CHIP-SCALE ATOMIC DEVICES: PRECISION ATOMIC INSTRUMENTS BASED ON MEMS

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We describe recent work at NIST to develop compact, low-power instruments based on a combination of precision atomic spectroscopy, advanced diode lasers and microelectromechanical systems (MEMS). Designed to be fabricated in parallel in large numbers, these "chip-scale" atomic devices may eventually impact a wide range of applications, from the global positioning system to magnetic resonance imaging and inertial navigation. We focus here on recent work to develop compact, high-performance magnetometers.

1. Introduction

The miniaturization of atomic frequency references and related instruments continues in 2008 to support considerable activity within the frequency control community. Throughout the 1990s, compact atomic clocks were developed for synchronization of wireless communication systems[1]. This development effort led to the commercial availability of atomic frequency references with volumes near 100 cm^3, power requirements of about 10 W and a fractional frequency instability below 10^{-11} at one hour of integration. These frequency references were lamp-pumped instruments in which the atomic vapor cell was placed in a microwave cavity and the clock transition excited by directly applying a microwave field.

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At the time of the 6th Symposium on Frequency Standards and Metrology in 2001, new ideas related to miniaturized instruments were rapidly emerging and the last seven years has seen many of these ideas realized. In particular, the use of micromachining is now being explored extensively for application to atomic frequency references. In addition to a number of key laboratory experiments and proof-of-principle demonstrations, substantial progress has also been made in engineering easily manufactured systems, with the goal of bringing a new generation of miniaturized atomic clocks to the marketplace.

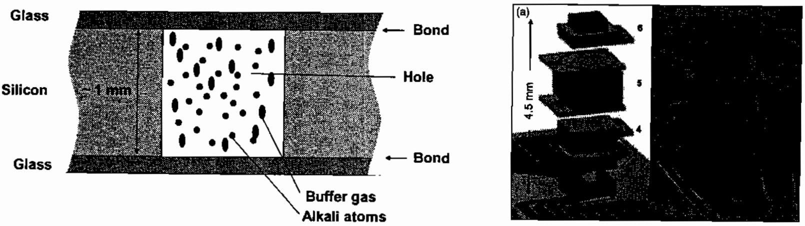
Micromachined vapor cell frequency references[2] are distinguished from their more conventional counterparts by the inclusion of key components fabricated by use of lithographically defined patterning and chemical etching of materials. The use of microelectromechanical systems (MEMS) allows not only for very small physics package size and correspondingly low power requirement but also makes possible the parallel fabrication of large numbers of units with a single process sequence. Since the first demonstration of a MEMS-based atomic clock physics package[3], significant advances in power dissipation[4], performance[5] and integration with electronics have been made[6-8]. At present, chip-scale atomic clocks are nearing commercial reality, and it is anticipated that large-scale manufacturing of units will begin soon.

At NIST, we are currently working to adapt the core technologies developed for chip-scale atomic clocks to use in other types of instruments, such as magnetometers, optical frequency references and gyroscopes. Micromachined alkali vapor cells[9], fabricated from etched silicon wafers, form the central component of all of these new types of instruments. We focus here on recent work to develop high-sensitivity magnetometers that share the size and power performance of their chip-scale frequency reference counterparts. Sensitivity levels to DC fields approaching those of magnetometers based on superconducting quantum interference devices (SQUIDs) have been achieved, opening the door to millimeter-scale uncooled sensors for a wide range of magnetic applications. These applications include magnetic anomaly detection, biomagnetic imaging, nuclear magnetic resonance and the measurement of magnetic fields in space.

2. Alkali Vapor Cells

The design and fabrication of MEMS-based alkali vapor cells at NIST has been discussed previously[9, 10] but is repeated here for completeness. Traditional methods for fabricating alkali vapor cells[11] are based on glass blowing techniques. This fabrication method has worked well for centimeter-scale physics packages for decades but suffers from some limitations with respect to highly miniaturized instruments, namely that cells must be fabricated one by one and that it is difficult to reduce the cell size below ~ 1 mm by use of a gas torch to heat the glass. While some alternative glass-blowing techniques have been developed in an attempt to overcome these problems[12, 13], the MEMS-based fabrication method described below still appears to be superior for most types of instruments.

