t - \phi_1)\right]. \qquad (4)$$

Let $[U]$ be the matrix of this wave. Then

$$[U] = \begin{bmatrix}0\\0\\0\\0\\be^{-j\phi_1}\\ae^{-j\phi_2}\end{bmatrix}e^{j\omega t}.$$

The lossy turnstile gives the following distribution:

$$[S_1''][U] = 1/\sqrt{2}\begin{bmatrix}b\cdot\exp(-j\phi_1)\\a\cdot\exp(-j\phi_2)\\-b\cdot\exp(-j\phi_1)\\-a\cdot\exp(-j\phi_2)\\0\\0\end{bmatrix}e^{j\omega t}. \qquad (5)$$

The waves which leave arms 1 and 2 of the turnstile have complex amplitudes $E_1 = (1/\sqrt{2})\cdot b\cdot\exp(-j\phi_1)$ and $E_2 = (1/\sqrt{2})\cdot a\cdot\exp(-j\phi_2)$. The waves coming from arms 3 and 4 are absorbed by the isolators I_3 and I_4 (Fig. 2).

The waves E_1 and E_2 can be used in several different ways, depending on what one is seeking to do. For example:

1) If one puts identical quadratic detectors in 1 and 2, one obtains

$$I_1' = \frac{1}{2} b^2 \quad \text{and} \quad I_2' = \frac{1}{2} a^2 \tag{6}$$

which gives only fragmentary information about the reflected wave. This arrangement is rather simplistic.

2) If one interferes with the waves coming from ports 1 and 2, it is possible to obtain the value of the rotation θ and the ellipticity β. However, the sensitivity is rather poor, no more than a few minutes of arc, if one takes great care.

3) When one uses a three-wave interferometer, based on the principle of phase detection, to interfere with the waves coming from ports 1 and 2, the sensitivity of the apparatus increases to a few seconds of arc. One can then use a recorder to continuously measure the changes in rotation and ellipticity as a function of external parameters (a magnetic field in our case).

The complete apparatus is shown in Fig. 2. Note that there is a third wave with complex amplitude $E_1' = a_1' \cdot \exp(-j\phi_1')$ whose phase ϕ_1' and amplitude a_1' can be adjusted by means of the phase shifter P_1' and the attenuator A_1'. If K_1 and K_2 are the attenuation coefficients of attenuators A_1 and A_2, then the amplitudes at the input of the comparator become $K_1 \cdot b/\sqrt{2}$ and $K_2 \cdot a/\sqrt{2}$. The phase difference between the waves E_1 and E_2 in the comparator is no longer $\phi_1 - \phi_2$ but $\phi_1 - \phi_2 + \eta$. The value of η which can be modified by means of P_2, takes into account the propagation in the rectangular waveguide, which gives a constant phase shift.

In the magic T junction (comparator) we have the sum and the difference of the three waves. Let E be this sum. A straightforward calculation of $I = E \cdot E^*$ gives

$$\begin{aligned} I = {} & \frac{1}{2} K_1^2 \cdot b^2 + \frac{1}{2} K_2^2 \cdot a^2 + a_1'^2 \\ & + K_1 \cdot K_2 \cdot a \cdot b \cdot \cos(\phi_1 - \phi_2 + \eta) \\ & + K_1 \cdot b \cdot \sqrt{2} \cdot a_1' \cdot \cos(\phi_1 - \phi_2) \\ & + K_2 \cdot a \cdot \sqrt{2} \cdot a_1' \cdot \cos(\phi_2 - \phi_1' - \eta). \end{aligned} \tag{7}$$

We now study the effect of small variations in the waves E_1 and E_2 with respect to E_1'. The wave E_1' is fixed during the measuring period and so $\Delta a_1' = 0$ and $\Delta \phi_1' = 0$. Note for future reference that in the absence of the wave $E_1'(a_1' = 0)$ one has a zero minimum in the comparator when the following conditions are satisfied:

$$\phi_1 - \phi_2 + \eta = (2k+1)\pi \quad \text{and} \quad K_1/K_2 = a/b.$$

Suppose that these conditions are satisfied and that in addition we have the wave E_1'. The expression for ΔI is

