MAROT – low noise MAgnetometeR based On Tunnel Junctions

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ABSTRACT

The MAROT instrument is a miniaturised low noise magnetometer whose design is based on innovative magnetic tunnel junctions combined with magnetic flux concentrators and biasing coils. This sensor is firstly intended for space and medical domains where the gain in terms of mass, dimensions and performances would be a real breakthrough compared to the state-of-the-art magnetometers currently employed on board satellites. Here we present the status of development (innovative tunnel junction, micro-manufacturing process, electronics) and the future steps of the project envisioned to issue an instrument usable in the targeted application domains.

Keywords: Magnetometer; Magnetic tunnel junction; Low noise; Micro-manufacturing.

1. INTRODUCTION

Magnetometers have a wide range of applications in various industrial and scientific domains such as non-destructive examination, magnetic compass, geophysics research, subsurface sounding, etc. Although the magnetometer MAROT (for low noise MAgnetometeR based On Tunnel Junctions) that we are developing could rapidly be of interest to several applications, it has been primarily thought to target the space and medical domains. In particular, magnetometers are widely employed onboard scientific satellites where mass and dimensions of all the equipment are crucial.

Magnetic field measurements in space currently rely on two magnetometers: fluxgate magnetometers measure the absolute value of the field and its very low frequency variations, while search coils magnetometers measure the field variations above 1Hz. These two types of magnetometers are employed in most international space missions. Through the real technological breakthrough provided by the gain in terms of mass and expected measurement performances, MAROT has the potential on its own to provide the measurement capabilities of these two current state-of-the-art magnetometers. MAROT is designed as a new type of miniaturised and ultra-sensitive magnetometer, based on magnetic tunnel junctions and using micro-manufacturing technology coming from microelectronic. This 1D magnetic sensor combines polarization coils, a magnetic circuit acting as a flux concentrator and magnetic tunnel junctions [1]. The magnetic field is amplified by the flux concentrator and measured through the electrical response of the junctions, whose resistivity depends on the magnetic field amplitude. Thanks to polarization coils, the measured magnetic field is modulated so that the sensor operates in a frequency range where its noise level is lower, resulting in better performances than the current magnetoresistive sensors [5].

Within the framework of the MAROT development, we designed an innovative magnetic tunnel junction [4] confirming the sensor capabilities in terms of detectivity. The micro-manufacturing process improvement and stabilisation is ongoing with the aim of a future industrialisation of the sensor. A first version of the associated detection electronic circuit was developed.

2. STATE OF THE ART

The present state-of-the-art space magnetometers are inductive type sensors. First, *fluxgates* magnetometers [2] are designed and employed for DC to low frequency measurements (magnetic field direction and amplitude). Second, *search coil* magnetometers [3] are designed and employed for fluctuating magnetic fields (AC) at low and medium frequencies. The cross-over frequency above which the search coil magnetometers become more sensitive than the fluxgate is typically 3Hz, with a sensitivity around 10^{-5}nT/Hz$^{1/2}$. Both instruments are mature and reach excellent performances, at the cost of important volume and mass (see Tab. 1).

The sensitive elements of MAROT is a magnetic tunnel junction. A magnetic tunnel junction is composed of two ferromagnetic layers separated by an insulating tunnel barrier about 1nm thick. Its electric resistance varies as a function of the relative magnetization orientation of the two ferromagnetic layers. Usually one of the ferromagnetic layers has a fixed magnetization (reference layer) while the other (sensitive layer) is likely to change its orientation when an external field is applied. Thus, the resistance of the junction varies as a function of the magnetic field applied, hence its massive use for the read-heads of hard disks in computers. However, the standard tunnel junctions have a recurrent defect for their implementation in our specific sensor: they change their working mode (and thus their calibration) when submitted to a strong magnetic field, drawback we intend to remove with the innovative tunnel junction we develop for MAROT.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The instrument we are developing brings major evolutions on two aspects compared to existing technologies:

- A technology breakthrough in space magnetometers, by considerably reducing the resources needed to measure magnetic fields, which is our main objective.
- The innovative junction we designed for MAROT is a major improvement in the existing technology of tunnel junctions as it can correct for a recurrent limitation of the standard junctions.

Tab. 1. Physical characteristics of the state-of-the-art magnetometers and MAROT.

