Microfabricated Atomic Clocks and Magnetometers

S. Knappe[1], P.D.D. Schwindt, V. Gerginov[2], V. Shah[1], L. Liew[3], J. Moreland[3], H.G. Robinson, L. Hollberg, and J. Kitching

Time and Frequency Division
National Institute of Standards and Technology,
Boulder, CO 80305

Abstract—**We demonstrate the critical subsystems of compact atomic clocks and magnetometers based on microfabricated physics packages. The clock components have a volume below 5 cm^3, a fractional frequency instability below $6\times10^{-10}/\tau^{1/2}$, and consume 200 mW of power. The magnetometer has a sensitivitiy below 40 pT/Hz$^{1/2}$ at 50 Hz.**

I. Introduction

While the long-term precision of atomic clocks is unsurpassed, the size and power required to run these devices has prevented their use in a variety of areas, particularly in those applications requiring portability or battery operation. The state of the art in compact commercial atomic frequency references are Rb vapor-cell devices with volumes near 100 cm^3 that operate on a few watts of power and cost about $1000.

Miniaturization based on micro electromechanical systems (MEMS) offers many of the same compelling advantages to atomic frequency references as it does to other large-scale technologies. In addition to small size, a corresponding improvement in the device power dissipation is gained because the heat lost to the environment via the device surface is smaller. MEMS also could enable high-volume, wafer-based production of atomic clocks, which would substantially reduce cost. Such improvements would make atomic timekeeping useful in a variety of advanced applications where quartz clocks are now used.

II. The Microfaricated Atomic Clock

A. The Physics Package

Recent work at NIST has focused on the development of the physics package, which is the heart of an atomic clock and contains the atoms which provide the frequency stability. The physics package takes the gigahertz-range signal from a local oscillator (LO) as its input, compares the LO frequency to the resonant frequency of the atoms, and generates an output signal proportional to the frequency difference between the two. This output signal is then used to lock the oscillator frequency to the atoms.

The central part of the physics package is an alkali vapor cell fabricated using MEMS techniques [1,2]: A hole is etched through a silicon wafer and a glass wafer is anodically bonded onto each side to form a hermetically sealed cavity with two windows. Alkali atoms, along with an appropriate buffer gas, are sealed in the volume between the glass wafers. A laser beam is transmitted though the windows of the cell and is monitored with a photodiode. The light is provided by a vertical-cavity surface-emitting laser (VCSEL) and is shaped by a micro-optics assembly, before entering the cell.

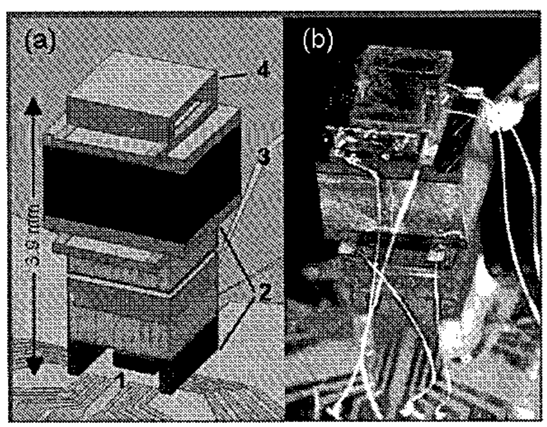

Fig. 1. (a) Schematic (a) and photograph of the chip-scale physics package. The components are: 1-VCSEL, 2-micro-optics, 3-^{87}Rb vapor cell, 4-photodiode. It can be run as a frequency reference as well as a magnetometer.

A photograph and schematic of such physics package [3] is shown in Fig. 1. The VCSEL emitts light at 795 nm, probing the D_1 line of the ^{87}Rb atoms contained in the vapor cell. The physics package has a total volume of 12 mm^3 and requires 195 mW of power at an ambient of 22 °C. It reaches a

[1] also with: University of Colorado, Boulder, CO 80309
[2] also with: University of Notre Dame, Notre Dame, IN 46556
[3] Electromagnetics Division, NIST, Boulder, CO 80305

0-7803-9278-7/05/$20.00©2005 IEEE

fractional frequency instability of 4×10^{-11} at one second of integration.

