Chip-Scale Atomic Frequency References

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BIOGRAPHY

John Kitching

Dr. Kitching received his B.Sc. in Physics from McGill University in 1990 and his M.Sc. and Ph.D. in Applied Physics from the California Institute of Technology in 1995. He is currently a physicist in the Time and Frequency Division of NIST in Boulder, CO. Dr. Kitching's research interests include atomic frequency standards, low-noise microwave oscillators, atomic magnetometers and gyroscopes. In 2001, he initiated the development of microfabricated atomic frequency references at NIST and is the Principal Investigator of the work.

Svenja Knappe

Dr. Knappe received her diploma in physics from the University of Bonn, Germany in 1998. The topic of her diploma thesis was the investigation of single cesium atoms in a magneto-optical trap. She obtained her PhD from the University of Bonn in 2001, with a thesis on dark resonance magnetometers and atomic clocks. Since 2001, she has held a guest-researcher appointment in the Time and Frequency Division at NIST. Her research interests include precision laser spectroscopy, atomic clocks and atomic magnetometers, laser cooling, and applications of semiconductor lasers to problems in atomic physics and frequency control.

Vladislav Gerginov

Dr. Gerginov was born in Sofia, Bulgaria, in 1970. He received his M.S. degree in physics from the Sofia University, Bulgaria in 1995, and his PhD degree in physics from the University of Notre Dame, USA, in 2003. In 2003, he joined the Optical Frequency Measurements group at NIST as a postdoctoral associate, and was engaged in optical frequency measurements in cesium using femtosecond lasers. Since 2004 he has been working on chip-scale atomic clocks.

John Moreland

Dr. Moreland received a B.S. degree in Chemistry and Physics from the University of Idaho in 1977 and a Ph.D. degree in Physics from the University of California Santa Barbara in 1984. He started at the National Institute of Standards and Technology (NIST) in 1984 – currently Dr. Moreland leads the Nanoprobe Imaging Project there. His project designs, fabricates, and tests microelectromechanical systems (MEMS) for measurement applications in support of data storage, genomics, and telecommunications industries. Project members are taking a chip-scale microsystems approach in efforts to advance metrology instrumentation by improving sensitivity, portability, and cost as well as traceability to the SI.

Alan Brannon

Mr. Brannon received a B.S. degree in electrical engineering from Clemson University in 2002 and a M.S. in electrical engineering from the University of Colorado in 2004. He is currently pursuing a Ph.D. in electrical engineering at the University of Colorado. Mr. Brannon has been awarded a National Science Foundation Graduate Research Fellowship and is a Tau Beta Pi fellow. His research is in the area of low phase noise oscillator design, specifically for application in miniature atomic frequency references. This year, Mr. Brannon is studying at the National Institute for Standards and Technology under a Graduate NIST Fellowship.

Zoya Popovic

Dr. Popovic received her Dipl.Ing. degree from the University of Belgrade, Serbia (1985) and her Ph.D. from Caltech (1990). She has since been with the University of Colorado, Boulder, where she is the Hudson Moore Jr. Professor of Electrical and Computer Engineering. Her research interests include high-efficiency / low-power microwave circuits, intelligent RF front ends, RF photonics, millimeter-wave quasi-optical techniques, and wireless powering. She is a Fellow of the IEEE, and received the Microwave Prize, the URSI Issac Koga Gold Medal, the NSF Presidential Faculty Fellow award, the ASEE/HP Terman Medal and the German Humboldt Research Award. She has graduated 22 doctoral students.

Leo Hollberg

Dr. Hollberg received a B.S. in physics from Stanford in 1976 and went on to complete a PhD in physics 1984 at the University of Colorado. Most of 1984 and 1985 were spent at AT&T Bell Laboratories as a postdoc. Since then he has been at NIST doing research on high-resolution spectroscopy of laser-cooled and -trapped atoms, the development of semiconductor lasers for scientific and technical applications, optical coherence effects of driven multilevel atoms, chip-scale-atomic-clocks, optical frequency standards, optical frequency combs and optical atomic clocks. Leo is currently the group leader of the Optical Frequency Measurements group at NIST, Boulder.

ABSTRACT

We describe recent efforts at NIST to develop chip-scale atomic frequency references based on microfabrication techniques commonly used in microelectromechanical systems (MEMS). These frequency references are projected to have a volume of 1 cm^3, a power dissipation of 30 mW and a fractional frequency instability of 10^{-11} at one hour of integration.