Type of magnetometer	mass	dimensions
Fluxgate [2]	270g	82.4x82.4mm
		122.7mm high
Search coil [3]	544g	104mm diameter
		158mm high
MAROT, 3D instrument	30g to 45g	40x50mm
(estimated)		60mm high

MAROT is not a miniaturised combination of the two state-of-the-art space magnetometers, but a really new instrumental concept intended to replace both. This will be done through a different sensor design, that will provide the technology breakthrough that allows to reduce by at least a factor 10 (see Tab. 1) the dimensions and mass allocated to the magnetometers (including electronics), while combining the respective measurement capabilities and reaching the same sensitivity. Dimensions and mass are two key constrains in space instrumentation; they are thoroughly examined for the selection of the instruments to be boarded on a space mission and are subject to a strong competition at international level. Moreover, the additional mass of the necessary boom bearing the instrument to move it away from the electromagnetically disturbing platform would also be reduced as a consequence of the low mass of MAROT.

The competitive advantage of the proposed instrument is therefore its very small size and its extreme lightness: the transducer (1D sensor, without the electronic) is made on a silicon substrate of 10x4mm and has a weight of approximately 1g per measurement channel.

The realization of MAROT comes also with a significant improvement on the tunnel junctions. As mentioned in §2, standard tunnel junctions change their working mode when submitted to a strong magnetic field. The concept of the innovative junction has several advantages:

- It corrects for this defect of the standard junction.
- The output amplitude is increased and thus the sensitivity can be improved.
- The operating temperature range is increased.

4. PROJECT RESULTS

4.1. MAROT design description

The proposed instrument is based on 1D magnetic sensor made of a chip (Fig. 1) with dimensions 10x4mm and a mass of 1g, including the following elements:

- 2 magnetic tunnel junctions acting as the sensitive units and biased in antiphase.
- 2 flux concentrators (composed of 2 branches) amplifying the magnetic field.
- 4 polarization coils generating the polarization magnetic field and enabling to modulate the measured field.

The sensor is associated with 2 electronic circuits:

- The circuit polarising the coils at 100kHz, a frequency below 1MHz, the cut-off frequency of the coils determined by impedance measurements.
- The amplification circuit receiving the signal from the tunnel junctions.

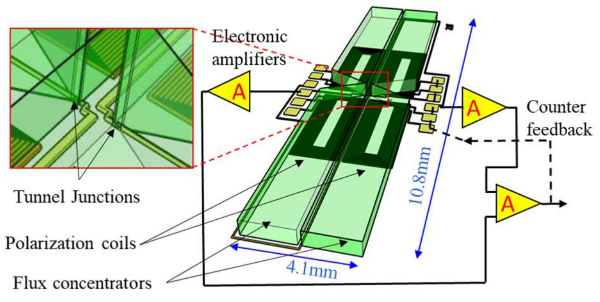

Fig. 1. MAROT principle: magnetometer connected to the electronics.

4.2. Innovative tunnel junction

Standard tunnel junctions composed of a reference layer and a sensing layer are not fully suitable for the specific application targeted here, where the junction should present an even response with the applied field. Therefore, we have proposed an innovative junction [4] with two sensing layers in magnetostatic coupling that allows a unique magnetic configuration at zero field. This innovative junction has also two advantages: a larger magnetoresistive response and a broader temperature working range.

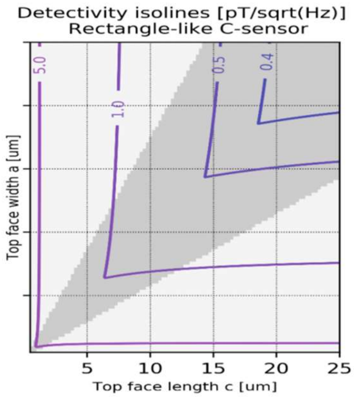

Fig. 2. Estimated detectivity of a sensor based on rectangular innovative junctions with 5nm thick ferromagnetic layers as a function of length and width. The white area corresponds to uniform magnetization, i.e. suitable shapes for proper operation.

We have estimated through analytical calculations the effect of shape, size and thickness of the innovative junction on the sensor's performances, assuming that the modulation by biasing coils suppresses 1/f noise. Since proper operation is only possible when the magnetization within the layer is uniform, we have estimated the condition for the absence of magnetic domains by using Van den Berg description [6]. The results (Fig. 2) show that our targeted detectivity (below $1pT/Hz^{1/2}$) should be obtained.

