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Power Absorption and Ferromagnetic Resonance in Co-Rich Metallic Glasses

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Abstract—The power absorption of Co-rich metallic glasses in the shape of ribbons and microwires has been measured in the microwave frequency range. The technique employed consists of replacing the dielectric of a coaxial transmission line by the amorphous sample to be measured. The ferromagnetic resonance frequency of the microwires has been obtained by analyzing the absorbed power as a function of an external magnetic field. From the evolution of this resonance frequency, the anisotropy field has been deduced and successfully compared to that obtained from low-frequency hysteresis loops.

Index Terms—Amorphous materials, ferromagnetic resonance, microwave materials.

I. INTRODUCTION

THE characterization of high-frequency properties of various types of magnetic materials has attracted much attention in the last few years in connection with their technological applications. Particular interest is being focused on peculiar properties such as magnetoimpedance and microwave behavior of extremely soft magnetic materials with metallic character. Such materials, typically amorphous, are fabricated in the shape of wires with diameters in the range from 1 to 150 μm, ribbons and tubes around 20-μm thick, and films in the range of 1 μm in thickness [1]–[5]. Although in most cases they are prepared by rapid solidification techniques, electrochemical deposition or sputtering methods are also alternatively employed. These materials have been proposed in applications as active elements in magnetic shielding [6] or to make use of their absorption characteristics.

Several techniques are currently being used to characterize the microwave behavior of different materials. Among them, we can mention the resonant cavity [7], the guided-wave technique [8], measurements in free space [9], the microstrip line [10], using a discontinuity in a coaxial line [11] or replacing the inner conductor [12] or the dielectric [13] by the magnetic material under study.

The aim of this work has been the determination of the power absorption and the ferromagnetic resonance characteristics in

metallic glasses such as microwires and melt-spun ribbons using an alternative method. The technique employed here consists of the insertion of the sample into a coaxial line replacing the dielectric between the inner and the outer conductor. The samples are placed in the coaxial line in different arrangements depending on the specific type of measurement. The absorption spectrum of the metallic glasses can be obtained by winding the samples around the inner conductor. In the case of microwires, the ferromagnetic resonance can also be obtained from the absorption measurements by placing the samples parallel to the axis of the coaxial line and applying a field parallel to it.

II. MEASUREMENT TECHNIQUES

A. Samples Used in the Experiments

Two kinds of metallic glasses have been used in the present study, both of them fabricated in the experimental facilities in our laboratory. Amorphous ribbons with nominal composition Co$_{77.5}$Si$_{15}$B$_{15}$ have been prepared by a conventional melt-spinning technique, being 17 μm thick and 0.6 mm wide. On the other hand, glass-coated Co$_{68.5}$B$_{15}$Si$_{10}$Mn$_{7}$ amorphous microwires were obtained by the Taylor–Ulitovsky technique, having a total diameter of around 5 μm and a metallic core of 2 μm. Recently, these types of amorphous wires have been intensively studied owing to their outstanding magnetic properties. A more detailed description of their characteristics can be found elsewhere [14], [15]. Low-frequency magnetic characteristics of the studied samples have been determined using vibrating sample magnetometry (VSM).

B. Power Absorption

The technique used to evaluate the power absorption is based on the measurement of the incident, the reflected, and the transmitted power through a modified coaxial transmission line. In this line, the sample is wound around the inner conductor, and replaces the dielectric [16]. A network is thus generated, consisting of three quadrupoles in cascade: the sections of coaxial line of lengths l_1 and l_2, and the sample between these sections, as schematically shown in Fig. 1(a).

