Miniature Absolute Scalar Magnetometer Based on the Rubidium Isotope ^{87}Rb

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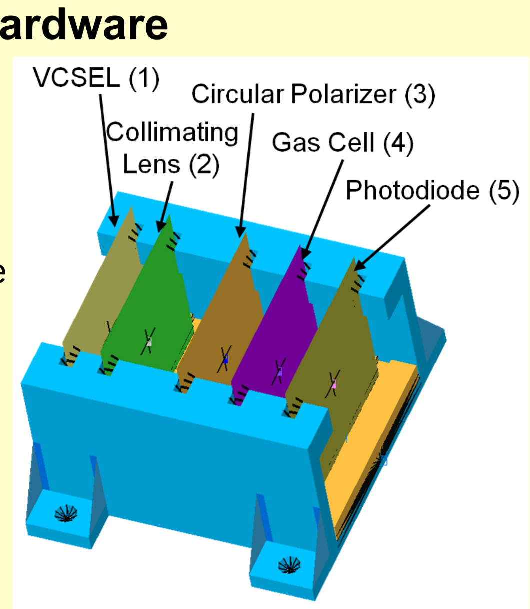
Summary

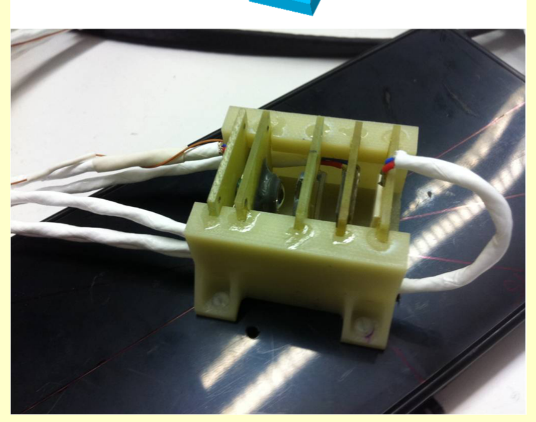
- We have developed a low-resource, miniaturized, absolute scalar magnetometer based on the rubidium isotope ^{87}Rb, which takes advantage of recent breakthroughs in micro-fabricated atomic devices.
- Demonstrated reductions of power requirements and mass by 1-2 orders of magnitude over conventional instruments.
- The resulting instrument has a **total mass of less than 500 g** and uses **0.5 W of power**, while maintaining **sensitivity**, **15 pT/√Hz at 1 Hz**, comparable to present state-of-the-art absolute magnetometers.

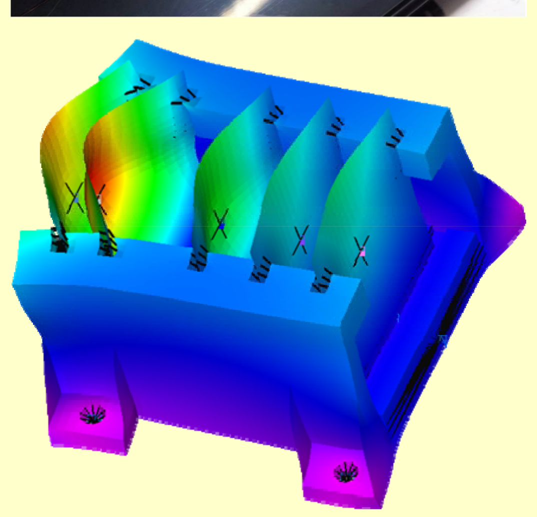
Operating Principle of Atomic Magnetometers

- Most atomic optically-pumped magnetometers are based on the **Larmor precession** of electron or nuclear spins in a magnetic field [1].
- A cell containing a suitable gas is illuminated with light with a wavelength that correspond to resonance with an optical (electronic) transition in the atoms. Under these conditions, atoms are optically pumped into a non-thermal population distribution and the gas cell becomes largely transparent to the optical beam.
- If the cell is then subjected to a radio frequency (rf) signal at the Larmor precession frequency, an oscillating population distribution is excited within the atoms, which causes a **time-dependent modulation of the optical absorption**.
- By detecting the **phase shift in the resonance** of the atomic response, the Larmor frequency can be determined and from that the magnetic field can be deduced.
- The most commonly used elements for optically pumped magnetometers are metastable helium and alkali metals like cesium, rubidium, potassium, and sodium.

