wopm 2024

Workshop on Optically Pumped Magnetometers

Book of Abstracts

Workshop on Optically Pumped Magnetometers, Saturday to Sunday, August 24th and 25th.
(Sydney, Australia, Satellite to Biomag 2024)

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Talks

Quantum magnetic gradiometer with entangled twin light beams

Shuhe Wu[12], Guzhi Bao[12], Jinxian Guo[12], Jun Chen[12], Wei Du[12], Minwei Shi[12], Peiyu Yang[12], Liqing Chen[23], Weiping Zhang[1245]

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In the past few decades, optical magnetometry has experienced remarkable development and reached to an outstanding sensitivity [1]. For magnetometry based on optical readout of atomic ensemble, the fundamental limitation of sensitivity is restricted by spin projection noise and photon shot noise. Meanwhile, in practical applications, ambient magnetic noise also greatly limits the sensitivity. To achieve the best sensitivity, it is essential to find an efficacious way to eliminate the noises from different sources, simultaneously. Here, we demonstrate a quantum magnetic gradiometer with sub-shot-noise sensitivity using entangled twin beams with differential detection. The quantum enhancement spans a frequency range from 7 Hz to 6 MHz with maximum squeezing of 5.5 dB below the quantum noise limit. The sensitivity of gradiometer reaches 18 fT/cm √Hz at 20 Hz [2]. Our study inspires future possibilities to use quantum-enhanced technology in developing sensitive magnetometry for practical applications in noisy and physically demanding environments.

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An improved closed-loop Herriott-cavity-assisted Xe isotope comagnetometer

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In this talk, we will report an improved Herriott-cavity-assisted Xe isotope NMR comagnetometer. Here the Herriott cavity is used to improve the detection sensitivity without using the common parametric modulation method. Previously, we have demonstrated an angle random walk (ARW) of 0.06 $^{o}/h^{1/2}$ and a bias stability better than 0.2 ^{o}/h using this system [1]. In this work, we made two major improvements on this system. First, we place the multipass cavity out of the cell to avoid collisions between atoms and cavity mirrors, with the help of better gradient field cancellation, the relaxation time of Xe atoms and the signal-to-noise ratio of this system are improved. Secondly, we operate the system in a special phase-locking point, where the rotation measurement results are independent of the environment temperature. This updated comagnetometer demonstrates an ARW of 0.015 $^{o}/h^{1/2}$ and a bias stability better than 0.06 ^{o}/h at 1000 s, as shown in Figure 1. We will also analyze the limiting factors on the performance of this system, and show its applications on Earth rotation measurement.

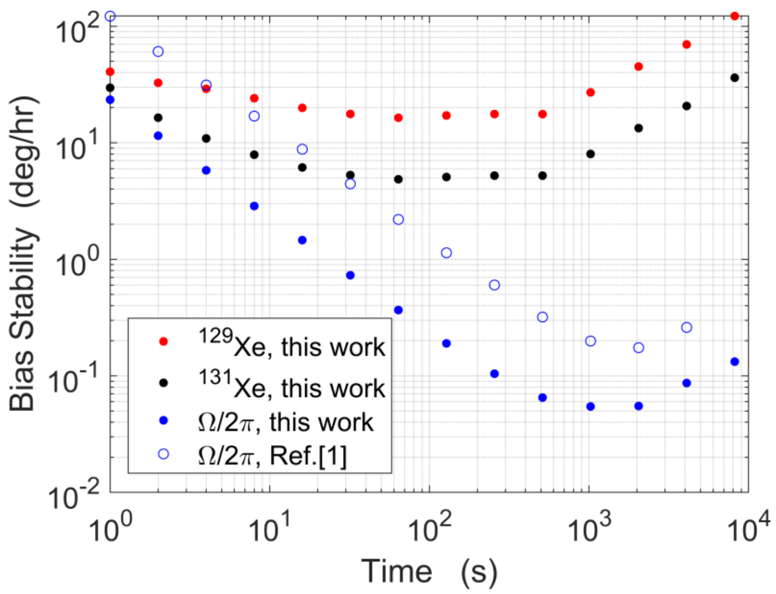

Figure 1: Comparison of the bias stability of Xe isotope NMR comagnetometer in Ref. [1] and this work.

References

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Observation of spontaneous polarization and light narrowing with ultra-long polarization lifetime paraffin-coated cells

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Alkali-metal atomic vapor cells with long-lived ground-state spin polarization play a core role in research and applications of atomic magnetometry. The ground-state polarization lifetime of coated cells with uniform coatings are mainly limited by the reservoir effect [1]. Here we eliminate the reservoir effect by blocking the capillary between the cell stem and tail with paraffin during the curing process. Utilizing the reversible fabrication method we have realized an over 17 s polarization lifetime in a paraffin-coated cell, which has bright prospects in fields of light-atom interactions. Within the coated cells we have successfully observed the spin bistability and spontaneous polarization at room temperature, as well as the light narrowing effect. The achieved ultra-narrow linewidth (within 0.5 Hz) and its temperature dependence show the great potential in improving the sensitivity and operating temperature adaptability of magnetometers.

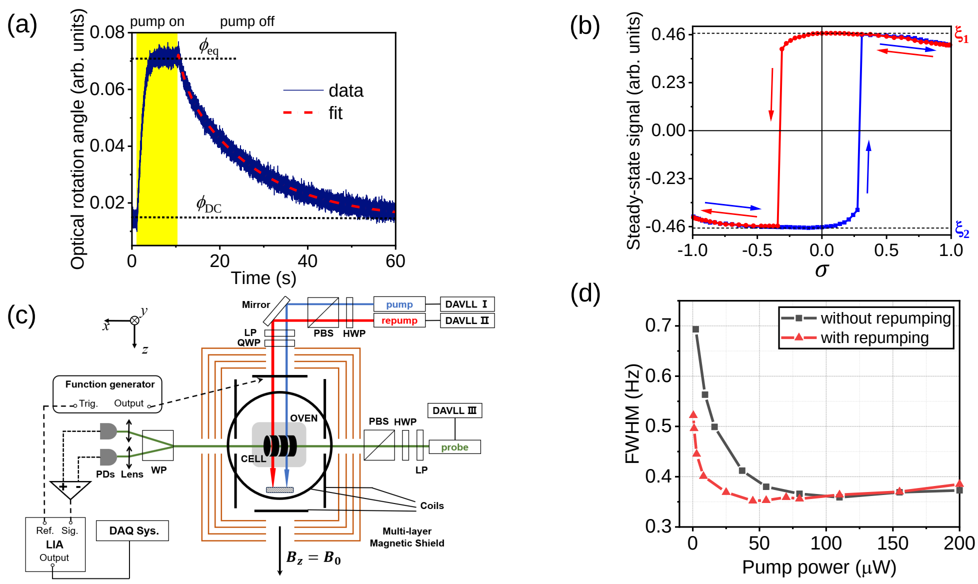

Figure 1: (a) The measured ground-state polarization lifetime 17.21 s via "relaxation in the dark" method. (b) The observed hysteresis loop and spin bistability ξ_1, ξ_2. (c) Experimental apparatus of the Mx magnetometer for observing light-narrowing effect. (d) The ultra-narrow linewidth and light narrowing realized in the coated cell with pumping and repumping beams.

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[1] M. A. Bouchiat and J. Brossel, Phys. Rev. **147**, 41 1966.

Mode Analysis of Spin Field of Thermal Atomic Ensembles

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The mean field analysis of spin dynamics in a thermal atomic vapor cell have been investigated thoroughly over the past decades and have proven to be successful in quantum science and technology. We will introduce a precise method for analytically analyzing the dynamics of the spin field in greater detail with a general analytical solution, enabling the effective evaluation of spatially non-uniform multi-physical fields coupling with the spin ensembles, as an example shown in FIG. 1(a). We demonstrate that the widely used mean field method is a particular case in our solution, corresponding to the uniform spatial mode. We show an improvement calculation of spin projection noise considering coupling effects, as seen in FIG. 1(b). We will also introduce the advancements in enhancing sensitivity and dynamic performance through the experimental study of spin coupling effects. Furthermore, we will discuss several potential application topics of our method, involving non-Hermitian physics, sensitivity improvement, quantum squeezing as well as entanglement of spin ensembles.

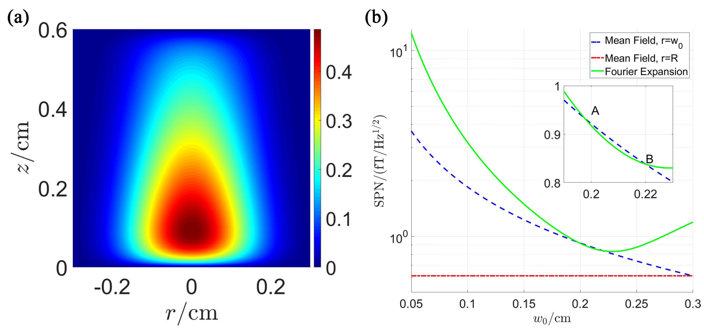

Figure 1: $(\mathbf{a})$ Calculated spin field distribution of $P_{\mathrm{ez}}(\boldsymbol{r})$ of ^{87}Rb by Dirichlet boundary condition. $(\mathbf{b})$ Spin projection noise for probe light with different radii by mean field method with $V_{\mathrm{eff}} = \pi w_0^2 L$ (blue line, [1]),$V_{\mathrm{eff}} = \pi R^2 L$ (red line, [2]) and Fourier expansion method (green line, this work [3]). A and B are the intersection points.

References

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Improving the efficacy of the signal space separation method for OPM-MEG data

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Background: The signal space separation (SSS) method is a powerful post-processing technique for magnetoencephalography (MEG). A magnetic multipole expansion isolates measured signals generated by sources inside a sensor array (such as neuromagnetic fields) from external interference. Arrays of multi-axis optically pumped magnetometers (OPMs) have an increased capability to identify and reject interference [1], which in principle should improve SSS performance [2]. However, this has yet to be demonstrated experimentally due to the limited calibration (i.e. our knowledge of the position, orientation and gain of each channel) accuracy of existing OPM-MEG arrays. Here, we used large external coils to improve system calibration, and therefore SSS efficacy.

Methods: We used the approach developed by Iivanainen et al. for calibration [3]. Briefly, we employed a triaxial fluxgate magnetometer with an optical tracking system to map the fields generated by 94 square coils placed on six faces of a 3x2.4x3 m^3 magnetically shielded room over a central 40x40x40 cm^3 volume. Field variations were fit to a spherical harmonic model. We then placed 64-triaxial OPMs (QuSpin Inc.) (192-channels) into an (empty) 3D-printed helmet in the same volume and simultaneously energised each coil at a known frequency. Minimisation was used to find the optimal position, orientation and gain for each channel that best fit the OPM data to the fluxgate model. We then applied SSS and calculated the shielding factor to the coil signals.

Results: Sensor positions were recovered within (mean and standard deviation) 3.6±1.2 mm (max/min 6.2/1.0 mm) of their expected positions (from the 3D print). Sensor orientations and gains varied more, by 11.4±7.5° (34.2/0.4°) and 5.3±4.1% (25.0/0.01%) respectively. Using the ‘assumed’ calibration the SSS shielding factor was 9.8, which improved to 127.2 (a factor of 12.9) following coil-guided calibration.

Discussion: Coil-guided sensor calibration greatly enhances the efficacy of SSS, opening possibilities for deploying OPM-MEG in the presence of strong interference.

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Using optically pumped magnetometers for paediatric MEG: experiences from SickKids

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Optically pumped magnetometers (OPMs) have brought about a new era of magnetoencephalography (MEG) [1]. The size, flexibility, and close-to-room temperature operation of OPM sensors has enabled the development of wearable and adaptable OPM-MEG systems, which critically, has enabled MEG scanning across the lifespan [2]. SickKids purchased the first Cerca Magnetics system in 2021 and have since been acquiring data from young children and adults across a range of paradigms [3]. Through this process, we have developed scanning set-ups, age-appropriate protocols, and analyses, allowing us to obtain excellent quality results from this nascent system (Figure 1).

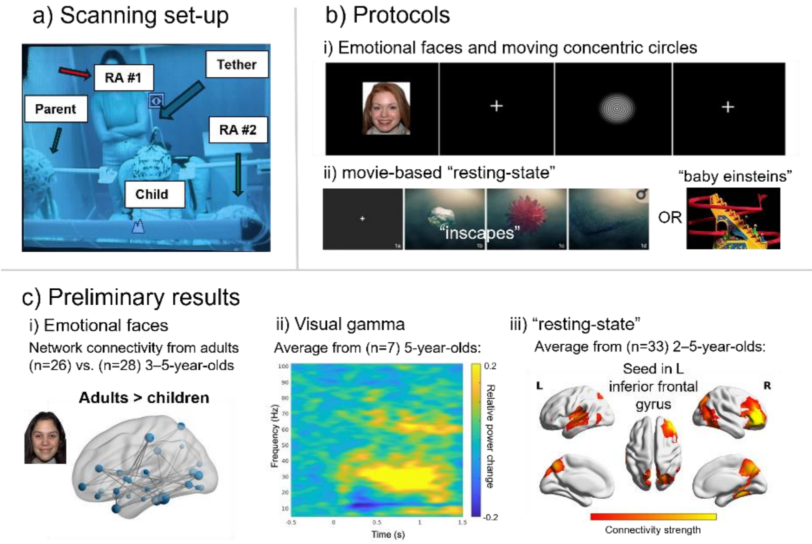

Figure 1: An overview of the SickKids OPM-MEG scanning set-up (a), protocols (b) and preliminary results (c).

Here, we describe the challenges faced and the solutions reached to acquire robust paediatric OPM-MEG results. We will showcase results in 1-5-year-old children and adults and discuss how systems could develop for broader paediatric applications. Through this, we hope to provide an overview of OPM-MEG's place in the future of paediatric neuroimaging.

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[3] Safar, K., et al. Scientific Reports **14**, 6513, (2024)

Miniaturizing MEG: The Future of Epileptic Signal Localization

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Background: This study aims to assess the efficacy of using a reduced number of Optically Pumped Magnetometers (OPM-MEG) sensors, within a 3D printed helmet (Fig.1) for localizing epileptic signals, and compare its performance against the traditional Superconducting Quantum Interference Device (SQUID-MEG) system, which is a more established but less portable and more cost-intensive method requiring cryogenic cooling.

Materials/Methods: The study involved 8 patients diagnosed with intractable focal epilepsy. Each participant first underwent a standard clinical scan using the SQUID-MEG system, followed by an analogous scan in the OPM-MEG suite, which included a series of tasks designed to prompt epileptic signals. Signal-to-noise ratio (SNR), source localization, and connectivity measurements from both systems were then compared.

Results/Discussion: The investigation revealed no significant differences in SNR,(Fig.2) source localization(Fig.3), or connectivity estimates(FIg.4) between the OPM-MEG system, which utilized only 10 sensors, and the traditional SQUID-MEG system, equipped with 306 sensors. These findings indicate that the OPM-MEG can effectively localize epileptic ictal spikes, matching the performance of the current SQUID-MEG systems.