To date, we have demonstrated the three critical subsystems of a frequency reference of this type with a total volume below 10 cm^3, a total power dissipation below 200 mW, and a fractional frequency instability below $6x10^{-10}/\sqrt{\tau}$. The physics package is fabricated and assembled using MEMS processing techniques, which allow unprecedented reductions in the size and power of this subsystem. The local oscillator (LO) subsystem, which is locked to the physics package resonance, is based on a micro-coaxial resonator. It has a footprint of 0.5 cm^3, runs on as little as 2 mW of DC electrical power, and can be locked to the physics package with a frequency instability below $2\times10^{-10}/\sqrt{\tau}$. Finally, compact control electronics currently based on an analog demodulator chip, but likely to be replaced by a microprocessor, lock the LO to the physics package.

INTRODUCTION

Atomic clocks and precision timing are at the core of almost every aspect of the Global Navigation Satellite System (GNSS). A GNSS receiver determines its position with respect to a subset of the constellation of orbiting satellites by measuring the time taken by a RF signal to travel the distance between the satellite and the receiver. Through a triangulation process, the receiver is able to determine its three spatial coordinates and clock offset from information from a minimum of four satellite signals. Nanosecond-level timing is typically required for positioning with a precision of 1 m.

In most GNSS receivers, the clock is in the form of a temperature compensated quartz crystal oscillator (TCXO). These small, low power and low cost frequency references are sufficient for most basic GNSS functions and allow the receiver to access, for example, the standard positioning service (SPS) for the global positioning system (GPS). In a normal positioning process, the receiver clock is implicitly synchronized to GNSS time by the algorithm that also determines the position.

However, in certain circumstances, it is advantageous to have a receiver reference clock more precise than a TCXO, particularly over long periods. Once initially synchronized, such a clock would allow, for example, positioning with only three satellites since one variable, the receiver time, would already be determined. Several other, more subtle advantages are discussed toward the end of this paper.

Over the last four years, NIST has been developing highly miniaturized, low power atomic frequency references for use in portable, battery-operated applications such as GNSS receivers. The goals of this program are to develop a fully integrated atomic clock with a volume below 1 cm^3, a power dissipation below 30 mW, and a fractional frequency instability below 10^{-11} at one hour of integration. If these goals are achieved, this would represent an improvement by a factor of 100 in size and power dissipation over the current state of the art in compact atomic standards [1]. Alternatively, it represents an improvement in frequency stability at one hour by over three orders of magnitude over what is typically achieved with a quartz crystal frequency reference of comparable size and power dissipation [2].

The heart of any atomic clock is the "physics package," which contains the atoms that provide the precise periodic oscillation on which the clock is based. Because of the importance of this element in the clock, and because of the role that fundamental physics plays in determining its size, our work has focused in large part on this aspect of the clock. However, any complete (passive) frequency reference also requires a local oscillator (LO) to generate the initial (unstable) frequency that interrogates the atoms, and a control system that implements the correction process. The interaction between these three subsystems is illustrated in Figure 1.

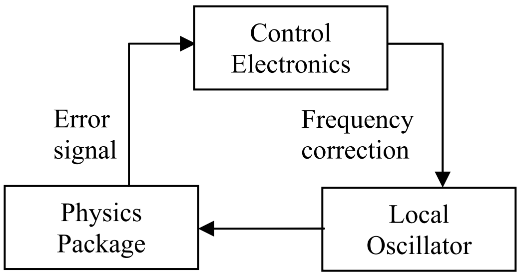


Figure 1 The three subsystems of a passive frequency reference and the interaction between them.

CLOCK PHYSICS PACKAGE

In a conventional vapor cell atomic clock [3] (see Figure 2a), the atomic transition is excited through the direct application of a microwave field to the atoms. Atoms are first prepared in one of the hyperfine-split ground state sublevels by an optical field from a lamp. The microwave field couples the two hyperfine split ground-state sublevels, generating an oscillating magnetic moment in the atom at the microwave frequency. The change of the atomic state implicit in this oscillating moment is monitored through the change in absorption of the optical field used to prepare the atoms.

One difficulty with this conventional vapor cell clock configuration is that the cell is typically placed inside a microwave cavity; the cavity confines the microwaves in the vicinity of the atoms and reduces Doppler shifts that can be present when a traveling wave microwave field is used. In order to be resonant, the simplest microwave cavities must be no smaller than roughly one half the wavelength of the microwave radiation (3.2 cm in the case of Cs). This imposes limits on how small the physics package can be made.

The microfabricated, chip-scale atomic clock physics packages we have developed are the result of two main innovations. The first of these is the use of coherent population trapping (CPT) excitation [4-7] (see Figure 2b) of the atomic transition used to stabilize the LO. In this technique, two light fields, separated in frequency by the atomic ground-state hyperfine splitting, are simultaneously incident on the atoms. The nonlinear behavior of the atoms generates a coherence (and therefore an oscillating magnetic moment) at the difference frequency of the two optical fields. The amplitude of this coherence can be measured by monitoring the absorption of the atomic sample: when the difference frequency between the optical fields is near the atomic hyperfine splitting, the absorption of the sample decreases.

