An Atomic Clock on a Chip[1]

John Kitching[2] shows how high precision time is becoming portable

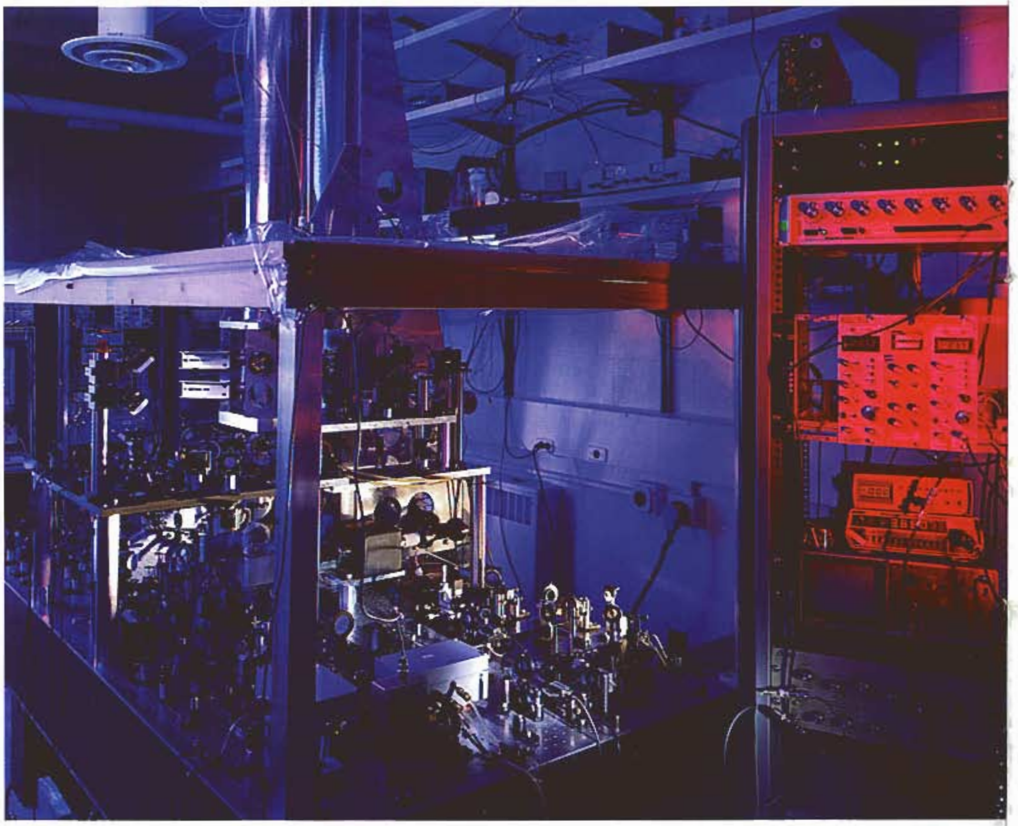
FOR OVER FIFTY YEARS, clocks based on electromagnetic oscillations of atoms have provided the most precise method of long-term timing. So precise are these 'atomic' clocks, that in 1967 the second was redefined to be the time taken for a caesium atom in a particular quantum state to undergo exactly 9,192,631,770 oscillations. More recently, atomic clocks have found application in a variety of critical infrastructures and scientific experiments that require highly precise timing. These include synchronization of communication networks, global positioning, and even tests of fundamental theories in physics such as Einstein's theory of relativity.

Most atomic clocks are passive devices in which the atoms serve as the basic frequency reference but do not oscillate on their own. In these devices, the atomic oscillation is excited through the application of an electromagnetic field that is generated from a secondary oscillator, usually based on a quartz crystal resonator. The frequency of this secondary oscillator is locked to the atomic oscillation frequency, creating an output that is highly stable over weeks or months of operation.

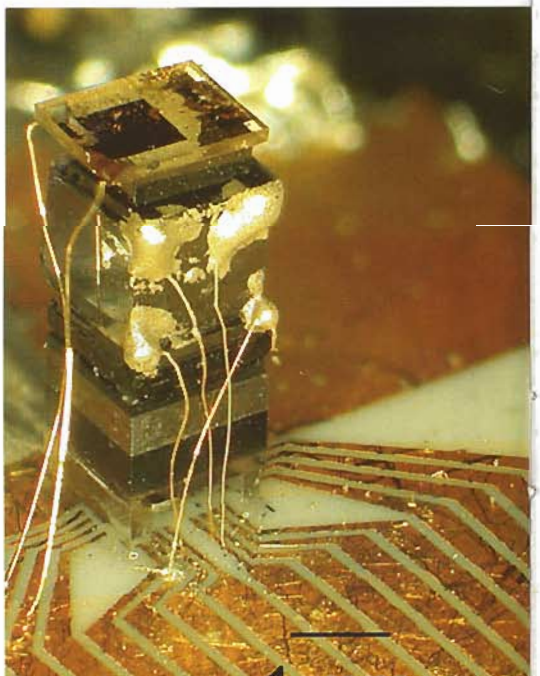
While the long-term precision of atomic clocks is unsurpassed, the size and power required to run these devices has prevented their use in a variety of areas, particularly applications requiring portability or battery operation. For example, the world's most accurate atomic clock, the NIST F-1 primary standard[3], **1**, occupies a large table and requires many hundreds of watts to operate. The state of the art in compact commercial atomic frequency references is a unit about the size of a television remote control that operates on a few watts of power.