$$\begin{aligned} \Delta I = {} & K_1^2 \cdot b \cdot \Delta b + K_2^2 \cdot a \cdot \Delta a - K_1 \cdot K_2 \cdot (a \cdot \Delta b + b \cdot \Delta a) \\ & + \sqrt{2} \cdot K_1 \cdot a_1' \cdot \Delta b \cdot \cos(\phi_1 - \phi_1') \\ & - \sqrt{2} \cdot K_1 \cdot b \cdot a_1' \cdot \sin(\phi_1 - \phi_1') \cdot \Delta(\phi_1 - \phi_1') \\ & + \sqrt{2} \cdot K_2 \cdot a_1' \cdot \Delta a \cdot \cos(\phi_2 - \phi_1' - \eta) \\ & - \sqrt{2} \cdot K_2 \cdot a \cdot a_1' \cdot \sin(\phi_2 - \phi_1' - \eta) \cdot \Delta(\phi_2 - \phi_1' - \eta). \end{aligned} \tag{8}$$

If we set the amplitude of E_1'

$$a_1' = K_1^2 \cdot b \cdot \sqrt{2}/2 \cdot n \quad \text{and} \quad \gamma = \phi_1 - \phi_1'$$

and recall that

$$\begin{aligned} & \Delta\phi_1' = 0 \qquad \Delta\eta = 0 \\ & \phi_2 - \phi_1' - \eta = \phi_1 - \phi_1' + (2k+1)\pi \\ & K_1/K_2 = a/b \end{aligned}$$

then a simple calculation gives

$$\begin{aligned} \Delta I = {} & (K_1 \cdot b/n)(K_1 \cdot \Delta b - K_2 \cdot \Delta a) \cdot \cos\gamma \\ & - K_1^2 \cdot b^2/n \cdot (\Delta\phi_1 - \Delta\phi_2) \cdot \sin\gamma. \end{aligned} \tag{9}$$

Write $\tan(\alpha) = b/a$ (with $0 < \alpha < \pi/2$). The major axis of the ellipse is inclined at an angle ψ (Fig. 3) with arm 6 of the turnstile and we have $\tan(2\psi) = \tan(2\alpha) \cdot \cos(\phi_1 - \phi_2)$. The ellipticity β, such that $\tan(\beta) = B/A$ (with $0 < \beta < \pi/4$), is given [8] by the formula $\sin(2\beta = \sin(2\alpha) \cdot \sin(\phi_1 - \phi_2)$. If we take as our reference the bisector of arms 5 and 6, we have $\psi = \theta + \pi/4$, and we obtain the equations

$$\begin{aligned} & \cot(2\theta) = -\tan(2\alpha) \cdot \cos(\phi_1 - \phi_2) \\ & \sin(2\beta) = \sin(2\alpha) \cdot \sin(\phi_1 - \phi_2). \end{aligned}$$

Since we have assumed that the variations in the waves are small, we can do Taylor expansions of the preceding expressions to give

$$\beta = (\phi_1 - \phi_2)/2 + k\pi \qquad \theta = \alpha + \pi/4 - k\pi/2$$

and by differentiation we obtain

$$\Delta\beta = \Delta(\phi_1 - \phi_2)/2 \tag{10}$$

$$\begin{aligned} \Delta\theta = \Delta\alpha & = (a \cdot \Delta b - b \cdot \Delta a)/(a^2 + b^2) \\ & = (K_1 \cdot \Delta b - K_2 \cdot \Delta a)/(K_1 \cdot a + K_2 \cdot b). \end{aligned} \tag{11}$$

We now place ΔI in the above expressions, and by setting a new value of $P_1'(\gamma = 0, \gamma = \pi/2, \gamma = \pi, \gamma = 3\pi/2)$ we obtain

$$\begin{aligned} \text{for} \quad & \gamma = 0 & \Delta I_0 & = (2a^2/n) \cdot \Delta\theta \\ & \gamma = \pi/2 & \Delta I_{\pi/2} & = -(2a^2/n) \cdot \Delta\beta \\ & \gamma = \pi & \Delta I_\pi & = -(2a^2/n) \cdot \Delta\theta \\ & \gamma = 3\pi/2 & \Delta I_{3\pi/2} & = (2a^2/n) \cdot \Delta\beta. \end{aligned} \tag{12}$$

Thus $\Delta I_0 + \Delta I_\pi$ leads to $\Delta\theta$, the rotation of the wave, and $\Delta I_{\pi/2} - \Delta I_{3\pi/2}$ leads to $\Delta\beta$, the change in ellipticity. We shall now apply the results to the case at hand.

