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Effect of Parasitic Capacitance on GMI Magnetic Sensor Performance

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Abstract. Magnetic sensors based on GMI devices are the subject of intensive research, as they appear promising for magnetometry applications. Performances of GMI magnetometers are often limited by the noise of the electronic setup. Thus, the present challenge is to increase the GMI device sensitivity (expressed in V/T) in order to decrease the equivalent magnetic noise of the system. In our previous work, we showed that the use of a pick-up coil in an off-diagonal configuration improves the magnetic sensor sensitivity and offers a promising approach for developing an inexpensive magnetometer with sub-pT/√Hz equivalent magnetic noise levels. Ideally, the use of a coil increases the sensitivity linearly as a function of the number of turns. However, this effect is reduced by the parasitic capacitance of the coil. This affects the device sensitivity, noise level and system performance. The parasitic capacitance can degrade all of these, but also induces a resonance effect, which can help to optimize magnetometer sensitivity, and thus, its noise level. We analyze the effects of the parasitic capacitance on the system (sensitivity and noise) and propose optimization routes. We have obtained sensor sensitivity as high as 700 fT/√Hz.

Introduction

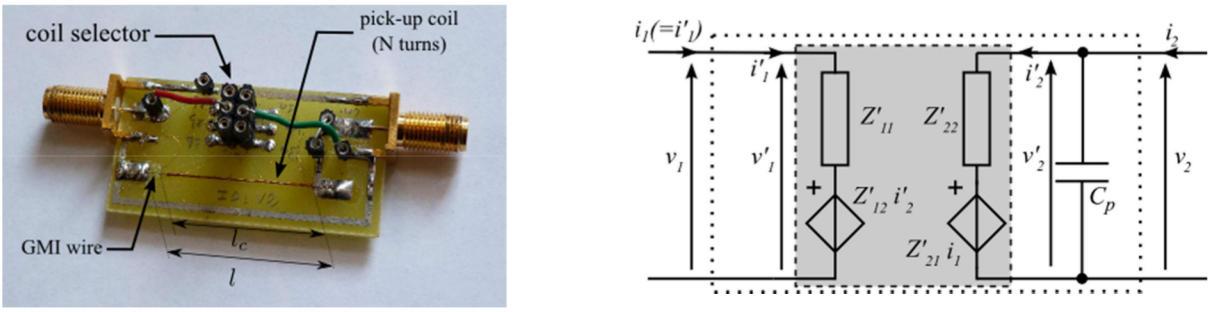
High-sensitivity magnetometry is a major research issue for many applications (NDE, biomagnetism, military, etc.). These require low-cost magnetometers with wide bandwidth, equivalent magnetic noise below 1 pT/√Hz close to 1 Hz, operating at room temperature. GMI magnetometers are good candidates to meet this challenge, since their theoretical noise level is about 10 fT/√Hz [1]. However, existing devices are limited by their electronics to approximately 3 pT/√Hz [2].

The equivalent magnetic noise of a magnetic sensor (in T/√Hz), b_n, may be described by the simple equation $b_n^2 = b_{ns}^2 + e_n^2/T_r^2$, where b_{ns} is the equivalent magnetic noise of the sensor (in T/√Hz), e_n is the output voltage noise of the electronic setup used (in V/√Hz), and T_r is the output sensitivity of the magnetic sensor (in V/T). For GMI magnetic sensors, experiments usually show that $b_n \approx e_n/T_r$. The reduction of electronic noise is difficult, since the electronic setup is often optimized. In this case, it is necessary to increase the intrinsic device sensitivity in order to improve system performance. In response to this problem, we have demonstrated [3.4] the interest of strongly-coupled thin pick-up coils associated with the GMI sensor wire. This configuration is often used, and described as off-diagonal GMI [5] or orthogonal flux-gate in the fundamental mode [6]. Here, we pursue this approach, and discuss the limitations and opportunities associated with this arrangement. In particular, we treat the effect of parasitic capacitance.

The paper is organized as follows. First, we recall the sensing element configuration and the principle of its implementation. The model of sensing element magnetic response, in the presence of parasitic capacitance, is then presented. We conclude after a discussion of the effect of this capacitance on intrinsic sensitivity.