B. System assembly

In order to have a fully functional, self-contained frequency reference, the physics package was integrated with a LO at 3.4 GHz (half the Rb ground state hyperfine splitting) and miniature control electronics. The voltage-controlled oscillator, developed by the group of Z. Popović, is based on a coaxial resonator. Its phase noise is below -92 dBc at 10 kHz, has a volume of roughly 0.15 cm^3, and consumes less than 5 mW of power [4]. The control electronics are based on a microprocessor chip, which includes four stabilization loops: two for the temperature of the VCSEL and the vapor cell, one for the laser frequency (i.e., laser current) and one for the LO frequency. It has a total volume of 2.5 cm^3 and requires 75 mW of power. Combining the three components, the frequency reference has a total volume of less than 5 cm^3 and requires 200 mW of power. It has a fractional frequency instability below $6\times10^{-10}/\tau^{1/2}$. Further miniaturization of the control electronics and lower power consumption of the physics package [5] seem possible. This could lead to chip-scale atomic frequency references of total volume 1 cm^3 consuming less than 50 mW of power. Furthermore, improvements of the local oscillator could lead to better frequency stabilities at short integration times. Finally, the design is amenable to wafer-level fabrication and integration (Fig. 2) which makes it appealing for commercialization.

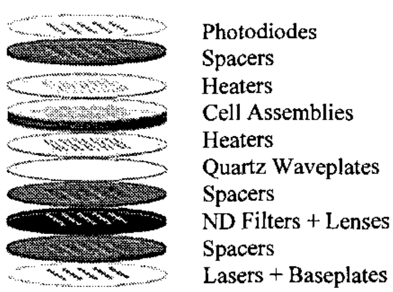

Fig. 2. Wafer-level design for chip-scale atomic clock physics packages. All components are fabricated on individual wafers. The wafers are stacked to assemble the packages and diced afterwards into individual physics packages.

III. The Mirofabricated Atomic Magnetometer

The technologies developed for chip-scale atomic clocks can have significant applications in other areas as well: One example is highly sensitive and accurate magnetometers [6] based on vapors of alkali atoms. While the clock measures the frequency of two atomic ground states that are independent of magnetic field in first order, the magnetometer uses a very similar technique to measure the frequency splitting of two atomic ground states which depends strongly on the magnetic field at the position of the atoms, i.e., the vapor cell. It is therefore possible to determine the local magnetic field by comparing the energy difference of magnetically sensitive states to the energy difference of magnetically insensitive states. A magnetometer of this type has been implemented at NIST [7] with a microfabricated structure shown in Fig. 1 based on the D1 line of ^{87}Rb atoms. The active volume of the magnetic sensor is 1 mm^3. With this device magnetic fields can be measured with a sensitivity of $40\,pT/\sqrt{Hz}$ over the frequency range of 10 Hz to 100 Hz.

Acknowledgment

The authors thank Z. Popović and A. Brannon for the development and fabrication of the voltage-controlled oscillator.

This work is supported by NIST and the Microsystems Technology Office of the Defense Advanced Research Projects Agency (DARPA). This work is a contribution of NIST, an agency of the US government, and is not subject to copyright.

References

[1] L. A. Liew, S. Knappe, J. Moreland, H. Robinson, L. Hollberg, and J. Kitching, "Microfabricated alkali atom vapor cells," *Applied Physics Letters*, vol. 84, pp. 2694-2696, 2004.

[2] S. Knappe, V. Velichansky, H. G. Robinson, L. Liew, J. Moreland, J. Kitching, and L. Hollberg, "Atomic Vapor Cells for Miniature Frequency References," presented at Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, 2003.

[3] S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L. A. Liew, and J. Moreland, "A microfabricated atomic clock," *Applied Physics Letters*, vol. 85, pp. 1460-1462, 2004.

[4] A. Brannon, J. Breitbarth, and Z. Popovic, "A Low-Power Low Phase Noise Local Oscillator for Chip-Scale Atomic Clocks," presented at 2005 IEEE MTT-S Int. Microwave Symp, 2005.

[5] R. Lutwak, J. Deng, W. Riley, M. Varghese, J. Leblanc, G. Tepolt, M. Mescher, D. K. Serkland, K. M. Geib, and G. M. Peake, "The Chip-Scale Atomic Clock – Low-Power Physics Package," presented at Proceedings of the 36th Annual Precise Time and Time Intervals Systems and Applications Meeting, Washington, DC, 2004.

[6] H. Dehmelt, "Modulation of a light beam by precessing absorbing atoms," *Phys. Rev.*, vol. 105, pp. 1924-1925, 1957.

[7] P. D. D. Schwindt, S. Knappe, V. Shah, L. Hollberg, J. Kitching, L. A. Liew, and J. Moreland, "Chip-scale atomic magnetometer," *Applied Physics Letters*, vol. 85, pp. 6409-6411, 2004.