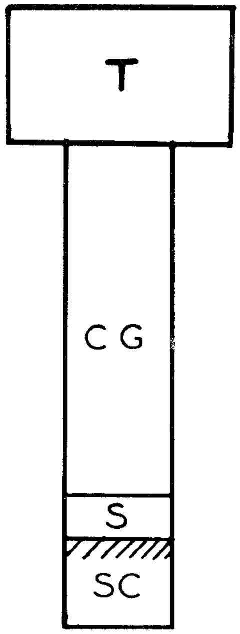

Fig. 4. Measurement arm. T—lossy turnstile junction; CG—circular guide; S—sample; SC—short-circuit.

III. Description of the Apparatus and Its Adjustment

The phase shifter P_2 and the magic T junction were replaced by a very good slotted line. This increased the precision of the measurements. Especially adapted isolators I_1 and I_2 were put at the ends of the line in such a way that I_2 absorbed the wave E_1 and I_1 the wave E_2 after they had passed through the slotted line. All the isolators in the apparatus had to be very well matched. In general, all the components, even those sold commercially, have to be very carefully checked and matched. The *VSWR* of each element must be as small as possible in order to avoid systematic errors, which can quickly become of the same order of magnitude as the effects being measured.

We used samples with the same diameter as the circular waveguide (12 mm). The samples were placed directly in front of a short circuit (Fig. 4). With no magnetic field the samples are isotropic. Consequently the wave reflected back to the turnstile is plane polarized, bisecting directions 5 and 6 (as in the incident wave). Thus waves E_1 and E_2 leaving the lossy turnstile have equal amplitude and are in phase.

There are several steps in the adjustment:

a) Find a zero minimum without the wave E_1': With no wave E_1' ($a_1' = 0$) one seeks a zero minimum in the slotted line by moving the probe and by equalizing the losses in arms 1 and 2 of the interferometer (by modifying A_1 and A_2).
b) Fix the phase of the wave E_1' with respect to the wave E_1: The probe stays fixed at the zero minimum so as to have a zero phase difference with respect to E_1. Increase the amplitude of wave E_2 slightly by means of A_2 (without modifying the phases of E_1 and E_2). The minimum is no longer zero. One progressively increases a_1' of wave E_1' (by means of A_1') while at the same time seeking, by means of P_1', the correct phase so as to establish the zero minimum in the slotted line. One then has E_1 and E_1' in phase ($\gamma = 0$).
c) Set E_2 to the amplitude that it had previously: One has $a_1' = 0$ by means of A_1', then by reducing E_2 (by means of A_2) so as to get back to the zero minimum.

In step (b), P_1' was adjusted so as to give $\gamma = 0$; it is necessary to reset the zero minimum as in (a) because the gradations of A_2 are not sufficiently accurate to do this directly.

The above adjustments (although lengthy to explain) are easy to carry out. Now we can give E_1' the amplitude a_1' and phase γ of our choice by setting A_1' and P_1' appropriately.

We now suppose a small variation, with respect to E_1', of E_1 and E_2 (which will occur when we apply a magnetic field to our sample). The wave returning to the turnstile will no longer be plane polarized at 45° to direction "6", but elliptic, having been rotated by $\Delta\theta$ and with ellipticity $\Delta\beta$. In our particular case ($a = b$), $n = a \cdot a_1'/\sqrt{2}$; hence from (12)

$$\Delta\theta = \frac{\Delta I_0 - \Delta I_\pi}{4a^2} \cdot \frac{a\sqrt{2}}{2a_1'} \tag{13}$$

$$\Delta\beta = \frac{\Delta I_{\pi/2} - \Delta I_{3\pi/2}}{4a^2} \cdot \frac{a\sqrt{2}}{2a_1'}. \tag{14}$$

As the magnetic field is varied one can easily measure ΔI_0, $\Delta I_{\pi/2}$, ΔI_π, and $\Delta I_{3\pi/2}$. The value of $4a^2$, in the case of quadratic detection, corresponds to the maximal value of I in the comparator when $a_1' = 0$. These values are all easily measured when the comparator is replaced by a slotted line. It suffices to move the probe by $\lambda g/4$. It is easy to obtain the ratio $a^2/a_1'^2$ of the intensities in the absence of a magnetic field, the amplitudes of E_1 and E_1'. Thus $\Delta\theta$ and $\Delta\beta$ are easily measured as the magnetic field is varied.

