Sensors and Actuators A 216 (2014) 386–393

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Towards a miniature atomic scalar magnetometer using a liquid crystal polarization rotator☆

J. Rutkowski[a], W. Fourcault[a], F. Bertrand[a], U. Rossini[a], S. Gétin[a], S. Le Calvez[a], T. Jager[a], E. Herth[b], C. Gorecki[b], M. Le Prado[a], J.M. Léger[a], S. Morales[a,*]

[a] CEA-LETI, Minatec, 38054 Grenoble, France
[b] Micro-Nano Sciences and Systems Department, FEMTO-ST, Besançon, France

ARTICLE INFO

*Article history:*
Received 30 September 2013
Received in revised form 30 April 2014
Accepted 5 May 2014
Available online 13 May 2014

*Keywords:*
Helium-4 isotropic magnetometer
Atomic magnetometer
Electron spin resonance
Microfabrication
Liquid crystal polarization rotator

ABSTRACT

This paper reviews the progress made in the miniaturization of an isotropic space-qualified optically pumped magnetometer. Sensor isotropy is provided by a liquid crystal polarization rotator that sets the linear pumping beam polarization at 90° with respect to the ambient magnetic field. It allows a continuous polarization rotation from 0 to more than 300° with response times compatible with mobile or space applications. This rotator is nonmagnetic and can be easily integrated close to the gas cell. The miniature helium-4 sensor reaches a sensitivity of 10 pT/√Hz in a bandwidth from DC to 100 Hz.



## 1. Introduction

Atomic magnetometers exhibit very rapid development in recent years. Since the discovery of nuclear magnetic resonance (NMR) by Bloch and Purcell in 1946 and the presentation of a first Earth's field atomic magnetometer in 1961 [1], this class of sensors has proven its proficiency in application fields including space exploration, geophysical prospecting and defence.

Spin Exchange Relaxation Free (SERF) magnetometers, the most sensitive atomic magnetometers presented up to date, are now able to compete with Superconducting Quantum Interference Devices (SQUIDs)[2]. SERF magnetometers achieve a sensitivity of 1–10 fT/√Hz by monitoring a high density vapor of alkali atoms precessing in near-zero magnetic field. Nevertheless, mobile Earth's field applications (like space exploration or magnetic anomaly detection) require the sensor to operate far from the near-zero magnetic field, optimal for the SERF regime. The sensitivity of unshielded SERF magnetometers, using coils to cancel out the external field, becomes significantly degraded (1–10 pT/√Hz) [3]. Earth's field applications generally rely on simpler constructions, based on Coherent Population Trapping (CPT), Mx or Bell-Bloom architectures, which provide similar performance.

Miniaturization of atomic magnetometers, and associated unit cost reduction, is an important step in addressing a wider field of applications. Works on chip scale atomic magnetometers began in the mid 2000. They were largely inspired by the earlier developments in the field of MEMS atomic clocks, closely related in principle to atomic magnetometers. All miniature constructions, presented up-to-date, use alkali metals (rubidium, cesium or potassium) as active medium. These sensors reach sensitivities in the range of 0.5–50 pT/√Hz but do not provide an isotropic measurement. No progress in the miniaturization of helium-4 atomic magnetometers has been presented up to date.

Dead zones and heading errors, inherent to all atomic sensors, are one of the key factors which limit their accuracy. Dead zones correspond to signal extinction for some orientations of the sensor with respect to the direction of the magnetic field. Heading errors may result from mechanical imperfections like residual magnetization or misalignment of Radio-Frequency (RF) excitation coils. They can be also caused by a nonlinear Zeeman shift caused by a nuclear magnetic moment. The advantage of the described $^4$He isotropic magnetometer lies in the fact that, contrary to alkali metals, helium-4 has no nuclear spin therefore the response of the sensor is a linear function of the applied magnetic field. Consequently its accuracy is unaffected by a nonlinear response due to hyperfine interactions. In order to meet the isotropy requirements

☆ Selected Paper based on the paper presented at The 17th International Conference on Solid-State Sensors, Actuators and Microsystems, June 16–20, 2013, Barcelona, Spain

* Corresponding author. Tel.: +33 438784787.
*E-mail address:* sophie.morales@cea.fr (S. Morales).

http://dx.doi.org/10.1016/j.sna.2014.05.003
0924-4247/

of mobile applications, atomic sensors use complex architectures, for example three orthogonally mounted sensors or multiple resonances (case of CPT sensors) [4].

The Laboratory of Electronics and Information Technology of the French Atomic Energy and Alternative Energies Commission (CEA-LETI) has successfully designed and manufactured an isotropic space-qualified $^4$He magnetometer with a 1 pT/$\sqrt{}$Hz resolution (DC-100 Hz) and accuracy better than 45 pT [5] in the framework of the SWARM space mission. Its isotropy is provided by a nonmagnetic servo-driven piezoelectric motor [6,7] which fixes the axis of linear polarization of pumping light at right angle with respect to the magnetic field to be measured. This paper presents the path chosen for the downscaling of this macroscopic sensor and early performance of the miniature isotropic $^4$He magnetometer.