The scattering parameters which can be measured belong to the whole system. However, the attenuation due to the coaxial lines next to the sample (l_1 and l_2) is negligible, and causes a displacement in the reference planes that affects only the phase of the scattering parameters but not their modulus. The scattering parameters of the whole system can then be associated with the properties of the sample under study.
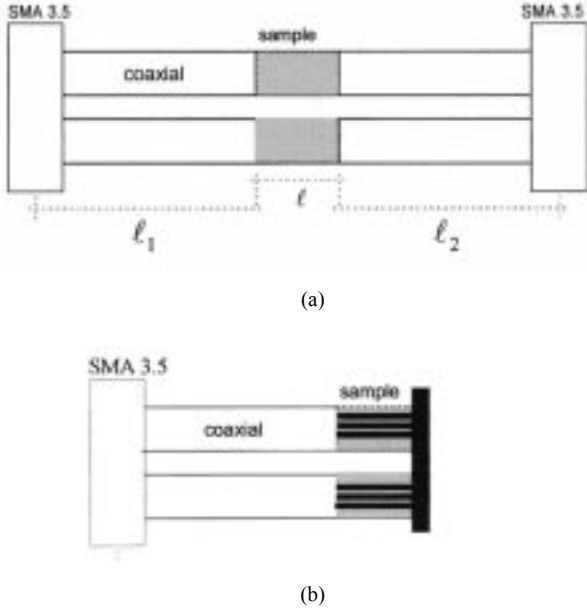
(a)

(b)

Fig. 1. Schematic view of the coaxial line arrangements used in the measurements. (a) Arrangement used for the measurement of the power absorption. The dielectric is substituted by the magnetic material. (b) Arrangement for the determination of the resonance frequency.
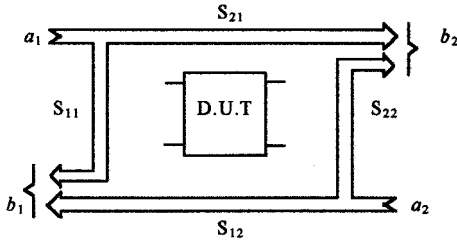

Fig. 2. Scheme for the determination of the scattering parameters (D.U.T. stands for device under test).

The total power absorbed by the system, $P_{\mathbf{abs}}$ can be normalized with respect to the power available from the source as

$$P_{\mathbf{abs}} = 1 - |S_{11}|^2 - |S_{21}|^2 \qquad (1)$$

where S_{11} and S_{21} are the scattering parameters of the network. As part of the available power from the source is reflected in the gate port (see Fig. 2), not all the radiation reaches the sample. Accordingly, the behavior of the material can be better characterized by normalizing the absorbed power with respect to the total power reaching the sample, that is, available power minus reflected power. The absorption coefficient, $C_{\mathbf{abs}}$, is then obtained as

$$C_{\mathbf{abs}} = \frac{1 - |S_{11}|^2 - |S_{21}|^2}{1 - |S_{11}|^2}. \qquad (2)$$

The scattering parameters are measured by means of a HP 8720-B network analyzer. An RG-58 coaxial line with a polyethylene dielectric ($\varepsilon_r = 2.28$) is used as a sample holder, showing an attenuation of 0.76 dB/m at 1 GHz. As the coaxial length of our setup is small (about 7 cm), the attenuation due
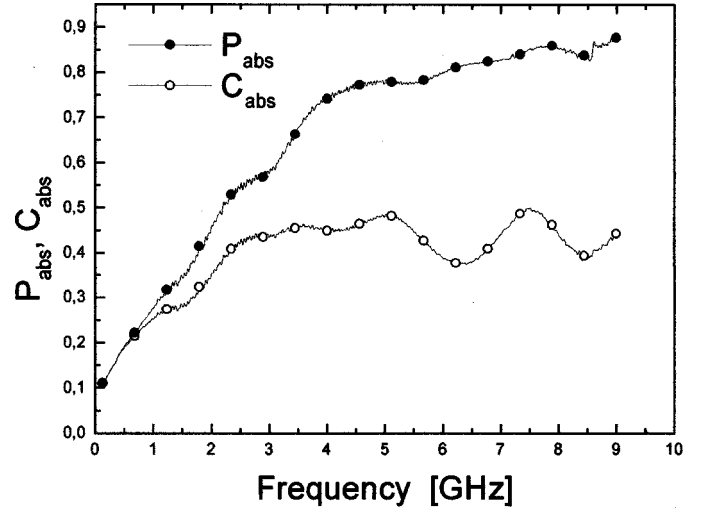