Conclusions: Our results suggest that OPM-MEG, with a smaller sensor array, provides data comparable to that of the more complex and expensive SQUID-MEG system. This discovery not only confirms the viability of OPM-MEG for clinical use, particularly in epilepsy localization, but also opens the door for its adoption in settings where the initial investment for a SQUID-MEG system is prohibitive. Future research will focus on expanding the sample size and including various neurological disease models to further validate OPM-MEG's effectiveness.

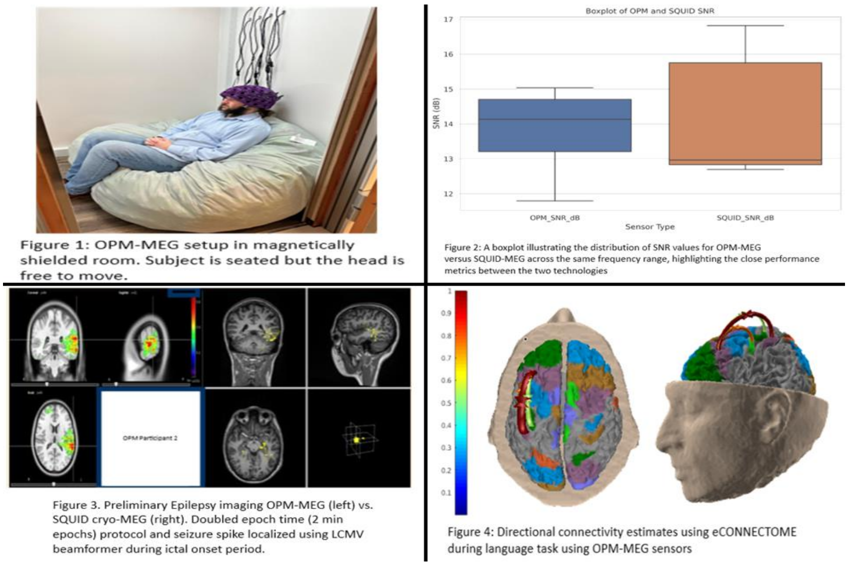

Figure 1: OPM-MEG setup in magnetically shielded room. Subject is seated but the head is free to move.

Figure 2: A boxplot illustrating the distribution of SNR values for OPM-MEG versus SQUID-MEG across the same frequency range, highlighting the close performance metrics between the two technologies

Figure 3. Preliminary Epilepsy imaging OPM-MEG (left) vs. SQUID cryo-MEG (right). Doubled epoch time (2 min epochs) protocol and seizure spike localized using LCMV beamformer during ictal onset period.

Figure 4: Directional connectivity estimates using eCONNECTOME during language task using OPM-MEG sensors

Figure 1: Montage of primary study results

An Alkali-Noble SERF co-magnetometer not reliant on passive compensation

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Alkali-Noble gas co-magnetometers[1] use the high density electron spins (e) of a SERF magnetometer to polarise and probe the nuclear spins (n) of an overlapping noble gas ensemble. This combination has an impressive record as a probe of new physics and application as a rotation sensor, but requires precise alignment and operating conditions to suppress the magnetic field and laser noise that typically limits it.

Here we consider a modified scheme that aims to distinguish these noise sources rather than hide them. It retains similar average behaviour and idealised sensitivity, but resolves the evolution of n independently of e. This allows the extraction of four signals instead of one: 2 magnetic fields and 2 rotations (or anomalous fields) in the axes transverse to the optical pump beam.

The scheme (Fig. 1) uses pulsed optical pumping for the alkali and alternating magnetic pulses to perturb the nuclear spins. The general strategy is to introduce rapid perturbations which preserve the usual average behaviour, while creating fast transients to reveal extra information. This allows improved noise rejection and operation at a range of bias fields, which we hope will improve sensitivity in future anomalous physics searches and gyroscopes.

We present modelling and proof of principle measurements with a ^{129}Xe-^{87}Rb cell.

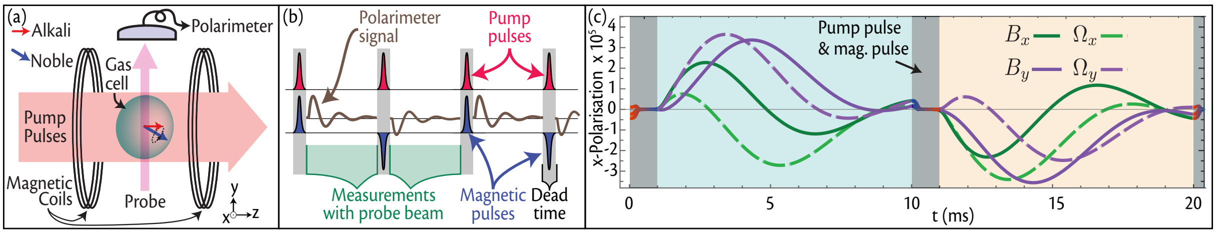

Figure 1: a) The perturbed co-magnetometer experiment is very similar to the DC type, consisting of orthogonal pump and probe beams, an oven and magnetic coils b) The pulse sequence consists of strong pump pulses simultaneous with alternating z-axis magnetic pulses. After each pulse, the alkali polarisation is measured with the pump off. c) A unique (modelled) transient signature results from small applied magnetic fields and rotations, allowing them to be distinguished by linear fitting.

References

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Optically pumped vector magnetometer with freely definable sensitive axis for use within Earth's magnetic field

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We present a novel approach which enables an optically pumped magnetometer (OPM) to be operated within the Earth's magnetic field as a vector magnetometer whose sensitive axis can be freely defined. Thus, vectorial measurements perpendicular to the Earth's magnetic field vector are also possible with high sensitivity.

The OPM uses a microfabricated cesium vapor cell with high nitrogen buffer gas pressure (≈150 mbar), which is immersed into a homogeneous bias field of about 700 µT. The bias field, which is more than an order of magnitude stronger than Earth's magnetic field, determines the sensitive axis of the OPM. The bias field is generated by solid-state magnets and was designed to exhibit a very low inhomogeneity (< 10^{-4} in relative units) within the vapor cell and features a point of vanishing temperature dependence at around 40°C.

The OPM uses the light-narrowing effect, which allows for an effective suppression of the spin-exchange relaxation even in such a strong magnetic field. By that, we demonstrate a white noise floor of < 100 fT/$\sqrt{Hz}$ above 100 Hz and a sensor bandwidth of > 2 kHz.

The sensor concept presented herein is intended to be used in the field of transient electromagnetics (TEM) for the exploration of ore deposits, where up to now SQUID sensors are the gold standard. However, the approach enables unshielded ultrasensitive vectorial measurement capabilities, also relevant in other important applications such as biomagnetism.

We gratefully acknowledge financial support from the Federal Ministry of Education and Research (BMBF) of Germany under Grant No. 13N15436 (OPTEM).

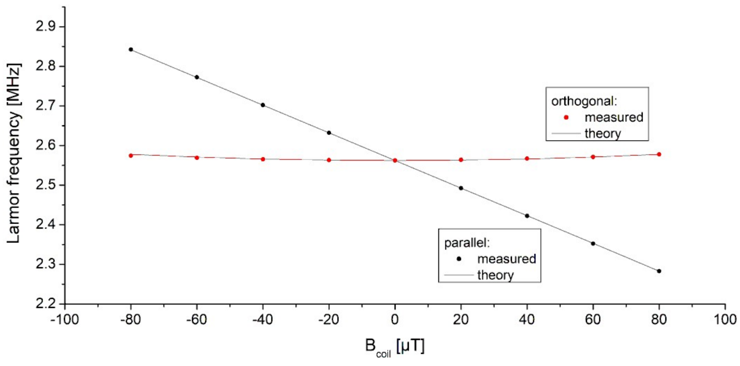

Figure 1: Proof of vectorial sensitivity: If a magnetic field is applied parallel to the bias field, it has a linear impact on the measured Larmor frequency. Orthogonally applied magnetic fields, in contrast, are strongly suppressed, exhibiting a very weak quadratic characteristic.

A free-induction-decay scalar magnetometer for precision measurements

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An optically pumped ^{87}Rb scalar magnetometer operating in a free-induction-decay mode is developed, as demonstrated in Fig. 1. This sensor uses a multi-pass cell with an interior size of $8 \times 8 \times 8.5$ mm^3, and demonstrates an Allan deviation better than 1 pT for an integration time of 100 s, which makes it suitable for monitoring magnetic fields in precision measurements. For practical operations, we also developed homemade electronics for this system, which includes controls of lasers, cell temperature, time sequence, and real-time data analysis. In this talk, we will report the performance of this system, and its application in the search of Electric Dipole Moment using cold ^{171}Yb atoms.

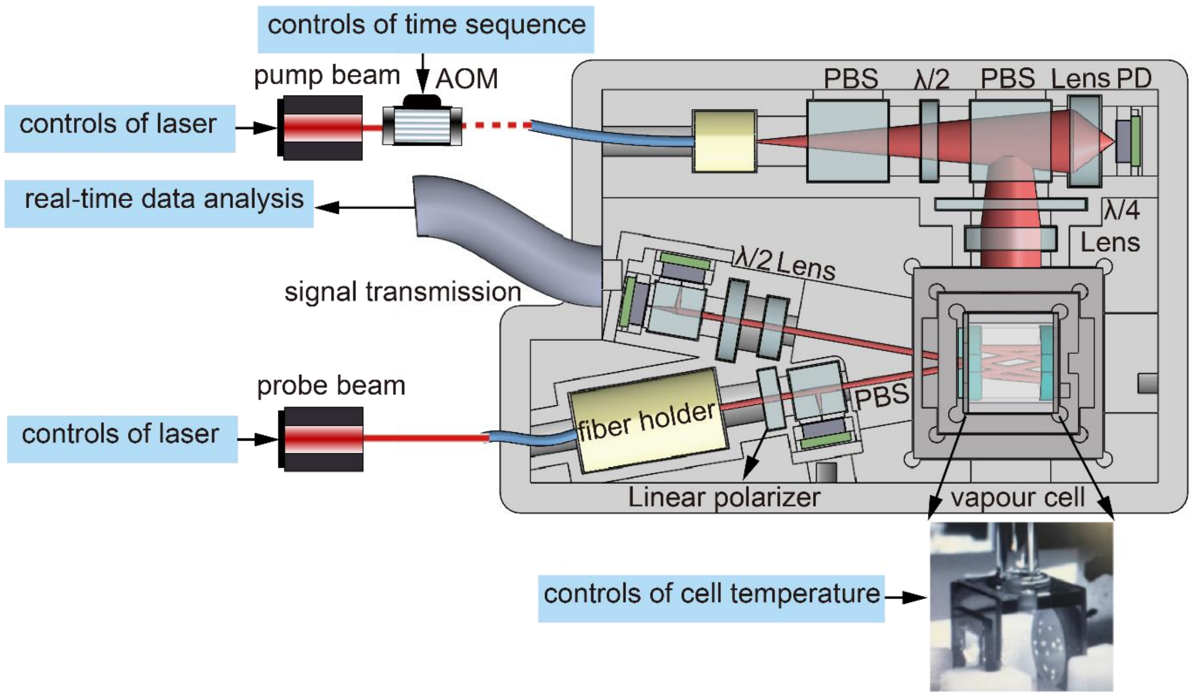

Figure 1: Illustration of the sensor setup.

Functionalized vapor cells and miniaturized biplanar coils for mass-producible miniature atomic sensors

H. Raghavan[1,*], M. C. D. Tayler[1,*], K. Mouloudakis[1], R. Rae[1], S. Lähteenmäki[2], R. Zetter[3], P. Laine[3], J. Haesler[4], L. Balet[4], T. Overstolz[4], S. Karlen[4] and M. W. Mitchell[1,5]

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$*$ The authors contributed equally.

Using a single-beam SERF OPM sensor comprised of mass producible components, we demonstrate femtotesla magnetometry. We describe the design and characterization of high-buffer-gas-pressure, mm-scale atomic vapor cells fabricated with MEMS techniques and integrating heating and thermometry functionality via surface metallization [1]; biplanar printed-circuit coils for homogeneous and localized magnetic field control [2] and package integration. The resulting sensor has been used for NMR [3], and has attractive features for clinical and biological applications. As time permits, we will describe our understanding of beyond-Bloch equation spin dynamics in this device.

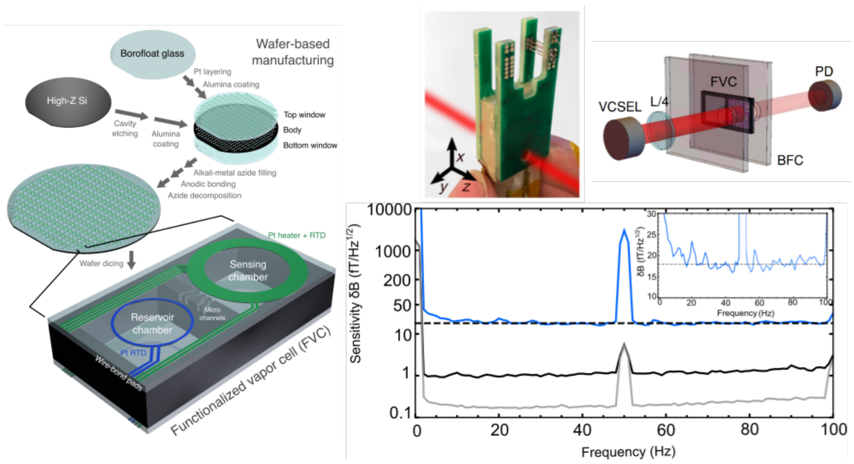

Figure 1: A functionalized MEMS ^{87}Rb vapor cell and miniature biplanar coils – two components of a mass-manufacturable atomic magnetometer demonstrating $18\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ sensitivity.

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Cavity-enhanced atomic magnetometer for micro-bio-magnetic measurements

M. Hernandez Ruiz[1], Y.Ma[1,2], H.Medhat[1], C. Kiehl[1], C. Mazzinghi[1,3], V. G. Lucivero[1,4], and M. W. Mitchell[1,5]

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As a step toward optically pumped magnetometers (OPMs) with sub-mm spatial resolution, we demonstrate optical-cavity-enhanced measurement of atomic vapor spin polarization in a microfabricated vapor cell [1]. The technique, based on the Pound-Drever-Hall (PDH) method, measures the line shift of a circularly-polarized cavity mode, caused by the spin-dependent circular birefringence of the vapor. In contrast to other OPM probing techniques, the optical observable is the phase of a single polarization, rather than a differential phase shift as in Faraday rotation. The method appears well-suited to improving the effective optical path in micro-fabricated atomic vapor cells, analogous to what has been done with multi-pass geometries in macroscopic cells. The signal enhancement will be proportional to the cavity finesse, $\mathcal{F} \approx 18$ in our case (for a blue detuning of $2\pi \times 115\,\mathrm{GHz}$). We describe the application of the OPM to study the ability of magnetotactic bacteria (MTB) to orient in an external magnetic field, which along with their ability to migrate towards regions depleted in oxygen, make MTB potential candidates for cancer treatment [2].