The basic structure of the MEMS-based vapor cells is shown in Figure 1(a). A hole with a typical dimension of 1 mm is etched in a silicon wafer by lithographic patterning and chemical etching. Glass wafers are bonded onto the top and bottom of the silicon wafer, and the alkali atoms, along with a buffer gas, are confined in the enclosed volume.



(a) (b)

Figure 1 (a) Basic structure of a micromachined alkali vapor cell. (b) Photograph of a chip-scale atomic magnetometer (after Ref. 14).

This MEMS-based cell structure offers several advantages when compared with glass blowing. The first is that small cells can be made quite easily, since the physical dimensions are defined by lithography. The size of the cells is also quite scalable: the fabrication of cells with dimensions smaller than 1 mm in principle requires changes only in the etch mask and the wafer thickness. At NIST, we have made cells with one transverse dimension as small as 100 μm. The second advantage is that the wafer-level fabrication potentially allows for large numbers of cells to be made with the same process sequence. While this parallel fabrication has yet to be demonstrated, at the wafer level, small arrays of cells have been demonstrated and the extension to full wafers is expected to be straightforward. Finally, the planar structure of the cell allows for easy integration with other optical components in a stacked assembly.

3. Chip-Scale Atomic Magnetometers

The cells shown in Figure 1(a) can be integrated with a laser, some optics, and a photodetector to form a number of different instrument physics packages. The first physics packages to be developed were for atomic frequency references[3, 4, 7, 8]. In these instruments, a coherent population trapping (CPT) resonance is excited by modulating the injection current of the diode laser and detected by monitoring the transmitted optical power with the photodiode.

The first chip-scale atomic magnetometer demonstrated at NIST[15] was in fact identical in structure to the NIST chip-scale atomic clock physics packages. The magnetic field was measured by exciting a magnetically sensitive hyperfine transition using CPT, and the sensitivity of this instrument was 40 pT/√Hz. A subsequent magnetometer physics package[14] based on the Mx geometry[16] showed an improvement in sensitivity to 6 pT/√Hz. In this magnetometer, shown in Figure 1(b), the spin precession about the magnetic field (Zeeman resonance) was excited with a pair of RF coils integrated into the component stack. Finally, we also implemented a magnetometer[17] using a microfabricated vapor cell in which spin-exchange collisions that broaden the linewidth at high alkali densities were suppressed[18, 19]. This magnetometer had a sensitivity of 70 fT/√Hz with a cell volume of only 6 mm^3.

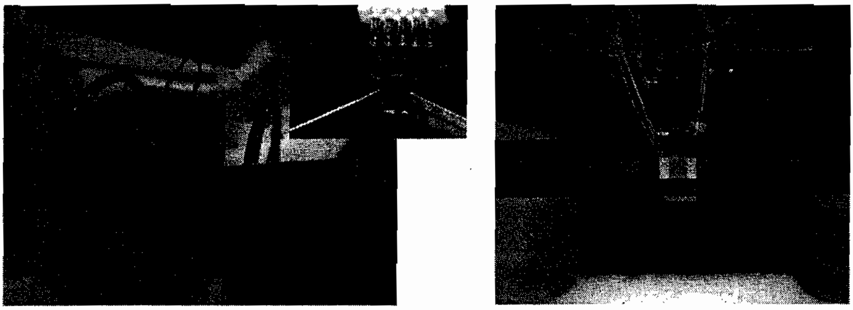
Atomic magnetometers are widely used to detect magnetic anomalies in the context of geophysical surveying, unexploded ordinance detection and perimeter monitoring. While miniaturized atomic magnetometers will likely impact these existing application areas, we are optimistic that the considerable reduction in size and power offered by chip-scale magnetometers will significantly broaden their utility.

