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A Portable Atomic Magnetometer with Pico-Tesla Sensitivity

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ABSTRACT

An atomic magnetometer is a highly sensitive device designed to measure magnetic fields with exceptional precision[1]. Unlike traditional magnetometers like flux gate magnetometers and MEMS based magnetometers, atomic magnetometers use the quantum properties of individual atoms to achieve unparalleled sensitivity. It works without any cryogenic cooling, unlike SQUIDS[2], making it suitable from the perspective of portability and maintenance. The magnetometer is able to work in Earth's magnetic field, allowing the user to measure environmental magnetic field fluctuations caused by the presence of some objects (say, a submarine or unexploded ordnance) made from magnetic material or due to some structural changes in Earth[3].

Keywords: Atomic magnetometer; Field cancellation coil; Nonlinear magneto-optical resonance; Portable sensor head

NOMENCLATURE

F : Total angular momentum quantum number
m_F : Magnetic quantum numbers
σ^+, σ^- : Two circularly polarized components of incident light
ω_0 : Resonance frequency of light
ω_L : Larmor frequency

1. INTRODUCTION

An atomic magnetometer is a sophisticated device designed to measure magnetic field with exceptional sensitivity and accuracy. These magnetometers capitalize on the quantum properties of atoms, making them fundamentally different from traditional magnetometers that rely on electrical currents or ferromagnetic materials[1]. The core principle behind an atomic magnetometer involves monitoring the spin states of atoms, which are influenced by external magnetic fields.

In atomic magnetometers, a gas of alkali atoms, such as rubidium or caesium, is typically used. These atoms are optically pumped into a specific spin state using laser light. When exposed to a magnetic field, the precession of the atomic spins occurs, similar to the wobbling of a spinning top under the influence of gravity. This precession alters the polarization of the light passing through the gas, and by measuring these changes, the strength and direction of the magnetic field can be determined with high precision.

The sensitivity of atomic magnetometers can reach levels that allow detection of minute magnetic fields, making them invaluable for a variety of applications. They have multiple applications in defence technologies. The extreme sensitivity exhibited by such magnetometers enable reliable detection of unexploded ordnance (UXO)[4] with extremely weak magnetic signature. These magnetometers can also be used to create very accurate magnetic maps of geographical locations and thus contribute to advanced navigation systems. One of the most critical defence applications is submarine detection and anomalies in the Earth's magnetic field indicating potential underground structures by sensing subtle magnetic signatures even from great distances. Their high sensitivity and ability to operate in challenging environments provide a significant technological advantage for national security and military operations.

DRDO Young Scientists' Laboratory for Quantum Technologies (DYSL-QT) in close collaboration with Dr. G. Rajalakshmi[5] TIFR Hyderabad has developed a single axis compact atomic magnetometer sensor head with pico-Tesla sensitivity. The principle of working is based on Nonlinear Magneto Optical Resonance Effect (NMOR)[6]. When an ensemble of alkali atoms is placed in a magnetic field and a resonant linearly polarised light is passed through the sample, the interaction of the atoms with the incident light causes rotation of the polarization of the light which is dependent on the magnetic field strength.

2. PRINCIPLE OF OPERATION

The fundamental component of an atomic magnetometer is the atomic vapor contained within a vapor cell. A light beam passing through this vapor interacts with the atoms in the presence of a magnetic field, altering the state of the atoms inside the vapor cell. This interaction induces an electric dipole moment in the atoms, which in turn affects the light beam, altering its electric field. Since the energy state of the atoms depends on both the magnetic field and the intensity of the

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light beam, the electric dipole moment of the atoms also varies accordingly. Thus, the light modifies the effective atomic properties, which in turn causes emerging lights polarization to be modified, leading to a nonlinear process. This forms the basis for the magnetic field detection in atomic magnetometers.

