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Temperature effect on GMI sensor: comparison between diagonal and off-diagonal response

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ABSTRACT

In this paper, the effect of temperature on Giant Magneto-Impedance (GMI) sensors is studied in amorphous wire Co-Fe-Si-B from Unitika. Both diagonal, Z_{11} , and the off-diagonal, Z_{21} , components of the impedance tensor are considered, with a primary focus on the changes of intrinsic sensitivity and offset, which are the most crucial relevant quantities for practical sensor implementation. Experiments are conducted in the almost industrial temperature range of $[-20\text{ }^{\circ}\text{C}, 120\text{ }^{\circ}\text{C}]$. For the component Z_{11} , the results show a maximum change of the offset of $-0.13\text{ (A/m)/}^{\circ}\text{C}$ ($170\text{ nT/}^{\circ}\text{C}$), at a 33 A/m bias field. The sensitivity at this field increases for temperatures between $-20\text{ }^{\circ}\text{C}$ and $+40\text{ }^{\circ}\text{C}$, and then it decreases (a maximum change of $-0.5\text{ \%}/^{\circ}\text{C}$). For the off-diagonal component, Z_{21} , the change of the offset near the zero-field is smaller ($-0.015\text{ (A/m)/}^{\circ}\text{C}$ or $-19\text{ nT/}^{\circ}\text{C}$), whereas the sensitivity increases with temperature by about $+0.4\text{ \%}/^{\circ}\text{C}$.

Keywords:

GMI sensor, diagonal, off-diagonal, sensitivity, offset, temperature, parameter of influence.

1. Introduction

Giant Magneto-Impedance (GMI) is the significant change of the high-frequency impedance of some soft magnetic conductors (amorphous wires, ribbons, thin-film structures) when they are submitted to an external magnetic field [1]. This effect can be used to implement magnetic sensors based on the measurement of the impedance of the conductor. This impedance is, in reality, a tensor, which has two main useful components, usually called diagonal, Z_{11} , and off-diagonal, Z_{21} [2]-[5]. One or the other of these components can be used to implement a GMI sensor.

GMI sensors are still not very widespread, especially for industrial applications. These applications may include- but are not limited to- the contactless measurement of electrical current and linear or angular positions as well as the nondestructive testing, etc. For these kinds of applications, different issues related to the use of the sensor in a real environment of measurement may be involved. In this context, the impact of the working temperature on the performance of the sensor is of major concern. The robustness of the sensor versus the temperature changes is a key feature for manufacturers and users. Therefore, the knowledge of the influence of temperature is crucial in order to be corrected by suitable strategies of sensor implementation.

By far, the studies dealing with the temperature effect on the GMI are not very numerous and they are generally non-systematic, especially for the case of amorphous wires. Some examples of these works, directly related to the GMI, can be found in [6]-[9]. Other works have investigated the temperature dependence of the GMI in ribbons [10]-[12] and in thin-film structures [13]. Temperature drift of a few GMI sensor prototypes was also reported in [12], [14], [15]. However, most of the works related to amorphous wires were focused on the temperature dependence of the diagonal component, Z_{11} . To the best of our knowledge, there are only some rare recent works dealing with the temperature dependence of the off-diagonal component Z_{21} [16]-[17]. In addition, the effect of different annealing temperatures on this component has been recently addressed [18]. In this context, it is very important to make a clear difference between the effect of treatments and annealing at relatively high temperatures, which is

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generally performed in most of the works, and the impact of the working temperature on the sensor response [13]. This impact, especially at the ambient and industrial temperature ranges, is by far poorly investigated in the literature.

In this paper, a study is carried out to firstly evaluate the temperature dependence of the off-diagonal component in an almost industrial temperature range $[-20^{\circ}\text{C}, 120^{\circ}\text{C}]$. Secondly, another main underlying idea of the study is to provide a clear and a comprehensive comparison of the temperature dependence between the diagonal and the off-diagonal responses. Finally, in the present investigation, the primary attention is paid to the change of most relevant parameters for sensor implementation, namely the offset and of the intrinsic sensitivity of both components, near a suitable working (or bias) point of the sensor. Indeed, most of the previous works considered the change of GMI ratio with temperature as a factor of merit. Despite the fact that this ratio allows describing the behavior of the diagonal component, it is generally not the most relevant quantity to consider for the sensor implementation. For example, amorphous wires may exhibit an important GMI ratio, and in the same time a poor sensitivity at the working point [19]. In addition, for some applications, especially the measurement of DC fields, the study of the change of the offset of the sensor with temperature may be more important than the evolution of the GMI ratio.

The section II of the paper presents the developed experimental setup, together with a description of the general approach of investigation as well as clear definitions of the considered quantities. The obtained results and discussions are provided throughout the section III.

2. Brief overview of the studied quantities and experimental setup

In typical implementations of GMI sensors, a high frequency current i_{ac} of constant amplitude is supplied to the amorphous wire (Fig. 1a).