The sensing element and its principle

The sensing element used is a common off-diagonal GMI configuration. As shown in Fig. 1a,. l and l_c are the lengths of the GMI wire and of the pick-up coil. The coil consists of three independent layers, of 600 turns each. By connecting them in series, it is easy to modify the number of turns, N (= 600, 1200 or 1800), without changing the experimental conditions for the magnetic wire. The inner layer is wound directly on the CoFeSiB amorphous ferromagnetic wire, 100 µm in diameter, called c3 in [7], chosen from a set of samples. It represents a good compromise between high sensitivity and robustness.



a) b)

Figure 1: a) Off-diagonal GMI sensing element. b) two-port network electric model. Here, the magnetic response elements, Z'_{ij}, represent the ideal behavior without parasitic capacitance, and the parasitic capacitance, C_p , is shown separately.

As we have shown elsewhere [3, 4], the best magnetic sensitivity is obtained when an rf current, of amplitude I_{ac} and frequency f_p, is applied to the wire, and the output signal is the open circuit voltage of the pick-up coil. The rf voltage appearing across the coil is ideally amplified at high frequency with gain G_1, and sensed by a diode peak-detector with gain G_{pd}, which shifts the signal, $v_S(t)$, to low frequency. This image of the small sensed applied magnetic field, $b(t)$, is amplified, with gain G_2, and filtered, classically. From an electrical point of view, the off-diagonal GMI can be modeled as a two-port network, described by its external magnetic field-dependent impedance matrix $[Z_{ij}]$. The Z_{21} term allows to describe the magnetic response of this system.

Considering a magnetic static working point B_0, Z_{21} can be obtained from a first order Taylor series: $Z_{21}\big(B_0 + b(t)\big) = Z_{21}(B_0) + \frac{\partial Z_{21}}{\partial B}(B_0)\, b(t)$. Then, $v_s = T_r\, b(t)$ where $T_r\left(= I_{ac} G_1 G_{pd} G_2 \frac{\partial Z_{21}}{\partial B}(B_0)\right)$ is the output sensitivity of the magnetic sensor (in V/T) and $\frac{\partial Z_{21}}{\partial B}(B_0)$ is the intrinsic sensitivity of the sensing element in the chosen set-up (in Ω/T).

Magnetic response of the sensing element

In the past, modeling of the system has not taken the parasitic capacitance into account. Then, modeling of the impedance matrix is directly connected to the model of the magnetic device via the surface impedance $[\zeta_s]$ [8]. This impedance can be considered as purely magnetic and written $[Z'_{ij}]$. In our case, the system consists of the impedance matrix $[Z'_{ij}]$ coupled with a capacitor C_p in parallel with the output port (*cf.* Fig. 1b). The Z_{21} term depends upon the magnetic terms Z'_{21} and Z'_{22} and capacitance C_p as

$$Z_{21} = \left.\frac{v_2}{i_1}\right|_{i_2=0} = \frac{Z'_{21}}{1 + j\, 2\pi f_p\, Z'_{22} C_p}. \tag{1}$$

By using the relationship between electrical signals, in the purely magnetic two-port, (i'_1, i'_2, v'_1, v'_2), and the electric and magnetic fields appearing at the ferromagnetic wire surface [9, 10], terms Z'_{21} and Z'_{22} can be determined from the magnetic, Z_M, and the non-magnetic, Z_N, impedances and

the angle θ_M, which characterizes the static magnetization direction. This yields: $Z'_{21} = N\,(Z_N - Z_M)\,\sin\theta_M\,\cos\theta_M$, and $Z'_{22} = \frac{2\pi\,a\,N^2}{l_c}\,(Z_N\cos^2\theta_M + Z_M\sin^2\theta_M)$. Then, Z_{21} may be written as:

$$Z_{21} = \frac{N\,(Z_N - Z_M)\,\sin\theta_M\,\cos\theta_M}{1 + j\,\frac{2\pi\,a\,N^2}{l_c}\,(Z_N\cos^2\theta_M + Z_M\sin^2\theta_M)\,C_p\,\omega_p}. \tag{2}$$

Figure 2 shows good agreement between the theoretical expression and measured value of Z'_{21}. We note that Eq. (2) correctly describes the inversion of the the imaginary part of Z_{21} between 500 kHz and 1 MHz, using -0.4 Oe bias field as the working point.