Sensor Hardware

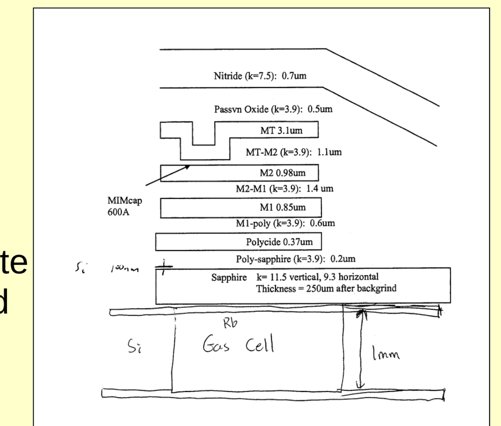


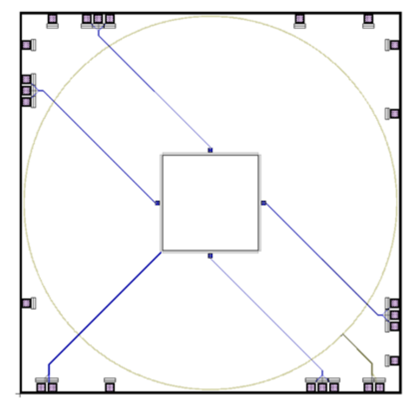


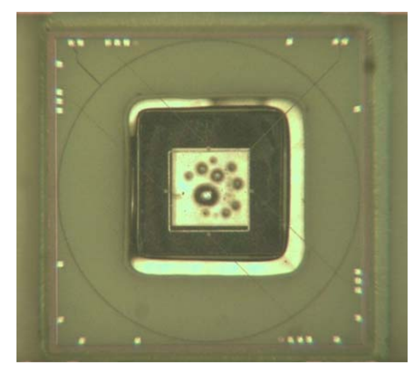


- Our device employs a low-power semiconductor laser and a miniature **rubidium vapor cell** of millimeter dimensions produced using modern **micro-fabrication processes** [2]. In recent years, MEMS vapor cells have been employed in chip-scale sensitive magnetometers [3].
- The combination of MEMS vapor cell and a semiconductor diode laser has allowed a **substantial reduction in mass, size, and power dissipation** of atomic magnetometers with only modest decrease in performance.
- **Sensor configuration:** The micro-fabricated rubidium vapor cell (4) is illuminated by light emitted from a vertical-cavity surface-emitting laser (VCSEL) (1). The laser light passes through an optics package, where the laser light is collimated (2) and circularly polarized (3). The resonant response of the atoms is detected using a discrete photodiode (5). The assembled prototype sensor, shown in Figure 1 (middle panel), measures 35 × 25 × 25 mm^3 and has a mass of 44 g; future reductions in size and mass are anticipated.
- **Vibration analysis:** Structural analysis yields 1st-mode frequency >3500 Hz and withstands static loading up to 150 G.
- **Environmental testing:** Sensor operation has been validated over temperature range –70 °C to +70 °C (**TRL 6**).