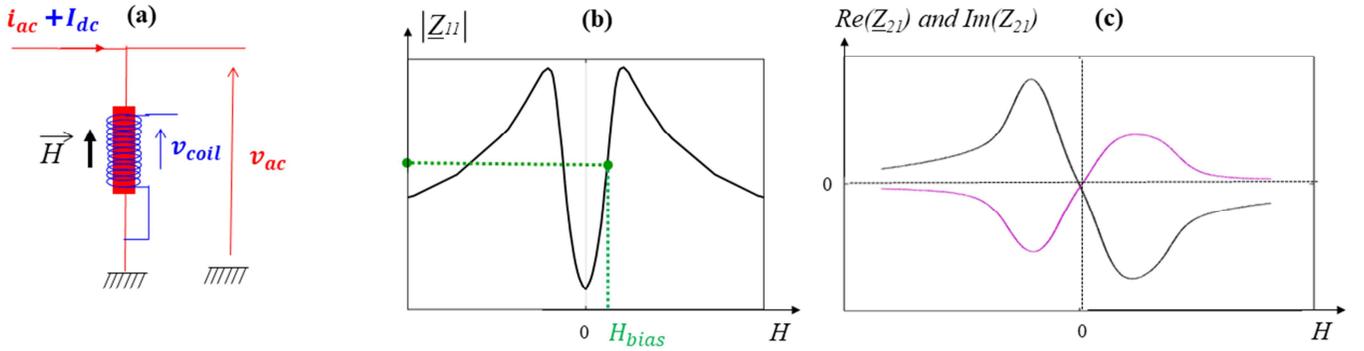


Fig. 1. Basic implementations of GMI sensor (a); and typical curves of the diagonal and off-diagonal responses (b) & (c).

A first method to implement the sensor makes use of the diagonal component, Z_{11} , which is defined as the ratio between the voltage v_{ac} across the wire and the current i_{ac} . This component exhibits a non-linear and even characteristics versus the magnetic field H as illustrated in Fig. 1b. Therefore, the application of an axial bias field H_{bias} is required to fix the working point of the sensor in the region where the response is almost linear and where the intrinsic sensitivity is high. This sensitivity, noted S_{11} , is defined as the derivative of the curve at the bias point according to (1):

$$S_{11}(H_{bias}) = \left. \frac{\partial |Z_{11}|}{\partial H} \right|_{H=H_{bias}} \quad (1)$$

This magnetic bias induces an offset, which is related to the impedance, $|Z_{11}(H_{bias})|$. Consequently, an offset cancelling circuit is necessary to obtain a zero output for a zero measured field.

A second promising method to implement the GMI sensor is based on the use of the off-diagonal component, Z_{21} . This component can be obtained through the measurement of the voltage induced in a pick-up coil wound around the GMI wire (Fig. 1c). The origin of this induced voltage is the appearance of an AC longitudinal magnetization of the wire. In amorphous wires with circumferential anisotropy, as the case of the wires used in the present experiments, a significant appearance of this longitudinal magnetization can be obtained by superimposing a DC static current I_{dc} to the high frequency current i_{ac} [2]-[5]. One of key features of the off-diagonal configuration is that the response is almost linear and odd near the zero-field for both real $\text{Re}\{Z_{21}\}$ and imaginary $\text{Im}\{Z_{21}\}$ parts of Z_{21} . Consequently, it is a priori possible to design the sensor without making use of a

bias field H_{bias} , which dramatically simplifies the implementation. In this case, the working point of the sensor is the zero-field. The offset $\text{Re}\{Z_{21}\}(0)$ or $\text{Im}\{Z_{21}\}(0)$ is almost null. The sensitivity at this point is defined by (2)

$$S_{21}(0) = \left. \frac{\partial \text{Re}\{Z_{21}\}}{\partial H} \right|_{H=0} \quad (2)$$

It is worth noting that $\text{Re}\{Z_{21}\}$ and $\text{Im}\{Z_{21}\}$ exhibit similar behaviors (Fig. 1). The sensor implementation may make use of one or the other of these parts. This is why, and without loss of generality, only the real part is considered in current study.

The temperature dependence of the offset and sensitivity may have influence on the choice of the method of sensor implementation for some applications. Indeed, the offset change would be of major concern when the sensor should be used for the measurement of DC magnetic fields or electrical currents. The intrinsic sensitivity, together with additional electronic amplification, determines the gain of the open-loop of the sensor. When the sensor operates in closed-loop, which is frequently the case, it is very important to guarantee a “high enough” open-loop gain for the proper functioning of closed-loop. The change of the intrinsic sensitivity with temperature may therefore affect this functioning.

In summary, the temperature dependence of the offset and sensitivity of GMI sensor is a major issue that by far is not intensively investigated. That is why a complete setup has been built for the characterization of the temperature dependence of the GMI. A simplified scheme of this setup is illustrated in Fig. 2.

