Free Space Microwave Stresses Sensing in Composites with Ferromagnetic Microwire Inclusions

Valentina Zhukova, Alvaro Gonzalez, Alfonso García-Gómez
Dept. Polym. Advanced Materials, Dept. Applied Physics and EHU Quantum Center, Univ. Basque Country, UPV/EHU, 20018 San Sebastian, Spain
e-mails: valentina.zhukova@ehu.es; alvaro.gonzalezv@ehu.eus; alfonso.garciag@ehu.eus

Johan Malm, Christer Johansson
RISE Research Institutes of Sweden, Digital Systems, Göteborg, Sweden
emails: johan.malm@ri.se; christer.johansson@ri.se

Rafael Garcia-Etxabe, Maitane Mendinueta
GAIKER Technology Centre, Basque Research and Technology Alliance (BRTA) and Department of Electricity and Electronics, University of Basque Country, UPV/EHU, 48940 Leioa, Spain
e-mail: etxabe@gaiker.es

Arcady Zhukov
Dept. Polym. Advanced Materials, Dept. Appl. Physics and EHU Quantum Center, Univ. Basque Country, UPV/EHU, 20018 San Sebastian and Ikerbasque, Bilbao, Spain
e-mail: arkadi.joukov@ehu.es

***Abstract*—In this work, we provide recent experimental results on free space microwave measurements of composites with ferromagnetic microwires inclusions. We observed that both hysteresis loops and the S_{12} parameter in the frequency range 2-4 GHz are affected by applied stress. Such stress sensitivity of studied composites is potentially suitable for contactless stress monitoring in civil engineering or in aircraft industry.**

Keywords-magnetic microwires; magnetic softness; carbon fiber composite; magnetoimpedance effect; applied stress.

I. INTRODUCTION

Amorphous soft magnetic wires, prepared by rapid melt quenching, are useful for numerous industrial applications, such as magnetic and magnetoelastic sensors [1]-[6]. Recently, great attention has been paid to the development of amorphous materials at micro-nano scale involving melt quenching with improved biocompatibility, corrosion and mechanical properties [7][8]. Glass-coated amorphous microwires prepared by the Taylor-Ulitovsky technique present a unique combination of physical properties: such magnetic microwires have extended diameters range (between 0.2 and 100 µm), covered with thin, insulating, biocompatible and flexible glass-coating and can present excellent mechanical and magnetic properties [7]-[10].

Recently, the stress and temperature dependence of hysteresis loops and Giant Magnetoimpedance (GMI) effect are proposed for the mechanical stresses monitoring in Fiber Reinforced Composites (FRC) with microwires inclusions and magnetoelastic sensors [11]- [14]. In particular, it was previously shown that the microwave response of a wire medium is affected by modifying the magnetic properties with external stimuli (magnetic field, stress, temperature). The aforementioned physical mechanism is based on a combination of the dispersion properties of the wire medium and the GMI effect [15]. The main advantage of this method is that it allows for contactless monitoring of external stimuli, like stress or temperature.

In this paper, we present our latest results on studies of magnetic properties of glass-coated Co-rich microwires and on wireless health monitoring of composites containing both carbon fibers and ferromagnetic glass-coated microwires.

This paper is organized as follows. In Section 2, the experimental methods are described. Section 3 deals with experimental results on free space microwave measurements of composites containing ferromagnetic glass-coated microwires. Finally, we conclude the paper in Section 4.

II. EXPERIMENTAL SYSTEM DETAILS

For the magnetic wire inclusions, we selected amorphous $Co_{64.6}Fe_5B_{16}Si_{11}Cr_{3.4}$ glass-coated microwires with metallic nucleus diameters, *d*, of about 38 µm and a total diameter, *D*, of about 45 µm manufactured by the aforementioned Taylor-Ulitovsky method. Recently, a high GMI effect with a GMI ratio above 700% has been reported in similar Co-rich microwires [16]. The morphology of studied microwires has been evaluated using Carl Zeiss -Axio Scope A1 microscope. As can be observed from Figure 1a, the studied microwire presents perfectly cylindrical geometry of the metallic nucleus and rather uniform glass-coating. The amorphous structure of the studied sample has been confirmed by a broad halo in the X-ray spectra obtained using X-ray diffraction (see Figure 1b). Typically, the crystallization of amorphous microwires was observed at Tann ≥ 500 °C [10].