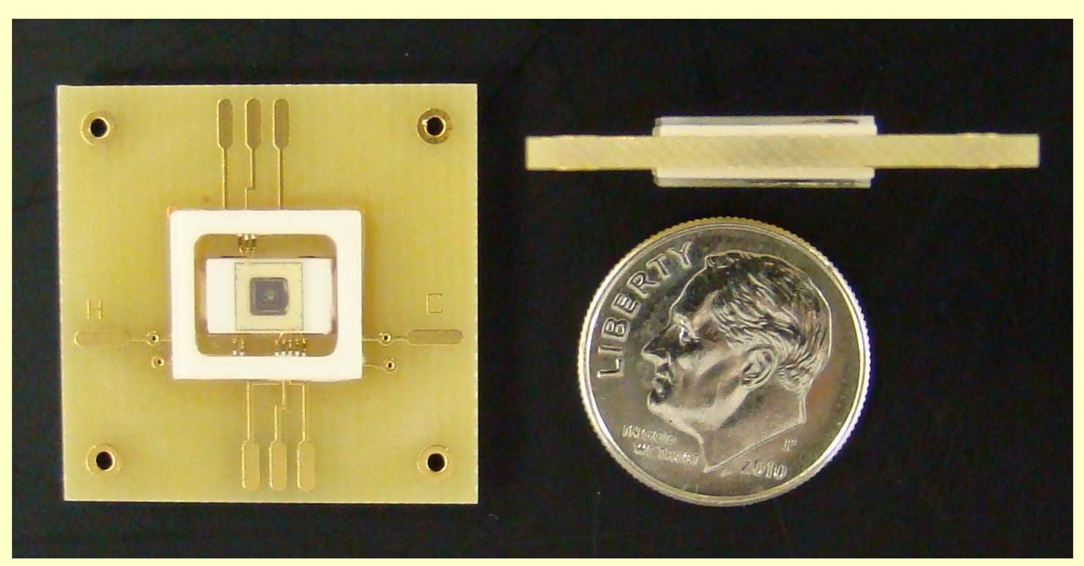
Multifunction ASIC







- Additional key aspect in the miniaturization of the device: monolithic integration of the vapor cell with heaters and Helmholtz coils using **silicon-on-sapphire (SOS-CMOS) technology**. Glued to the two faces of the vapor cell perpendicular to the optical axis.
- The SOS-CMOS technology: sapphire substrate is **intrinsically transparent** to the light emitted at the wavelength of the laser.
- **Function 1:**The SOS-CMOS chips heat the vapor cell to its operating temperature of about 100 °C using 0.5 W of power generated by a 10 mA current from a 50 V power supply.
- Extreme care in the implementation of the heater: Flow of current generates a contamination magnetic field in close vicinity of the detection volume.
- To minimize interference with the measurement of the ambient field, the integrated conductor widths and spacing are on micrometer scales, and near-perfect magnetic compensation was achieved using two sets of dual square loops arranged in neighboring conducting layers of the chip.
- The contamination due to the heater was measured to be less than 10 nT; the finite residual field is largely due to limitations in the accuracy of the alignment of the two SOS-CMOS dies.
- **Function 2:** Generate the rf magnetic field necessary to establish the atomic resonance via two single-turn circular coils in Helmholtz arrangement.
- **Function 3:** SOS-CMOS die includes circuits for temperature measurements and signal conditioning. (The system reported in this paper does not use the latter electronic circuits to stay compatible with external instrumentation.)



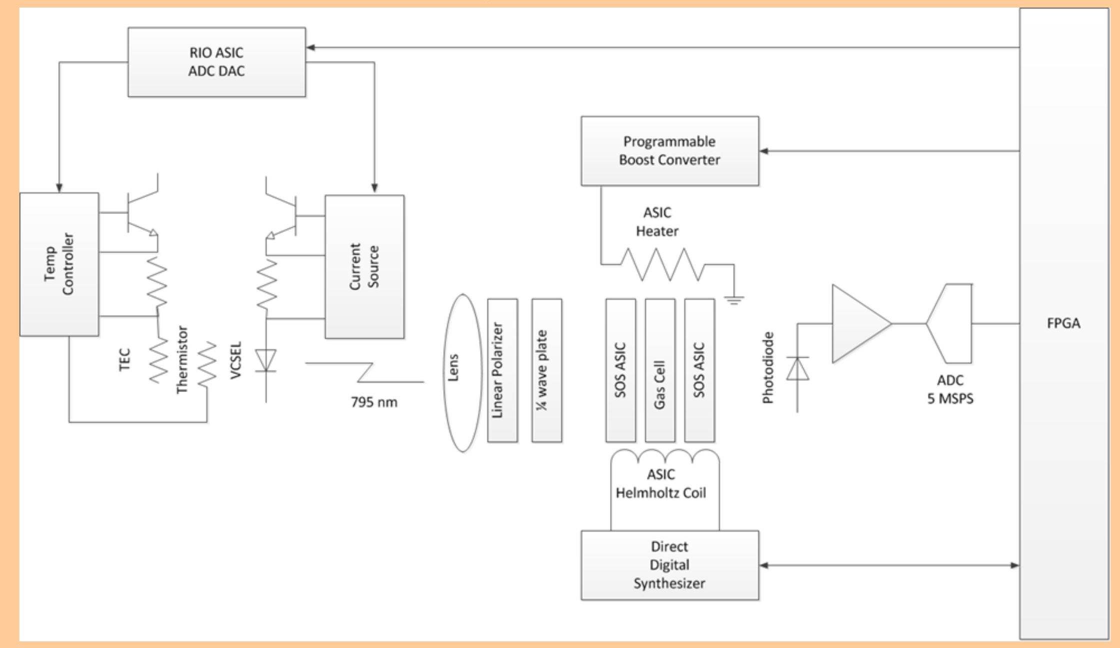
The assembled vapor cell including transparent SOS-CMOS dies.

