Magnetoimpedance effect in amorphous Co-rich ferromagnetic microwires and its application as low-field sensor

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Abstract. The magnetoimpedance in amorphous microwires with a nominal composition of Co67Fe4Si14B15 has been investigated. The measurements were carried out with an Agilent 4395A network analyzer in the frequency range from 100 kHz to 60 MHz. The experimental setup for magnetoimpedance measurements and the analysis of the results are presented. Our results show that an optimum frequency exists, where the magnetoimpedance ratio is maximum for all studied frequencies. In this frequency, the amorphous microwire is very sensitive to variations of the dc magnetic field. Therefore, we propose a possible application as a low dc field sensor.

1. Introduction
Magnetoimpedance (MI) is a classical electromagnetic phenomenon that can be observed in conductive soft ferromagnetic materials, such as amorphous microwires. This phenomenon is due to the interaction between the magnetic field created by an ac current and the magnetic domains of microwires [1]. Magnetic domain walls dynamics and magnetization spin rotation are the magnetic processes that originate the magnetoimpedance effect [2]. Both magnetization processes originate dynamical magnetization due to circumferential magnetic permeability and the skin depth effect. The magnetic processes depend on the frequency (table 1).

The microwire impedance is defined in equation 1 [3]:

\[ Z = R + iX = R_{DC} + \frac{R_{DC} k a}{2} \frac{J_0(k a)}{J_1(k a)} \]

Where \( R_{DC} \) is the electrical dc resistance, \( a \) is the wire radius, \( J_i \) are the first kind Bessel functions of the impedance magnitude as a function of magnetic field instead of the analysis of real and imaginary parts of the impedance.

| Frequency       | Magnetization Process                          |
|-----------------|-----------------------------------------------|
| Below 100kHz    | Magneto-inductive process                     |
| 1000kHz-100MHz   | Domain wall bending magnetization             |
| 100MHz-1GHz      | Magnetization rotation                        |
| Above 1GHz       | Ferromagnetic resonance (FMR)                 |

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The wire impedance change is normalized and often presented as the MI ratio \([4]\), defined in equation:

\[
MI[\%] = \frac{Z(H) - Z(H_{\text{max}})}{Z(H_{\text{max}})}
\]  

(2)

where \(Z(H)\) is the impedance of the microwire given an external magnetic field \(H\), and \(Z(H_{\text{max}})\) is the impedance with the maximum magnetic field applied to the wire which is assumed to be the saturation field. The \(MI\) ratio quantifies impedance variations and depends on the maximum magnetic field controlled with an experimental setup.

The magnetoimpedance effect is widely used in sensor devices. The MI is studied in amorphous materials with cylindrical geometries and transversal permeability due to their bamboo-like magnetic domains and high sensitivity to axial magnetic fields. Moreover, amorphous Co-rich microwires are one of the most popular elements due to their negative near zero-magnetostriction properties and circumferential anisotropy.

Several studies have documented the use of ferromagnetic microwires as nanoparticle detector \([5]\), biomolecule sensor \([6]\) and magnetoelastic sensor \([7]\). Moreover, low magnetic field applications have also been reported with promising results \([8]\) \([9]\).

2. Experimental details

MI measurements were carried out in the 100 kHz - 60 MHz range, on amorphous Co67Fe4Si14B15 microwires \([10]\) with a 3mm length. A typical MI experimental setup is shown in figure 1a. An ac current flows through an amorphous microwire generating a transverse magnetic ac field that induces magnetization processes. As a consequence, an additional inductive potential appears in the material. An external dc field is applied parallel to the microwire axis as well.

\(MI\) measurements require two simultaneous signals applied to the microwire: an ac electromagnetic signal to induce a circumferential magnetization and a static magnetic field to modify the magnetization direction and the domain structure. The ac signal is provided by a (Agilent, 4395A) network analyzer while the static field is controlled with a set of Helmholtz coils.

A magnetoimpedance effect sensor was developed, with an amorphous microwire as its sensing element. The sensor (figure 1b) is based on a microstrip transmission line designed for a 50\(\Omega\) impedance. The radial axis of the sensor must be positioned parallel to the magnetic field lines to achieve the highest field sensitivity.

(a) Schematic of experimental setup.  (b) Magnetoimpedance sensor with amorphous microwire.

Figure 1: Experimental setup.

The network analyzer is used to energize and detect impedance changes with the RF I-V method. Consequently, the sensor is energized with 0 dBm at frequencies from 100 kHz to 60 MHz. For the possible use as a sensor, we propose a set of experiments with the cobalt foil; the foil was located over the microwire without any contact and with a constant position for the remaining tests.
3. Results

The MI response as function of the frequency between 100 kHz to 60 MHz is shown in figure 2. Magneto-inductive processes were not observed in this frequency range.