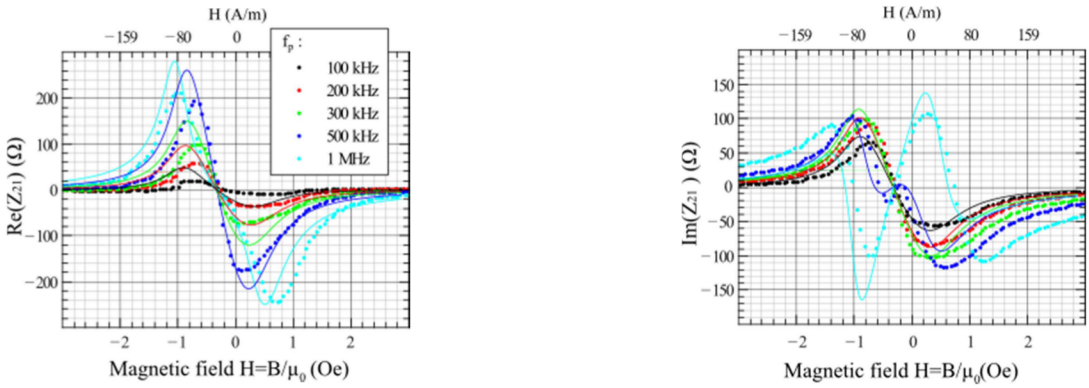
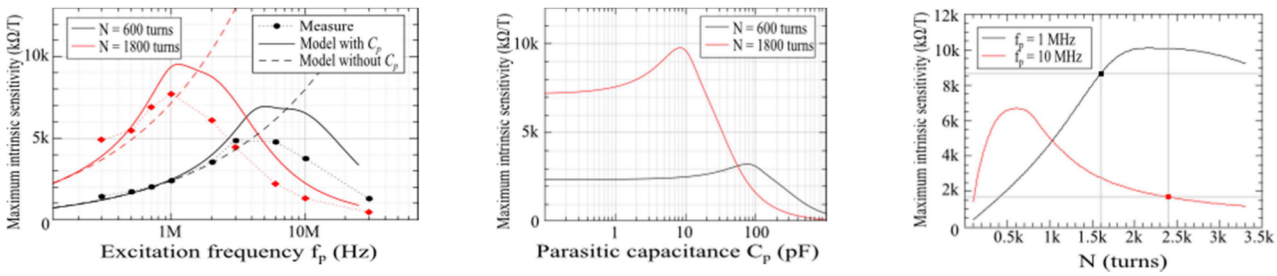


Figure 2: Real and imaginary parts of Z_{21}, measured (solid) and computed (dotted) using Eq. (2) and parameters reported in [7]) for five different frequencies, f_p.

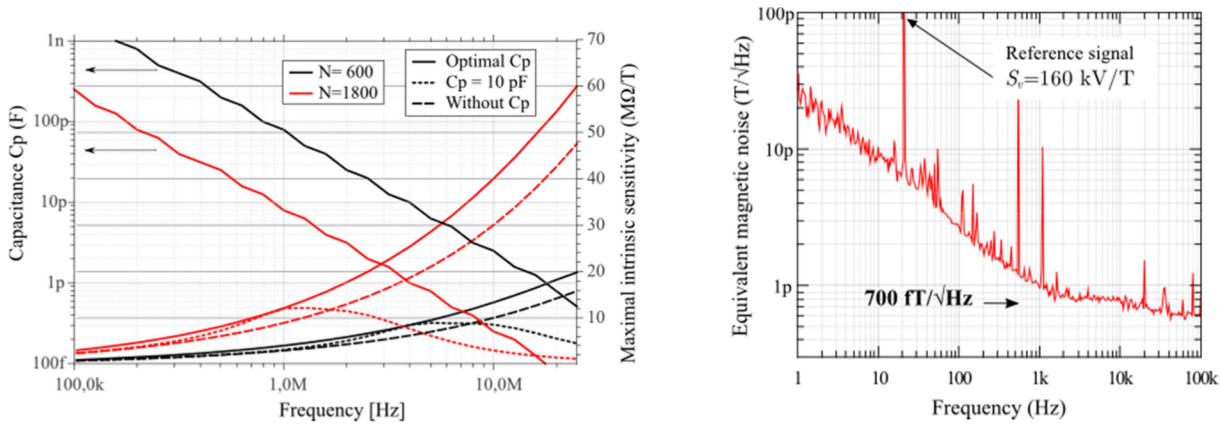
Optimization of the sensitivity by parasitic capacitance adjustment