Radiation Testing

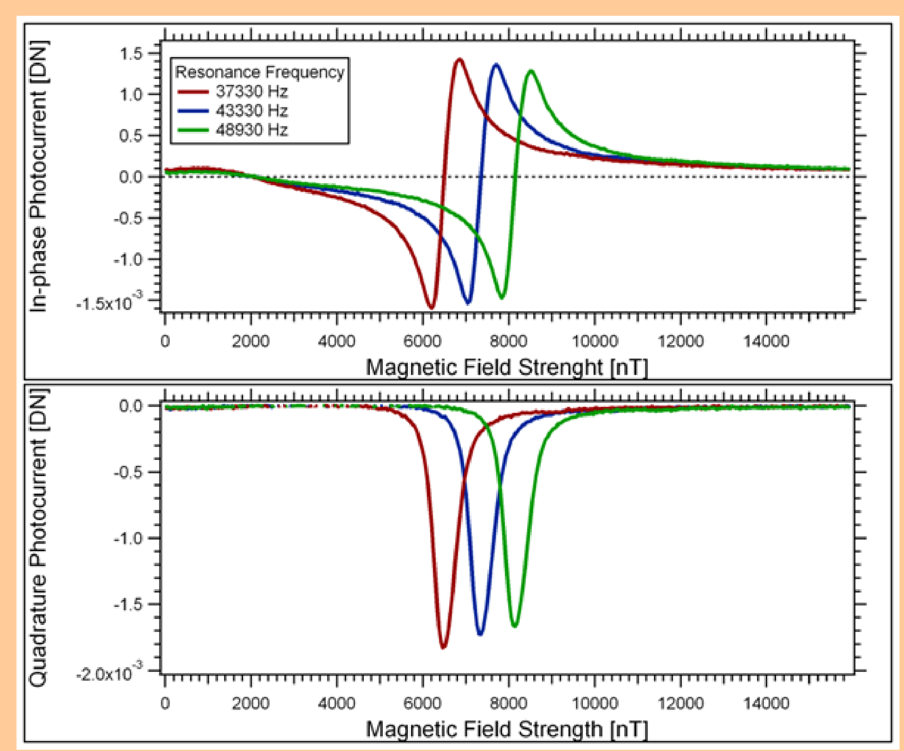
- Active and passive sensor optical components have been exposed to **high-energy proton** and **γ-radiation** with a maximum total dose of 50 krad(Si) each.
- **Findings:** (1) Variations in transparency of the components <3%; (2) Decrease of VCSEL output power by 2%;
  (3) Decrease in photodiode sensitivity by 14%; and
  (4) increased photodiode dark current after exposure still two orders of magnitude lower than the photocurrent modulation induced by the Larmor precession.
- The technology is thus **suitable for operation** even in high-radiation **space environments** using appropriate shielding.

Signal Processing

- The sensor is controlled digitally by a field-programmable gate array (FPGA): (1) generate the signal to excite the rubidium atoms within the vapor cell; (2) measure and process the resonant response; (3) track Larmor frequency; and (4) provides an interface to a host laptop computer.
- The control electronics block diagram illustrates the sensor operation.