Fig. 3. Normalized absorbed power ($P_{\mathbf{abs}}$) and absorption coefficient ($C_{\mathbf{abs}}$) evolution from 0.15 up to 9 GHz for a $Co_{77.5}Si_{13.5}B_9$ ribbon, 77 mg in weight.

to the line (0.05 dB) is negligible compared to that due to the metallic glass in the frequency interval used which ranges from 0.15 up to 9 GHz.

C. Resonance Frequency

The analysis of the ferromagnetic resonance phenomena [17] gives information about intrinsic parameters of the material under study. The determination of the ferromagnetic resonance spectrum is achieved using a different arrangement of the samples. In this case, the coaxial line RG 402 has been used as a sample holder. The microwires are now placed parallel to the coaxial axis instead of being wound around the inner conductor. A short circuit is attached at one of the edges of the line, so that the absorption properties are fully determined by the S_{11} parameter [see Fig. 1(b)]. The coaxial line is introduced into a solenoid which supplies a longitudinal (parallel to the axis of the sample) dc magnetic field in order to nearly saturate the magnetization of the sample and to excite the resonance. A perpendicular ac magnetic field of a transverse electromagnetic (TEM) propagating mode in the coaxial line provides the energy required for the precession of the magnetization. The resonance frequency is evaluated through the measurement of the scattering parameter S_{11} since the energy absorption reaches a maximum at the resonance.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Absorption Measurements

The evolution of the normalized absorbed power as well as the absorption coefficient from 0.15 up to 9 GHz for a $Co_{77.5}Si_{13.5}B_9$ ribbon (77 mg weight) are shown in Fig. 3. The normalized absorbed power seemingly shows an oscillation for frequencies above 4 GHz. This oscillation may be attributed to the modification of the reflection properties of the sample holder, and not to intrinsic changes in the material. The absorption coefficient increases almost linearly with the frequency in the whole measured range and shows a change in the slope at around 4 GHz.
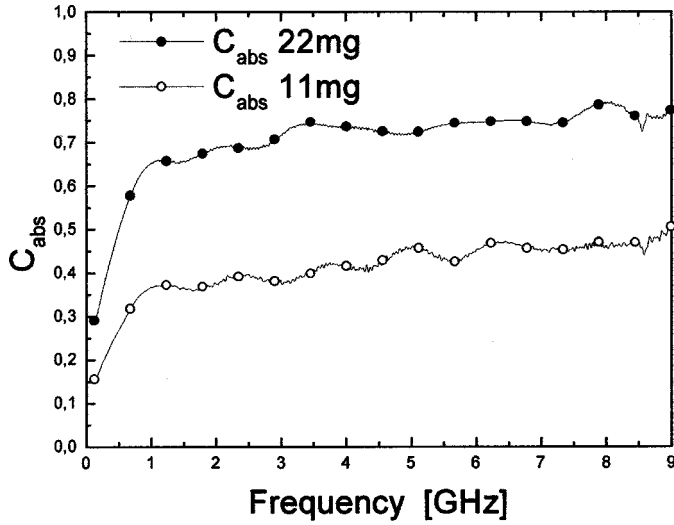
Fig. 4. Absorption coefficient evolution for $Co_{68}B_{15}Si_{10}Mn_7$ microwires, 22 mg in weight (solid circles), and for a sample which has been built by interweaving 11 mg of such Co-rich microwires with 31 mg of nylon (open circles).