4.3. Manufacturing process

The manufacturing process required further improvement and stabilization especially concerning biasing coils. We have improved the photolithography quality in terms of resist adhesion and profile stiffness. Fig. 3 shows a pattern obtained with 3µm thick resist with a steep profile, and the coil wires obtained after metal evaporation and lift-off. Since narrow wires of 2.5µm are more prone to defects than larger ones, new coil and flux concentrator designs were tested by magnetic simulations with the following objectives: i) uniform gain of 400 within the flux-concentrator's air-gap; ii) easy access to the inner coil's contact. Two alternative designs fulfil these objectives and will be experimentally tested.

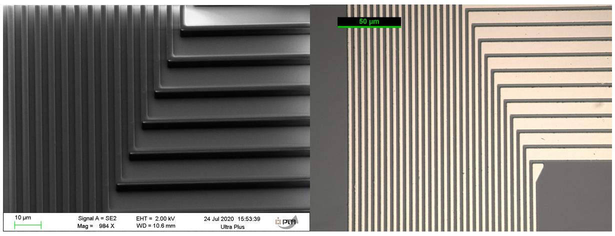

Fig. 3. Left: resist pattern obtained by photolithography; Right: coil's micron size wires (9.5µm and 2.5µm wide).

Finally, we have also performed thermal simulations to evaluate Joule heating due to the large current density in the coils (Fig. 4). A temperature increase of 105°C is calculated in absence of any heat sink except air convection. Although it is not critical, it is nevertheless necessary to address this issue by using more realistic conditions.

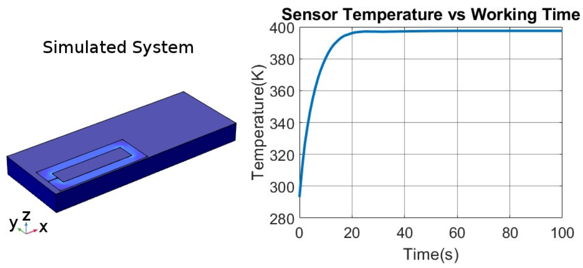

Fig. 4. Temperature simulation under high current density in the micron-size coil (12V applied).

4.4. Electronic amplification circuit

As presented on the instrument block diagram (Fig. 5), the amplification circuit is defined in 4 steps. First, the input stage is the most critical for the instrument performances: small resistance variations of the junctions (Rj1, Rj2) must be detected. Since the junctions are polarised with a fixed voltage, the variation of resistance is detected by the variation of the current. The input stage is thus composed of two transimpedance amplifiers (one per junction) which is the most adapted structure to measure very low currents. The second stage is a differential amplifier receiving the signal of the two junctions. The third stage is a synchronous detector enabling to separate the signal issued from the measured magnetic field from the biasing one. The last stage is a typical gain stage whose value was set to 40dB, high enough to guarantee the efficiency of the counter feedback, enabling an optimal operating point.

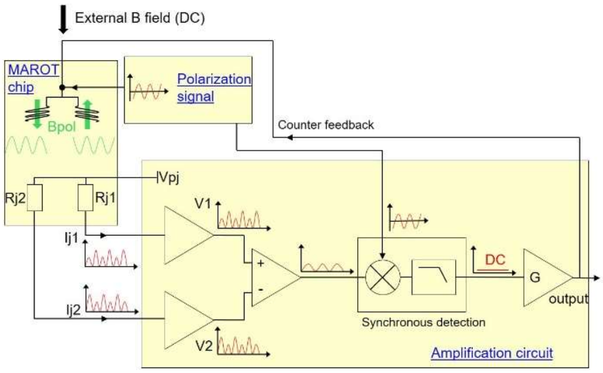

Fig. 5. Block diagram of MAROT sensor.