IV. Experimental Results

In order to verify the sound performance of the instrument and to demonstrate its possibilities, we have, first, established the paramagnetic resonance of MnSO4, H_2O (the curves of which are well known), and then studied a magnetic composite for which ϵ and μ vary in relation to the concentration of the magnetite.

Manganese sulfate, in powder form (Rhone Poulenc), was compressed under a pressure of 2700 kg/cm^2 into cylindrical samples 12 mm in diameter. The composites consisted of mixtures of PVC powder (Aldrich Chemical Co.) and magnetite (Fe_3O_4) (Rhone Poulenc) mixed homogeneously and then compressed at a pressure of 2700 kg/cm into cylindrical samples 12 mm in diameter.

The samples filled the waveguide (Fig. 4). A short circuit was placed against the sample and a magnetic field was applied with an electromagnet. The magnetic field was

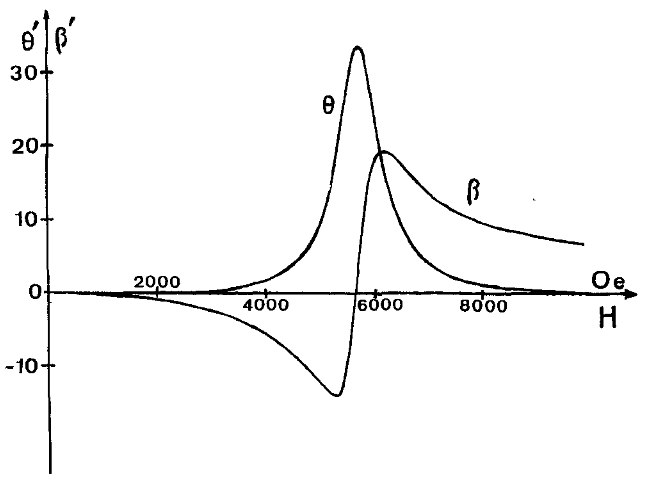

Fig. 5. Rotation θ and ellipticity β for $MnSO_4$, H_2O; length of the sample = 1.15 mm. The magnetic field was perpendicular to the direction of the wave propagation and at 45° to the direction of the vector E.

perpendicular to the direction of wave propagation and at 45° to the direction "6." This experimental setup is analogous to that used in optics by Cotton and Mouton and we will refer to it as the Cotton–Mouton configuration.

Our study was concerned with neither the magnetic aftereffect [9] nor hysteresis. To avoid this latter phenomenon we subjected the sample to several cycles of the magnetic field. The measurements were all made with an increasing magnetic field. Reversing the polarity of the applied magnetic field does not modify the shapes of the curves obtained.

Fig. 5 shows the standard rotation and ellipticity curves of $MnSO_4$, H_2O and requires no further comment. When interpreting parts (a), (b), and (c) of Fig. 6 some precaution is needed, for ferrimagnetic resonance is involved and there is a problem concerning the presence of various peaks.

The experiments show that for concentration of 10 percent by weight of Fe_3O_4 (Fig. 6(a)) the curve of θ versus H has only one resonance peak. For the 10 percent sample the half-maximum line width of the peak is 3700 Oe and the maximum is at 4250 Oe. For Fe_3O_4 concentrations of 40 percent or more the experiments show that for certain sample lengths it is possible to have several resonance peaks. In general, there are two peaks with the magnetic field we used. We note that other studies [10], [11] of compressed paramagnetic powders have never shown a second peak as a function of the sample thickness. In parts (b) and (c) of Fig. 6, we see the modification due to the variation in the length of the sample.

All the curves obtained for the sample with 30 percent or more of Fe_3O_4 have a maximum at 3000 Oe regardless of the length of the sample. A complex curve can be represented as the sum of several simple resonances. One is always at 3000 Oe; the others vary with the thickness of the sample. A similar phenomenon has been observed in similar conditions with permalloy: a practically constant peak and other peaks varying with the thickness. In this