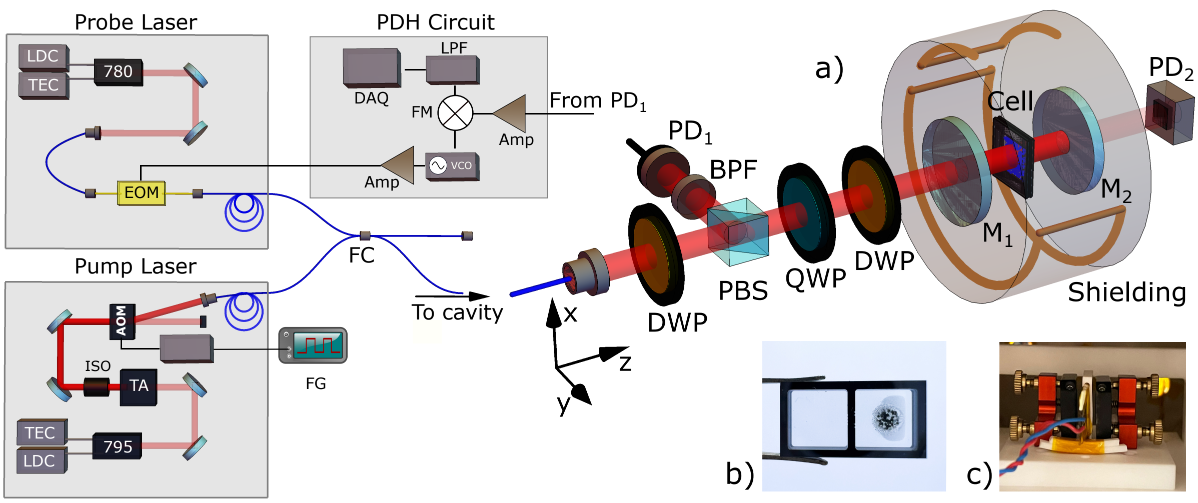

Figure 1: Experimental setup for cavity-based detection of atomic polarization.

References

[1] M. Hernandez Ruiz, et al., *arXiv:2312.12256, (2024)* (to appear in PRApplied).
[2] M. Marmon et al, Rev. Mod. Phys. **96**, 021001 (2024).

A preliminary study of an ultra-wide range Fast Field Cycling (FFC) NMR relaxometry based on compact atomic magnetometer array

Qianyue Qu[1], Jun Guo[1], Zeming Li[1], Yunxi Lv[1,2], Zhiqing Fan[1,2], Li Wang[1,2], Zheng Tan[1,2], Xianping Sun[1,2], Yinan Hu[1,2], Xin Zhou[1,2*]

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[2] University of Chinese Academy of Sciences, Beijing 100049, China.

Nuclear spin relaxation rate could provide complete information about molecular dynamics in a variety of substances and materials, and the FFC NMR relaxometry allows the relaxation rate measurement over a wide range of magnetic field strengths (usually from a few kHz up to around 100 MHz) in one equipment[1]. Nowadays, atomic magnetometer shows its ability in low frequence (0.1 Hz-5 kHz) FID measurement[2]. Herein, a novel FFC NMR relaxometry was developed utilizing an atomic magnetometer array with the measurement of the field strength over the range of 3 Hz to 84 MHz, improved by more than 2 orders of magnitude. Compared to traditional methods, a motor-driven shuttle system has been used to improve the speed of field cycling, with less than 100 ms switch time between any other two different field strengths (Figure 1a). The results show that the relaxation rate of the sample (water) increases as the magnetic field strength decreases. At ultra-low field, the relaxation rate of the sample is 0.79 s^{-1}, which is nearly twice that measured at high field (Figure 1b). The ultra-wide range relaxometry could extend the application of FFC NMR relaxometry in weak intermolecular interactions (absent of magnetic field), and because of the capability of the low frequency signal detection, this method is not affected by inhomogeneity of sample's magnetic susceptibility, which would render the technique highly applicable in evaluation of metal-based MRI contrast agents, food science, petroleum industry.

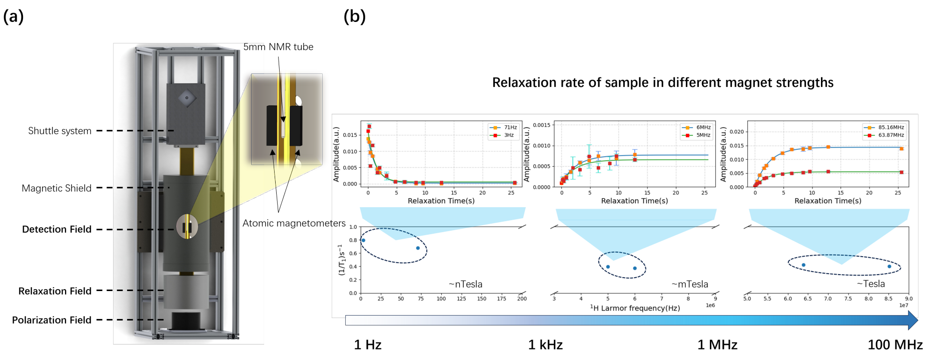

Figure 1. a) Expriment setup. b) The relaxation rate in different magnetic strengths

References

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Atomic Microwave Spectrum Analyzer based on MEMS Vapor Cells

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Atomic vapor cell-based quantum sensors have found successful applications in atomic clocks, magnetometry and gyroscopes. Recent efforts have also focused on leveraging these sensors to detect and image high-frequency electromagnetic fields, primarily by measuring field strength.

Here, we report an atomic microwave (MW) spectrum analyzer capable of measuring the frequency spectrum of incident microwave signals with *broad instantaneous bandwidth* [1]. We position a microfabricated ^{87}Rb vapor cell, which is filled with nitrogen buffer gas, in a large static magnetic field gradient. Localized ^{87}Rb atoms are pumped, interact with on-resonant microwave signals, and generate a spin-flip image pattern signal by a probe laser pulse on a CMOS camera, thus discriminating different MW frequency components. We measured frequency modulated signals with increased frequency deviations, as well as a frequency-swept signal (Figure 1).

Our atomic spectrum analyzer demonstrates an instantaneous bandwidth of 1 GHz, centered at 13.165 GHz, with a frequency resolution of 3 MHz and a refresh rate of 2 kHz. We theoretically study the underlying spin dynamics by quantitatively modeling all processes. Based on the simulation, an optimized setup is proposed that can reach 25 GHz instantaneous bandwidth. Such technique is potentially promising for future broadband real-time MW spectrum analyzer, which is currently bottlenecked by the bandwidth of fast electronics (ADCs and FFT processes).

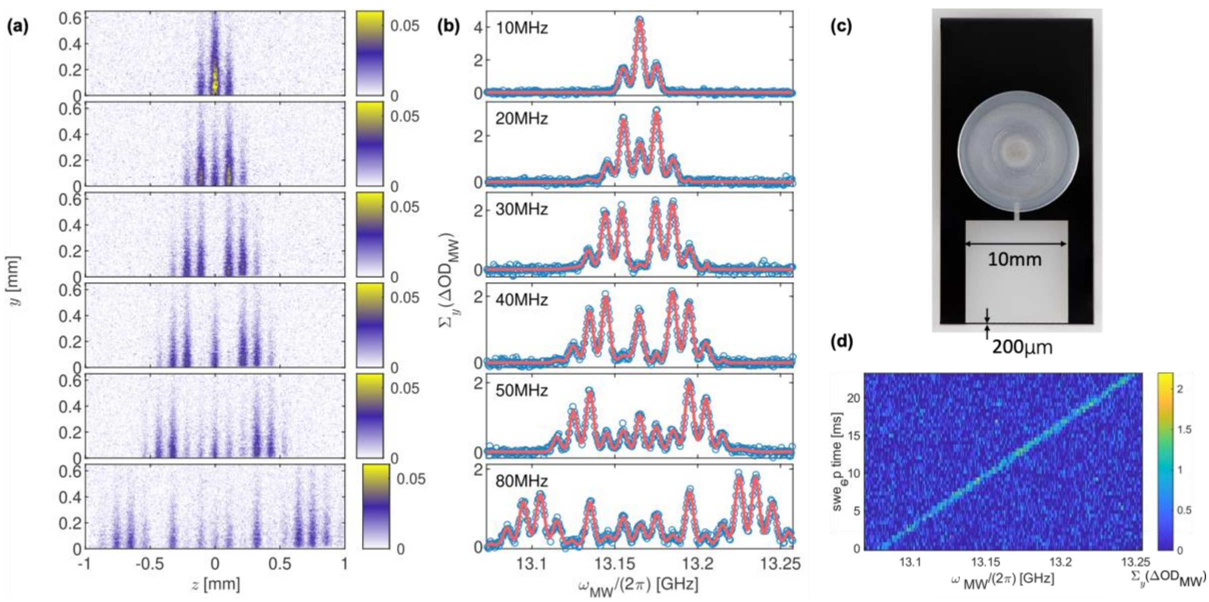

Figure 1: (a) Atomic spectrum analyzer images of frequency-modulated MW signals. (b) Corresponding integrated spectra $\sum_y(\Delta \mathrm{OD}_{\mathrm{MW}})$ with multi-peak Gaussian fits. (c) MEMS atomic vapor cell. (d) Spectrogram measurement for a frequency-swept MW signal.

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High-order atomic coherences for the elimination of nonlinear Zeeman splitting error in atomic magnetometers

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Various strategies exist for the mitigation of the nonlinear Zeeman effect (NLZ) error of atomic magnetometers in the geomagnetic field – 50 μT (see [1] and references therein). The common idea among these strategies is to compensate the error using various theoretical or physical techniques or to address atomic states for which the NLZ effect is reduced for example using a spin-locking field induced via vector light shift [1]. In our project we explore the most straightforward approach – to use those magnetic sublevels of states with definite angular momentum whose energy changes in a strictly linear fashion with magnetic field, such as the F=2, m=2 and F=2, m=−2 magnetic sublevels of atomic ^{87}Rb in the ground state $5^2S_{1/2}$. These magnetic sublevels must be excited coherently in order to gain access to a signal that is linearly dependent on the external magnetic field, which means that higher-order multipoles (K=4, see Fig. 1) of the density matrix must be created and observed. We build on previous work where this type of coherences were created and observed via optical rotation of the probe beam [2]. Likewise, we intend to increase the accuracy of ^{87}Rb atomic magnetometers by completely eliminating the NLZ heading error via the creation of hexadecapole moments (Δm=4 coherences) with a precise sequence of modulation pulses and to improve sensitivity by using fluorescence instead of optical rotation.

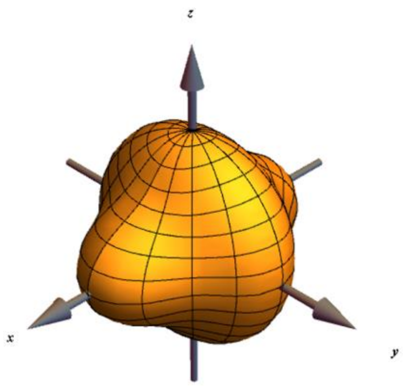

Figure 1: The simulation of a hexadecapole angular momentum probability surface.

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Biplanar coil cancellation system for OPM-MEG using PCB

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Optically pumped magnetometers (OPMs) are a promising sensor technology for non-invasive on-scalp measurement of human electrophysiological signals. Despite the promise, these sensors are yet to be widely adapted due to the difficulty of operating the sensors with minimal shielding in clinical environments. OPM groups have proposed biplanar field cancellation coils to remove the constant and gradient component of the magnetic field. As opposed to Helmoltz coil designs, these biplanar coils provide subjects an unobstructed front view while allowing movements within a predefined region.

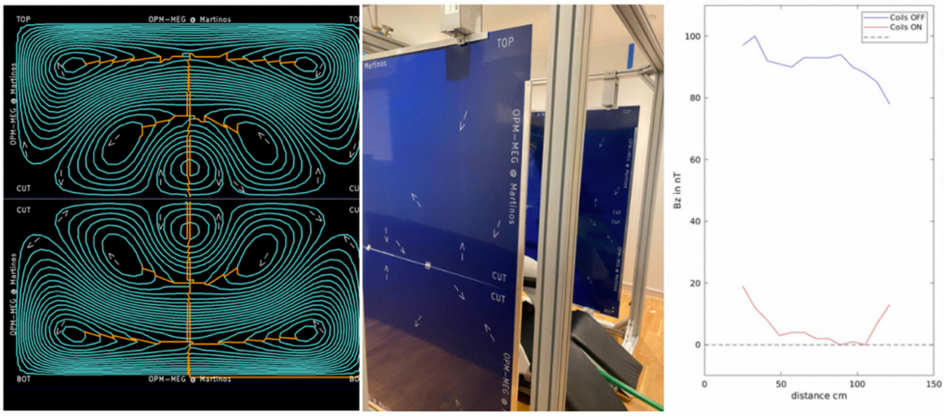

Fig 1. A. Optimized coil design for printed circuit board (PCB), and **B.** Installed PCB inside a one-layer shielded room at the Martinos Center, MGH, and **C.** Background field profile between the coil centers before and after turning on the coil pair to remove a constant field component.

However, until now, biplanar coils were expensive to manufacture, involving error-prone manual winding of >1000 meters of copper wire. In this work, we designed and fabricated field cancellation coils (3 constant field and 3 field gradients) on a two-layer Printed Circuit Board (PCB). We used the bfieldtools package to compute the current loops that produce the target magnetic field (constant or gradient) in a region of interest. These current loops were connected into a continuous conducting path (**Fig 1A**) using in-house interactive software, manufactured as pairs of 1.5 m x 0.75 m PCBs (2 oz copper) cut along the symmetry axis, soldered together and mounted on a sliding aluminum frame (**Fig 1B**). Preliminary results suggest that these coils can achieve lower resistance, higher accuracy and higher efficiency. This innovation paves the way for commercial OPM-MEG systems with cheaper and more robust (replicable and geometrically accurate) coil-cancellation systems.

A compact OPM-MEG system

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Optically pumped magnetometers (OPMs) have recently gained traction as sensors in magnetoencephalography (MEG). Typically, OPM-MEG systems are deployed in magnetically shielded rooms (MSRs), similarly to those used with conventional SQUID-sensor-based MEG systems. However, OPM systems have smaller footprints than SQUID systems, so for OPMs a compact person-sized shield (PSS) would be a sufficient, cost-effective alternative to the large MSR [1,2].

We have designed together with the shield manufacturer (Vacuumschmelze GmbH & Co. KG, Hanau, Germany) a 2-layer (mu-Al-mu) cuboid-shaped PSS. The shield is 2.4 m long with a transverse outer cross-section of 1.4x1.4 m^2. The total weight of the shield is 1000 kg and its inner cross-section for subject access is 1x1 m^2 with an always-open feet-end opening of 0.8x0.8 m^2. The subject is brought in the shield on a non-magnetic sliding bed to which the OPM helmet is attached. The helmet has 99 sensor-slots with depth adjustment, which enables on-scalp measurements of different head sizes. The center-to-center distance between sensors is 30 mm, striking a balance between the modulation-field crosstalk and field-sampling density.