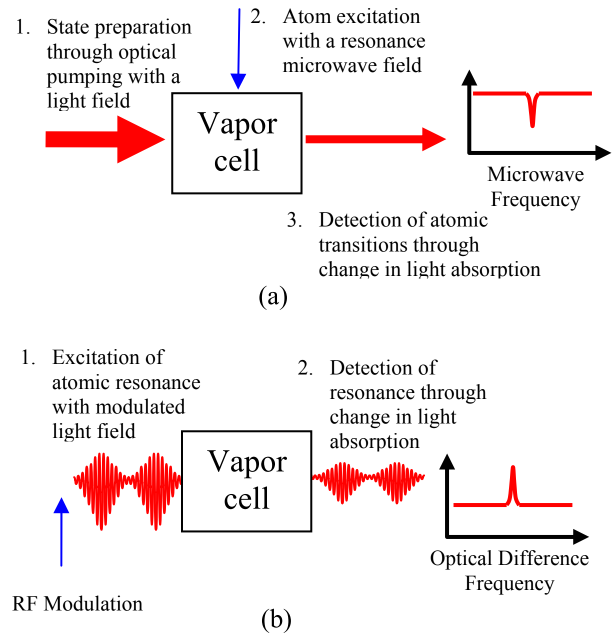


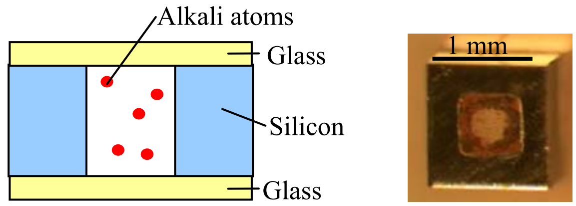
Figure 2 Physical mechanisms involved in (a) conventional microwave-excited vapor cell frequency references and (b) frequency references based on coherent population trapping.

A convenient way of generating the two-frequency optical field is through modulation of the injection current of a diode laser [8-10]. When locked to the atomic transition, this modulation frequency (generated initially by the LO) is therefore stabilized over long periods and becomes the output of the atomic clock.

Atomic clocks based on this CPT excitation mechanism are not restricted in size by the wavelength of the microwave radiation, because no microwave field is applied to the atoms, and no microwave cavity is required. As a result, a highly compact atomic clock can be made with this method. Table-top experiments [11-13] implementing atomic clocks based on this method have achieved short-term fractional frequency instabilities below $2 \times 10^{-12}/\sqrt{\tau}$.

The second key innovation that led to the development of chip-scale atomic clocks was the use of MEMS, first proposed in [14]. The idea is to fabricate the critical components of the atomic clock, namely the cell that contains the atoms, using microfabrication techniques.

The first MEMS alkali vapor cells [15] were made by etching a hole in a silicon wafer a few hundred micrometers thick, and then bonding thin glass wafers on the top and bottom surface. Alkali atoms were confined in the interior volume of the structure before the second glass wafer was attached. A schematic of the MEMS cell geometry and photographs of complete cells are shown in Figure 3.



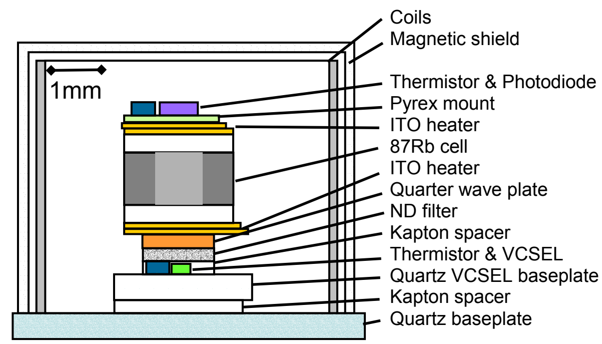
(a) (b)

Figure 3 (a) Basic MEMS cell geometry (side view) and (b) photograph of millimeter-scale cells made at NIST in 2003 (top view).

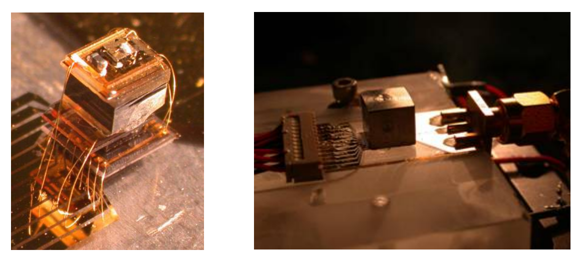
Cell fabrication with this method has several critical advantages over the conventional method of making alkali vapor cells, which is based on glass blowing techniques. First, the method enables the fabrication of cells with very small volumes, since the hole in the silicon wafer is defined by lithographic patterning. Second, the method is highly scalable. The cells typically fabricated for our physics packages are about 1 mm in size; however, almost no changes to the basic cell filling process would be required to make cells of considerably smaller size. Third, the method allows many cells to be made simultaneously on a single wafer stack with the same process sequence. This should lead to a substantial reduction in cost for atomic clock physics packages. Finally, the planar structure allows for easy integration with other optics and electronics. In particular, the light field required for CPT excitation of the atoms can conveniently enter and leave the cell through the glass windows.