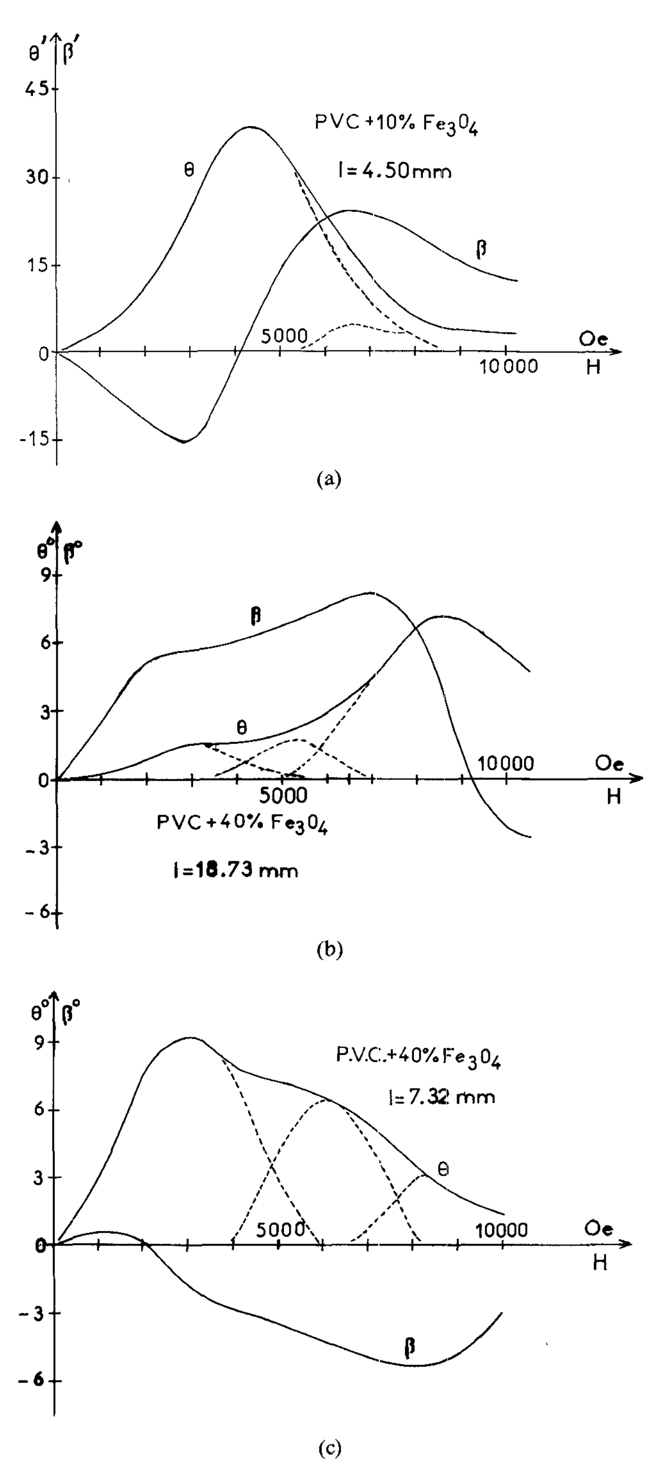

Fig. 6. Rotation θ and ellipticity β for various concentrations and sample lengths. The magnetic field was perpendicular to the direction of wave propagation and at 45° to the direction of the vector E. When one has a complex curve it can be representated as a sum of several simple resonances (shown in dotted line).

case the phenomenon is due to the spin waves [12]. It is possible that there is a similar phenomenon for the magnetic powders. When the magnetic particles are far apart one has a single peak; the interaction between the particles is weak. When the particles are closer together, their spins can interact, with the possible existence of a spin wave. This phenomenon is probably a function of such factors as the pressure used during the compression of the sample, the size of the particles, the temperature, and the magnetic anisotropy.

V. Conclusion

We have built an interferential reflecto-ellipso-polarimeter working at 16 GHz. The principal component is a lossy turnstile junction. The analysis of the elliptical components is done with a three-wave interferometer, which greatly increases the sensitivity of the apparatus. One can measure rotations and ellipticities of the order of a few seconds of arc.

The apparatus has been used to measure the rotations and ellipticities of $MnSO_4$, H_2O and PVC–Fe_3O_4 composites in a magnetic field. We have shown, for certain concentrations of ferrite particles, the existence of a phenomenon which seems to be related to interactions between the magnetic particles (a kind of "magnetic contact"). By analogy with electric percolation, due to contact between conducting particles, we suggest calling the phenomenon magnetic percolation. We are continuing our study and the detailed experimental results will be published elsewhere [13].

Acknowledgment

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