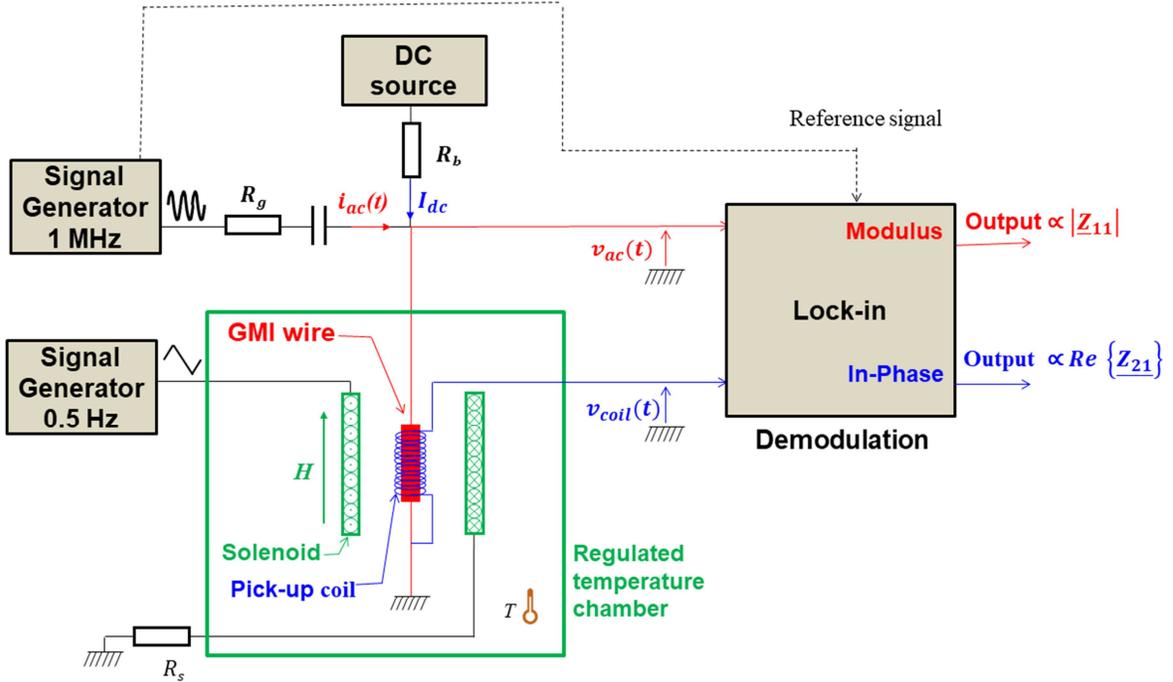


Fig. 2. Experimental setup for the temperature characterization of the diagonal and off-diagonal responses.

An amorphous GMI wire of Co-Fe-Si-B type with a 100 μm diameter and 5 cm long, manufactured by Unitika, is used in the experiments. The choice of a relatively long wire was actually related to the context in which the present studied was carried out. Indeed, the work aimed to develop a toroidal current sensor based on the GMI. In such application, the sensitive element forms a loop (of at least several centimeters) around the conductor carrying the current of interest. This current produces a circumferential magnetic field, which is measured by the sensitive element. It may be worth noting that in applications requiring high spatial resolution, the use of shorter wires is necessary. In this case, the wire from Unitika may exhibit limitations related to the presence of a large demagnetization field near the ends of the wire [20]. This demagnetization field is due to the presence of large longitudinal magnetization associated with the uniformly magnetized core of such wires [21]. Consequently, it is by far difficult to make a GMI sensor having length smaller than 1 cm. If the spatial resolution is an issue, glass-coated wires should be preferred since they may allow realizing sensitive elements with a length less than 0.5 cm [22]. This is related to the fact that longitudinal magnetization is close to zero, as the exchange core in the center of the wire is quite small [23].

A pick-up coil of about 800 turns was wound over the entire length of 5 cm of used wire. The excitation current, i_{ac} , was provided by the combination of a sinusoidal voltage generator and the resistor R_g . A DC current I_{dc} , could also be superimposed using a DC voltage source and the resistor R_b . A capacitor prevents the DC power from reaching the AC source.

For the off-diagonal operation, the frequency of the AC current i_{ac} is limited by the resonance of the pick-up coil, due to parasitic capacitance between turns. For our device, the resonance frequency of the coil was about a few megahertz. It should be noted that the input capacitance of the lock-in detector can interfere with the measurement by reducing resonance frequency of the coil. This is why a relatively low excitation frequency of 1 MHz is chosen. Furthermore, a relatively low amplitude (5 mA) of the excitation current is used in the experiment in order to ensure a linear regime of the GMI [24].

The measured field H is applied using a solenoid powered by a low-frequency AC source. This source could generate triangle-shaped current at 0.5 Hz, giving a linear “scan” of the field to be measured. The coil current is known by measuring the voltage across a shunt R_s , giving the field value. The maximum field available H_{max} is about 1 kA/m. The GMI wire is placed in a thermal chamber. The temperature in this chamber was regulated. The components Z_{11} and Z_{21} are measured for the temperature range of -20°C to $+120^\circ\text{C}$.

3. Results and discussions

3.1. The diagonal component

The amorphous wire is supplied by a high-frequency current i_{ac} having 1 MHz of frequency and 5 mA of amplitude. No DC current is added. **Fig.3(a)** shows the impedance modulus $|Z_{11}|$ as a function of the magnetic field, H , for different temperatures. To simplify the presentation of the curves, and without loss of generality, only the parts of curves corresponding to positive fields are shown.

It can be seen that this impedance exhibits a significant temperature dependence. For a first description of the general behavior of the GMI effect with temperature, the GMI ratio is used, despite the fact that it is not the most relevant parameter for sensor implementation as it was mentioned in Section 1. Indeed, this ratio is still useful for the comparison purposes because it is widely used in the existing literature on the GMI effect.

The GMI ratio, which is a relative change of the impedance with the magnetic field, is defined by (3)

$$\Delta|Z_{11}|/|Z_{11}| (\%) = \frac{|Z_{11}|(H) - |Z_{11}|(H_{max})}{|Z_{11}|(H_{max})} \times 100 \quad (3)$$

where H_{max} is the maximum field available.

At each temperature, the GMI ratio has a maximum, denoted $(\Delta|Z_{11}|/|Z_{11}|)_{max}$. This maximum is plotted as a function of temperature in Fig. 3(b). It increases with the temperature between -20°C and $+20^\circ\text{C}$, then decreases between $+20^\circ\text{C}$ and $+120^\circ\text{C}$. This observation is consistent with the results that have been reported in some works. For example, Chiriac *et. al.* have showed that the maximum GMI ratio $(\Delta|Z_{11}|/|Z_{11}|)_{max}$ increased with temperature up to slightly higher than the ambient temperature (between 20°C and 50°C), then decreased [6]. The experiment was conducted on a Co-Fe-Si-B amorphous wire of 120 μm diameter, excited by a 1 MHz/15 mA high-frequency current.

