Chip-Scale Absolute Scalar Magnetometer for Space Applications

H. Korth, K. Strohbehn*, F. Tejada†, A. Andreou†, S. McVeigh†, J. Kitching‡, and S. Knappe‡*

**JHU Applied Physics Laboratory, Laurel, MD; †JHU Department of Electrical and Computer Engineering, Baltimore, MD; and ‡National Institute of Standards and Technology (NIST), Boulder, CO*

Precise and absolute measurement of magnetic fields is central for future planetary, solar, and interplanetary missions. Atomic magnetometers have a history in space dating back more than 40 years, and they have flown in space vehicles ranging from high-altitude balloons to high-profile interplanetary missions. Present instruments of this type require significant resources, and their size, mass, and power impose significant constraints on their use in space. Recent breakthroughs in microfabricated atomic devices have demonstrated reductions of resources by one to two orders of magnitude over conventional instruments by incorporating micromachined elements into the devices and by using lasers rather than lamps as the excitation source. In a joint research project, APL, the JHU Department of Electrical and Computer Engineering, and the Atomic Devices and Instruments Group at NIST are developing this technology for use in space and expect to gain corresponding advantages over existing space-based instruments.

The fundamental technology is a miniature rubidium (Rb) vapor cell of chip-scale dimensions fabricated by using microelectromechanical systems (MEMS) techniques developed by NIST. These vapor cells have been used as frequency references in clocks,[1,2] but using suitable atomic transitions, they also function as magnetometers.[3–5] The Rb vapor cell is enclosed by a ceramic heater (Fig. 1) and finally fabricated into a magnetic field sensor (Fig. 2), all optical components of which have been evaluated for radiation tolerance to at least 50 krad(Si) of both proton and gamma radiation. In the assembled sensor, the microfabricated Rb vapor cell is illuminated with circular-polarized light from a vertical-cavity surface-emitting laser (VCSEL), and the resonant response of the atoms is detected by a photodiode. Ultimately, the size of the sensor may be significantly reduced, and a sensor package that measures <5 mm in height and occupies a volume of about 20 mm^3 has previously been demonstrated by using commercial, non-space components.[5] Dedicated control electronics to operate the sensor in closed-loop control have also been designed and fabricated by using radiation-hard components.

To measure the magnetic field, the laser must first be tuned to the magnetically sensitive D_1 atomic transition. That is, the wavelength must be adjusted until the emitted photons have just the right amount of energy to be absorbed and change the energy state of the atom. The absorption of the photon is evidenced in a reduction of light intensity sensed by the photodiode, thus minimizing the photocurrent. The VCSEL wavelength is sensitive to both the laser temperature and the laser cur-

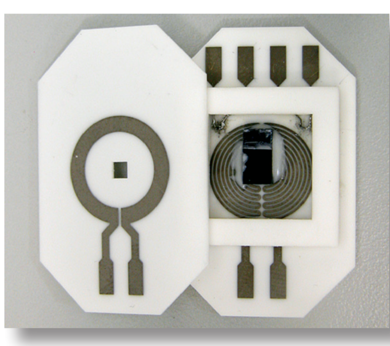

Figure 1. Rb vapor cell package.

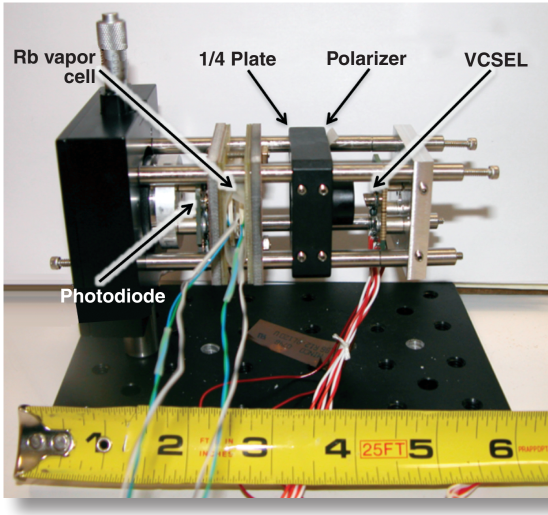

Figure 2. Magnetometer sensor optical assembly.

rent, and either quantity can be used for tuning. Figure 3 shows the variation of the photocurrent as function of the difference in the wavelength due to changes in temperature. The D_1 line width of ~0.05 nm full width at half maximum (FWHM) is consistent with the line width of 18 GHz cited by Schwindt et al.[5]