Magnetic hysteresis loops of studied microwires have been measured using the fluxmetric method, previously described in detail elsewhere [17]. The hysteresis loops were represented as the dependence of normalized magnetization, M/M_0 (where M is the magnetic moment at a given magnetic field and M_0 is the magnetic moment of the sample at the maximum magnetic field amplitude almost at magnetic

 ISBN: 978-1-68558-273-9

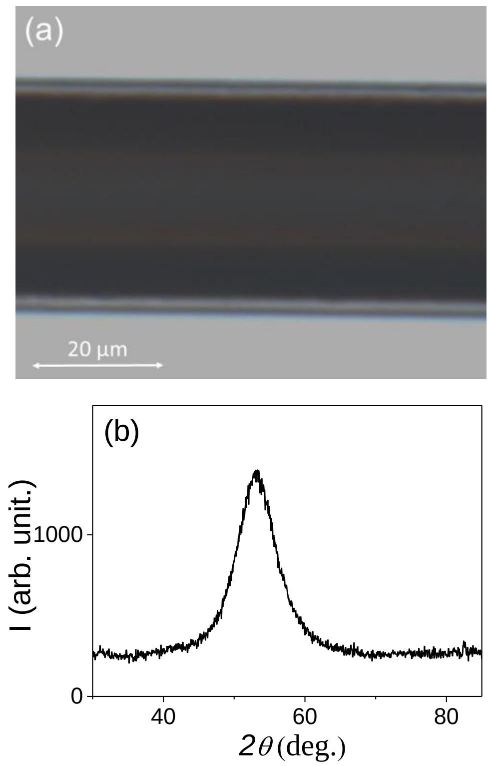

Figure 1. Image obtained using optical microscope (a) and XRD pattern (b) of studied sample.

saturation) versus the magnetic field, *H*. Such format of hysteresis loops allows better comparison of microwires with different chemical composition and diameters. The homogeneous axial magnetic field was produced by a long solenoid (about 1 cm in diameter and 12 cm in length). All the measurements were performed at low magnetic field frequencies (100 Hz).

The composites containing ferromagnetic glass-coated microwires embedded in polymeric matrix were manufactured at Gaiker facilities. The detailed description on fabrication of composites is provided elsewhere [18]. An epoxy system was used to manufacture the polymeric matrix: SICOMIN SR Infugreen 810 resin catalyzed with SICOMIN SD 8822.

The sample impedance, *Z*, in extended frequency range has been evaluated using the micro-strip sample holder from the reflection coefficient, S_{11}, obtained using Vector Network Analyzer (VNA), as previously described [19]. Such micro-strip holder with samples has been placed inside a long solenoid generating a homogeneous magnetic field, *H*. The experimental facility allows to measure the GMI effect up to GHz frequencies, *f*. The GMI ratio, ΔZ/Z, is obtained from *Z(H)* dependence as:

$$\Delta Z/Z = [Z(H) - Z(H_{max})]/Z(H_{max}), \quad (1)$$

where H and H_{max} are given and maximum applied fields, respectively.