As it is mentioned in the Section 1, the primary focus of the current study concerns the sensitivity and offset changes. The intrinsic sensitivity S_{11} was obtained by calculating the derivative of the curves of Fig. 3(a) with respect to the magnetic field. The results are illustrated in Fig. 3(c), where the sensitivity at each temperature is plotted as a function of the magnetic field. The maximum of this sensitivity, denoted S_{11-max} , is represented versus temperature in Fig. 3(d). It can be seen that S_{11-max} increases with the temperatures up to about 40°C , then decreases for temperatures between 40°C and 120°C . The relative change, between the lowest sensitivity (at 120°C) and the highest one (at 40°C), is about $0.9 \Omega/(\text{A/m})$. Furthermore, it is worth noting that the magnetic field corresponding to S_{11-max} decreases when the temperature increases.

For a GMI sensor based on the diagonal component, the use of an axial bias field H_{bias} is necessary, as it was mentioned in Section 2. Usually, this bias field is chosen to maximize the sensitivity at room temperature (20°C for example). At this temperature S_{11-max} is obtained at a field of about 33 A/m (H_{bias} in Fig. 3(a)). One of the most important points for the sensor design is the gain of the open-loop, which is proportional to the value of the sensitivity at H_{bias} . This sensitivity $S_{11}(H_{bias})$ is shown in Fig.3(e) as a function of temperature. It varies at most between $2.1 \Omega/(\text{A/m})$ at 20°C and about $1 \Omega/(\text{A/m})$ at 120°C . This yields a temperature coefficient of sensitivity of about $-0.5\% / ^\circ\text{C}$. A value of the same order of magnitude ($0.2\% / ^\circ\text{C}$) was reported in amorphous ribbon samples [15].

The bias field determines also the value of the offset of the sensor, which is proportional to $|Z_{11}(H_{bias})|$. This quantity is represented in Fig. 3(f) as a function of temperature. $|Z_{11}(H_{bias})|$ varies at most between 43Ω (at 20°C) and 32Ω (at -20°C). The relative change is about $-0.28 \Omega/^\circ\text{C}$. This change could be converted into a measurement drift of the magnetic field by

introducing the temperature coefficient of offset expressed in (A/m)/°C (or in T/°C). For an intrinsic sensitivity of 2.1 Ω /(A/m) at 20 °C, a change of -0.28 Ω /°C of the offset corresponds to a temperature coefficient of about -0.13 (A/m)/°C (or -170 nT/°C). A temperature coefficient of 340 nT/K was reported in [12] for a sample of amorphous ribbon of composition Co-Fe-Cr-Si-B.