To illustrate the principle of an atomic magnetometer, consider a model system where the atomic vapor is represented as a three-energy level system (Fig. 1). In this model, the excited state has a total angular momentum quantum number of F=1, and the ground state has F=0. The energy difference between these levels is $\hbar\omega_0$. The ground state with F=1 consists of three states with corresponding magnetic quantum numbers m_F=-1,0,1. The excited state with F'=0 has only one state and can take magnetic quantum number m_F=0

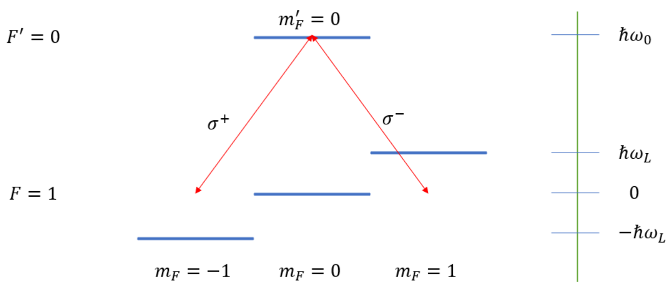


Figure 1. Model energy level diagram of atomic system showing the participating ground state with hyperfine splitting and the optical transition involved in the atomic magnetometry.

The three levels that play a role in the magnetometer are F=1, m_F=±1, and F'=0, m_F=0. When a linearly polarized light beam, polarized in the x-direction, passes through the vapor cell, its polarization plane is altered. This linearly polarized light can be resolved into two circularly polarized components: σ^+ and σ^-. The σ^+ component connects atomic states with Δm_F=+1, while the σ^- component connects atomic states with Δm_F=-1 as per the selection rules. When, a magnetic field is applied in the z-direction, it lifts the degeneracy of the states in F=1 manifold, causing the energy levels to shift proportionally to the magnetic field.

In the absence of a magnetic field, the states in F=1 ground state manifold is degenerate, and σ^+ and σ^- components have the same resonance frequency ω_0. Therefore, their absorption and dispersion profiles overlap, resulting in zero net rotation of the linearly polarized light beam after passing through the vapor cell. However, when a magnetic field is present, the degeneracy is lifted, and the resonant frequencies of σ^+ and σ^- components shift by $\pm\hbar\omega_L$ is proportional to the magnetic field strength, where ω_L is the Larmor frequency.

This shift in resonant frequencies causes a difference in the absorption and dispersion profiles of the σ^+ and σ^- components, leading to a non-zero rotation of the linearly polarized light beam. The magnitude of this rotation depends on the magnetic field strength, providing a measure of the magnetic field.

In summary, atomic magnetometers utilize the interaction between light and atomic vapor in the presence of a magnetic field to detect magnetic fields. The induced electric dipole moment in the atoms alters the light beam, with the extent of this alteration providing a measure of the magnetic field strength. Enhanced sensitivity can be achieved through optical pumping and understanding relaxation mechanisms, making atomic magnetometers powerful tools for magnetic field detection [7].

3. EXPERIMENTAL SETUP

In the present experiment, the experimental setup[5] was recreated and the sensitivity was analysed. A laser diode was used to generate light tuned to the F=2→F'=1 transition of the Rubidium D1 line (795 nm). The laser beam is first polarised using a linear polariser and then passed through an atomic ensemble enclosed in an Octadecyltrichlorosilane (OTS) coated pyrex vapor cell of 1 cm^3 in volume. In the present experimental setup, no magnetic shielding has been used. Magnetic field is applied via a field cancellation coil which is driven by a high current operational amplifier. In one input of the Op Amp, a DC voltage from a sourcemeter was applied and in the other input an AC voltage was applied from a signal generator. The cell was placed inside the field cancellation coil consisting of two solenoids which is able to produce a maximum field strength of 140 µT along the direction of laser. All the instruments are being controlled from a computer using in house routines. A DC magnetic field was applied to cancel Earth's field in addition to an AC magnetic field to check the sensitivity of the setup.