For wireless measurements, we used the free space measurement setup (see Figure 2) consisting of two broadband horn antennas ($1 \leq f \leq 17$ GHz) fixed to the anechoic chamber and a vector network analyzer, previously employed for the characterization of the composites with magnetic wire inclusions [11][15]. Such setup allows to characterize the composite of 20 x 20 cm^2. As recently

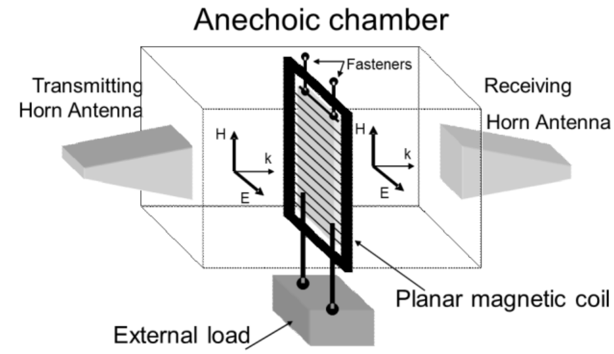

Figure 2. Sketch of the free-space setup.

described, applied magnetic modulation field during the microwave scattering measurements allows to separate the signal from magnetic microwires inclusions from the signal originated by the conductive matrix [20]. The magnetic field is produced by the planar magnetic coil. The mechanical load attached to the composite produced the tensile mechanical stress. We used an universal tension machine (SERVOSIS) allowing to apply tensile stress, augmenting the applied load by increments of 1 kN and simultaneously measuring *S* parameters [18]. As previously described [18], tensile stress is applied in a vertical way, both microwires and polarization direction of the antennas were oriented in that way.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The hysteresis loop of studied microwires is provided in Figure 3. As observed from Figure 3, the studied microwire shows good magnetic softness: a coercivity, H_c, of about 20 A/m and a magnetic anisotropy field, H_k, of about 150 A/ m.

Figure 4 shows the results on GMI effect of the studied

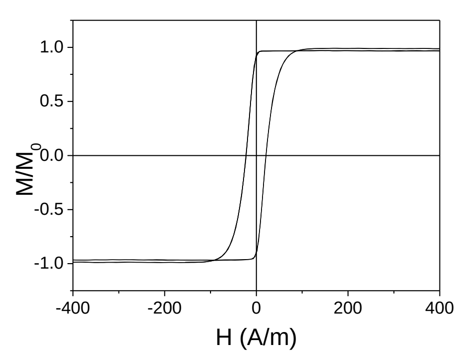

Figure 3. Hysteresis loop of studied sample

Copyright (c) IARIA, 2025. ISBN: 978-1-68558-273-9

microwire. As evidenced from Figure 4, the studied microwire presents a high GMI effect with maximum *ΔZ/Z*, $\Delta Z/Z_m$, of slightly above 200 % at frequencies of about 100-150 MHz. Such H_c, H_k, and $\Delta Z/Z_m$ -values are typical for Co-rich microwires with vanishing magnetostriction coefficients [7] [10] [17].

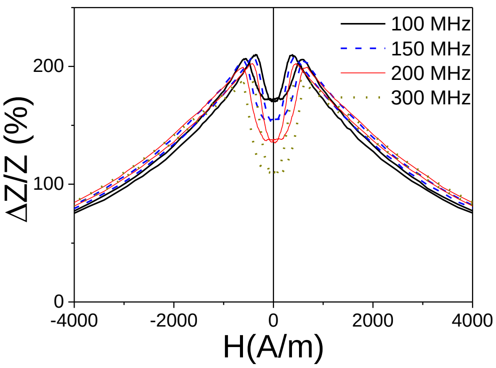

Figure 4. *ΔZ/Z (H)* dependencies of studied sample measured at different *f*.

As reported elsewhere [14] [21], magnetic properties and GMI effect of amorphous Co-rich microwires are substantially affected by applied stress and by heating. Therefore, we expect that utilizing magnetic microwires inclusions in carbon fiber composites can be suitable for stress and/or temperature monitoring.

As can be observed from Figure 5, the composites with these microwires in glass composites revealed that the S_{12} parameter is sensitive to applied force, F_a: there is a clear difference in the S_{12} parameter in the frequency range 2-4 GHz measured at F_a = 1 kN and F_a = 5 kN, due to the stress dependence of the impedance of the magnetic microwire.