The heart of the first microfabricated atomic clock[4], **2**, was recently developed at NIST. About the size of a grain of rice, this 'physics package' contains the caesium atoms that provide the stable frequency reference as well as a semiconductor laser that is used to excite the atomic oscillations, and a photodetector, which detects them. At the heart of the physics package is an atomic vapour cell[5] that confines the caesium. The cell is fabricated by use of techniques common to the microelectronics and micromachining communities. Patterns are lithographically defined on the surface of a silicon wafer, and then holes are selectively chemically etched through the wafer. Glass wafers are then bonded to the top and bottom of the silicon, creating a cavity in which the caesium atoms are confined. This method of fabricating atomic vapor cells allows not only for very small sizes resulting from the lithographic patterning, but also for many cells (possibly thousands) to be made at the same time on a single set of wafers. A photograph of a cell made at NIST in mid-2003 is shown in figure **3**.

The micro fabricated vapour cell is assembled into a layered, vertically integrated structure, **4**. At the very bottom, a semiconductor laser sits on a



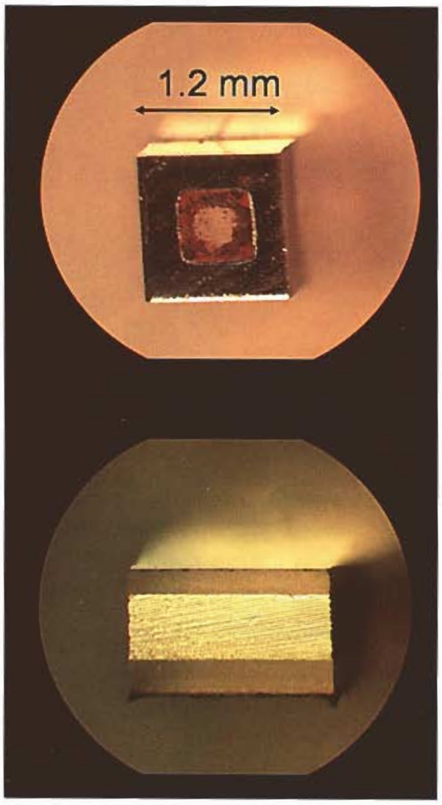
1. The NIST F-1 primary frequency standard.



2. A physics package of a chip-scale atomic clock.

Photographs provided by the author

1. This work is a contribution of NIST, an agency of the US government, and is not subject to copyright.
2. Time and Frequency Division, NIST
3. S. R. Jefferts, et al, "Accuracy Evaluation of NIST-F1," Metrologia, 39, 321, 2002.
4. S. Knappe, L. Liew, V. Shah, P. Schwindt, J. Moreland, L. Hollberg, and J. Kitching, "A microfabricated atomic clock," Appl. Phys. Lett. 85, 1460, 2004.
5. L-A. Liew, S. Knappe, J. Moreland, H. Robinson, L. Hollberg and J. Kitching, "Microfabricated alkali atom vapor cells," Appl. Phys. Lett. 84, 2694, 2004.



3. Microfabricated caesium vapor cells.

baseplate on which electrically conducting gold traces have been etched. The electrical current that drives the laser is modulated (switched on and off) at a frequency near that of the atomic oscillation. The laser emits light vertically, which travels through an optics assembly to the cell. The optics assembly collimates the diverging laser beam, reduces the power and polarizes the light field appropriately. The beam then passes through the cell, where it excites the atomic oscillation. The light power transmitted through the cell changes when the laser modulation frequency coincides with the atomic oscillation frequency. By monitoring this transmitted power with a photodiode, the frequency of the laser modulation can be corrected to correspond to the atomic resonance frequency.

Preliminary testing of the device shown in figure **2** indicated that the fractional frequency instability was 2.5×10^{-11} at one second of averaging. If this stability were to hold out to long averaging times, this would correspond to the clock neither gaining nor losing a second in 300 years! While not as precise as other types of atomic clocks (NIST F-1 would neither gain nor lose a second in 30 million years), the small size of the chip-scale clock and the low power requirement (currently under 100 mW) will allow atomically precise timekeeping to be used in portable, battery-operated devices such as global positioning system (GPS) receivers and wireless communication devices.