Measured with a fluxgate magnetometer and two OPMs (FieldLine Inc., Boulder, CO, USA), the DC field outside and inside the non-degaussed PSS was 50 uT and 5 nT, respectively. At 0.1 Hz and 10 Hz, the shielding factor was 50–60 dB and 70–100 dB, respectively, depending on the direction of the external field relative to the PSS orientation. This performance readily enables using our OPMs (QZFM gen-2, QuSpin Inc., Louisville, CO, USA) in the shield.

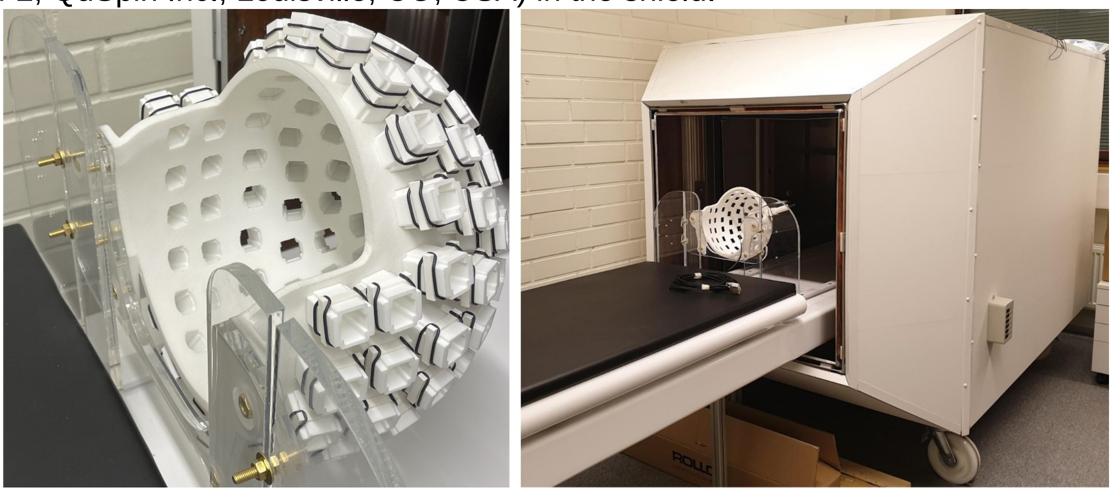

Figure 1: OPM sensor helmet and compact person-sized shield.

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Optical magnetometry using NV centers in diamond for neurosurgical applications

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The Quantum Neuro Analyzer (QNA) is an endoscopic device that utilizes a magnetic sensor to image neural activity in the brain during neurosurgical procedures. The sensor, which features diamond with point defects known as nitrogen-vacancy (NV) color centers, is designed to capture the magnetic response of the brain tissue. The optical excitation and read-out of the color centers in diamond are executed in a handheld endoscopic device. The sensor head's design addresses several technical challenges, including precision, sensitivity, and thermal management ensuring its suitability for neurosurgical applications. The biological sample can be positioned as close as 100 micrometers to the sensor, facilitating the detection of magnetic activity with enhanced spatial and temporal resolution. The QNA targets a sensitivity level in the pico-tesla range, a bandwidth in the kilohertz range, and a spatial resolution of 0.1 millimeters. This work, DIAmond-based QuaNtum sensing for neurosurgery (DIAQNOS) [1], is a part of a lighthouse project of the German government's quantum initiative. The consortium comprises partners developing the physics and engineering aspects, as well as institute partners testing brain tissues using the developed magnetic sensor.

[1] DiaQNOS, DIAmond based Quantum sensing for Neurosurgery <https://www.diaqnos.de >

Application of UnShielded SERF Atomic Magnetometers in Earth Exploration

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To meet the need for detecting the Earth's polarization parameters and acquiring low-frequency vector weak magnetic field signals, we designed an unshielded spin-exchange relaxation-free (SERF) atomic magnetometer system. Two single-beam SERF atomic magnetometers were vertically oriented to obtain the three-axis magnetic field, and an additional magnetic flux gate sensor was incorporated to provide ignition start-up capability. Ultimately, unshielded magnetic field measurement was achieved by solely relying on the feedback from the SERF atomic magnetometers themselves. In the two optimized directions, the noise performance of the SERF atomic magnetometers was better than $80\mathrm{fT}/\sqrt{\mathrm{Hz}}@10\mathrm{Hz}$. To enable feedback operation of the SERF atomic magnetometers in the geomagnetic environment and achieve optimal performance, we custom-built a large dynamic range, ultra-low noise current source with a current noise of $28.3\mathrm{pA}/\sqrt{\mathrm{Hz}}@10\mathrm{Hz}$ at the maximum output of ±202 mA [1]. Simultaneously, we implemented a fast demodulation feedback system to ensure system stability and prevent oscillations. This approach will facilitate the acquisition of more abundant data from the Earth's interior.

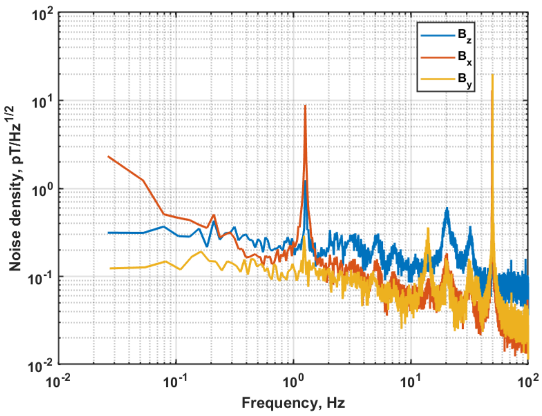

Figure 1: The three-axis noise-density frequency spectrum of the SERF atomic magnetometers involved in the closed-loop feedback.

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Posters

Fabrication and characterization of antirelaxation coated multipass cells

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The multipass cell is widely used in laser spectroscopy [1], providing long optical path lengths and amplifying the detection signal. Recent multipass cells based on internal spherical mirrors or external flat mirrors are also implemented in atomic magnetometer research [2][3]. However, there are no reports about internal multipass cell coated with anti-relaxation coating. Here we demonstrate a high quality antirelaxation coated compact multipass atomic vapor cell. Pair of window pieces pre-coated with reflective dielectric film is sealed onto the open end of the glass frame by optical-bonding. Compare to previous multipass cell, our scheme has a more compact structure and simpler inner geometry, while providing larger beam coverage volume.

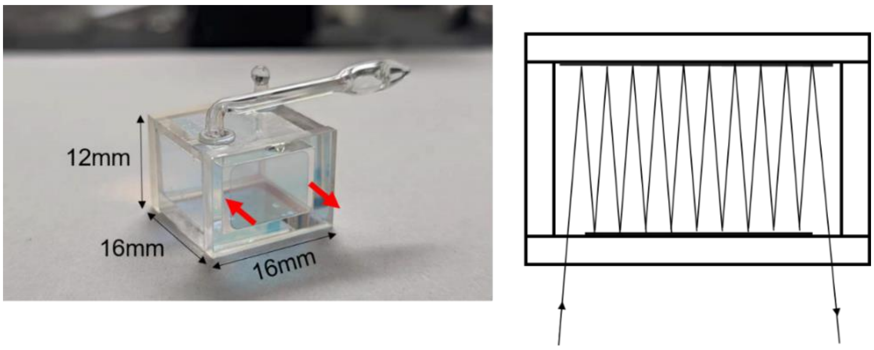

Figure 1: Photo and light pattern of the multipass cell.

The cell is coated with long chain paraffin with care taken to prevent excess wax from condensing on the reflection surfaces. Using this method, we fabricated a cell with 2mm thick wall and an external dimension of 16*16*12 mm and obtained 20 plus optical passes with a photon transmissivity of over 60%. The cell is filled with Rb87 vapor with a longitudinal relaxation time of 1s at room temperature corresponding to 41,000 spin preserving collisions. The spin noise spectrum and magnetometer sensitivity are measured when the cell works in multipass mode and single-pass mode. The result proves the superiority of multipass cells in magnetometer detection and spin noise analysis.

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Attempt at Multi-Point Measurement Using M-Sequence Modulation of Pump Beams in Optically Pumped Magnetometers

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Optically pumped magnetometers (OPMs) are ultra-sensitive sensors for biomagnetic-field measurements. We previously reported sinusoidal modulation of pump beams for frequency division of multiple signals [1]. However, this method was affected by the frequency characteristics of the OPMs, as shown in Fig.1. In this study, we designed multi-channel OPMs using M-sequence modulation of pump beams with large sensor cells.

The method used in this study is based on spread spectrum method. By M-sequence modulating the pump beams of pump-probe type OPMs, signals from different locations can be distinguished. We simulated the OPMs with M-sequence modulating the pump beams, and evaluated the ability of the multi-channel sensing.

Pump beams were modulated using sinusoidal waves at various frequencies and M-sequence. The sinusoidal modulation resulted in a maximum signal-to-noise ratio (SNR) approximately 28 times higher than that of M-sequence modulation. Conversely, the minimum SNR of the sinusoidal modulation was half that of the M-sequence modulation due to the OPMs' narrow frequency bandwidth. As the modulation frequency increased, the SNR of the sinusoidal modulation decreased. M-sequence modulation maintained a consistent SNR across all channels.

Our assessment confirmed that OPMs with large sensor cells are feasible for multi-point measurements. The spatial uniformity of the SNR was better with M-sequence modulation compared to sinusoidal modulation. In the presentation, the effect of the pulse width and period of the M sequence will be discussed.

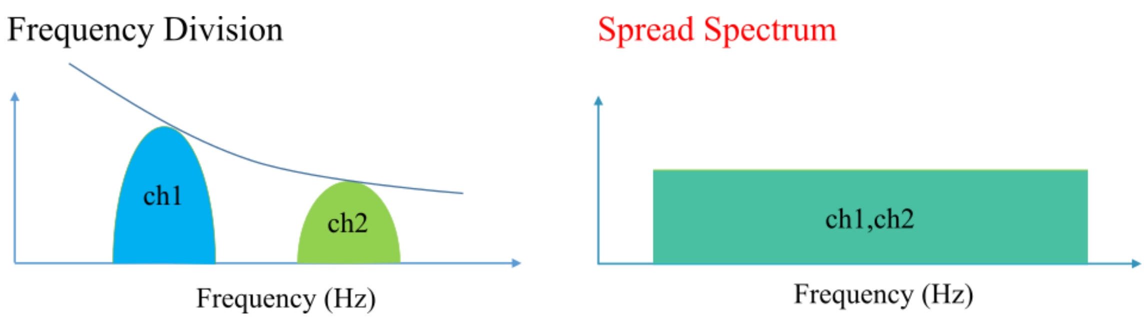

Figure 1: Concept of Spread spectrum.

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Shot-noise-limited optical polarimetry with Decoupled spin-alignment and magnetism

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Quantum non-demolition measurement with an off-resonance polarized probe is a widely utilized technique for atomic sensors. We observe **the previously unexplored atomic spin-alignment induced by the linearly far-detuned off-resonance probe in an optical-modulation-based polarimetry** [1]. The evolution of probe-generated multipole moments exacerbates probe noise due to strong magnetic couplings. We demonstrate a method to decouple spin-alignment from magnetic fields by manipulating the multipole moments in zero-fields. The probe noise is suppressed by 8.2 dB@1Hz and 10.4 dB@10Hz. The obtained probe noise is comparable to the photon shot noise, and it is expected to further reduce the probe noise of state-of-art comagnetometer that search for new physics beyond the standard model [2] by about three times.

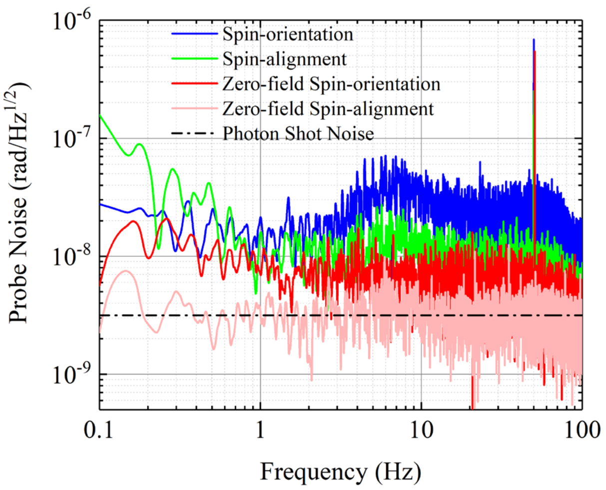

Figure 1: Comparison of proportions of probe noise in the optical-modulation-based polarimetry under several conditions.

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Integrated optomechanical magnetometer

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Magnetometers has applications in medicine, geospatial navigation, defence, and mining. Our work focus on developing an on-chip integrated optomechanical magnetometer to be used as a wireless sensor.

Optomechanical magnetometers are a new class of magnetic sensors. They are small in size, weight and power (SWaP), works in room temperature, and can be fabricated in mass production. On top of that, they can present sensitivities as good as 26 pT/√(Hz) [1]. Their working principal is based on observing a frequency shift of an optically coupled cavity due to a magnetic field [2].

In this work, we present our unique design and nanofabrication process that allowed the integration of this class of magnetometer on silicon-on-insulator and bonded with a single-side tapered fiber (see Figure).

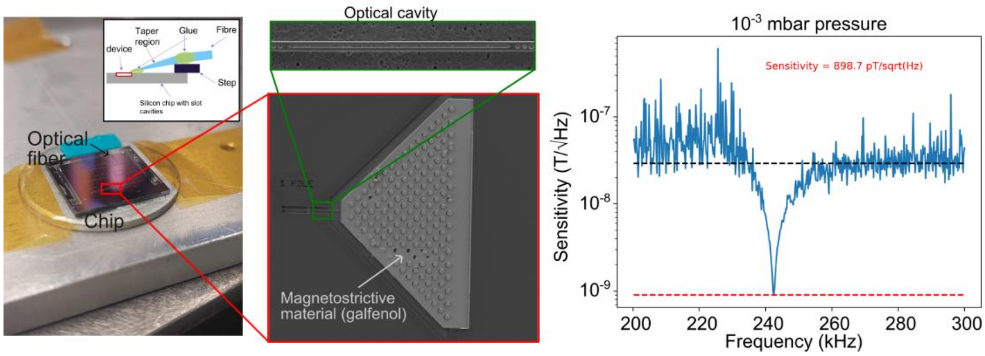

Figure 1: Integrated sensor show SEM images of the device. The plot shows the sensitivity at a pressure of 1x10^{-3} mbar.

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Quantum-enhanced Electrometer based on Microwave-dressed Rydberg Atoms

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Rydberg atoms have been shown remarkable performance in sensing microwave field. The sensitivity of such an electrometer based on optical readout of atomic ensemble has been demonstrated to approach the photon-shot-noise limit. However, the sensitivity can not be promoted infinitely by increasing the power of probe light due to the increased collision rates and power broadening. Compared with classical light, the use of quantum light may lead to a better sensitivity with lower number of photons. In this paper, we exploit entanglement in a microwave-dressed Rydberg electrometer to suppress the fluctuation of noise. The results show a sensitivity enhancement beating the shot noise limit in both cold and hot atom schemes. Through optimizing the transmission of optical readout, our quantum advantage can be maintained with different absorptive index of atomic vapor, which makes it possible to apply quantum light source in the absorptive electrometer.