Due to their tiny dimensions, samples in the shape of microwires are extremely difficult to handle. In order to overcome this problem and facilitate their manipulation, samples are usually prepared by interweaving the microwires under study with another material. Fig. 4 compares the absorption coefficient spectrum in the range from 0.15 to 9 GHz for $Co_{68}B_{15}Si_{10}Mn_7$ microwires having a weight of 22 mg (solid circles) and for a sample which has been built by interweaving 11 mg of such Co-rich microwires with 31 mg of nylon (open circles). As can be concluded from Fig. 4, the nylon does not affect the behavior of the material in the microwave frequency range, as the general qualitative trend is the same in both cases. The absorption increases steeply until 1 GHz and then remains nearly constant for higher frequencies. The qualitative discrepancy between both curves is easily ascribed to the difference in the weight of active magnetic material in both samples. The absorption coefficient is roughly proportional to the weight of magnetic material contained in the samples.

B. Resonance Measurements

According to previous experiments [18], [19], Co-rich microwires exhibit a magnetic domain structure characterized by a circumferential easy axis arising from the distribution of the magnetoelastic anisotropy. That forces the magnetization to lie along the surface of the wire perpendicular to its axis. This circumferential magnetization near the surface of the wire is strongly affected by the circular and oscillating magnetic field of the TEM mode which propagates along the coaxial line.

Consequently, unrolling the outer shell into a plane results in a configuration similar to that of a film with an in-plane magnetic anisotropy which is perpendicular to the in-plane static magnetic field [20]. The following coordinate system is considered: the dc magnetic field is applied along the z axis, while the y axis is taken as the easy direction for the magnetization, and the x axis is perpendicular to the thin-film surface. Considering both the demagnetizing effects and the magnetic anisotropy ac-
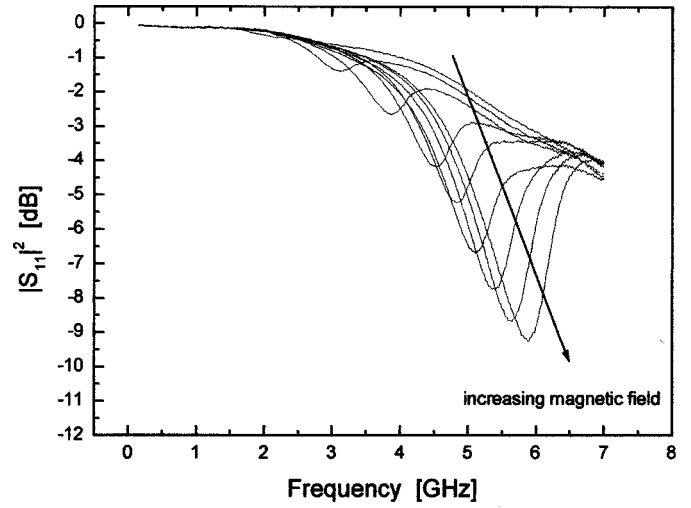

Fig. 5. Evolution of the square of the scattering parameter with the frequency for different values of the increasing applied field up to 700 Oe.
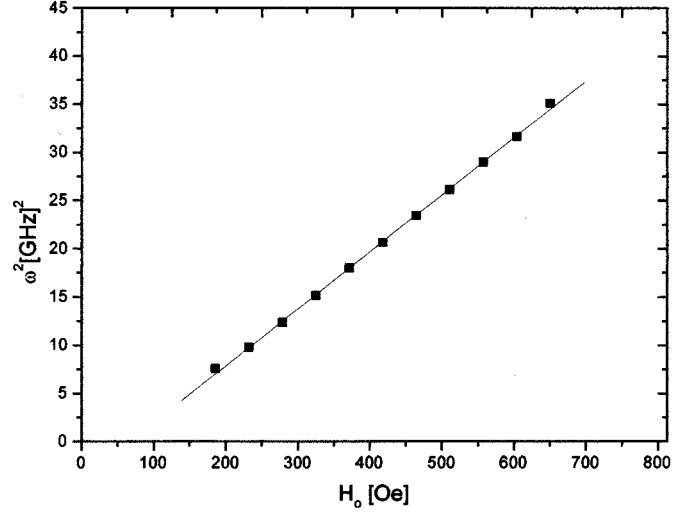