Even at the lowest frequency, the axial domain was not visible in the magnetoimpedance curves; we assume that the size of the core is smaller than expected. MI measurements show symmetrical double peaks as function of H (fig 2a) which is a consequence of the predominantly circular domains, confirming bamboo-like magnetic structure. The separation between both peaks is associated to the circumferential anisotropy field; the obtained separation ranges from 183.48 to 307.92 A/m.

For frequencies between 100 kHz to 10 MHz, MI effect is originated mainly due to the dependence of the skin depth with changes in the circumferential permeability. At higher frequencies, the current is distributed throughout the surface due to skin depth phenomenon. The linear response from the magnetoimpedance effect was confined into the 100 kHz to 3 MHz range (fig 2b). Between 4 and 40 MHz, the MI curves exhibit contributions from MI and FMR effects. Above 50 MHz, ferromagnetic resonance is predominant.

The linear region, peak separation, maximum MI ratio and sensitivity for each frequency are described in table 2. The linear region is the central region of the MI curves where a linear response is expected from the microwire. This region can be divided in positive and negative linear regions: from the upper limit (right peak) to 0 A/m and from 0 A/m to the lower limit (left peak). The separation of right and left peaks increases with frequency as well as the peak MI percentage.

For every frequency, the MI magnitude of right and left peak were identical. Thus, the sensibility of the sensor is equal in its negative and positive linear regions. The highest sensitivity is achieved at 1 and 2 MHz. This would be particularly important for the design of magnetic field sensors under 100 A/m.

![Figure 2: Frequency response of MI sensor with Co-rich microwire.](image)

| Frequency [MHz] | Linear region [A/m] | Peak separation [A/m] | Maximum MI ratio [%] | Sensitivity [%/A/m] |
|-----------------|---------------------|-----------------------|----------------------|-------------------|
| 0.1             | -91.74 to 91.74     | 183.48                | 11                   | 0.1192            |
| 0.5             | -91.74 to 92.53     | 184.27                | 11.1                 | 0.1176            |
| 1               | -91.74 to 92.53     | 184.27                | 11.2                 | 0.1204            |
| 2               | -102.77 to 102.77   | 205.54                | 12.6                 | 0.1226            |
| 3               | -122.85 to 122.85   | 245.70                | 13.3                 | 0.1082            |
| 5               | -153.16 to 153.96   | 307.12                | 15.3                 | 0.0994            |
| 8               | -153.96 to 153.96   | 307.92                | 16.7                 | 0.1085            |
| 10              | -153.16 to 153.96   | 307.12                | 17.6                 | 0.1143            |
3.1. MI sensor with cobalt foil

The frequencies used for the following tests were 1 to 5 MHz. However, above 3 MHz the MI curves show deformations on both peaks which may be caused by FMR contributions in localized surfaces of the microwire. Since the objective is to measure low magnetic fields by means of magnetoimpedance effect, the test range is defined between 1 and 3 MHz.

The sensitivity of the microwire allows to measure subtle modifications in the MI curves caused by the cobalt foil. Dashed curves in figure 3 show the microwire response without any foil and plain curves show the response with cobalt foil as sample.

A slight increase in magnitude is displayed as the highest point of the curves (peak) with sample is 1.2% higher than the one without the foil. The same difference is reported in center of the curves. Plain curves have different MI relations in right and left peaks. The MI ratio difference increases with the frequency starting at 0.2% at 1 MHz and 0.6% at 5 MHz. No significant changes in the shape of the curves are observed.

Left-wise or right-wise shifts in the curve were quantified. MI curves suffered a right-wise shift as result of the presence of the foil. A 528 A/m shift is caused by the cobalt foil presence above the microwire; the shift is independent of the frequency. Measurements with a Hall effect sensor showed a magnetic field of 470 A/m, 5mm above the cobalt foil. The magnetic field magnitude obtained with MI effect sensors anisotropy of the cobalt foil.

![figure 3. Detection of ferromagnetic foil over magnetoimpedance sensor.](image)

4. Conclusion

We successfully developed a magnetoimpedance sensor with a Co-rich amorphous ferromagnetic microwire as its sensing element. The sensor was studied in a frequency range from 100 kHz to 60 MHz. Magnetoimpedance and ferromagnetic resonance effects were detected. We used the MI sensor to detect a ferromagnetic sample with a magnetic field with a magnitude lower than 800 A/m.

Acknowledgments

This work is supported by DGAPA-UNAM (PAPIIT IG100517). We would like to thank MSc Alejandro Esparza (ICAT, UNAM). Carmen H. López-Ortega acknowledges CONACyT for the corresponding graduate studies scholarship.

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