Implementation of an atomic free induction decay magnetometer targeted at medical diagnostics

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We report on the progress of implementing our own atomic magnetometer based on free induction decay (FID) using our in-house manufactured rubidium MEMS (micro-electromechanical systems) vapor cells. The magnetometer currently exhibits a sensitivity of 2.5 $\mathrm{pT/Hz^{1/2}}$ with a bandwidth of 625 Hz and is targeted at medical diagnostics, specifically for the detection of cardiac signals. Figure 1 depicts a sample measurement of a synthetic cardiac signal, with an amplitude that is comparable to the cardiac magnetic field strength in proximity to the human chest.

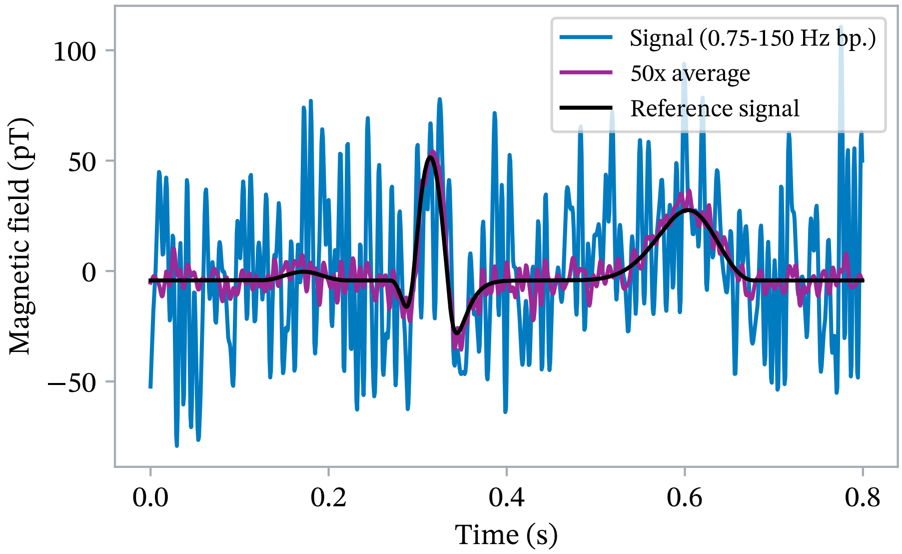

Figure 1: Magnetometer measurement of a synthetic cardiac signal with an 80 pT peak-peak amplitude. The blue data points represent the measured magnetic field (with a 0.75-150Hz bandpass applied) and the purple lines show the average of this signal over 50 heart beats.

A Low-frequency Sensitivity Enhancement Method for Compact Magnetic-field-modulation-free SERF Magnetometers

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High-density, low-noise optically pumped magnetometers (OPMs) are crucial for improving singal and source imaging quality of magnetoencephalography (MEG). However, the sensitivity of magnetic-field-modulation-free (MFMF) spin-exchange-relaxation-free (SERF) OPMs can be significantly compromised by technical noise from the pump beam, particularly at low frequencies (< 10 Hz). We demonstrate a novel method to enhance low-frequency sensitivity in miniaturized stand-alone MFMF OPM by utilizing redundant information from multiple sensors within an OPM. This sensor fusion method adpots a Kalman filter with a switch filter to effectively identify technical noises to be removed without additional equipment. This method can increase the low-frequency sensitivity of OPMs by up to 270% while maintaining a signal distortion ratio of less than 5% under challenging environmental conditions (e.g., those encountered in high-density OPM-MEG detection arrays). Our proposed method holds the potential to fully exploit the advantages of MFMF OPMs for high-density detection by enahncing their resistance to low-frequency technical noise, making them ideal for more accurate biomagnetic imaging with improved spatial resolution.

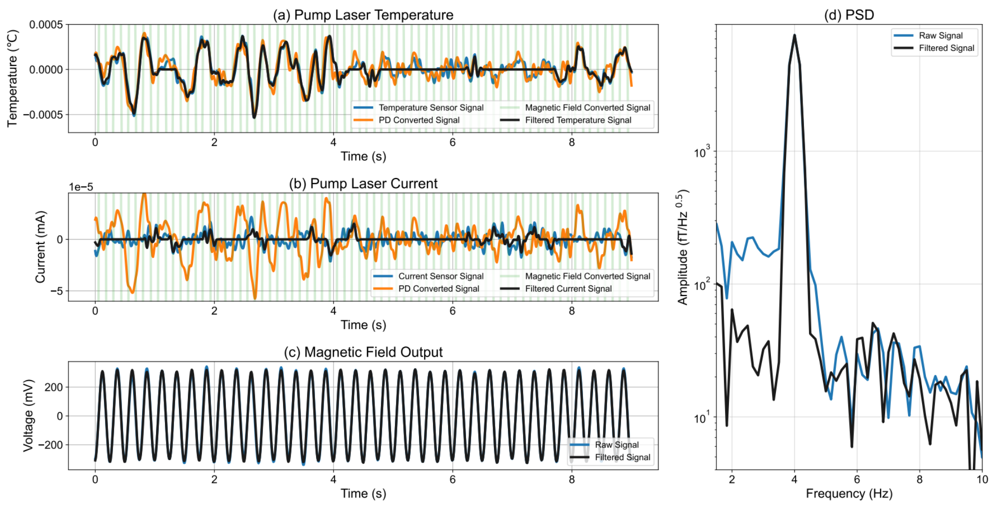

Figure 1: The performance of the low-frequency sensitivity enhancement method. The time course of (a) temperature noise, (b) current noise, and (c) magnetic field output are shown. Additionally, the calibrated magnetic signal's power spectrum densities (PSDs) before and after enhancement are displayed in (d).

Single-Beam Vector Atomic Magnetometer using Parametric Modulation

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We demonstrate a single-beam atomic magnetometer using transmission measurement. Circularly polarized resonant light pumps atoms into specific ground spin states, increasing spin polarization and aligning atomic spins with the propagation direction of light. The transmitted power is proportional to the projection of the polarization of the atomic spin alignment onto the direction of the incident light [1]. The polarization of the atomic spins is derived from the Bloch equation and depends on the magnetic fields in three axes. To eliminate ambient noise and amplify the signal, we modulate the y-axis magnetic field under a far-off resonance condition and measure the x-axis magnetic field using phase-sensitive detection with a lock-in amplifier (LIA) [2, 3].

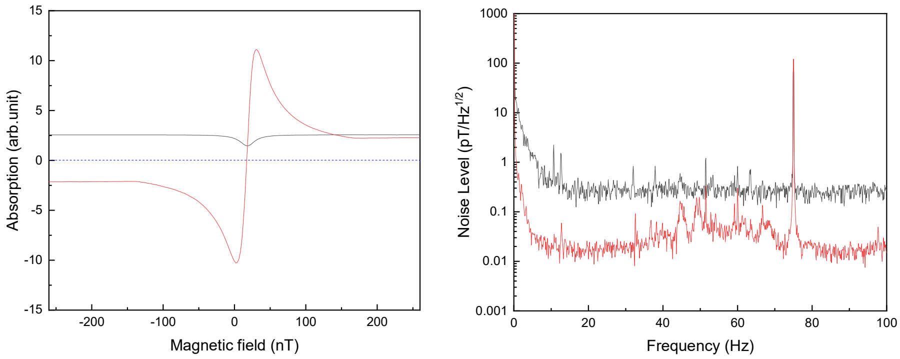

Figure 1: Transmission measurement and LIA signal. Black line: Absorption signal with changes in Bx, Red line: LIA signal of the absorption signal, Reference field: 120 pT at 75 Hz, Noise floor: 260 fT/√Hz (Black) and 34 fT/√Hz (Red)

In Figure 1, the black line represents the absorption of light, while the red line depicts its corresponding LIA signal, which varies with changes in the x-axis magnetic field. The noise floor for the absorption signal is 260 fT/√Hz, while for the LIA signal, it is 34 fT/√Hz.

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Ultra-sensitive triaxial zero-field atomic magnetometry

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Ultra-sensitive spin-exchange relaxation-free (SERF) atomic magnetometers with triaxial measurement capabilities are critical for applications such as cutting-edge research, biomagnetism, and material magnetic measurements. Existing SERF atomic magnetometers operate primarily in quasi-static or modulated modes. The former relies on the orthogonal pump-probe configuration to achieve high sensitivity, while only uniaxial magnetic field measurement can be achieved without applying polarizability modulation. The latter supports the measurement of biaxial or triaxial magnetic field vectors by applying high-frequency large-amplitude modulation fields with specific phases and frequencies, but results in a substantial increase in spin-exchange relaxation.

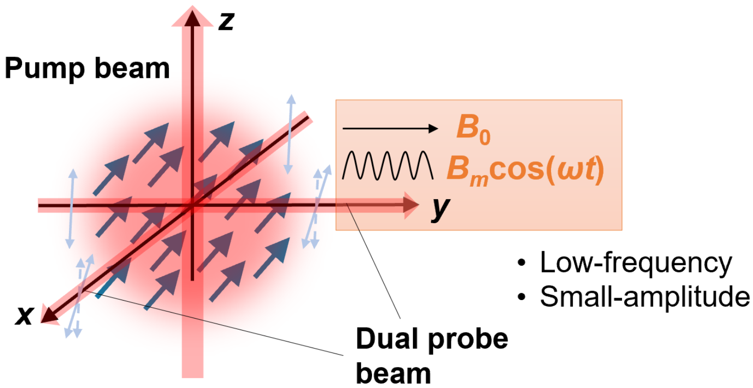

Figure 1: Schematic of ultra-sensitive triaxial zero-field atomic magnetometry.

Therefore, we introduce an atomic magnetometry under the combined action of bias and low-frequency small-amplitude modulation fields to achieve both high sensitivity and triaxial measurement capabilities. The dynamic process is decomposed by Dupont–Roc perturbation and simplified in analytical form by solvable and perturbed parts, supporting field decoupling and interference correction in transverse polarizability. This system can innovatively realize the direct extraction of the longitudinal magnetic field based on the derived analytical model. To improve detection sensitivity, we further apply dual orthogonal polarization detection to extract independent triaxial magnetic fields. By leveraging these manipulation effects, our research provides a revolutionary triaxial atomic magnetometry eliminating the barrier between triaxial detection mode and introduced magnetic field relaxation. It is expected to improve the sensitivity of triaxial magnetic field measurement to fT/Hz$^{1/2}$ or even sub-fT/Hz$^{1/2}$ level.

Atomic Spin Relaxation Measurement Instrument for Different Atomic Vapor Cells: Various Types of Relaxation Time Measurements

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Measuring the spin relaxation time of the cell is essential for evaluating cell performance and enhancing the precision of atomic measurement instruments, such as atomic magnetometers and atomic gyroscopes.Currently, there are various methods for measuring relaxation time, such as the delayed pulse method, the FID method, and the Franzen method. These different measurement techniques correspond to various combinations of optical switching or RF magnetic field timing, resulting in relatively complex control. Additionally, different optical path structures are sometimes required.

We demonstrate an atomic spin relaxation measurement instrument capable of measuring different types of relaxation times for various vapor cells using a single optical structure. By integrating LabVIEW, we achieve automated control, data acquisition, and measurement. This instrument features multifunctionality, automation, high-precision measurement, and remote control capabilities.

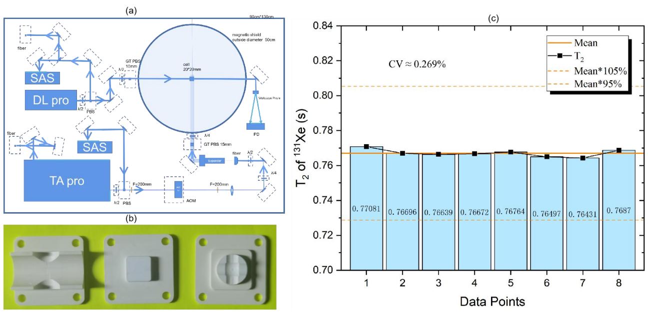

Figure 1: Diagram of Instrument Components and Measurement Results of T_2.

Preliminary testing has demonstrate that the instrument successfully performs the basic functions of measuring various types of relaxation times, including the transverse relaxation time of alkali atoms, the longitudinal relaxation time of alkali atoms, the transverse relaxation time of noble atoms, and the longitudinal relaxation time of noble atoms. The coefficient of Variation of the relaxation time measurements reaches to 0.269 %.

Our research is significant for the automated measurement of atomic relaxation times and the development of high-precision sensors. Combined with high-performance miniature magnetic shielding, there is potential for future miniaturization.

In-situ measurement method of diffusion constant in SERF atomic magnetometer

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To simplify the complexity of theoretical and simulation analysis for SERF atomic magnetometer, the spatial distribution of the spin polarization is often neglected. However, as the expansion of the operation mode of the SERF magnetometers, such as differential detection mode and three-axis measurement mode, the spatial distribution of the spin polarization, which is mainly determined by diffusion constant ***D***, should be fully considered. The diffusion constant represents the ability of the diffusion of the alkali atoms from the polarized region to non-polarized region in cell. For multi-axis measurement conducted in different regions of a single cell, the spatial resolution of the magnetometer is dependent on the diffusion constant. Our method proposed here provides a means of measuring the diffusion constant under different cell conditions. We used a pump beam with great optical power to polarize the alkali atoms and measure the optical rotation angle ϕ under pumping beam with different diameters. By calculation of the following equation, we can derive the diffusion constant. This method can achieve in-situ measurement of the diffusion constant and can be generally applied to different measurement modes.

$$\phi = 2k\left(R\frac{\gamma_e}{R_{rel}}\left(P_{z0} - P_{z0}{}^2\right) + P_{z0}\sqrt{\frac{Dq(P)}{R_{\mathrm{rel}}}}\left(1 - e^{C(R)}\right) - \frac{1}{2}P_{z0}{}^2\sqrt{\frac{Dq(P)}{R_{\mathrm{rel}}}}\left(1 - e^{2C(R)}\right)\right)$$

where $C(R) = \sqrt{\frac{R_{\mathrm{rel}}}{Dq(P)}}(R - d/2)$.