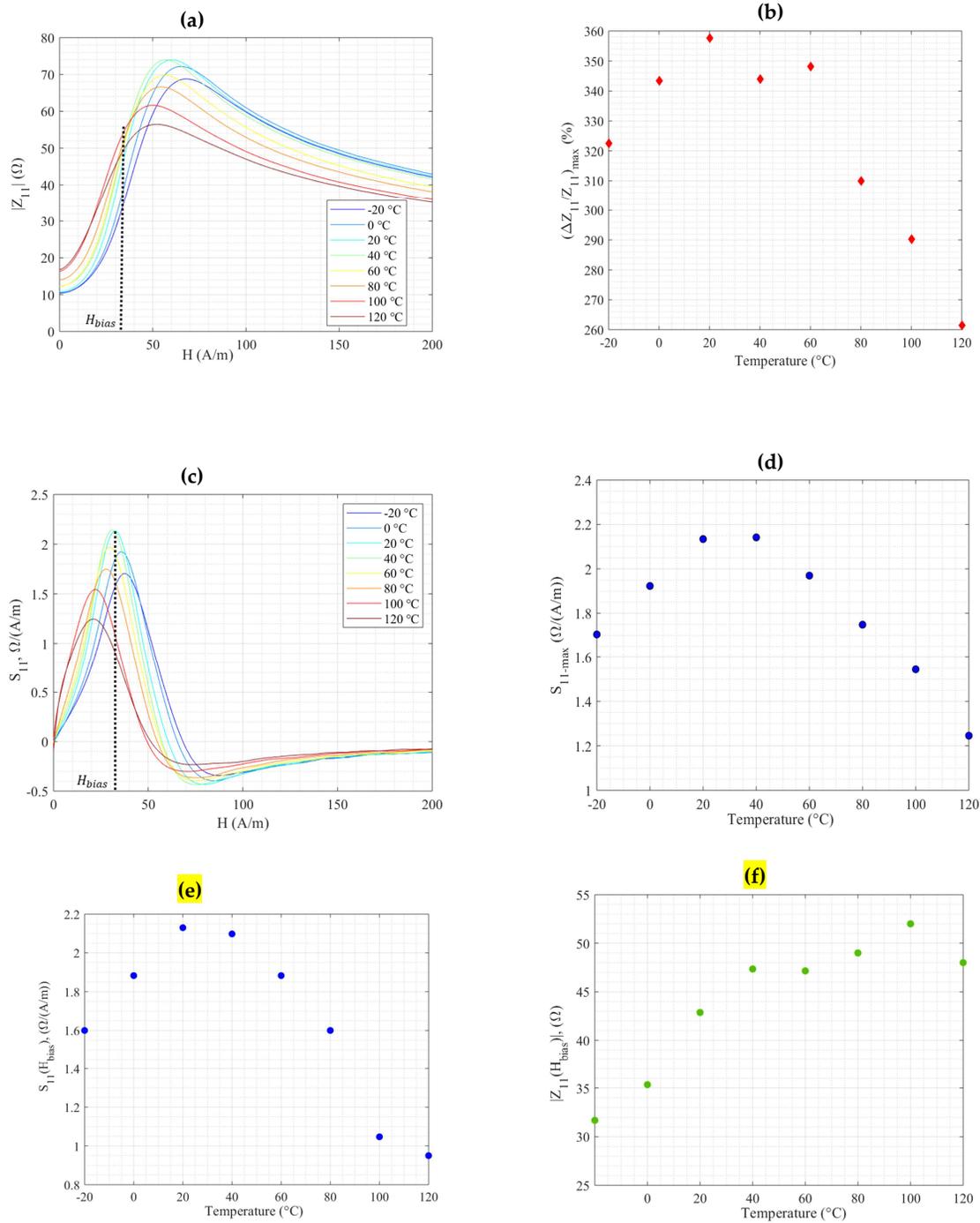


Fig. 3. Temperature dependence of the diagonal component for an amorphous wire of Co-Fe-Si-B type (100 μ m diameter, 5 cm long) excited by a high-frequency current i_{ac} of 5 mA amplitude and 1 MHz frequency. **(a)** Modulus $|Z_{11}(H)|$ at different temperatures; **(b)** GMI ratio versus temperature; **(c)** Sensitivity S_{11} versus magnetic field at different temperatures; **(d)** Maximum of sensitivity S_{11-max} versus temperature; **(e)** Sensitivity $S_{11}(H_{bias})$ at the bias field of about 33 A/m; **(f)** Offset/ $|Z_{11}(H_{bias})|$ as a function of temperature.

When considering the origin of the GMI, this temperature dependence could be explained by the change of circumferential permeability. Indeed, as it is well-known, in the intermediate frequency regime of (roughly from 100 kHz to 100 MHz); the GMI results from the modification of the skin depth of the high frequency current in the wire. This skin depth depends on the

resistivity and on the circumferential permeability. The modification of the impedance with the applied field is directly related to the significant change of this permeability.

The temperature dependence of the GMI may by far have two origins: the change of electrical resistivity and the change of the permeability. However, in the range of temperatures studied, the modification of the resistivity does not explain the observed temperature dependence of the diagonal component. This was confirmed by the measurement of the static resistance R_{DC} of the wire in the temperature range of 20 °C to 80 °C as illustrated in Fig. 4. The relative change of this resistance is about 0.007 %/°C, which is very small when compared to the relative changes of sensitivity, offset and GMI ratio.

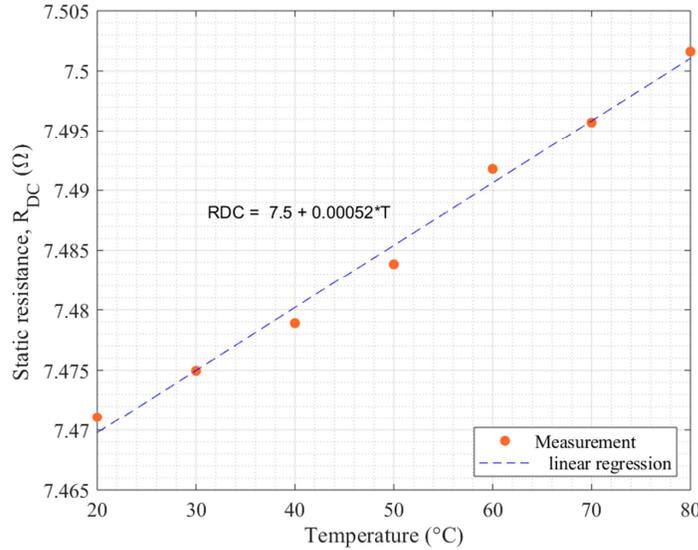


Fig. 4. Static resistance, R_{DC} , of the wire versus temperature.

Therefore, the most likely interpretation of this temperature dependence is the modification of the circumferential permeability [9], [16]-[17], [25]-[26]. This interpretation is also consistent with the observed modification of the field of maximum impedance, which decreases with the temperature elevation (Fig. 3(a)). As this field of maximum impedance is close to the field of anisotropy, the temperature dependence of the diagonal component is directly related to the modification of anisotropy, which in turn modifies the sensitivity. This temperature instability of the anisotropy may originate from internal residual stresses in the wire. These stresses are due to the fabrication process by rapid solidification. The temperature elevation induces a partial release or a change of the stress distribution, resulting in the change of the anisotropy and consequently the GMI response and sensitivity.

3.2. The off-diagonal component

For this experiment, the same high-frequency current as in Section 3.1 is used. A DC current ($I_{dc} = 10$ mA) is also superimposed in order to observe the off-diagonal component in wires with circumferential anisotropy [2]-[5]. This current is also needed to stabilize the almost linear response of the off-diagonal component [27]. Fig. 5 shows the real part $\text{Re}\{\underline{Z}_{21}\}$ and the

sensitivity $S_{21} = \left. \frac{\partial \text{Re}\{\underline{Z}_{21}\}}{\partial H} \right\}$ of this component at different temperatures as a function of the magnetic field. In Fig. 5 (a), the curves exhibit the almost odd symmetry of the curves with respect to the zero-field point. It can however be noticed a slight asymmetry of the responses for positive and negative fields due to the presence of a weak helical anisotropy in the used wires [27].

