Magnetic characterization of CoFe-based glass covered amorphous wires at high frequency

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Abstract- Many metallic glasses are well known as soft magnetic materials, because of their amorphous structure which presumes the absence of magneto-crystalline anisotropy. It has been shown that amorphous materials are not fully isotropic, but rather have small induced anisotropies because of the cooling strains. The ferromagnetic resonance is an important tool for characterizing the magnetic materials because of the small penetration depth of the microwave radiation used in such experiments. The aim of this paper is to present a new method for magnetic properties study by FMR for as-cast CoFe-based glass covered amorphous wires, employing a vector network analyzer and microwave guide transmission line. The method can be also employed and for other magnetic sample like as thin layers and nanowire arrays.

I. Introduction

The physical properties of amorphous glass-covered micro-wires have been widely investigated in the last years. The most important scientifically applications of these materials are: new type magnetic sensors and transducers, magnetic recording device, components for electronics device for high frequency. Amorphous metallic materials are used in that applications based on their magnetic properties, vanish of the magneto-crystalline anisotropy allow there utilization as high permeability magnetic materials [1]. The achievement of the energetically metastable amorphous state requires the use of preparation methods that allow rapid solidification of liquid metallic melts in order to avoid the crystallization.

The most experimentally methods for study the magnetic properties are magnetometer methods (VSM, MOKE) for low frequency signal up to few MHz. For high frequency domain, more than 1 GHz it is necessary to use dynamics methods like ferromagnetic resonance (FMR), or based on the giant magneto-impedance effect (GMI).

The aim of this paper is to present a new method for magnetic properties study by FMR for as-cast CoFe-based glass covered amorphous wires, employing a vector network analyzer and microwave guide as transmission line.

II. The experimental method

Ferromagnetic resonance is a powerful technique for magnetic properties characterization in the high frequency range of magnetic materials with submicron dimensions. The magnetic fields dependence of the RF susceptibility offer information about g-factor, the magnetization Ms and magnetic anisotropy. At the ferromagnetic resonance field, the permeability is reaching its maximum and the microwave radiation penetrates only a thin surface layer of the ferromagnetic material ($\sim 10^3$ Å). This behavior is mainly related to the magnetic anisotropies induced by the longitudinal and circumferential stresses.

Amorphous glass-covered wires with nearly zero magnetostriction with nominal composition $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ were produced by the Taylor-Ulitovsky modified technique with an amorphous nucleus of $\varphi m \cong 22\mu m$ and with the thickness of glass between 2 μm and 15μm. The samples were cut in 10mm long piece.

The classical method for FMR measurements employs the modulation technique of external dc magnetic field. The sample is fixed in an X (or P)-band homodyne spectrometer, in the position where the microwave magnetic field have the maximum value [2]. Perpendicular to this HF field h(t), a strong homogeneous magnetizing field H_{dc} is applied, bringing the sample to magnetic saturation. If the condition

$$h\nu o = g\mu_B H_{dc} \qquad (1)$$

is satisfied, than the oscillating field will induce transition between neighboring Zeeman sublevels of the ferromagnetic system separated from each other by $g\mu_B H_{eff}$ (H_{eff} is the effective internal field in the ferromagnetic material, μ_B is the Bohr magneton, and g the spectroscopic splitting factor, analogous to the Lande` g-factor in optical spectroscopy). In experimental studies of ferromagnetic resonance, the frequency of the high frequency radiation is kept constant for purely experimental reasons, while the intensity of the external field H_{dc} is varied, thus changing the effective field H_{eff}.

The derivatives of the resonance absorption curves were obtained by the d.c. magnetic field modulation technique. An a.c. modulation field:

$$H_{mod}=H_o \sin 2\pi\nu_{mod}t \qquad (2)$$

with ν_{mod}=1KHz, and an amplitude Ho = ±5 Oe, it is superposed upon a d.c. field *Hdc* in a parallel configuration. Thus, the d.c. field is modulated by the a.c. field, which determines the modulation amplitude of the absorption field. When the amplitude of the a.c. field, *Ho*, is smaller than the line-width ΔH, the derivative signal is obtained on the output of the phase-sensitive-detector, having the reference frequency equal to the frequency of the a.c. field.