Fig. 6. Dependence of the second power of the ferromagnetic resonance frequency on the static applied field.

cording to the notation given by Craik [21], the demagnetizing factors are $D_x = 1$, $D_z = D_y = 0$, and the anisotropy factors are given by $D_x^k = D_z^k = 0$, $D_y^k = -2K/\mu_o M_s^2$, K being the uniaxial anisotropy energy, μ_o the free-space magnetic permeability, and $\boldsymbol{M_s}$ the saturation magnetization. Consequently, the resonance frequency can be written as

$$\omega = \gamma\mu_0\sqrt{(H_0 + M_s)\left(H_0 - \frac{2K}{\mu_0 M_s}\right)} \qquad (3)$$

H_0 being the dc applied field and γ the gyromagnetic constant. As the saturation magnetization is much larger than the maximum applied field ($M_s \gg H_0$), the resonance frequency can be approximated as follows:

$$\omega = \gamma\mu_0\sqrt{M_s(H_0 - H_k)} \qquad (4)$$

where $H_k = 2K/\mu_0 M_s$ is the transverse anisotropy field.

Fig. 5 shows the evolution of $|S_{11}|^2$ with the frequency for increasing values of the static applied field. The minimum of each curve corresponds to the resonance frequency for a given field.
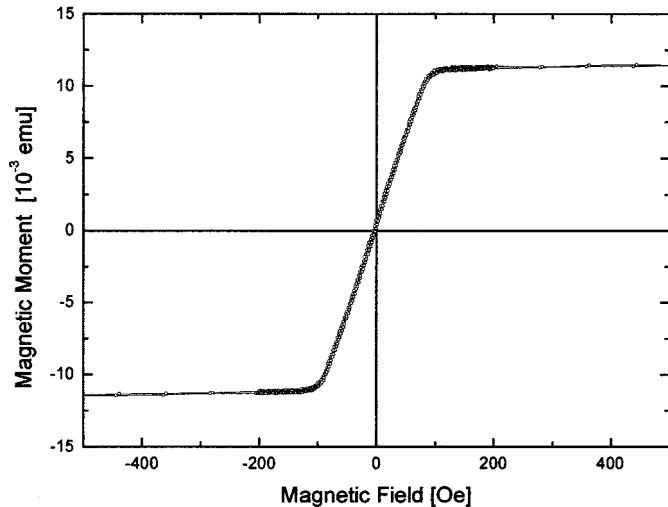
Fig. 7. Hysteresis loop of $Co_{68}B_{15}Si_{10}Mn_7$ microwires measured using a vibrating sample magnetometer.

As can be deduced from (4), the second power of the resonance frequency increases linearly with the applied field H_0.

Fig. 6 shows the experimental data of the squared resonance frequency as a function of the applied field, and their fitting to a linear behavior. The anisotropy field obtained from the extrapolation of the fitting down to $\omega = 0$ is $\boldsymbol{H_k} = 68$ Oe. In order to check the validity of this technique to obtain information on the magnetic anisotropy, the longitudinal hysteresis loop was obtained using VSM. From the loop (see Fig. 7) a transverse anisotropy field of 80 Oe can be easily deduced, which agrees reasonably with that obtained by the resonance technique.

IV. CONCLUSION

In summary, an alternative method has been successfully employed to determine the power absorption in the microwave range of Co-rich metallic glasses in the shape of ribbons and microwires.

A coaxial line is modified by the substitution of the dielectric by the ferromagnetic sample. The change in the scattering parameters produced depends on the properties of the ferromagnetic sample and its arrangement in the coaxial line. This has allowed us to determine the absorption properties of the studied samples. When the microwires are parallel to the coaxial axis and a dc magnetic field is applied along this direction, the ferromagnetic resonance frequency can also be found. Furthermore, the anisotropy field of the microwires has been inferred from the linear increase of the second power of the ferromagnetic resonance frequency with the applied field, and the consequent value fits reasonably with that deduced from the low-frequency hysteresis loop.

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