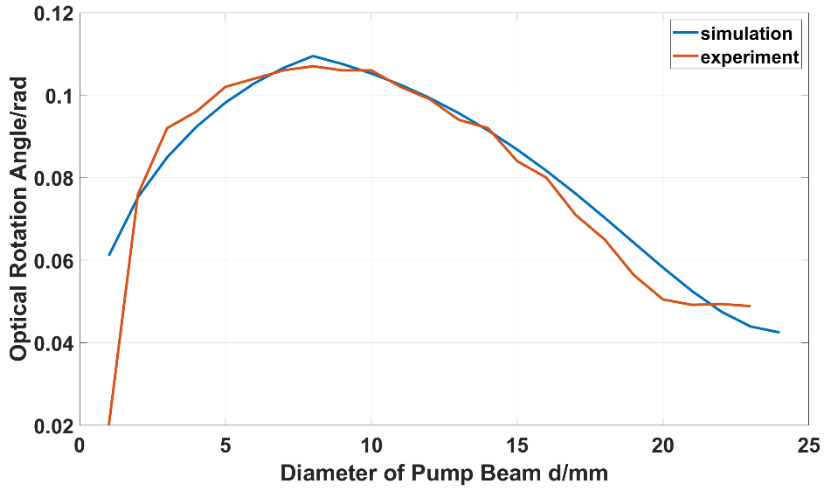

Figure 1: The dependence of the optical rotation angle on the pump beam with different diameters when the diffusion constant D=160mm^2/s

An absolute residual magnetic field order evaluation method of SERF atomic magnetometer

D. Zhan[1] and Y. G. Wang[2]

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Maintaining a near-zero magnetic field condition is a requisite for atomic magnetometer under spin-exchange relaxation-free (SERF) regime. To reduce the ambient magnetic fields more effectively, active magnetic field compensation using triaxial coils is usually the first and significant step during magnetic field measurement and generally applied along with the magnetic shield mounted outside the magnetometer. However, for those magnetic field compensation methods which have been previously proposed, how to effectively value the validity of the magnetic field compensation is still a challenge. Therefore, we proposed an absolute residual magnetic field order evaluation method, which can provide an important perspective to evaluate the validity of different magnetic field compensation methods. We use the transient response after shutting down the pump beam. When the response of polarization along the x-axis P_x arrives at its first extreme value, the measurement time t is recorded. We find that t decreases as the residual magnetic field B_y increases. When B_y tends to be zero, t reaches its maximum value, which is also the function of the relaxation rate R_{rel} and the slowing-down factor q. Therefore, the absolute residual magnetic field can be derived by the given R_{rel} and q. This method can measure the order of the residual magnetic field and further evaluate the effectiveness of magnetic field compensation.

$$t = \frac{q(P)}{\gamma^e B_y} \arctan\left(\frac{\gamma^e B_y}{R_{\mathrm{rel}}}\right)\Bigg|_{\gamma^e B_y \ll R_{\mathrm{rel}}} = \frac{q(P)}{R_{\mathrm{rel}}}$$

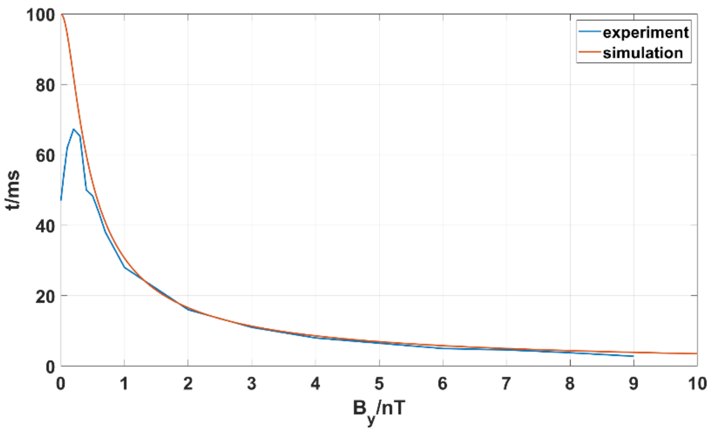

Figure 1: Measurement time t under different residual magnetic field B_y

In-situ Self-Calibration of a SERF Atomic Magnetometer

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Spin-Exchange Relaxation-Free (SERF) magnetometers are renowned for their exceptional sensitivity but face challenges in accuracy and stability due to their high sensitivity to environmental changes and the relative nature of their measurements. Traditional calibration methods, involving standard coils and other highly accurate magnetometers such as fluxgate magnetometers, are inconvenient for real-time applications and prone to positional and directional deviations.

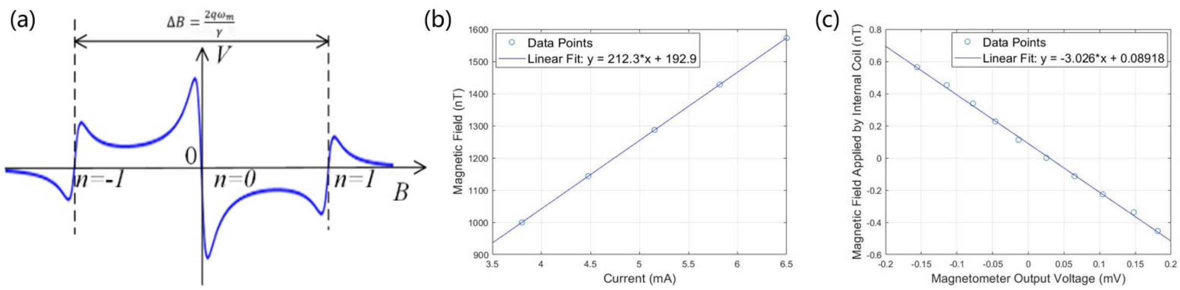

Figure 1: (a) Principle of in-situ coil calibration principle using Bell-Bloom magneto-optical resonance ; (b) Calibration of the internal coil constant through absolute measurement; (c) Determination of the scale factor of a SERF magnetometer using the calibrated internal coil.

We propose an in-situ self-calibration method for a SERF magnetometer. This method operates in two modes: an absolute measurement mode using Bell-Bloom magneto-optical resonance to determine the internal coils' constant, and a SERF measurement mode to calibrate the magnetometer signal via the magnetic field applied by the internal coils.

Compared with existing in-situ coil calibration methods based on free induction decay (FID) signals[1] or spin polarization transfer[2], our proposed in-situ coil calibration method does not require the addition of other components in the gas cell, additional feedback control equipment, or complex nonlinear fitting. This coil calibration method allows for quick switching between normal SERF operation mode and calibration mode based on an FPGA- based signal processing code. Our In-situ Self-Calibration method ensures reliable and efficient accuracy for ultra-weak magnetic measurements over extended periods.

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Toward an Optically Pumped Magnetometer Magnetoencephalography System with Full Head Coverage

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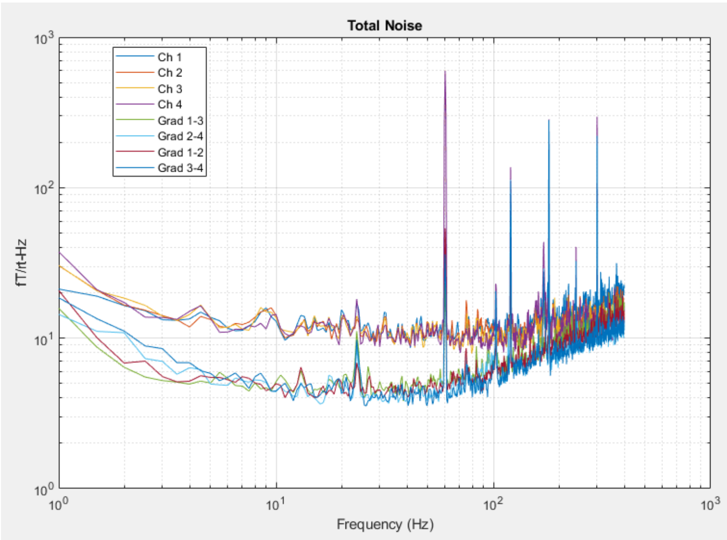
We will present various aspects of our development effort to implement a 108-channel optically pumped magnetometer (OPM) array in a magnetically shielded room (MSR). Our four-channel OPM [1] has been redesigned [2] to ease manufacturing, reduce the external temperature, improve the magnetic field control and uniformity, and reduce the required optical power, while maintaining or improving the sensitivity (see Figure 1) and bandwidth. With laser light delivered to our OPM modules via optical fiber, we have implemented a light distribution system for our two-color pump/probe OPM. Finally, we will discuss efforts to develop custom control hardware and software, OPM array calibration approaches, an MSR with magnetic field control, and installation of the OPMs into the MSR.



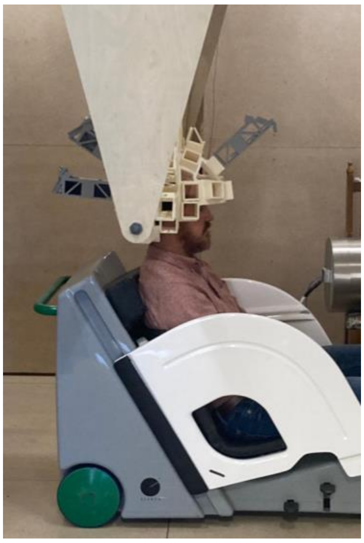


Figure 1: (Left) Magnetic sensitivity and gradiometric-inferred sensitivity of the four channels of the OPM module. (Right) Photo of a 3D-printed OPM array holder placed over a subject's head.

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A textile cap for simultaneous measurements of EEG and OPM-MEG

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Magnetoencephalography (MEG) using Optically Pumped Magnetometers (OPMs) is gaining popularity among researchers as whole-head OPM-MEG systems are becoming commercially available. Due to their modularity, OPMs can be directly attached to the scalp, allowing for ideal integration with other modalities and ensuring that OPMs perform equally well for each head size. To use these features to full capacity, we created a textile cap which combines EEG electrodes and OPMs.

Figure 1: Textile cap for simultaneous EEG and OPM-MEG measurements.

A commercial, 64-channel EEG cap (ANT waveguard original^{TM}) was modified by adding 3D-printed OPM mounts between the electrodes. The cap was designed for a clinical study, where healthy controls and schizophrenia patients undergo visual and auditory steady state paradigms. Ten OPMs (QuSpin QZFM Gen2) were mounted over the region of interest, which depended on the paradigm. We demonstrate that our textile cap is capable of measuring EEG and OPM-MEG with high signal quality by presenting exemplary results from our clinical study.

Optimizing pre-processing for magnetometer arrays applied in multivariate pattern analysis

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Multivariate pattern analysis (MVPA) has proven an important tool in cognitive neuroscience for identifying representational-specific neuronal patterns. The approach holds a strong promise when using optically-pumped magnetometer-based magnetoencephalography (OPM-MEG). This is because data from OPM-MEG systems offer a higher spatial resolution than conventional MEG systems.

Our study lays the groundwork for OPM-MEG based experiments designed for MVPA using data collected from a SQUID-based MEGIN system. We aimed to optimize the analysis pipeline for MVPA using magnetometers-only arrays, by considering noise-rejection algorithms as well as the number of magnetometers required. We used a paradigm in which pictures were presented and then classified according to their respective categories using MVPA based on a standard support vector machine.

Our findings[1] suggest that the standard MVPA pipeline[2], which includes signal-space separation (SSS) to reduce external noise, lowers classification accuracy for magnetometer arrays due to an increased broad-band noise introduced by the algorithm. Instead, alternative noise reduction approaches such as signal-space projection (SSP) or homogeneous field correction (HFC), are recommended for MVPA as they reduce the external interference while not increasing the noise floor. Our results also indicate that an array of ~30 equally distributed magnetometers is sufficient for a reliable MVPA classification as using more sensors only improves the accuracy marginally.

In the future, we aim to compare OPM-MEG to SQUID-based MEG to assess if the higher spatial resolution of the on-scalp OPM sensors improves classification based on MVPA.

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Conventional and on-scalp measurements of MEG signals from the human cerebellum during self-paced saccades

Santeri Ruuskanen[1], Joonas Iivanainen[1], Santtu Lauronen[1], Veikko Jousmäki[1], Mikael Grön[1], Lauri Parkkonen[1], and Matti Hämäläinen[1]

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The human cerebellum is involved in sensorimotor control and cognitive functions. Non-invasive electrophysiological measurements of the cerebellum have been considered demanding due to the depth of the sources and partial signal cancellation in the highly folded cerebellar cortex. Nevertheless, several MEG and EEG studies have observed signals possibly of cerebellar origin [2]. A recent modeling study showed that cerebellar signals are only 30–60% weaker than those from the neocortex [3]. The use of OPMs may result in better resolution and accuracy of source estimates [4]. We demonstrate MEG signals associated with visually-guided saccades using both OPMs and a conventional 306-channel SQUID system. We constrain the sources to the cerebral and cerebellar cortices using a realistic model reconstructed from individual MRIs [6]. Our preliminary source estimation results show focal activation in the cerebellum (Figure 1). We demonstrate the feasibility of detecting cerebellar activations with both OPM and SQUID MEG devices and illustrate the potential of source estimates employing realistic anatomical constraints.

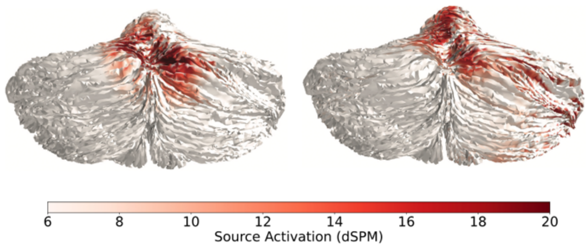

Figure 1: Source estimates (dSPM) showing focal activity at 130 ms following the onset of leftward saccades. **Left:** Source estimate from a 306-channel SQUID measurement. **Right:** Source estimate from an 8-channel OPM measurement.

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The advantage of triaxial OPM-MEG in imaging temporal-correlated sources: A simulation study

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Optically pumped magnetometers (OPMs) enable magnetoencephalography (MEG) with sensors that can be freely arranged and measure brain magnetic field in different directions at the same position on the scalp. This flexibility has sparked interest in its potential to improve MEG source imaging performance, though its full advantages under various scenarios remains largely unexplored. Here, we report a simulation study on how the quantity and type of OPM sensors affect source imaging performance for multiple sources with different levels of temporal correlation (also known as source leakage, which complicates source imaging). We placed 8 simulated sources at random locations on the cortical surface across 50 epochs. The metric used to evaluate source imaging accuracy was the ratio of the number of simulated sources (i.e., 8) to the number of active sources detected in each epoch. We found that the accuracy of an MEG system with triaxial OPMs is significantly higher than that with the same number of biaxial or uniaxial OPMs. Notably, with a high-density array consisting of 256 sensors, the advantage of a triaxial MEG system grows more pronounced compared with a biaxial system as the level of temporal correlation level increases (p-value$<$0.01, $<$0.05 and $>$0.05 for high, moderate and no correlation, respectively). In conclusion, we demonstrate that the high-density triaxial OPM-MEG system has higher information capacity, particularly for dealing with highly correlated sources, suggesting its potential for studying dynamic brain networks and decoding complex neuronal activities.