The maximum of sensitivity is obtained for a field close to zero for all the temperatures studied, as shown in Fig. 5(b). This field is almost the same, unlike the previous results obtained with diagonal component. The sensitivity at zero-field $S_{21}(0)$ increases with temperature as seen in Fig. 6(a). It varies between 2 Ω / (A/m) at 20 °C and 2.7 Ω / (A/m) at 120 °C, which is an increase of 35%. This percentage corresponds to a temperature coefficient of sensitivity of +0.4% / °C. The almost zero offset of $\text{Re}\{\underline{Z}_{21}\}$ at zero-field is roughly unchanged with temperature as illustrated in Fig. 6(b). This offset varies at most by 2 Ω (from about 0 Ω at 20 °C to -2 Ω at 80 °C) as shown in Fig. 6(b). That is to say a change of 2 % of the 200 Ω of full scale of $\text{Re}\{\underline{Z}_{21}\}$.

With an intrinsic sensitivity $S_{21}(0)$ of $2 \text{ } \Omega / (\text{A/m})$ at $20 \text{ } ^\circ\text{C}$, this change of $-0.03 \text{ } \Omega / ^\circ\text{C}$ corresponds to a temperature coefficient of offset (or a drift) of $-0.015 \text{ (A/m)} / ^\circ\text{C}$, or $-19 \text{ nT} / ^\circ\text{C}$.

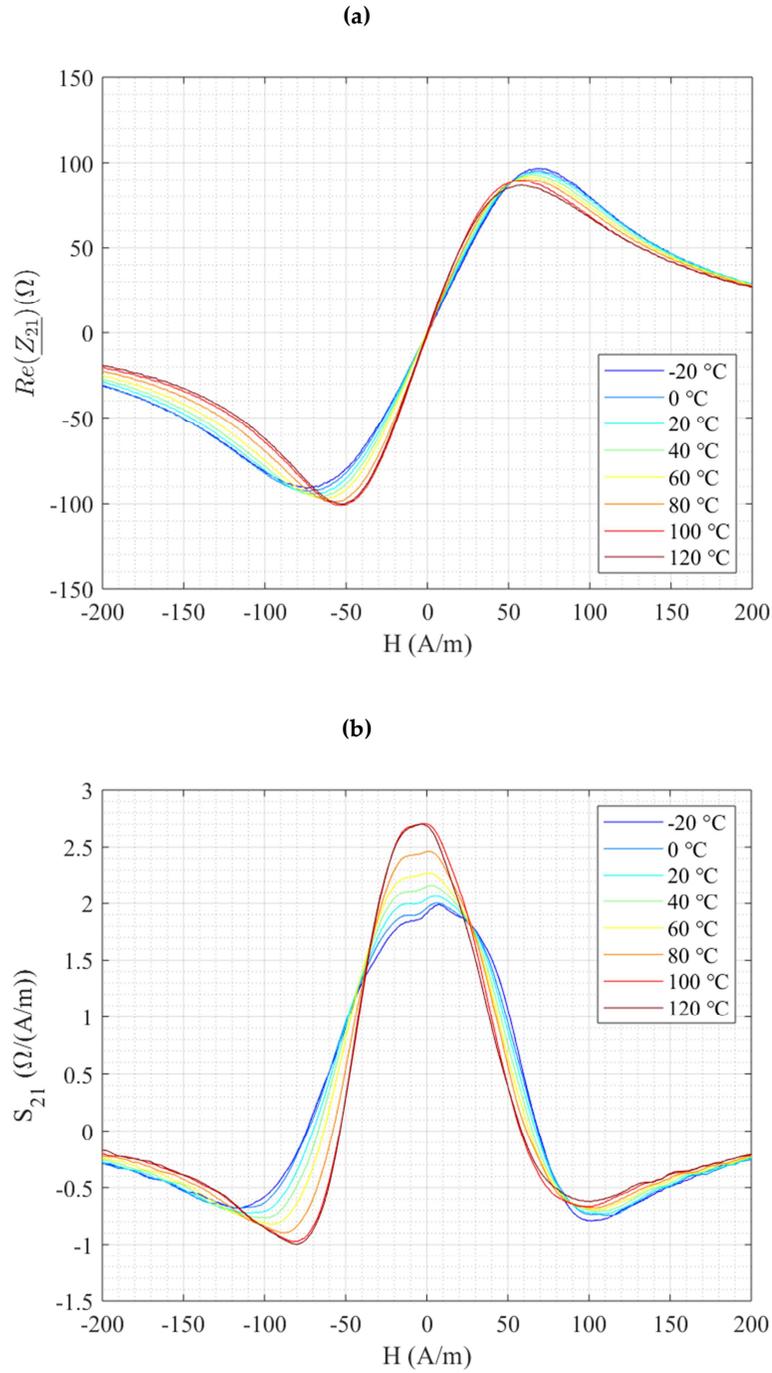


Fig. 5. Temperature dependence of the off-diagonal component for an amorphous wire of Co-Fe-Si-B type (100 μm diameter, 5 cm long) supplied by a high-frequency current i_{ac} (amplitude 5 mA, frequency 1 MHz) and a DC current ($I_{DC} = 10$ mA). **(a)** $\text{Re}\{Z_{21}\}$ versus magnetic field at different temperatures; **(b)** Sensitivity S_{21} versus magnetic field at different temperatures.