4. RESULTS

The DC magnetic field is selected using variation of DC voltage from the source meter, such that maximum amplitude is obtained from the balanced detector for a fixed applied AC magnetic field. Then the polarization rotation of the light is measured using a balanced polarimetry setup consisting of Wollaston prism and balanced photodetector PCB (Designed by DYSL-QT and printed by PCB Power). The data has been taken using a Digital Oscilloscope and analysed using MATLAB (Fig. 4). For estimation of the sensitivity two time series data was taken: firstly, when both the AC and DC magnetic field was applied and secondly, when only DC magnetic field was applied. The DC magnetic field would give

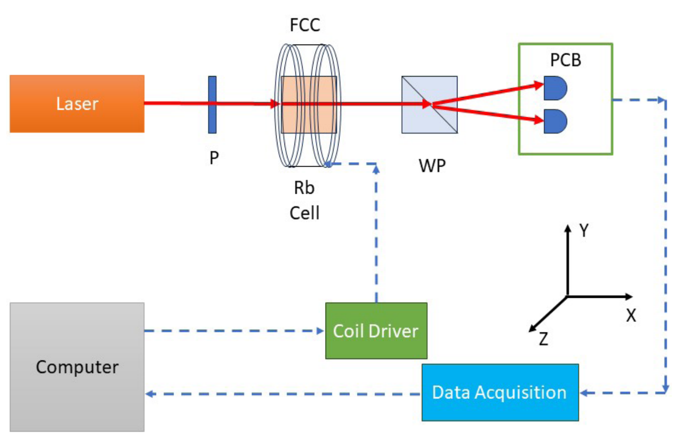


Figure 2. Schematic of the experimental setup for magnetic field detection. P: linear polariser, FCC: field cancellation coil, WP: Wollaston Prism, PCB: PCB mounted balanced detector.

rise to a voltage signal that would appear at 0 Hz, while the fluctuations at frequencies close to 1024 Hz are due to various noise sources. The first data is termed as "signal data" and the second data is termed as "noise data". Then Fourier Transform was taken for both the data. From the Fourier Transform of the signal data, the value of the voltage at 1024 Hz was measured, which corresponded to the strength of the applied AC magnetic field of the same frequency. This value was denoted by **S**, say. Similarly, from the Fourier Transform of the noise data, the mean voltage value across 5 Hz band with 1024 Hz at the centre was measured. This value was denoted by **N**, say. So, the Signal to Noise ratio (**SNR**) of the system became **(S-N)/N**, as noise was present while measurement of the signal data too. For estimation of the sensitivity the following formula was used:

$$sensitivity = N * Ba / (SNR * \sqrt{BW})$$

where, Ba is the amplitude of the applied AC magnetic field, BW is the bandwidth of the signal. With the measured values, the achieved sensitivity was better than 50 pT/√Hz @1024 Hz. The peaks/notches appearing in the noise spectrum are harmonics