4. Advanced Chip-Scale Atomic Magnetometers

4.1. *Chip-scale atomic magnetometers with flux concentrators*

To improve the sensitivity of the magnetometers even further, we have begun integrating the micromachined alkali vapor cells with flux concentrators[20]. The effect of the concentrator is to capture flux from an area larger than the vapor cell cross-section and concentrate this flux through the cell. For a fixed sensitivity associated with the vapor cell, the concentrator therefore improves the overall system sensitivity by a factor approximately equal to the concentrator enhancement factor. While the size of the complete instrument increases with the addition of the concentrator, only the small vapor cell needs to be heated, implying reduced power consumption compared with a magnetometer with no concentrator but based on a large cell.

Two types of flux concentrators were used: a pair of thin triangular prisms machined from high-permeability metal (Figure 2(a)) and a pair of cylindrical rods made from ferrite (Figure 2(b)). It was expected that the additional noise introduced by the concentrators would be different for the two materials[21].

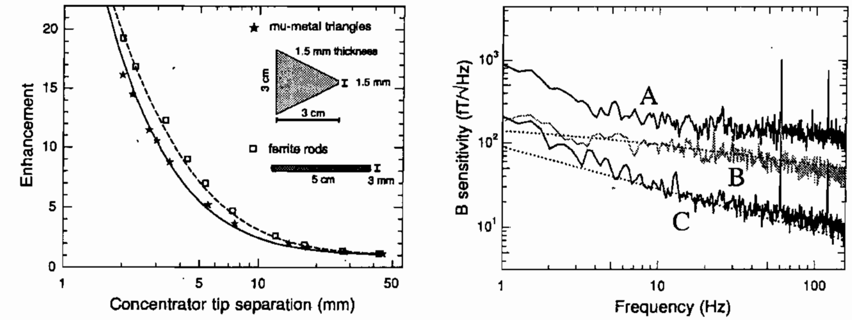


(a) (b)

Figure 2 Photographs of the flux concentrators used in the experiments. (a) Triangular prism concentrators machined from high-permeability metal. (b) Cylindrical concentrators made from ferrite.

The magnetometer was operated in the single-beam spin-exchange relaxation-free (SERF) geometry[17] at a cell temperature of 160 °C. The enhancement factor was measured as a function of the separation of the tips of the flux concentrators. The enhancement is expected to increase as the distance between the concentrators decreases, due to the increased conductivity of the magnetic path through the concentrators. The enhancement factors of the two concentrator systems as a function of tip spacing is shown in Figure 3(a). An enhancement of the magnetic field by a factor of about 20 is obtained for a tip spacing of 2 mm. The noise was determined by measuring both the dispersive zero-field resonance at the output of the lock-in detector and the noise at the same output with a FFT spectrum analyzer. The sensitivity is shown in Figure 3(b).

We find that the magnetometers incorporating the flux concentrators are imited by fundamental thermal noise associated with dissipation processes in the concentrator material. In the case of metallic concentrators, this noise is due to thermal currents in the conductive material, whereas for the ferrite concentrators, this noise is due to magnetic dissipation (hysteresis) in the material. Predictions from modeling following Ref. 21 are shown as dashed lines in Figure 3(b).



(a) (b)

Figure 3 (a) Enhancement factor for two types of flux concentrators. The lines are the results of simulations and agree well with the measured data. (b) Magnetometer sensitivity for a chip-scale magnetometer. Trace A is for the case with no flux concentrators, Trace B is for the triangular (high permeability metal) concentrators and Trace C is for the ferrite concentrators. The dashed lines show the expected sensitivity based on modeling described in Ref. 21.