The good agreement between theory and experiment is also true for the sensitivity, as shown in Fig. 3a. Without C_p, the intrinsic sensitivity should increase linearly with N and with f_p. The decrease of the sensitivity at high frequency, observed in practice, is explained by the presence of parasitic capacitance in the model. The peak in intrinsic sensitivity corresponds to RLC resonance. Figure 3b shows intrinsic sensitivity behavior as a function of C_p. It suggests how sensitivity may be optimized. If the capacity is too high, the sensitivity decreases drastically. It should be noted that, because of this, the sensitivity at 10 MHz and 1800 turns may be less than at 1 MHz and 600 turns, as given in figure 3c. The presence of capacitance allows for higher sensitivity than in its absence, as shown in Fig. 4a, but eventually degrades it at high frequency.



a) b) c)

Figure 3: a) Maximum intrinsic sensitivity vs. excitation frequency f_p, measured and computed for two values of N, 600 and 1800. b) Maximum intrinsic sensitivity vs. parasitic capacitance value C_p computed for two values of N. c) Maximum sensitivity vs. N computed for 1 and 10 MHz, with C_p = 10 pF. The points indicate maximal intrinsic sensitivity for two examples: f_p = 1 MHz, N = 1600 turns, and f_p = 10 MHz, N = 2400 turns.



a) b)

Figure 4: a) Optimal capacitance value and maximal intrinsic sensitivity vs. excitation frequency for N=600 and 1800, for three choices of capacitance:.at each frequency the capacitance is adapted to maximize intrinsic sensitivity (solid), the capacitance value is fixed at 10 pF (dotted), the two-port network is ideal (no parasitic capacitance) (dashed). b).Experimental equivalent magnetic noise spectral density vs. frequency for an optimized sensor.

Conclusion

From the results presented here, it is clear that for a given value of parasitic capacitance, C_p, the sensitivity can be optimized by the proper choice of N, the number of turns, and f_p,, the excitation frequency. However, the intrinsic sensitivity is intrinsically limited by the parasitic capacitance.. The use of this analysis give us the opportunity to design and operate such a sensor. As shown in Fig. 4b, it has an equivalent magnetic input sensor white noise level of 700 fT/Hz more than competitive with current commercial technologies.

References

[1] L.G.C. Melo, D. Menard, A. Yelon, L. Ding, S. Saez, C. Dolabdjian: J. Appl. Phys. (103), 033903 (2008)

[2] L. Ding, S. Saez, C. Dolabdjian, L. G. C. Melo, A. Yelon, D. Ménard: IEEE Sensors J., 9 (2), 159–168 (2009)

[3] B. Dufay, S. Saez, C. Dolabdjian, D. Seddaoui, A. Yelon, D. Ménard: Sensor Letters, 7, 334–338 (2009)

[4] B. Dufay, S. Saez, C. Dolabdjian,D. Menard, A. Yelon: IEEE Sensors J., 11 (6), 1317–1324 (2011)

[5] S. Sandacci, D. Makhnovskiy, L. Panina, K. Mohri, and Y. Honkura: IEEE Trans. Mag., 40 (6), 3505–3511 (2004)

[6] E. Paperno: Sensors and Actuators A: Physical, 116 (3), 405–409 (2004)

[7] B. Dufay, S. Saez, C. Dolabdjian, D. Menard, A. Yelon: JMMM, 324 (13), 2091–2099 (2012)

[8] L. Landau, E. Lifshitz, *Electrodynamics of continuous media.* Pergamon Press, Oxford, 1960.

[9] D. Makhnovskiy, L. Panina, and D. Mapps: Journal of Applied Physics, 87 (9), 4804–4806, 2000

[10] D. Ménard, A. Yelon: Journal of Applied Physics, 88 (1), 379–393, 2000.