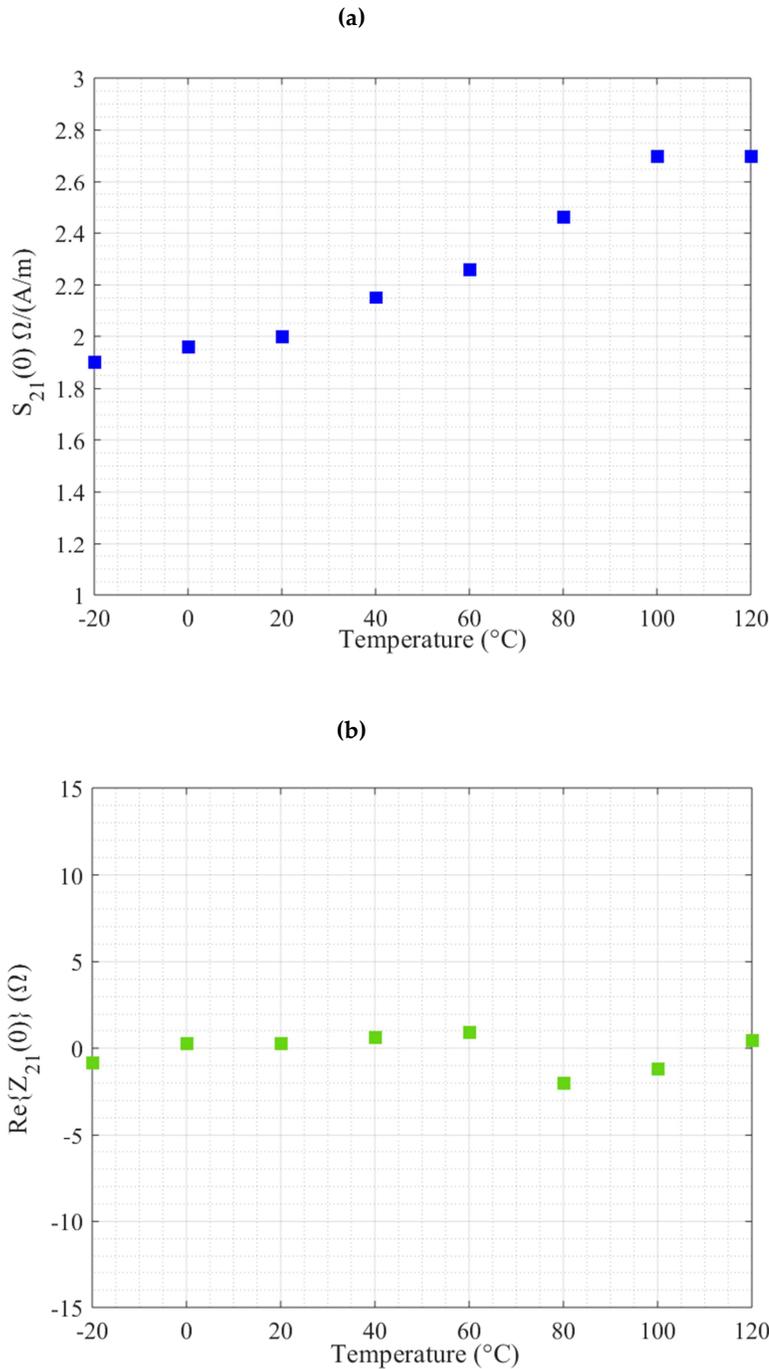


Fig. 6. Temperature dependence of the offset and sensitivity of the off-diagonal component for an amorphous wire of Co-Fe-Si-B type (100 μm diameter, 5 cm long) supplied by a high-frequency current, i_{ac} (amplitude 5 mA, frequency 1 MHz) and a DC current ($I_{DC}= 10$ mA). (a) Sensitivity at zero-field $S_{21}(0)$ versus temperature, (b) Offset at zero-field $\text{Re}\{Z_{21}(0)\}$ versus temperature.

In the same way as for Z_{11} , these modifications of the off-diagonal response could also be attributed to the change of the anisotropy and the circumferential permeability of the wire with temperature [9], [16], [18]. In Reference [16], Panina et.al have investigated the temperature dependence of the off-diagonal component in glass-coated amorphous wires (CoFeNiMoSi) having a total diameter of 42 μm (36 μm of metallic core). The experiments were conducted for an excitation frequency of 20 MHz. The temperature dependence of the off-diagonal component was interpreted by a modification of the anisotropy, which is due to the change of the stress distribution. It is to note that, compared to the used wires from Unitika, the residual internal stress distribution in glass-coated wires is different. It can result from different contributions. Indeed, in addition to stress resulting from the fabrication by rapid solidification or inhomogeneous quenching, the different thermal coefficients of expansion of metal

and glass contribute also to stress distribution and consequently to the temperature dependence of the GMI [9], [18]. All of these contributions exhibit strong temperature dependence. Panina *et al.* have showed an increase of the sensitivity of the off-diagonal response in glass-coated wires for temperatures between 20 °C and 60 °C, then a decrease for temperatures up to 100 °C [16]. Globally, these results were consistent with those obtained in the present study, in the sense that the temperature changes induced a modification of the response and of the sensitivity. However, the behavior of the sensitivity with temperature was different between the two studies. In reference [16], the decrease of the sensitivity started from 60 °C, whereas in the present study this decrease was observed from a temperature of 120 °C. This may be due to the different stress distributions and different mechanisms of stress relaxation between the two types of wires.