A first amplification circuit was achieved during ATTRACT project and has enabled to validate the concept and to confirm the design of the three last stages. The first stage will soon be implemented for validation.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Once the updates mentioned in §4 will be achieved during the last months of the project, the following steps will be to gather all the sensor elements on a single chip to get a fully manufactured sensor demonstrating its capabilities. Afterwards, two further steps are planned for the sensor chip:

- The first is the technology adaptation to industrial requirements, which is partly accounted in the project: indeed, the difficulty in the manufacturing process of MAROT instrument is the number of technological steps (8 mask levels and 40 steps of various processes to master), and the coexistence of small structures of micro- or nanometric size with large structures of millimetric size. It is one key step of the project to optimise the manufacturing process reliability to obtain more operational sensors on the same wafer. TRL 5 will be reached at the end of this step. In that process, attention will be given to the packaging of the chip since the demonstrator will be obtained and verified on a test packaging.
- The second is the adaptation to the application domain if it is necessary. For a use in the space domain, the adaptation will consist in developing a version of the instrument compatible with space environment and the specifications related to space and satellites design. TRL 7 will be reached at the end of this step.

In parallel to the miniaturised sensor, the prototype of the electronic developed during phase 1 on a standard circuit board shall be miniaturised. The plan is to design and manufacture an ASIC chip with the specifications inferred from the prototype.

5.2. Project Synergies and Outreach

To achieve the industrialization (technology adaptation) of MAROT instrument, it is planned to contact sensors companies in Europe such as Melexis, Allegro or GlobalFoundries.
For the objective of building a space instrument, contacts have already been taken with the French space agency (CNES). Contacts can also be considered with public or private actors involved in the emerging domain of small satellites (Cubesats), since MAROT instrument is well adapted for this kind of satellites.
Public dissemination will be performed through scientific communications in various conferences either in actuators' domain or during space science meetings. In addition, both SPINTEC and LPC2E laboratories are associated with a university enabling the dissemination in the academic field.

5.3. Technology application and demonstration cases

Among the wide range of applications of magnetometers in various industrial and scientific domains, MAROT is designed to first mainly target space and medical applications.

Indeed, magnetometers are widely employed onboard scientific satellites to study a variety of phenomena related to the Earth's magnetosphere, the Sun–Earth interactions, or for exploratory planetary missions. Space exploration is now witnessing a strong evolution characterised by the emergence of small spacecraft platforms (Cubesats and other nanosats) that are now considered as a next step in space exploration: multi-spacecraft measurements, exploiting nanosatellites constellations, enable to improve our knowledge of space physics. MAROT, whose size and mass make it perfectly suited to small platforms, is therefore a natural candidate for magnetic fields measurements on the future Cubesats and multi-nanosatellites missions. This is the main demonstration case considered, MAROT being a candidate for INTERMAG Sat network which is the envisioned successor of NanoMagSat network (SWARM-delta, ESA mission) currently monitoring the Earth magnetic field.

The other field of foreseen application is the medical domain, as MAROT will be able to detect the low magnetic field generated by the heart activity (magnetocardiography). With its small dimensions, MAROT is very well adapted to nomadic applications outside the hospitals for the continuous monitoring of risky people or athletes. Medical imaging such as Nuclear Magnetic Resonance (NMR) also resorts to magnetometers to measure the signals and could be a direct field of application. Importantly, such non-intrusive medical applications do not need as strong toxicity or preclinical test as intrusive applications, and would not require an important "adaptation" step as planned for the space application.

5.4. Technology commercialization

The two laboratories involved in MAROT project come with their skills in the application domains targeted:

- LPC2E laboratory is specialised in the realization of magnetic sensors for various national and international space missions and is thus already in touch with several actors in the domain. Contacts have already been taken with the French space agency (CNES) as mentioned in §5.2 and an R&T project has already been funded.
- SPINTEC laboratory has already launched four start-ups (Crocus-Technology, Evaderis, Hprobe, Antaïos); contacting investors is part of the know-how of the laboratory.

5.5. Envisioned risks

One of the envisioned risks is that the full instrument performances do not match expectations according to the simulations. The main risk is the modulation efficiency in reducing the noise level. However, even if the promising value of $100fT/Hz^{1/2}$ is not reached, a detectivity of 1-$4pT/Hz^{1/2}$ will still be of interest compared to the existing magnetometers thanks to the sensor miniaturization.

5.6. Liaison with Student Teams and Socio-Economic Study

It is planned that MSc. students will be integrated to the team and will be invited to all the meetings or teleconferences organised. A visit of the laboratories will be proposed to get a concrete vision of the project and technology.

The team will contribute to the socio-economic study by providing to the experts the materials they need for that purpose (document related to the technology application …) and invite them to the project meetings if relevant.

6. ACKNOWLEDGEMENT

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