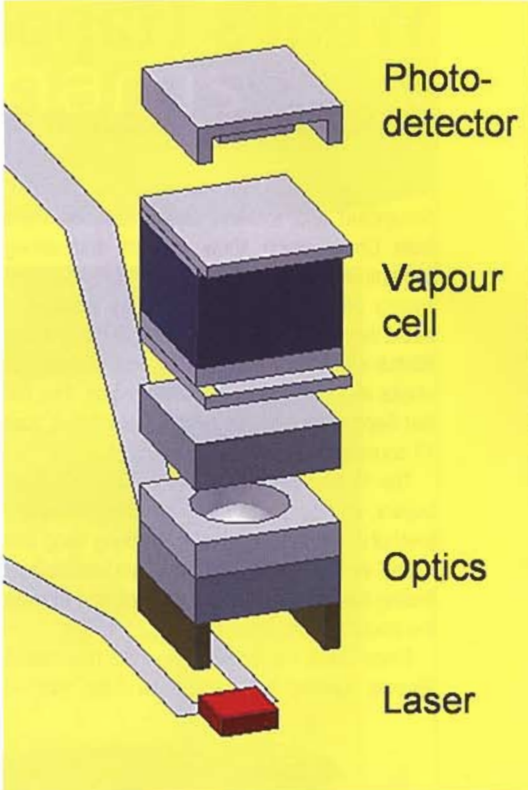
While the physics package is perhaps the most important element in a complete atomic frequency reference, the miniaturization of the other components, a secondary oscillator and the control electronics, is also a significant challenge. It is likely that quartz crystal oscillators will be too large to be accommodated conveniently in the final package, and the frequency multiplication chain needed to multiply the quartz frequency up to the multi-gigahertz frequencies that excite the atoms will consume too much power. Ongoing research is being carried out to develop advanced, highly compact low-power oscillators for integration with the physics package. In addition, control systems based on microprocessors or application-specific integrated circuits are under development. When finally integrated into a functioning device, it is anticipated that the size of the complete frequency reference will be below 1 cm^3 and the power requirements below 30 mW.

It is interesting to note that at least some of the critical issues that must still be addressed in these devices are similar to those encountered by John Harrison in his efforts to develop chronometers for navigation in the early eighteenth century. One such issue is the sensitivity of the clock to temperature. In a traditional pendulum clock, changes in ambient temperature cause corresponding changes in the length of the pendulum arm, which alter the clock frequency. Harrison addressed this issue by using a bimetallic strip[6] in his clocks: the strip changed shape with temperature and could be designed to compensate for the temperature sensitivity of the pendulums.

In current atomic clocks, changes in temperature cause changes in the interaction of the caesium atoms with other gases contained in the cell. This modified interaction alters the frequency of oscillation of the caesium atoms in a way that depends on temperature. In the chip-scale atomic clocks being developed at NIST (and in other atomic clocks based on vapor cells) this temperature dependence will be reduced and in some cases eliminated in the future by combining different gas species inside the cell with the caesium atoms. This use of two different gases is compellingly similar to Harrison's use of two different metals to compensate for temperature-induced frequency shifts.

A second interesting parallel involves the motivation for building the clocks. In Harrison's time, the primary application for which the new clocks were being developed was navigation, and specifically the determination of longitude on ships. The compact atomic clocks of today are also likely to significantly impact navigation by enhancing the performance of the global positioning system. A GPS receiver containing a precise clock can determine its position using fewer satellites, and therefore is more robust, particularly in urban environments where satellites are more likely to be obscured by buildings or other obstacles.

Over the centuries, precise, portable timekeeping has played a critical role in human endeavour. The work described here is just one small step in a long history of technological advances in timing that have enabled exploration to the furthest reaches of the known world. New technologies still on the horizon, such as optical clocks[7] perhaps combined with nanoscience[8], will continue to improve the timing capabilities of small, low-power devices and permit an even wider use of atomic clocks in a variety of emerging applications. ❐



4. Schematic diagram of the assembly of the physics package of a chip-scale atomic clock.

6. *John Harrison and the Longitude Problem*, web site of the National Maritime Museum, Royal Observatory, Greenwitch, http://www.nmm.ac.uk
7. S Diddams, J C Bergquist, S R Jefferts and C W Oates, 'Standards of time and frequency at the outset of the 21st century,' *Science*, 306, 1318, 2004.
8. See *Scientific American*, Special Issue on Nanotechnology, 285 September, 2001.