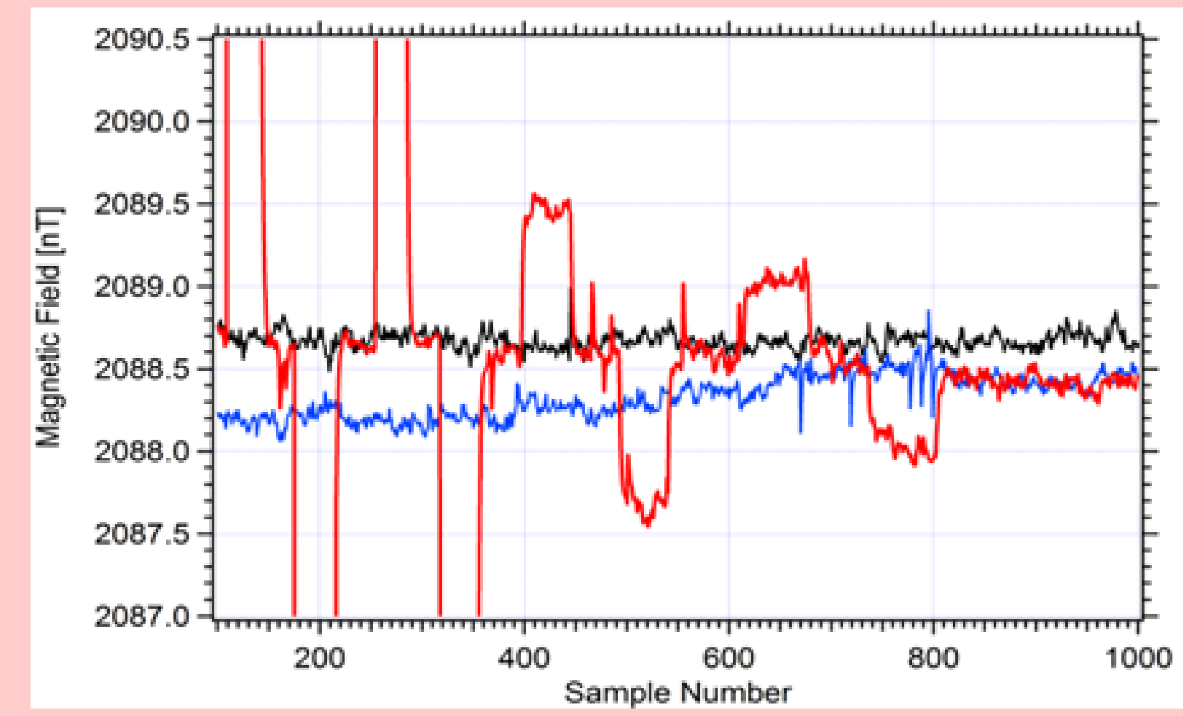
- Light from the VCSEL is collimated by a lens, circularly polarized, passed through the vapor cell, and finally detected with a silicon photodiode. A transimpedance amplifier converts the photocurrent to a voltage, which is digitized to 12 bits at 5 Msps and read by the FPGA. This digitized photocurrent signal contains all the sensor information.
- **Function 1:** The FPGA controls the **vapor cell temperature** by adjusting a pulse-width modulated (PWM) signal provided to the heater boost converter. The vapor cell temperature is typically regulated to approximately 110 °C.
- **Function 2:** The FPGA controls both **VCSEL drive current source and temperature** to tune the VCSEL to the D1 line of ^{87}Rb at 795 nm. At fixed current, the temperature is swept slowly to modify the wavelength until the digitized light level reaches a minimum at the center of the 795-nm absorption line.
- **Function 3:** The FPGA controls a direct digital synthesis (DDS) circuit with 32-bit frequency resolution to **excite the Helmholtz coils** hosted on the SOS -CMOS ASICs. As described earlier, the digitized photodiode signal is modulated at the Helmholtz drive frequency, and exhibits a maximum amplitude and 90° phase shift when the Helmholtz coil drive frequency is equal to the Larmor frequency. This modulated signal is detected with a digital lock-in amplifier implemented in the FPGA.



- **Function 4:** The FPGA **tracks the Larmor frequency** to allow for continuous magnetic field measurement. Both the in-phase and quadrature signals are used to digitally servo the DDS to null the in-phase signal at the Larmor frequency. The Larmor frequency is then determined by the commanded 32-bit DDS command word.
- The tracking loop is set to output 10 samples per second. This permits 100 msec of integration time per sample.
- The prototype signal processing electronics is implemented on a 15 × 10 cm^2 printed circuit board and has a mass of 440 g, but the layout is not yet optimized to minimize resources.

Test Data

- The resonance frequency is tracked by a control loop implemented in the instrument's FPGA and the magnetic field magnitude sampled at a cadence of **10 samples per second**.
- The sensor response to different step-like changes in the magnetic field magnitude between 0.5 nT to 2 nT:



- The sensor has a **sensitivity is 15 pT/√Hz at 1 Hz** or about **0.1 nT rms**.
- Solenoid power supply is stable to 0.03%, or 0.3 nT, for a current of 1 mA, so substantial fraction of observed **variability likely originates external to the instrument**.
- **The prototype instrument demonstrates that absolute magnetometers can be miniaturized to serve future planetary missions even under severe resource constraints.**

References

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