Experimentally resonance magnetic field (H_{res}) is defined as the field where the dP/dH=0 line cut the dP/dH versus H curve or alternatively as the field where dP/dH possesses half the peak-to-peak value if the dP/dH versus H curve is symmetrical about the baseline. The set-up for FMR measurements by modulation technique is depicted in figure 1.
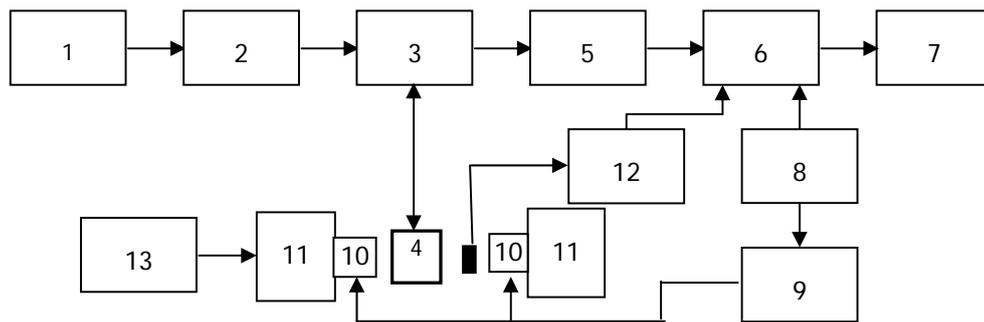

Figure 1. The diagram of X-band homodyne spectrometer:

1-klystron generator; 2-ferrite isolator; 3-port circulator; 4-microwave guide with short-circuit;
5-signal detector diode; 6-Lock-in amplifier; 7-CPU; 8-sinusoidal function generator;
9-power amplifier; 10-modulation coils; 11-electromagnet; 12-gaussmeter with Hall magnetic
sensor; 13-electromagnet power supply.

The accuracy of this technique involves utilization of a detection diode with very high sensibility at the microwave's amplitude changes when the resonance absorption occurs. The non parallelism between ac modulation magnetic field direction and dc magnetic field direction can also reduce the accuracy of measurements.

Another important technical parameter it is the modulation frequency of ac magnetic field. As we may see in figure 2, the amplitude of FMR pick decrease when the value of modulation frequency increase from ν_{mod}=1 KHz to ν_{mod}=2 KHz. For all specters the resonant magnetic field has the same value H_{res}=1.2 kGs at F=9.5 GHz but the peak-to-peak line-width ΔHpp decrease from 160 Gs at ν_{mod}= 1 KHz to 150 Gs at ν_{mod}= 2.5 KHz.
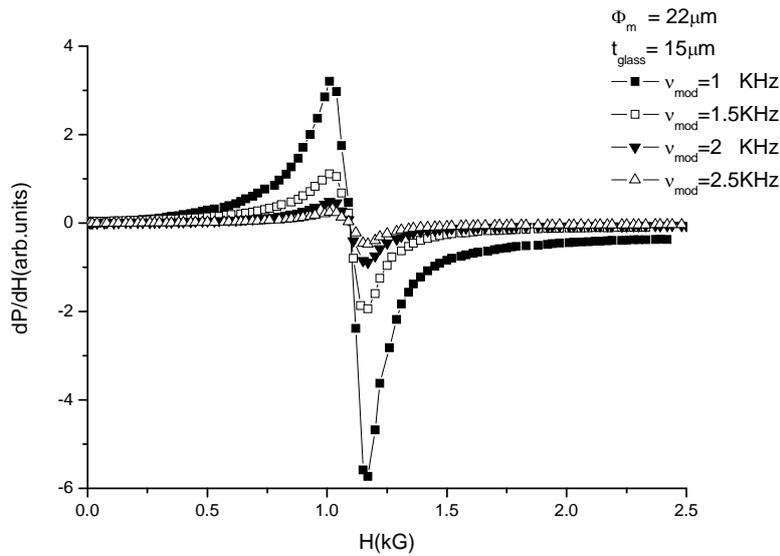
Figure 2. FMR specters for $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ –GCAW at different modulation frequencies of ac field.

In this paper it is presented a new method for magnetic properties study by FMR for as-cast CoFe-based glass covered amorphous wires, employing a vector network analyzer and a microwave guide transmission line. The method can be also employed for other magnetic sample like as thin layers, and nanowire arrays.