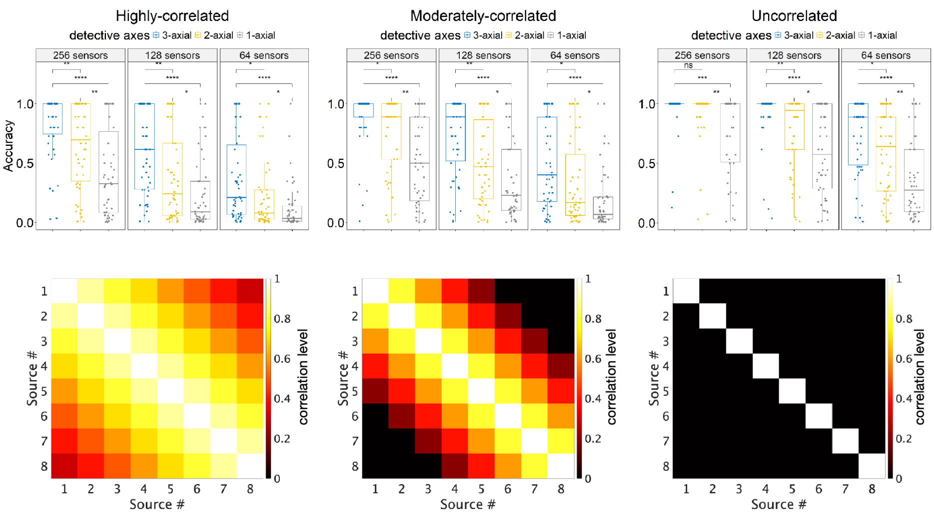

Figure 1: Simulation results of source imaging accuracy given different quantity (i.e., 64, 128 and 256) and types (i.e., triaxial - one radial & two tangential , biaxial - one radial & one tangential, and uniaxial - one radial) of OPMs for (left) highly-correlated, (middle) moderately-correlated and (right) uncorrelated sources. Correlation level stands for the cross coefficient between each sources.

Test-retest reliability of resting-state human brain microstates with OPM-MEG

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The aim of this study is to investigate the capability of OPM-MEG technology in detecting the human brain microstates and explore its test-retest reliability.

Closed-eye resting-state data were collected from 16 healthy participants during two sessions using an 80-channel full-head OPM-MEG system (QuanMag Healthcare Co., Beijing, China). *K*-means clustering of the OPM-MEG data revealed four microstate patterns (Fig.1A). To assess the consistency of the microstates across sessions, Pearson correlation coefficients (PCCs) were computed. Our results show a high spatial correlation exceeding 0.9 for all four microstates in two sessions (Fig.1B). The temporal reliability of the OPM-MEG microstates was evaluated by calculating Intraclass correlation coefficients (ICCs) of the microstate characteristics, most of which exceeded 0.6, indicating the reliability of the OPM-MEG recordings. Furthermore, we analyzed the effect of varying the number of OPM-MEG channels on microstate fitting. With three different channel counts of 55, 70, and 80, PCCs remained at a high level and increased with the number of channels (Fig.1C).

Our findings provide a foundation for future studies to delve deeper into the intricacies of OPM-MEG microstates, potentially revealing novel insights into the neural mechanisms underlying cognitive processes. Moreover, the scalability of OPM-MEG systems, evidenced by improved reliability with increasing channel counts, opens avenues for utilizing larger OPM arrays to elucidate the complex interplay of spatial and temporal dynamics in cognition.

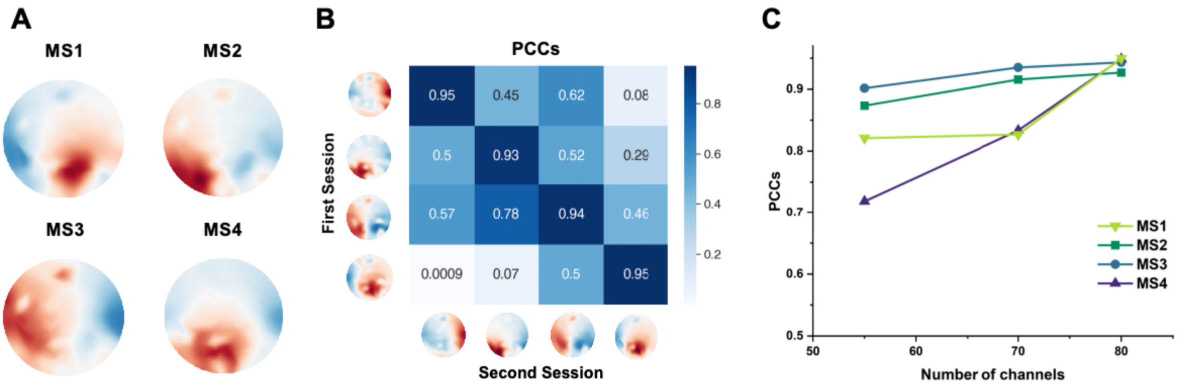

Figure 1. (A) Topographies of the four microstates. (B) Pearson correlation coefficients (PCCs) between microstates from two sessions. (C) The highest PCCs of each microstate, which was obtained from two sessions with different numbers of channels.

Signal-to-noise ratio of event-related responses: OPM vs. SQUID sensors

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Optically pumped magnetometers (OPMs) can be placed closer to the scalp than conventional superconducting quantum interference devices (SQUIDs). This enables substantially higher magnetoencephalography (MEG) signal amplitudes, due to the inverse-square dependence of the magnetic field on the distance to a current dipole source. We examined the signal-to-noise ratio (SNR) of event-related MEG data, assuming that the main contribution to the noise comes from spontaneous brain activity unrelated to the event. Simulated event-related responses were calculated for current dipoles at different depths, and their magnitudes were compared with the background noise level to obtain SNR values. The difference in the evoked response magnitude for superficial vs. deep sources is larger for OPM than for SQUID sensors. The signal from the dipole is higher for the OPMs at all source depths. However, depending on the background brain noise, the SNR depth-dependence curves for OPMs and SQUIDs may intersect, such that the SNR is larger for superficial sources but smaller for deep sources for OPMs than for SQUIDS. The relative magnitudes of event-related data and spontaneous background activity differ for on-scalp OPMs and cryogenic SQUIDs, potentially allowing SNR-based optimization of the detection of neural activity.

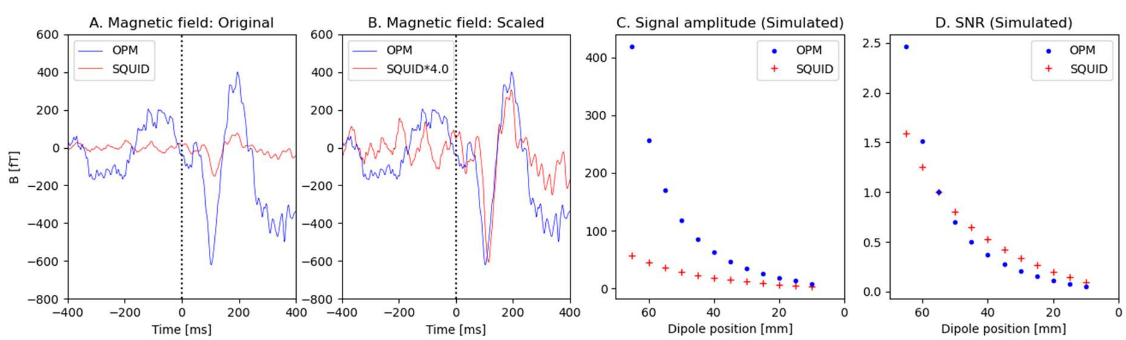

Figure 1: Comparison of the SNR in OPM vs. SQUID sensors. A: Averaged auditory evoked response in one OPM and one SQUID sensor. B: Same as A but with SQUID data scaled by a factor of four to match the N100m peak amplitude in the two sensors. After the scaling, the pre-stimulus baseline noise level is also comparable. C: Simulated peak signal for a current dipole at different depths; the dipole position is given as distance from a sphere model origin. D: Simulated SNR obtained by normalizing the peak values such that the amplitudes match for a dipole at 55 mm from the origin. In this example, the SNR would be higher in OPM than in SQUID for superficial, but lower for deep sources.

Optimizing the configurations of OPM-MCG for myocardial ischemia detection

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The aim of this study is to quantify the effects of the interval between adjacent sensors (*h*) and the signal-to-noise ratio (*SNR*) of magnetocardiography (MCG) on the detection of myocardial ischemia, and yield optimization results to fulfill the potential of this technology.

Multichannel MCG signals, both normal and ischemic, were generated by a 3D heart-torso model (Fig.1A, upper panel), and magnetic field mapping (MFM) were interpolated across various *h* and *SNR* settings. Youden Index was introduced to gauge diagnostic performance, calculated as a function of *h* and *SNR* according to predefined diagnostic standards [1]. The optimal *h* and *SNR* were identified by analyzing the Youden Index contours (Fig.1A, lower panel), and a linear regression was fitted that ensured a high Youden Index even at lower *SNR* and larger *h*, aligning with clinical needs.

Our optimization results were further validated by experiments utilizing 32 OPM sensors housed in a magnetically shielded room (Fig.1B). Data were collected by 3 different arrays (Fig.1C). These experiments offer significant insights for the development of MCG systems tailored for myocardial ischemia detection.

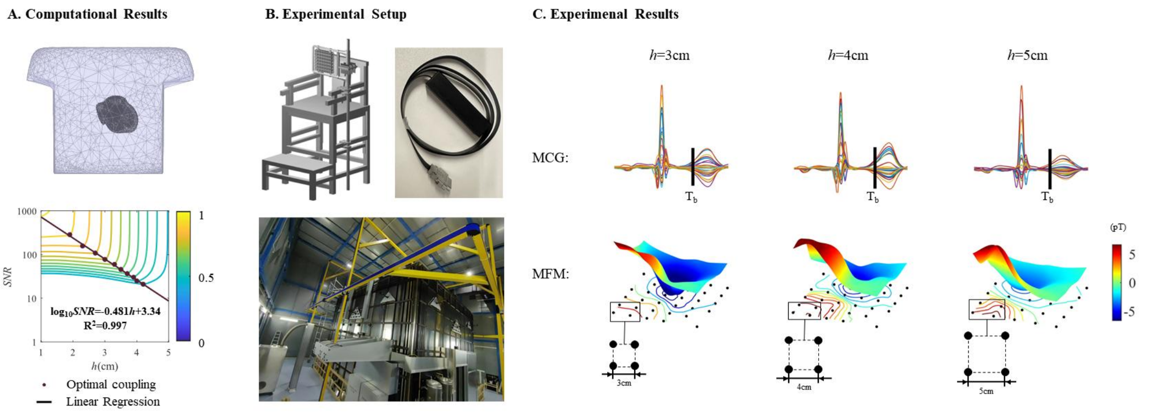

Figure 1: (A) Upper plot: 3D Heart-torso model; lower plot: optimization results. (B) Upper left plot: illustration of the toolings used for data collections; upper right plot: photograph of an OPM sensor; lower plot: photograph of the magnetically shielded room. (C) Upper plots: time course of multichannel MCG signals; lower plots: corresponding MFM at the beginning of T-wave (T_b) and arrays for data collections.

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Miniaturising Magnetic Field Compensation Systems for Quantum Devices

A. Davis[1], P.J. Hobson[1], J. Zipfel[2], P. Bevington[2], B. Searle[3], F. C. Casado[3], L. Rushton[2], L. Ellis[2], T. Wotherspoon[3], W. Chalupczak[2], T. M. Fromhold[1]

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Many quantum devices require uniform bias fields to manipulate atomic samples during measurement. In radio-frequency atomic magnetometers – used for non-invasive magnetic induction tomography, cardiac and neurological assessment, and beyond – they are required to determine a frequency dependent resonance, and the magnetic fields must be uniform to avoid line-width broadening. However, as the sensor miniaturises, alignment and manufacturing difficulties become more pressing.

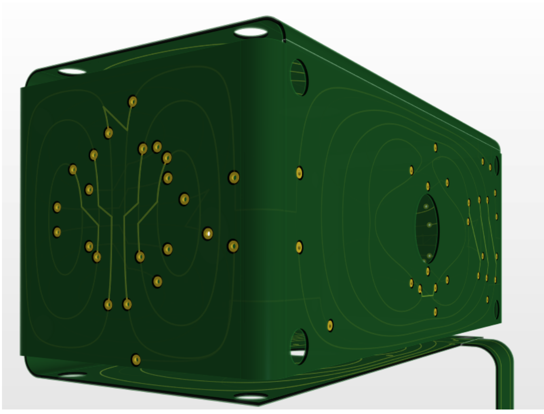

Figure 1: Coil render produced in `Altium:PCB Design Software & Tools` generating two uniform transverse fields for a compensation system for a radio frequency magnetometer.

We present a novel approach to miniaturise a magnetic biasing system that can be precisely aligned in reference to the vapor cell. We design for planar geometries, generating two (B_x and B_y) uniform transverse fields housed on a rigid backed, flexible printed circuit board (PCB) of dimensions $21 \times 21 \times 47\mathrm{mm}^3$. The system is comprised of two independent layers for each coil with current-carrying elements on all six faces of the system. There are four terminals (two for each transverse field direction) to independently control the biases (shown in the bottom right corner of figure 1). The simulated efficiencies of both coils is calculated to be $B_x/I = 285\ \mu\mathrm{T/A}$ and $B_y/I = 241\ \mu\mathrm{T/A}$ with maximum deviations from uniformity of $\max(\Delta B) = 0.2\%$ within the central $5 \times 5 \times 5\ \mathrm{mm}^3$ volume. The coils will be tested over the coming months through experimental field profile measurements and by examining the linewidth broadening when implemented into the physics package.

Transportable magnetic control environment for imaging infants using Optically Pumped Magnetometers (OPMs)

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(Dated: May 31, 2024)

Background: Zero-field OPMs require low ambient magnetic field to achieve optimal gain and sensitivity to detect weak signals from the body. Magnetically Shielded Rooms (MSRs) typically create these environments. However, such rooms are expensive, hard to site, and impractical for scenarios where the shield must be transported, such as within hospital wards or patients' homes. Here, we develop a transportable cylindrical magnetic shield with an open end designed for imaging infants aged $0 - 1$ year.

Methods: A high level of magnetic shielding is attained through the combined use of passive shielding (mu-metal and copper) and coupled coil systems positioned on the internal shield surface. These coils generate target fields that counteract flux leakage through the open hole. This field is further controlled through the application of a 'matrix' of simple loops which dynamically regulate the field.

Results: The outcome is a substantial shielded volume measuring $15 \times 15 \times 15$ cm^3, designed to accommodate an infant's head. The shield weighs < 80 kg, facilitating its transportation within a clinical setting. It is engineered to be connected to a standard electrical outlet. We anticipate a two-order-of-magnitude enhancement in shielding efficiency when utilising the coils and shield in conjunction compared to the passive shield alone, up to a frequency of 10 Hz. Currently, the system is being fabricated, with preparations for assessment utilising QuSpin zero-field OPMS.

Discussion: This advancement will give neuroscience laboratories a fundamentally new instrument for exploring the neurodevelopmental trajectory during the crucial initial days of life.