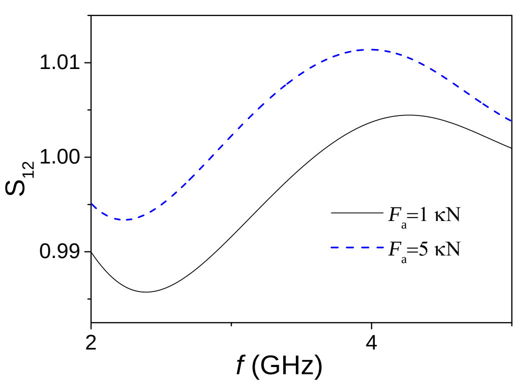

Figure 5. Effect of applied force on S_{12} (transmission) measured in the frequency range from 2 to 5 GHz.

The aforementioned experimental results provide the routes for development of tunable composites with magnetically soft amorphous glass-coated microwires inclusions sensitive to applied stresses.

It must be noted that, in the case of the composites with the carbon fibers and magnetically soft amorphous glass-coated microwires inclusions, the use of a low frequency modulating magnetic field is required to distinguish the microwave signals originated by ferromagnetic microwires inclusions from that generated by the carbon fibers [18]. The use of magnetic microwires inclusions in composite materials is potentially suitable for contactless stress monitoring in civil engineering or in aircraft industry.

IV. Conclusions and Future Work

We have explored the feasibility of developing composites with glass-coated magnetic microwires inclusions using the free space microwave spectroscopy for stresses monitoring. For the preparation of such composites, we selected Co-rich microwires with good magnetic softness and high GMI effect. We experimentally observed that the S_{12} parameter is sensitive to applied force in the frequency range 2-4 GHz. The observed sensitivity of such composites with microwire inclusions is potentially suitable for contactless stress monitoring in civil engineering or in aircraft industry. Future studies of the temperature on S_{12} parameter might be helpful for potential applications. Developing a portable reader is one of the next steps towards real applications.

Acknowledgment

This work was supported by EU under "INFINITE" (HORIZON-CL5-2021-D5-01-06) and "Harmony" (HORIZON-CL4-2023-RESILIENCE-01) projects, by the Spanish MICIN under PID2022-141373NB-I00, by the Government of the Basque Country under Elkartek (ATLANTIS and MOSINCO) projects and under the scheme of "Ayuda a Grupos Consolidados" (ref. IT1670-22). The authors thank for the technical and human support provided by SGIker (Medidas Magnéticas Gipuzkoa) (UPV/EHU, ERDF, EU).

References

[1] V. Zhukova et al., "Electronic Surveillance and Security Applications of Magnetic Microwires", Chemosensors, vol. 9, p.100, 2021.

[2] K. Mohri, T. Uchiyama, L. P. Shen, C. M. Cai, and L. V. Panina, "Amorphous wire and CMOS IC-based sensitive micro-magnetic sensors (MI sensor and SI sensor) for intelligent measurements and controls", J. Magn. Magn. Mater., vol. 249, pp. 351-356, 2001.

[3] T. Uchiyama, K. Mohri, and Sh. Nakayama, "Measurement of Spontaneous Oscillatory Magnetic Field of Guinea-Pig Smooth Muscle Preparation Using Pico-Tesla Resolution Amorphous Wire Magneto-Impedance Sensor", IEEE Trans. Magn., vol. 47, pp. 3070-3073, 2011.

[4] Y. Honkura, "Development of amorphous wire type MI sensors for automobile use", J. Magn. Magn. Mater., vol. 249, pp. 375-381, 2002.

[5] A. Zhukov et al., "Magnetoelastic sensor of level of the liquid based on magnetoelastic properties of Co-rich microwires", Sens. Actuat. A Phys., vol. 81, no. 1-3, pp.129-133, 2000.