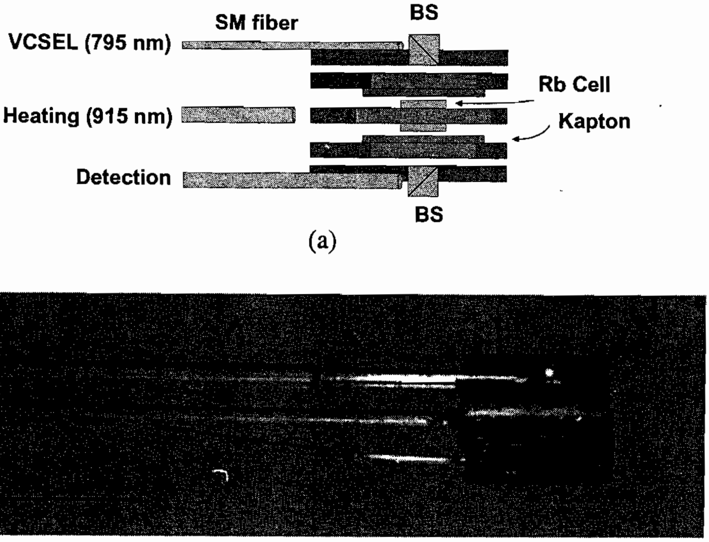
4.2. *"Photonic" Magnetometer*

In many cases, atomic magnetometers themselves generate magnetic fields that can interfere with the sensor reading or the readings of surrounding sensors if implemented in an array. These spurious field sources include DC currents in the laser and cell heaters, thermal currents in conductive material near the cell, and even the drive field required to excite the spin resonance. For very low-field applications or use in arrays, it is therefore desirable to develop sensors that generate as little field of their own as possible.

We are therefore exploring a chip-scale atomic magnetometer design in which all inputs to and outputs from the sensor head are optical[22]. In this "photonic" magnetometer, the Larmor resonance is excited and detected with a modulated optical field[23]; no oscillating magnetic field is therefore needed and the light can be transmitted to and from the cell through optical fibers[24]. In addition, the cell is heated to its operating temperature by use of light from a laser transmitted through an optical fiber and absorbed by the silicon cell material. Laser-induced temperature control of a magnetic sensor based on a SQUID was demonstrated in Ref. 25.

The basic design of the photonic magnetometer sensor head is shown in Figure 4(a). The vapor cell is suspended in an evacuated enclosure with thin polyimide tethers similar to those described in Ref. 4. Light from a broad area diode laser at 915 nm is transmitted through multi-mode optical fiber into the cell enclosure and illuminates the cell, heating it to its operating temperature.

Light from a second semiconductor laser (either a vertical cavity surface emitting laser or distributed Bragg reflector laser) is coupled into single-mode polarization-maintaining fiber and reflected into the cell by a small cube beamsplitter. After passing through the cell, the light is collected with a large-core multi-mode fiber for transmittal back to a photodetector. Figure 4(b) is a photograph of the complete sensor head.



(a)

(b)

igure 4 (a) Photonic magnetometer design. (b) Photograph of a completed instrument.

The sensitivity of the magnetometer measured in a magnetic field of 7 μT vas approximately 2 pT/√Hz. This is comparable to the sensitivity of the chip-cale Mx magnetometer described in Ref. 14.

. Conclusion and outlook

The technology developed for chip-scale atomic clocks is being adapted for variety of other instruments. Among these, atomic magnetometers based on icrofabricated alkali vapor cells are now achieving sensitivity levels omparable to those of SQUID-based magnetometers and offer the potential for igh-performance sensing in a highly compact, noncryogenic instrument. Recent ork to integrate flux concentrators with these magnetometers has resulted in otentially low-power instruments with a sensitivity of 10 fT/√Hz. In addition, novel designs such as the "photonic" magnetometer may allow microfabricated atomic magnetometers to be used in more unique situations, such as high-voltage environments or under water.

Beyond magnetometers, a variety of other instruments could be miniaturized by use of these same techniques. For example, chip-scale saturation spectrometers have already been demonstrated[26] and could prove useful in future general atomic physics experiments. Gyroscopes based on nuclear spins[27] also appear possible and would enhance inertial navigation, particularly on platforms with limited power and space such as unmanned aerial vehicles.

Acknowledgments

This work is a contribution of NIST, an agency of the US Government, and is not subject to copyright. This work was supported by NIST, the Defense Advanced Research Projects Agency (DARPA) and the Strategic Environmental Research end Development Agency (SERDP).

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