The magnetic behavior of GCAW was study with a vector network analyzer-VNA Agilent N5230 (see figure 3) and a microwave-guide transmission line for X-band (F= 8.2 GHz to 12.4 GHz) and for P-band (F= 12.4 GHz to 18 GHz) respectively. The power of microwave signal was keep constant at -15dBm. The FMR spectra were measured in parallel configuration at few resonant frequencies.
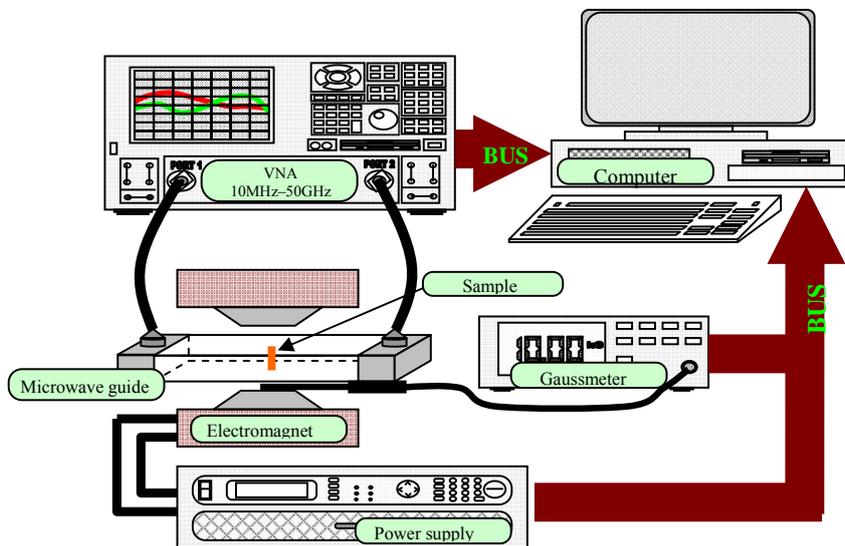

Figure 3. Experimental set-up for FMR study of CoFe-based GCAW

The connections between VNA and microwave guide were made with 50Ω flexible test port cables. After a very high sensitive TRL (Thru-Reflect-Line) calibration for VNA, the microwave-guide was connected between Port 1 (signal emission port) and Port 2 (signal reception port). Each sample was locked in quartz tube

with 75 μm diameter and then vertical fixed in the middle of transversal section of microwave-guide in the position where the microwave magnetic field have the maximum value.

The external dc magnetic field it was applied by an electromagnet connected to a power supply and was measured with a Hall sensor connected to a gaussmeter. The S21 parameter of VNA, which it is considerate a measure of linear amplitude of microwave signal transmitted from port 1 to port 2, it was used for recording the absorption curves S21=f(H). Finally, a PC makes the acquisition. The FMR spectrum (dS21/dH=f (H)) was extracted by first order mathematical derivation of these curve.

III. Experimental results

The magnetic behavior of as-cast CoFe-based glass covered amorphous wires (GCAW) strongly depend on their composition, which is directly responsible for the sign and magnitude of their magnetostriction constant ($\lambda_s \approx -1 \times 10^{-7}$), and also for the values and distribution of internal stress induced during preparation. By mean of magneto-elastic energy, these induced stress controls the easy magnetization axis and magnetic domain structure formation in these wires [3].

For CoFe-based GCAW the magnetic domain structure consists of the central inner core magnetized along the wires axis and the outer shell consisting of circular domains circumferentially magnetized [4]. The diameter of the inner core can represent less 30% from the wire diameter. If the skin depth is smaller in comparison with the thickness of the outer shell of the wire, the FMR spectrum present only a single peak associated to the magnetic domain structure of the outer shell.

In figure 4 are depicted the FMR specters for GCAW with 2.85 μm glass thickness.

One observes that all three curves for X-band and P-band respectively, present a single resonance peak due to the response of the outer shell. The skin depth of microwave it is smaller than 2μm. The peaks are narrower due to the fact that the circumferential stress induced during the preparation is higher in GCAW and results in a strong circumferential anisotropy, but also due to the demagnetization field what appears between the ends of samples. The resonant magnetic field shifts to higher values when the resonance frequency increases.
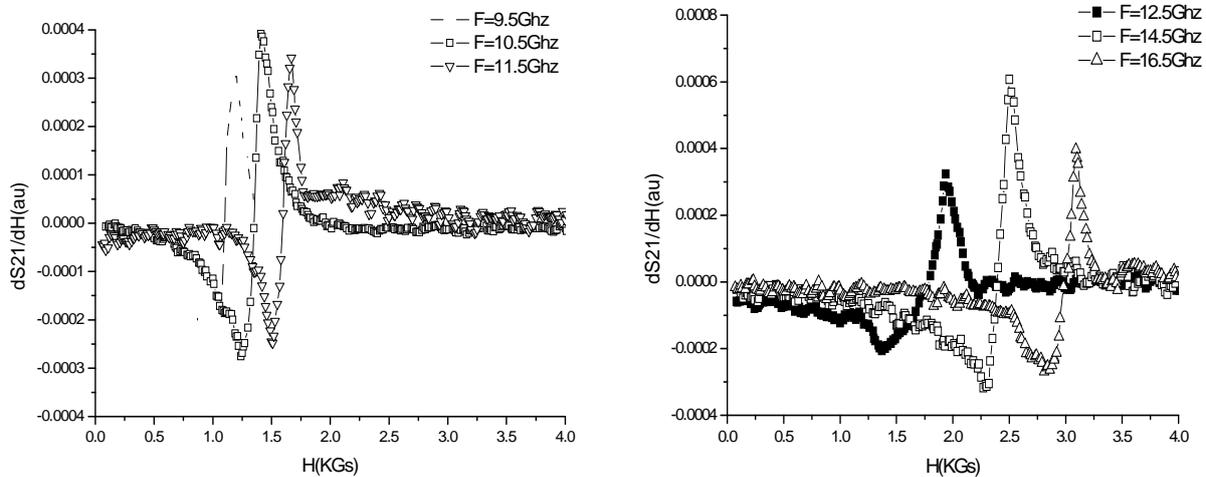

