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A Novel Concept for a Hanle Vector Magnetometer for Space Application

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Summary:
A novel sensor design for a Hanle vector magnetometer is presented. Linearly and circularly polarized light beams are used in parallel to enable magnetic field measurements with an isotropic noise floor that is stable down to 10^{-1} Hz. The level is three times lower compared to a state-of-the-art fluxgate magnetometer at 1 Hz. The first functional test shows no intrinsic crosstalk between the sensor axes. With the possibility to add an absolute scalar measurement mode, this sensor has the potential to replace the combination of a fluxgate and absolute reference magnetometer on space missions.

Keywords: space, quantum, optical, zero-field, magnetometer

Introduction

Magnetic field measurements in space have advanced the knowledge in various space sciences, such as plasma, Helio- and planetary physics. Therefore, magnetometers are part of many scientific space missions. Fluxgate magnetometers (FGMs) are the preferred technology, due to their low size, weight and power requirements as well as high reliability. However, their systematic offset drifts necessitate in-flight calibration using for example spacecraft roll maneuvers or an additional onboard absolute reference sensor. For the latter, quantum magnetometers are used, as they derive the magnetic field measurement from fundamental atomic properties [1]. A recent example is the scalar instrument on board ESA's Jupiter Icy Moons Explorer mission. This optically pumped magnetometer (OPM) is based on the 'Coupled Dark State Magnetometer' (CDSM) design and provides dead-zone-free reference values of the absolute magnetic field strength to calibrate the accompanying FGMs [2]. In order to reduce the need for in-flight calibration altogether and to improve the sensitivity of vector measurements, Hanle effect based zero-field magnetometers are a potential replacement for FGMs. Here, we present a proof-of-concept laboratory model for a novel sensor design, with the main goal of enabling vector measurements with isotropic sensitivity and outperforming FGMs in terms of long-term stability.

Method

The Hanle effect describes resonances in the absorption of laser light by an atomic species, as the ambient magnetic field components of either of two principal axes are scanned through zero. The orientation of the third 'insensitive' axis with respect to the optical axis depends on the light polarization state (see [3]). Most Hanle magnetometers favor a single-beam setup for its mechanical simplicity and extract the third vector component with lower sensitivity through a special lock-in detection scheme [4]. Our setup uses two beams in parallel configuration, one linearly polarized, the other circularly (see Fig. 1). This avoids the mutually exclusive insensitive axes and enables isotropic measurement sensitivity. The linearly polarized beam yields the magnetic field component parallel to the beam direction and the circular beam detects the transverse components.

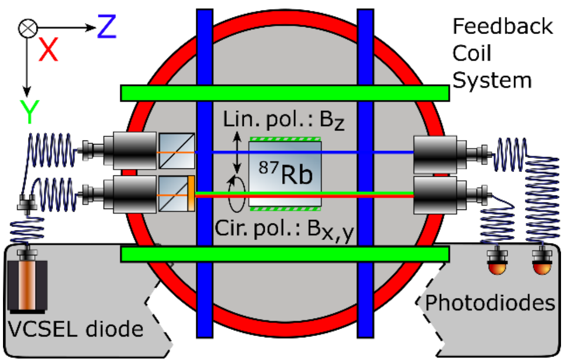

Fig. 1. Schematic of sensor concept.

For the laboratory setup, the feedback current source (design from [5]) and two external photodiodes are realized as separate units. Closed-loop operation is initialized through iterative magnetic field scans, with superimposed AC-fields with a distinct frequency for each axis. This enables the use of phase sensitive lock-in detection for increased signal to noise ratio.

First Results

The functionality and sensitivity of the sensor were tested within a μ-metal shielding with a residual ambient magnetic field of less than 5 nT. Fig. 2 shows the triaxial sensor response to a sinusoidal test field applied along the Z-axis. The amplitude of <0.2% (of the applied test field) in the X- and Y-axes indicates a misalignment between sensor and test coil, rather than a systematic measurement error.

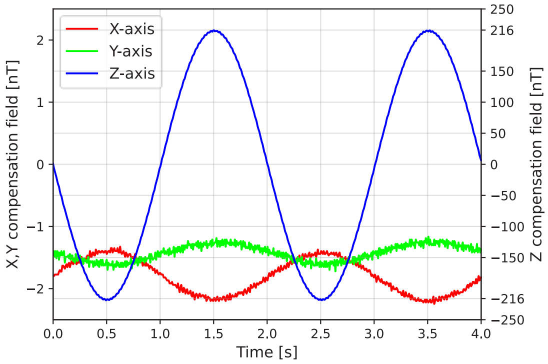

Fig. 2. Time domain instrument response to a sinusoidal test signal applied along the sensor Z-axis, with 216 nT amplitude and 0.5 Hz frequency.

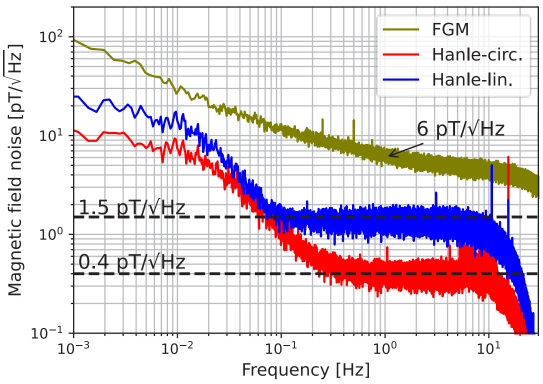

Fig. 3. Noise spectral density of a representative FGM axis and both optical paths of the Hanle magnetometer.

Fig. 3 compares the sensitivity performance between both polarization paths of the Hanle setup (circular pol=X; linear pol.=Z) and a representative axis of an FGM. The used FGM is one of the flight models for ESA's Comet Interceptor mission. The Hanle sensor achieves a noise floor at least four times lower than the FGM at 1 Hz and maintains a stable level down to ca. 0.5 Hz. The different noise levels in both polarization paths are likely due to the choice of frequencies for lock-in detection. In principle, a sensitivity of less than 20 pT/√Hz at 1 mHz has been achieved for both polarization states in all axes when operated individually.

Discussion and Outlook

The initial results obtained with this laboratory setup demonstrate the capability of this novel sensor concept to measure the full magnetic field vector with a near isotropic sensitivity that is higher than from a state-of-the art FGM. Due to the multidimensional parameter space, such as the three different lock-in detection frequencies, there is still room for improvement for lowering the 1/f noise below 10^{-1} Hz. The next development step for this setup is to demonstrate operation in a dynamic range of ±5000 nT. With the addition of a single hardware component (microwave oscillator), the current setup could technically also be operated as a CDSM. The combination of a vector and absolute scalar measurement mode would enable the use of a single, self-calibrating magnetometer instead of two separate instruments on future space missions.

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