[6] L. Ding et al., “Development of a high sensitivity Giant Magneto-Impedance magnetometer: comparison with a commercial Flux-Gate”, IEEE Sensors, vol. 9, no.2, pp. 159-168, 2009.

[7] V. Zhukova et al., “Development of Magnetically Soft Amorphous Microwires for Technological Applications”, Chemosensors, vol. 10, p. 26, 2022

[8] D. Kozejova et.al., “Biomedical applications of glass-coated microwires”, J. Magn. Magn. Mater., vol. 470, pp. 2-5, 2019.

[9] T. Goto, M. Nagano, and N. Wehara, “Mechanical properties of amorphous $Fe_{80}P_{16}C_3B_1$ filament produced by glass-coated melt spinning”, Trans. JIM, vol. 18, pp. 759–764, 1977.

[10] A. Zhukov et al., “Advanced functional magnetic microwires for technological applications”, J. Phys. D: Appl. Phys., vol. 55, p. 253003, 2022.

[11] D. Makhnovskiy, A. Zhukov, V. Zhukova, and J. Gonzalez, “Tunable and self-sensing microwave composite materials incorporating ferromagnetic microwires”, Advances in Science and Technology, vol. 54, pp 201-210, 2008.

[12] F. Qin and H. X. Peng, “Ferromagnetic microwires enabled multifunctional composite materials”, Prog. Mater. Sci., vol. 58, no. 2, pp.183-259, 2013.

[13] A. Allue et al., “Smart composites with embedded magnetic microwire inclusions allowing non-contact stresses and temperature monitoring”, Compos. Part A Appl., vol. 120, pp. 12-20, 2019, DOI: 10.1016/j.compositesa.2019.02.014

[14] P. Corte -Leon et al., ”Effect of temperature on magnetic properties and magnetoimpedance effect in Fe -rich microwires”, J. Alloys Compound. vol. 946, p.169419, 2023, doi: https://doi.org/10.1016/j.jallcom.2023.169419

[15] L. Panina, M. Ipatov, V. Zhukova, J. Gonzalez, and A. Zhukov, “Tuneable composites containing magnetic microwires”, ch. 22, pp.431-460, doi: 10.5772/21423 in Book: Metal, ceramic and polymeric composites for various uses, Edited by John Cuppoletti, 2011, DOI: 10.5772/1428 ISBN: 978-953-307-353-8 (ISBN 978-953-307-1098-3) InTech - Open Access Publisher (www.intechweb.org), Janeza Trdine, 9, 51000 Rijeka, Croatia.

[16] P. Corte-León et al., “Optimization of giant magnetoimpedance effect in Co-rich glass-coated microwires by annealing”, J. Alloys Compound, vol. 999, p.175023, 2024.

[17] L. Gonzalez-Legarreta et al., “Optimization of magnetic properties and GMI effect of Thin Co-rich Microwires for GMI Microsensors”. Sensors, vol. 20, p.1558, 2020.

[18] R. Garcia-Etxabe et al., “Influence of Tensile Stress on Microwave Scattering Parameters of Continuous Ferromagnetic Microwire Embedded Into Glass Reinforced Composites”, IEEE Trans. Magn., doi: 10.1109/TMAG.2024.3488079

[19] A. Zhukov et al., “Routes for Optimization of Giant Magnetoimpedance Effect in Magnetic Microwires”, IEEE Instrumentation & Measurement Magazine, vol. 23, no. 1, pp. 56-63, 2020, doi: 10.1109/MIM.2020.8979525

[20] V. Zhukova et al., “Free Space Microwave Sensing of Carbon Fiber Composites With Ferromagnetic Microwire Inclusions”, IEEE Sens. Lett., vol. 8, No. 1, p. 2500104, 2024.

[21] P. Corte-Leon et al., “Stress dependence of the magnetic properties of glass-coated amorphous microwires” J. Alloys Compound, vol. 789, pp. 201-208, 2019, doi: 10.1016/j.jallcom.2019.03.044