Figure 4. FMR specters for GCAW with Φ_m=22.3μm and glass thickness t_{glass}=2.85μm.

For all others wires investigated it was observed that the value of resonant magnetic field, for a fixed microwave signal frequency, it is independent from glass thickness of wires. The H_{res} vary between 1,1 kG for F= 9,5 GHz to 3 kG for F= 16,5 Ghz.

In figure 5 are depicted the absorption specters measured in frequency range kipping constant the dc external magnetic field. The spectra of the transmission coefficient (S_{21}) through the sample touch a minimum value at resonance when, due to the change-conductibility effect, the Foucault current distribution in wires is affected by wire impedance changing both the resonance frequency and absorption. In magnetic wires the

surface impedance has a minimum for a circumferential anisotropy and H_{dc} =0. Thus, a deep minimum in transmission is seen when no field is applied. At higher magnetic field the transmission spectrum is very broad with the resonance minimum shifted to higher frequencies.
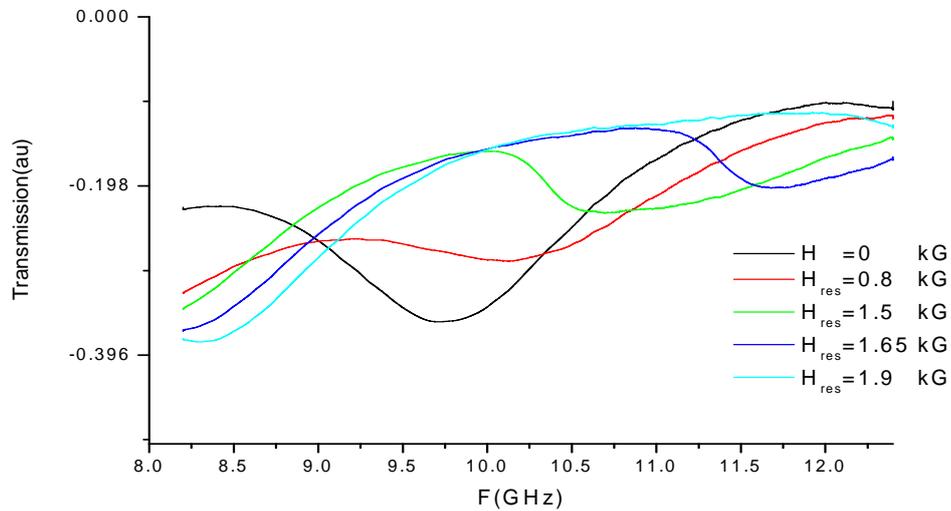

Figure 5. FMR specters for GCAW with Φ_m=22.3µm and glass thickness t_{glass}=6.6µm.

IV. Conclusion

A new method, employing a vector network analyzer, for magnetic characterization at high frequencies by FMR of amorphous materials with micrometer dimensions was presented. The accuracy of this technique is higher comparatively with the classical method by modulation technique.

V. Bibliography

[1] Chiriac H. and Ovari T.-A., "AGCMW: Preparation, Properties, Aplication", *Progress in Materials Science*, vol. 40, pp. 333-407, 1996.
[2] Chiriac H., Colesniuc C.N., Ovari T.-A., and Ticusan M., "In-situ investigation of the magnetization processes in AGCW by FMR measurement", *Journal of Applied Physics*, vol. 85, pp. 5453-5455, 1999.
[3] Carara M., Sossmeier K.D., Viegas A.D.C., Chiriac H., Sommer R.L., "Study of CoFeSiB GCAW under applied stress", *Journal of Applied Physics*, vol. 98, pp. 033902-1 – 033902-6, 2005.
[4] Heinrich B.: "The theory of FMR in Metal Whiskers", *Czechoslovak Journal of Physics*, vol. B17, pp. 142-145, 1996.