4. Conclusions

This study showed a temperature dependence of the both diagonal and off-diagonal responses of the GMI in the studied amorphous wire. In the temperature range considered, the comparison between the sensitivities of the diagonal response at a given bias field and of the off-diagonal one at zero-field shows that the change is almost in the same order of magnitude (-0.5% / °C and +0.4 % / °C, respectively). The off-diagonal response exhibited better offset stability than the diagonal one (changes were almost ten times lower).

From practical point of view, the temperature dependence may determine the choice of either diagonal or off-diagonal configuration many applications of GMI sensors. Both configurations have a roughly equivalent change of the sensitivity in the considered temperature range. However, when DC field measurements are issues, the offset stability of the off-diagonal response is clearly a high advantage.

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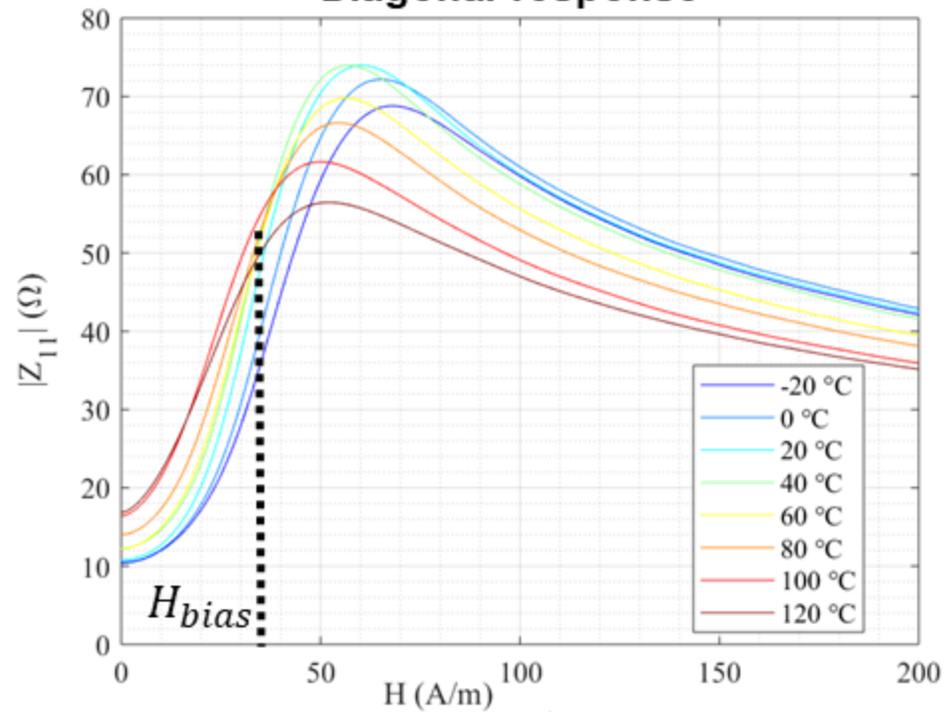
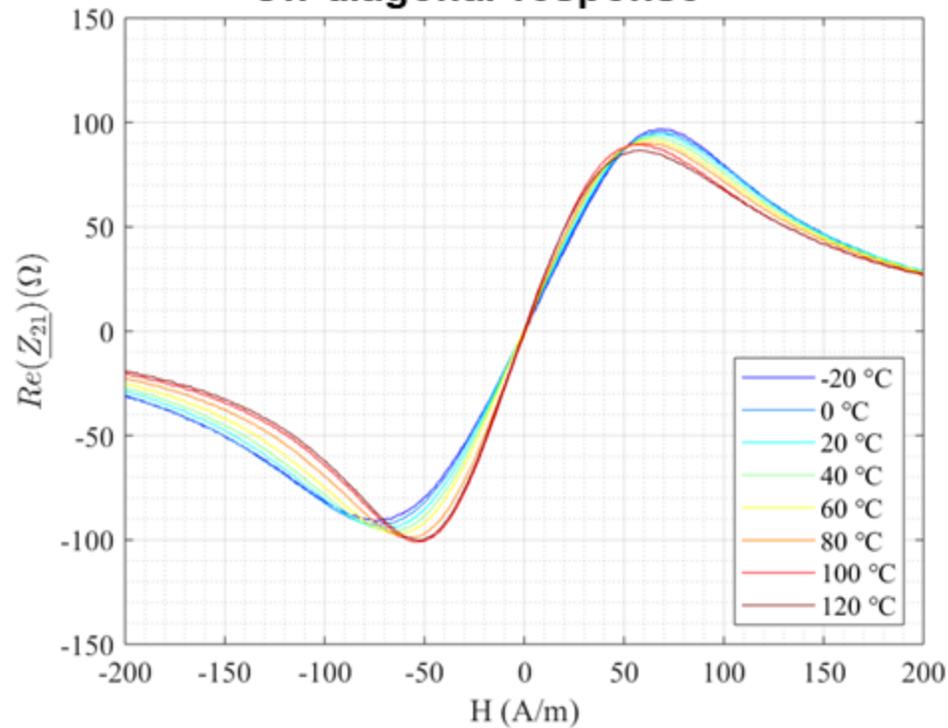
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Diagonal response**Off-diagonal response**

Sensitivity
 $S_{11-max} = \max \left. \frac{\partial |Z_{11}|}{\partial H} \right|$

Offset
 $|Z_{11}(H_{bias})|$

Sensitivity
 $S_{21}(0) = \left. \frac{\partial Re\{Z_{21}\}}{\partial H} \right|_{H=0}$

Offset
 $Re\{Z_{21}\}(0)$