Magnetomyography Targeted Performance Characterization of Commercial OPMs

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Optically pumped magnetometers (OPMs) enable highly sensitive measurements of biomagnetic fields with a small sensing volume, thus allowing for mm-scale spatial resolution. Combined with the possibility of adapting the placement of sensors to specific anatomical shapes, this has led to a renewed interest in magnetomyography (MMG). Although commercially available OPMs are so far manufactured for magnetoencephalography (MEG) they are being employed for MMG as well [1]. This is coupled with certain limitations, as the MMG signals either cannot be fully resolved in time, or the sensors must be used beyond their specified bandwidth. Here, we investigate these limitations in a mobile testbed where arbitrarily oriented magnetic field patterns can be applied to OPMs in a shielded environment. Test signals such as chirps and artificial MMG signals based on Rosenfalck model functions [2] are applied at several discrete orientations to analyze the frequency-dependent vector performance of commercial zero-field OPMs. We describe and quantify artifacts such as ringing, cross-axis leakage (e.g., tilting of the effective measurement axis), and signal distortion. Furthermore, post-processing techniques are presented that partially correct for observed sensor deficiencies at higher frequencies. Although our sensor characterization mainly focuses on applications in MMG, the results are to a certain extent also valid in cases where high-frequency perturbations are present among low-frequency signals of interest, as in MEG.

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Mobile total field optically pumped magnetometers for navigation

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Global navigation satellite systems (GNSS) are at the forefront of navigation and are ubiquitous in everyday life. However, GNSS has limitations for use cases where satellite reception is limited (such as underground navigation). Dependence on the upkeep of existing satellite infrastructure, as well as the prevalence of jamming and spoofing devices limit the reliability of GNSS for the localisation of critical hardware. One alternative solution that does not suffer from these drawbacks is magnetic field navigation [1]. This technique uses maps of local magnetic field anomalies and map-matching algorithms to determine position.

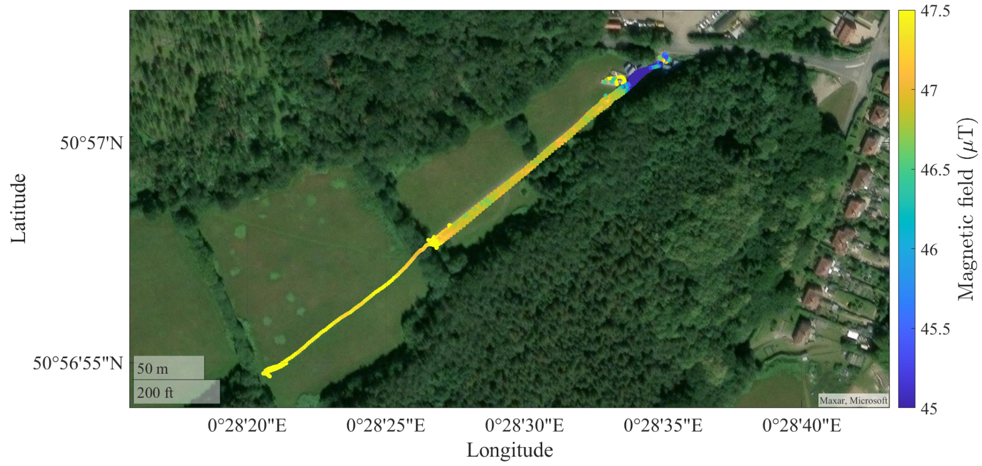

Figure 1: GNSS localised magnetic field data obtained using the mobile OPM system.

We present a modular total field optically pumped magnetometer (OPM) system [2] capable of operating within Earth's magnetic field. Battery operated control electronics allow for the OPM setup to be mounted on vehicles for the mapping of local magnetic fields. The pairing of this system with a conventional GNSS system enables the evaluation of map-matching algorithms.

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Magnetic field measurement over 100 kHz using ^{4}He-OPM towards ultra-low-field MRI

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Ultra-low field MRI (ULF-MRI) with a static magnetic field of approximately 10 mT or less has the advantages of low cost and miniaturization. On the other hand, the MR signals in ULF-MRI are small and the bandwidths are narrow, so that its measurement requires a receiving sensor with high sensitivity in the frequency range over 100 kHz. Therefore, an optically pumped magnetometer (OPM) is considered suitable as a receiving sensor for ULF-MRI [1]. Previous studies reported that the OPM using alkali metal atoms such as K and Rb detected MR signals on the order of 100 kHz [1, 2]. However, no reports demonstrated the detection of 100 kHz MR signals by OPM using ^{4}He (^{4}He-OPM). In this study, a 100 kHz sinusoidal signal was measured using ^{4}He-OPM, and the noise floor at around 100 kHz was approximately 90 fT/Hz$^{1/2}$. Since the required sensitivity of the sensor for ULF-MRI is a few fT/Hz$^{1/2}$, further improvement of the sensitivity of ^{4}He-OPM is necessary.

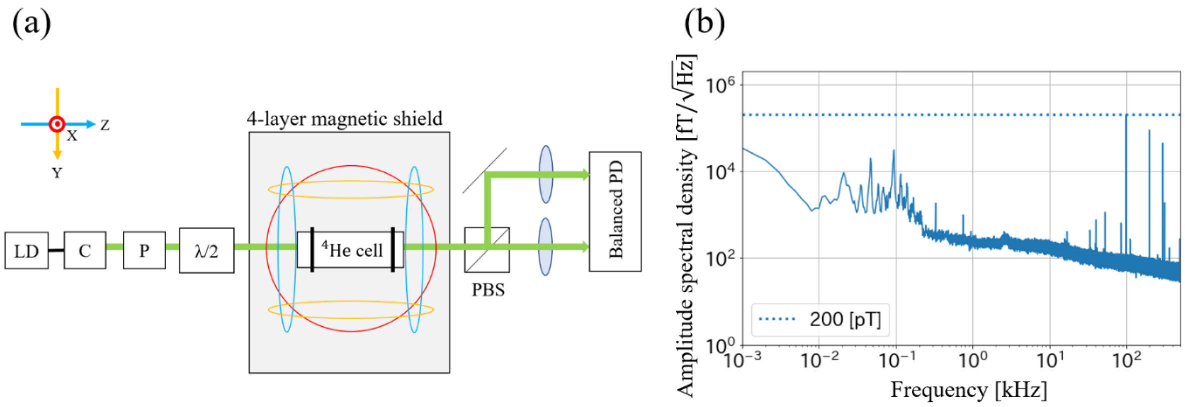

Figure 1: (a) Schematic diagram of ^{4}He-OPM experimental setup. LD: laser diode; C: collimator; P: polarizer; $\lambda/2$: half-wave plate; PBS: polarization beam splitter; PD: photo diode. (b) Amplitude spectral density for 200 pT$_{rms}$ sinusoidal signals applied at 100, 200, and 300 kHz.

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Tabletop magnetic field scanning system based on OPAM and 3D current density reconstruction from scanned magnetic fields

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Magnetic field imaging of Li-ion battery's exterior space could reveal information about internal current distribution of the battery, which could solve one of the major concerns for quality control of Li-ion based secondary battery manufacturers. Magnetic image scanning has usually been performed with highly sensitive magnetometers like magnetoresistive (xMR) sensors and fluxgate magnetometers. These sensors have magnetic field sensitivity in the order 1 to 10 $pT/sqrt(Hz)$. Here, we present magnetic field imaging study of Li-ion polymer battery with OPAM (QuSpin QZFM Gen. 3 triaxial), with magnetic field sensitivity of less than 23 $fT/sqrt(Hz)$, based on tabletop scanning system with magnetic shields. Three-dimensional current density reconstruction from scanned magnetic field images with inverse problem solution method based on Tikhonov Regularization will be presented along with discussions and suggestions to improve magnetic field imaging with OPAMs.

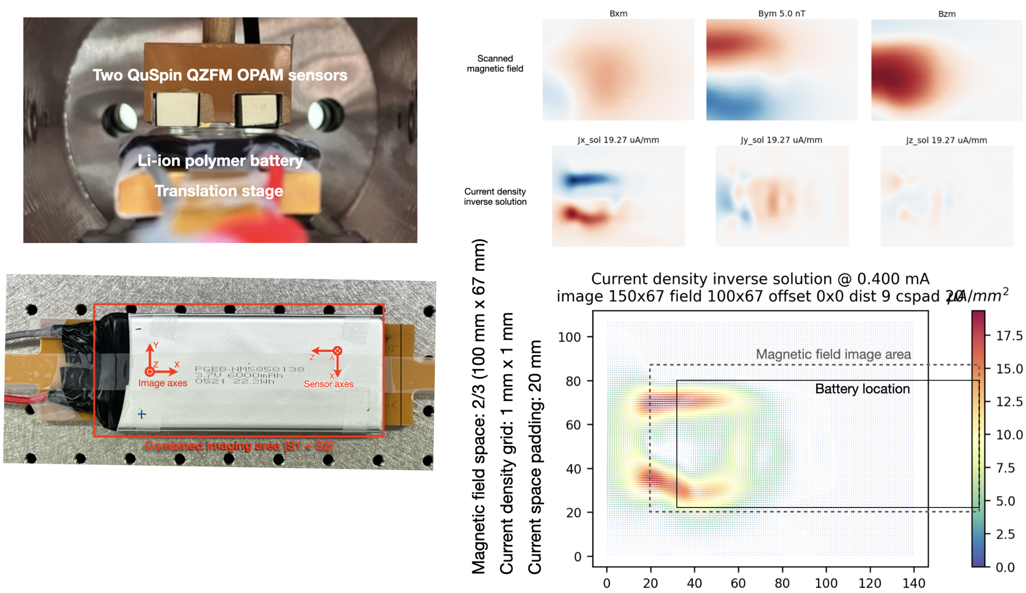

Figure 1: Tabletop magnetic field imaging of a 6000 mAh Li-ion polymer battery with QuSpin QZFM(Gen. 3 triaxial) sensor. Upper left image shows the imaging stage with the battery and two QZFM sensors inside a magnetic shielding can (Twinleaf MS-2). Lower left image shows battery along with directions of sensor axes and image axes. Upper right images show magnetic fields from electric current only (via zero-current background subtraction) and 3D current density inverse solution from Tikhonov Regularization. Lower right image shows vector field presentation from two transverse axes of current density inverse solution.

Chip-scale magnetic resonance imaging via atomic magnetometers

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Magnetic Resonance Imaging (MRI) is currently an indispensable technique for health diagnostics and therapeutics in vivo, with ongoing translation to microfluidic devices used in bioengineering research, such as tissue-on-a-chip.

While in principle high-field MRI is an ideal tool for studying fluidic “chips”, in practice meaningful images can be hard to achieve. This is because of: (i) the very small volumes of liquid involved, and (ii) magnetic field distortion due to susceptibility gradients at materials boundaries, e.g., glass, metal, plastic.

In this work, we demonstrate successes of low-field (near-earth’s-field) MRI detection with an optically pumped ^{87}Rb magnetometer (OPM). The OPM detects signals in the kHz frequency band [1] and is sensitive enough for ^{1}H imaging with sub-mm spatial resolution of model fluidic structures – see Figure 1. We show examples of in situ 1D and 2D imaging, each with T_1 and T_2 relaxation-weighted contrast. We also discuss extensions to samples containing hyperpolarized nuclear spins, plus magnetometry protocols that give increased efficiency.

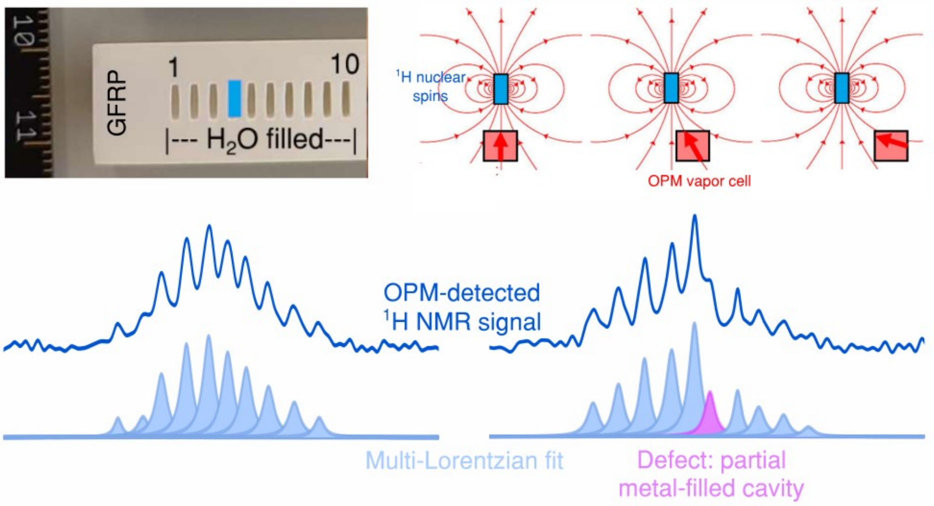

Figure 1: 1D ^{1}H-density imaging at 10 μT of a 3d-printed fiberglass structure containing water (H_2O) in a series of ten cavities (width 1 mm, spacing 1 mm, ~25 μL volume per cavity). The liquid is prepolarized in situ at ~0.03 T.

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A Miniaturized Tri-axial Vector Atomic Magnetometer using Optical Fiber

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In miniaturized atomic magnetometers, laser-based approaches [1] via polarization-maintaining fiber offer cost reduction compared to methods using integrated Vertical-Cavity Surface-Emitting Lasers (VCSELs) for multi-channel biomagnetic imaging. However, incorporating polarization-maintaining fiber increases probe complexity. Achieving three-axis vector detection with a single laser requires additional optical components for beam splitting, posing new challenges in magnetometer miniaturization .

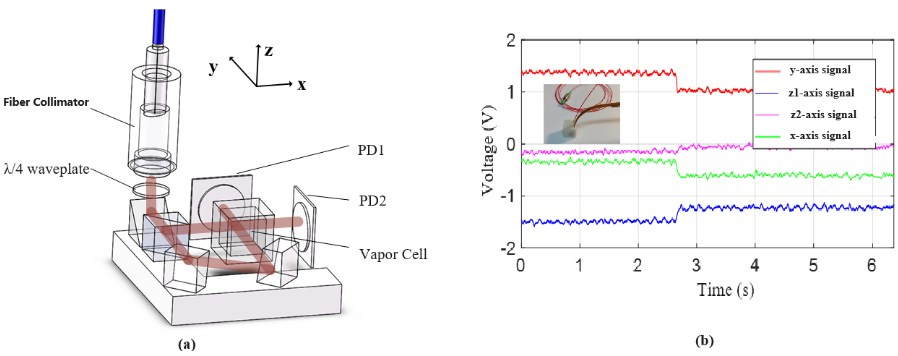

Figure 1: (a) Optical layout of the tri-axial vector SERF magnetometer employing a two-beam configuration; (b) Response of the fiber-based SERF magnetomter (inlet) to a tri-axial magnetic field.

We have introduced a novel design for a triaxial vector atomic magnetometer based on an optical fiber, utilizing triaxial magnetic field separation modulation and a spatially separated double beam configuration for sensitive magnetic detection. To achieve miniaturization, we employed quartz tubes to assemble specialized fiber collimators. Additionally, our unique prism design enables spatial division and separation of the laser beam. Furthermore, we developed a silicon-based heating sheet using Micro Electro-Mechanical System (MEMS) technology, integrating platinum thermal resistors. The resulting magnetometer sensor head measures 16.7 mm×17.8 mm×20 mm.

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