With the VCSEL wavelength tuned to the D_1 atomic transition, the Larmor frequency identifying the magnetic field strength is detected by searching for the resonance between the atomic spin precession and the RF magnetic field applied via the Helmholtz coils. When the RF magnetic field oscillates at the Larmor frequency, both an amplitude change in the photocurrent and a difference in phase shift of 90° between the applied RF magnetic field and the resonant response are observed, and these features will be identified and tracked by a control loop implemented in the instrument's field-programmable gate array. Figure 4 shows the photocurrent amplitude (upper) and phase shift (lower) as function of the applied Helmholtz coil frequency, where the three colors represent different ambient magnetic field strengths ranging from 8880 nT to 9680 nT applied via the solenoid. The Larmor frequency is found at the inflection point (sign change in second derivative) of the phase shift curve, which is found at approximately 46.5, 52.0, and 57.5 kHz for the blue, green, and red curves, respectively. The difference between these frequencies of ~5.5 kHz, corresponding to 786 nT (gyromagnetic ratio is 7 nT/Hz), agrees with the 800 nT steps in the applied solenoid field to better than 5%. For an applied solenoid field of 8080 nT, the sensor measures a Larmor frequency of 52.0 kHz, which corresponds to an absolute magnetic field strength of ~7400 nT. The 600 nT DC offset is likely caused by the residual magnetic field generated by the heater.

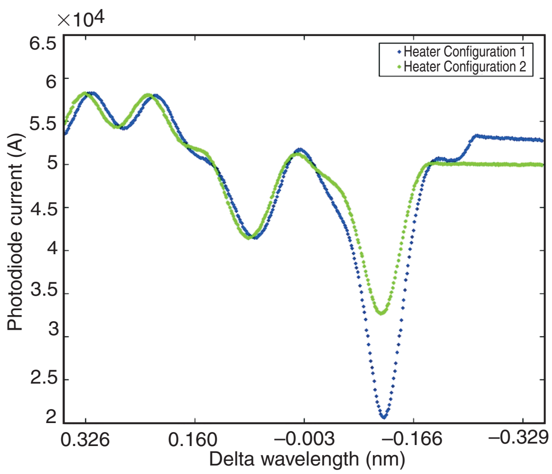

Figure 3. Rb atomic line detection using laser temperature to control the VCSEL wavelength.

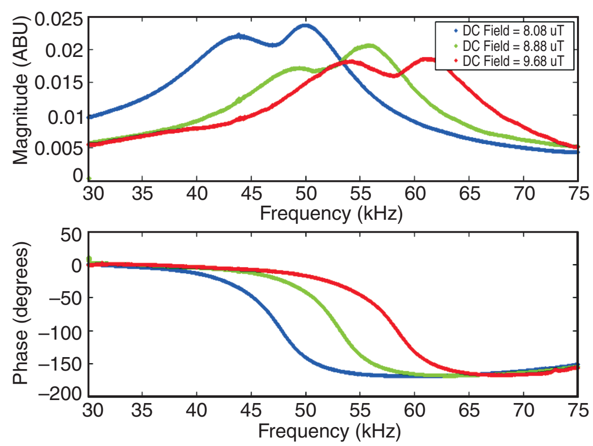

Figure 4. Demonstration of magnetic sensitivity by sweeping the drive frequency of the Helmholtz coil RF magnetic field for three different ambient magnetic field strengths..

For further information on the work reported here, see the references below or contact haje.korth@jhuapl.edu.

[1]Kitching, J., Knappe, S., and Hollberg, L., "Miniature Vapor-Cell Atomic-Frequency References," *Appl. Phys. Lett.* 81, 553–555 (2002).

[2]Knappe, S., Shah, V., Schwindt, P. D. D., Hollberg, L., Kitching, J., Liew, L. A., and Moreland, J., "A Microfabricated Atomic Clock," *Appl. Phys. Lett.* 85, 1460–1462 (2004).

[3]Schwindt, P. D. D., Hollberg, L., and Kitching, J., "Self-Oscillating Rubidium Magnetometer Using Nonlinear Magneto-Optical Rotation," *Rev. Sci. Instrum.* 76, 126103, doi: 10.1063/1.2136885 (2005).

[4]Schwindt, P. D. D., Knappe, S., Shah, V., Hollberg, L., Kitching, J., Liew, L. A., and Moreland, J., "Chip-Scale Atomic Magnetometer," *Appl. Phys. Lett.* 85, 6409–6411 (2004).

[5]Schwindt, P. D. D., Lindseth, B., Knappe, S., Shah, V., Kitching, J., and Liew, L. A., "Chip-Scale Atomic Magnetometer with Improved Sensitivity by Use of the Mx Technique," *Appl. Phys. Lett.* 90, 081102, doi: 10.1063/1.2709532 (2007).