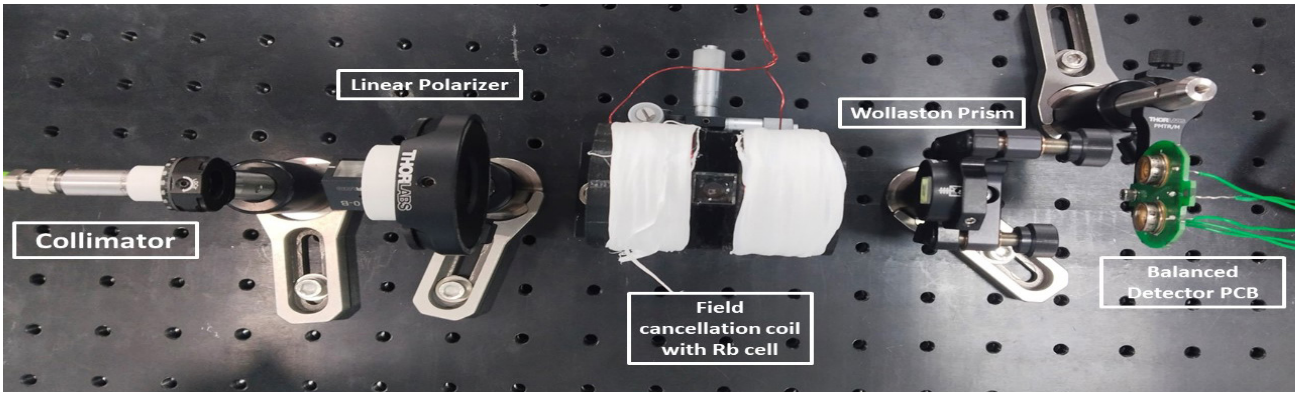


Figure 3. Picture of experimental setup. The collimated laser beam of 795 nm wavelength and 5mm diameter is first linearly polarised and then passed through the Rb vapor cell, followed by wollaston prism and balanced detector.

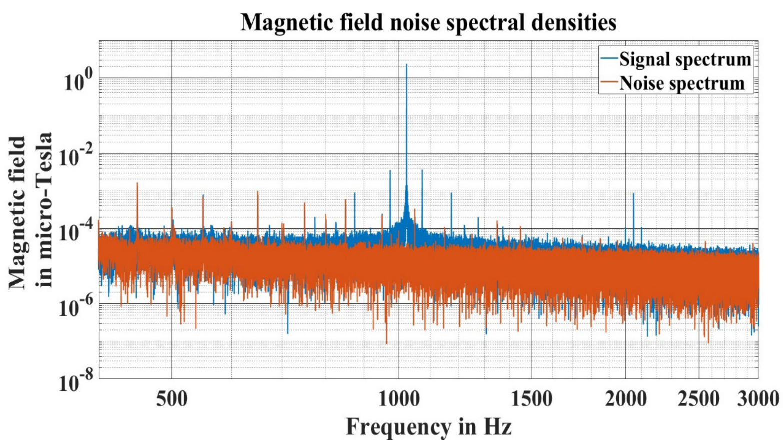
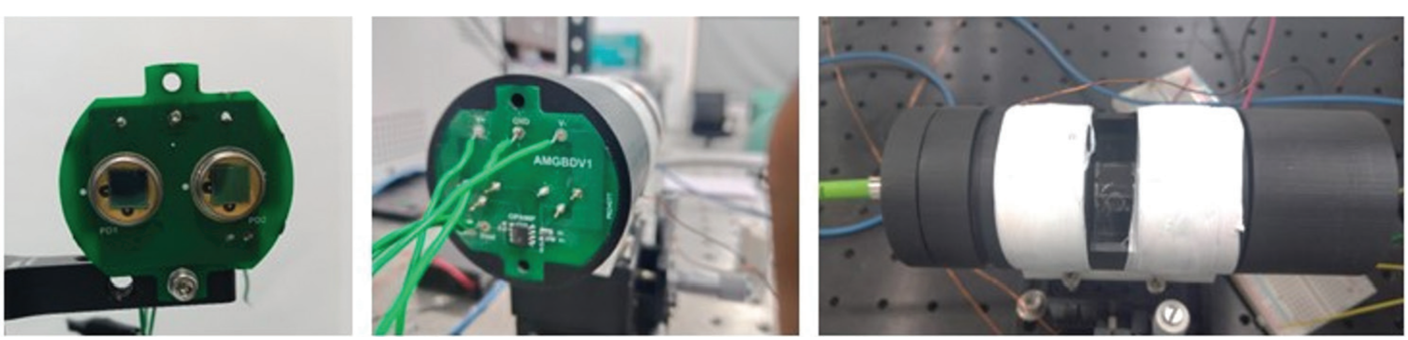


Figure 4. Plot shows frequency response of the balanced detector output. Blue data points correspond to situation when the calibration field of 2 µT was on. The mean noise floor of the red data points at 1024 Hz corresponds to sensitivity better than 50pT/√Hz.