## 2. Helium-4 atomic magnetometer and scaling of helium pressure

### 2.1. Operating principle

The presented Atomic Scalar Magnetometer (ASM) is an optically pumped helium-4 magnetometer based on electronic paramagnetic resonance induced in helium triplet metastable states. A weak High Frequency (HF) capacitively coupled discharge is ignited inside a glass cell filled with helium (c.f. Fig. 1a). The discharge excites a part of the atoms from the fundamental state to the $2^3S_1$ metastable level (c.f. Fig. 2). A radiative decay back to the fundamental level is forbidden, which makes this state relatively long-lived. The ambient magnetic field $B_0$ splits the $2^3S_1$ level into three Zeeman sublevels. Resonant transitions are induced between those levels by means of weak RF magnetic field produced by a saddle coil fixed around the cell. Resonance occurs when the frequency of the applied RF field matches the Larmor frequency of the precessing magnetic moments, given by:

$$f_L = \frac{\gamma}{2\pi} B_0, \tag{1}$$

where $\gamma$ stands for the gyromagnetic ratio of the $2^3S_1$ metastable level ($\gamma/2\pi = 28$ Hz/nT). At thermal equilibrium the Zeeman sublevels are almost equally populated therefore no significant signal is induced at resonance. In order to detect resonance, an alignment of magnetic moments is performed through a selective optical pumping applied on the $D_0$ line (c.f. Fig. 1a and 2). This is done with a frequency-tuned, linearly polarized laser beam. The resulting disequilibrium between the Zeeman-sublevel populations amplifies the resonance signal amplitude. Resonance induces additional absorption appearing on the $D_0$ line. It can be observed as a continuous absorption signal or as a modulation of the light at $f_L$ and $2f_L$.

### 2.2. Sensitivity and scaling aspects

The spin projection noise (the fundamental limit to sensitivity of atomic magnetometers) is expressed by [2]:

$$\delta B = \frac{1}{\gamma\sqrt{n_m V \tau_2}}, \tag{2}$$

where $n_m$ is the density of helium metastable atoms, $V$ is the volume and $\tau_2$ is the transverse spin relaxation time. The two main parameters which influence the fundamental sensitivity limit of an atomic magnetometer are therefore the metastable density and their transverse relaxation time. Miniaturization of the active element triggers an inevitable decrease of both.

The development of alkali-vapor sensors followed the path of increasing the density of alkali metals, which in their context means increasing the cell temperature. In such a system the species density is quite easily predictable using an approximate logarithmic function which relates it with temperature of the cell. By adding literature values of rate constants describing spin relaxation processes simple approximate models, describing the scaling of the maximum sensitivity with size, can be developed [2]. Such an analysis is largely more complicated when it comes to helium magnetometers since the two important parameters – $2^3S_1$ metastable atom density and their relaxation time are a consequence of multiple complex phenomena taking place in the helium-4 plasma. The cells used in the macroscopic version of the sensor (c.f. Fig. 1b) were filled to 2 Torr of high-purity helium, which was an empirically determined value. In order to maximize the sensitivity of the developed sensor, while decreasing the volume of the gas cell, an optimal value of helium pressure needs to be found. For this purpose an approximate numerical model was developed.

A very reliable picture of all interrelationships in the discharge can be obtained using particle-in-cell or fluid numerical models. Nevertheless, such models, conventionally used in plasma physics, are difficult to implement and require relatively big computational expense. Since the analysis of optimal pressure value for the sensor does not need to be that much exhaustive, it was chosen to proceed with a simplified zero-dimensional description presented in ref. [8].

#### 2.2.1. Metastable atom density

The existence of metastable atoms is a result of balance between mechanisms responsible for their creation and destruction. The evolution of density of the triplet metastable atoms can be described by:

$$-D_m \nabla^2 n_m = k_3 n_g n_e - k_4 n_m n_e - k_5 n_m^2 - k_6 n_g^2 n_m \tag{3}$$

where $D_m$ stands for the metastable diffusion coefficient ($470/p$ cm$^2$/s, with $p$ – pressure in Torr) and $n_e$, $n_g$ and $n_m$ are electron, neutral and metastable atom densities respectively. The rate coefficients ($k$) determine the rates at which reactions taken into account in the calculation (c.f. Table 1) take place. The metastable atoms are created by electron impact ionization (reaction 3), the influence of other mechanisms is supposed to be negligible. The mechanisms responsible for the destruction of metastable atoms, which were taken into account, are:

- diffusion and collisions with cell walls (left-hand side of Eq. (3)),
- stepwise ionization through electron impact collisions (reaction 4 in Table 1),
- Penning ionization – collisions between two metastable atoms (reaction 5 in Table 1),
- three-body collisions of a metastable atom and two fundamental state helium atoms (reaction 6 in Table 1).

The first two parameters to determine are temperature and density of electrons in the plasma, which is done using a simplified algorithm [8] which expresses them as a function of pressure, geometry and power dissipated into the discharge (5 mW – value derived from an electrical analysis of the matching network used to ignite and sustain the discharge). Eq. (3) is solved for $n_m$ using a numerical method presented in [9]. The results of calculation for two cells of different volume are compared with experimental values (c.f. Fig. 3) measured by means of absorption spectroscopy.

#### 2.2.2. Metastable density distribution

Which adds to the complexity of the description of the problem is the fact that the distribution of metastable atoms inside the cell changes along with the increasing value of pressure. Fig. 4 presents the absorption profiles, measured on the $D_0$ line, along the cross section of the pumping beam (beam of 4 mm of diameter centered on a helium-4 cell of 5 mm in diameter) for three 100 mm$^3$