(a) (b) (c)

Figure 5. Compact probe design. (a) PCB of balanced detector; (b) PCB fitted at the end of the probe; and (c) Full probe with Laser input on the left side and PCB output on the right side.

of 50 Hz. They will reduce if one uses filtered power supply for the whole set up and perform the measurement in shielded environment. The magnetic field response of Rubidium vapor cell is highly sensitive and linear up to a field of about 10 μT, beyond which its response becomes nonlinear and sensitivity decreases. But using the field cancellation coil one can always keep the Rubidium cell within its linear or highly sensitive regime. The current through the field cancellation coil and hence the applied magnetic field through the coil is a known parameter. Once rubidium cell is at its linear regime, the magnetic anomalies can be measured with the probe by monitoring both the coil applied field as well as the balanced detector voltage output. One can think this as measurement of length using a vernier calipers. Where the vernier scale is analogous to the rubidium signal and the coarse scale is analogous to the applied coil field. It is worth mentioning that, upon raising the cell temperature about 20-30 °C higher than the room temperature will improve the sensitivity further.

5. CONCLUSION

Currently efforts are ongoing to implement modulation schemes such as amplitude[6] or frequency modulation[7] of the laser to improve the sensitivity at lower frequency or near DC regime where the 1/f noise dominates.

Since the setup needed very few optical components of relatively small size than the coil, they were fit together in a cylindrical probe to make a compact portable probe for outdoor testing and demonstration. A 3d cylindrical structure was designed in collaboration with DIAT, Pune and printed using a commercial polymer 3d printer. The structure was able to hold all the optical parts as well as the balanced detector PCB. The length and diameter of the cylindrical structure was less than 20 cm and 7 cm respectively. The weight was less than 500 gm. This was used as the portable sensor head which was connected via optical fibre and electric wires with a main unit, housing laser source and the necessary electronics. In the present setup the control electronics and laser power supply are powered from mains power supply i.e. 220V AC supply. In future, for a field-deployable sensor head, it will certainly be useful to power the sensor head by batteries, instead of direct line power which will improve the noise performance immensely and get rid of the harmonics as well. The measured sensitivity of the probe is similar to that obtained from the tabletop setup.

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CONTRIBUTORS

Mr Akash Bain obtained his Master of Science degree in Physics from Jadavpur University, Kolkata. He joined DRDO, DYSL-QT. His area of interest include: Development of a portable atomic magnetometer as part of the Quantum Sensing group. In the current study, he did research, experiments and design from concept to product.

George Kurian K.K. obtained his Bachelors in Electronics and Communication Engineering from Cochin University of Science and Technology. He is working as a Senior Research Fellow at Tata Institute of Fundamental Research (TIFR), Hyderabad. His research interest include: NMR Spectrometer, atomic magnetometer based on non linear magneto optical rotation.
In the current study, the experimental schematics were co-developed.

Mr Binoy Nambiar obtained a Bachelors in Electronics and Communication Engineering from Sardar Vallabhbhai National Institute of Technology, Surat. He is working as a Scientist B at DRDO-CSL. He has been working in DYSL-QT as part of quantum computing team and quantum sensing team. His areas of research inclue: Control theory, quantum computing, quantum sensing.
In the current study, he contributed to the literature review of research methods and selection of the test methods.

Mr Rajarshi Biswas is working as a Scientist at DRDO-DYSL-QT. His areas of research includes: Digital signal processing, adaptive and statistical signal processing, quantum computing, quantum sensing.
In the current study he contributes to quantum computing and sensing primarily in aspects of signal processing and estimation.

Dr G. Rajalakshmi obtained her PhD in experimental gravitation from Indian Institute of Astrophysics and working as a Scientist at Tata Institute of Fundamental Research, Hyderabad. Her prime interest is in developing experimental techniques for probing fundamental aspects of science. Her areas of interest include: Built experiments for precision measurements of gravity and other fundamental interaction employing torsion balances, laser cooled atoms, and optical interferometers. In TIFR she has been working on experiments on spectroscopy of low temperature atoms, gravitational wave detection using the LIGO interferometers and more recently nuclear magnetic resonance and atomic magnetometry.
In the current study, the physics package of this sensor was conceived by her.