Because of their small size, the cells must be heated to near 100 °C in order to have a sufficient vapor pressure of alkali atoms to substantially absorb the light. Cell heaters were fabricated by depositing a thin (30 nm) layer of Indium Tin Oxide (ITO) onto a glass substrate. ITO is a convenient material for this type of heater since it is both transparent and conductive. It therefore allows current to be passed through it (to heat the cell) and also can be placed over the cell windows to make good thermal contact with the cell without obstructing the passage of the light.

The cell, with ITO heaters on top and bottom, was integrated with an optics assembly, which generated the light beam used to excite the atoms. The optics assembly comprised a diode laser die mounted on an insulating baseplate, covered with a micro-optics stack. We use vertical-cavity surface-emitting lasers (VCSELs) because of their low power dissipation, high modulation bandwidth, low cost and vertical light emission. The stack contained spacer units to prevent the upper components from damaging those underneath and to provide thermal isolation; a neutral density (ND) filter to attenuate the light power; and a thin piece of quartz to change the polarization from linear to circular. A collimated light beam was therefore emitted from the top of the optics assembly with a power of about 10 μW, a diameter of about 250 μm, and circular polarization.



(a)



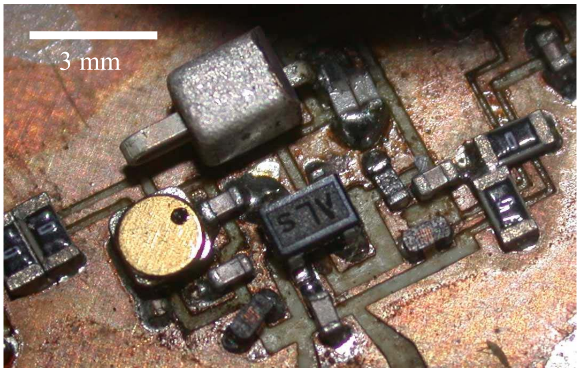
(b) (c)

Figure 4 Physics package for a chip-scale atomic clock. (a) Schematic of the shielded physics package. (b) Photograph of the (unshielded) package and (c) photograph of the shielded unit.

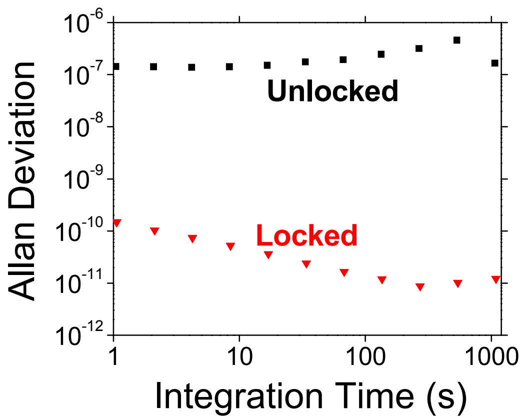
The cell assembly, with heaters, was placed on top of the optics assembly. The entire structure was capped with a photodetector subassembly that detected power in the optical field transmitted through the cell. A schematic and photographs of the entire physics package structure and shielding are shown in Figure 4.

LOCAL OSCILLATOR AND CONTROL SYSTEM

A compact, low power oscillator generating a signal at 3.4 GHz was implemented [16]. This subsystem was based on a commercially available ceramic micro-coaxial resonator with a loaded Q-factor of ~125. The oscillator operated with a DC power less than 5 mW and was typically run at ~ 2 mW; at this power level it produced about 0.25 mW



(a)



(b)

Figure 5 The local oscillation subsystem of the NIST chip-scale atomic clock. (a) Photograph of the LO, which is based on a micro-coaxial resonator at 3.4 GHz. (b) The fractional frequency stability of the LO running both unlocked and locked to a large-scale, high-performance CPT physics package with large control electronics.

of RF power at 3.4 GHz into a 50 Ω load. It could be tuned by ~ 3 MHz with a weakly coupled varactor diode. A photograph of the LO, which had a footprint of only 0.5 cm^3, is shown in Figure 5a.

The signal generated by the local oscillator was used to modulate the injection current of the diode laser in the physics package and excite the CPT resonance in the atoms. The resulting signal from the physics package photodiode was used to lock the LO frequency to the atomic resonance. This was done by modulating the frequency of the LO at ~ 3 kHz and then using lock-in detection to determine the center of the resonance line. This error signal was integrated before being fed back into the LO tuning port. The unity-gain bandwidth was about 1 kHz.

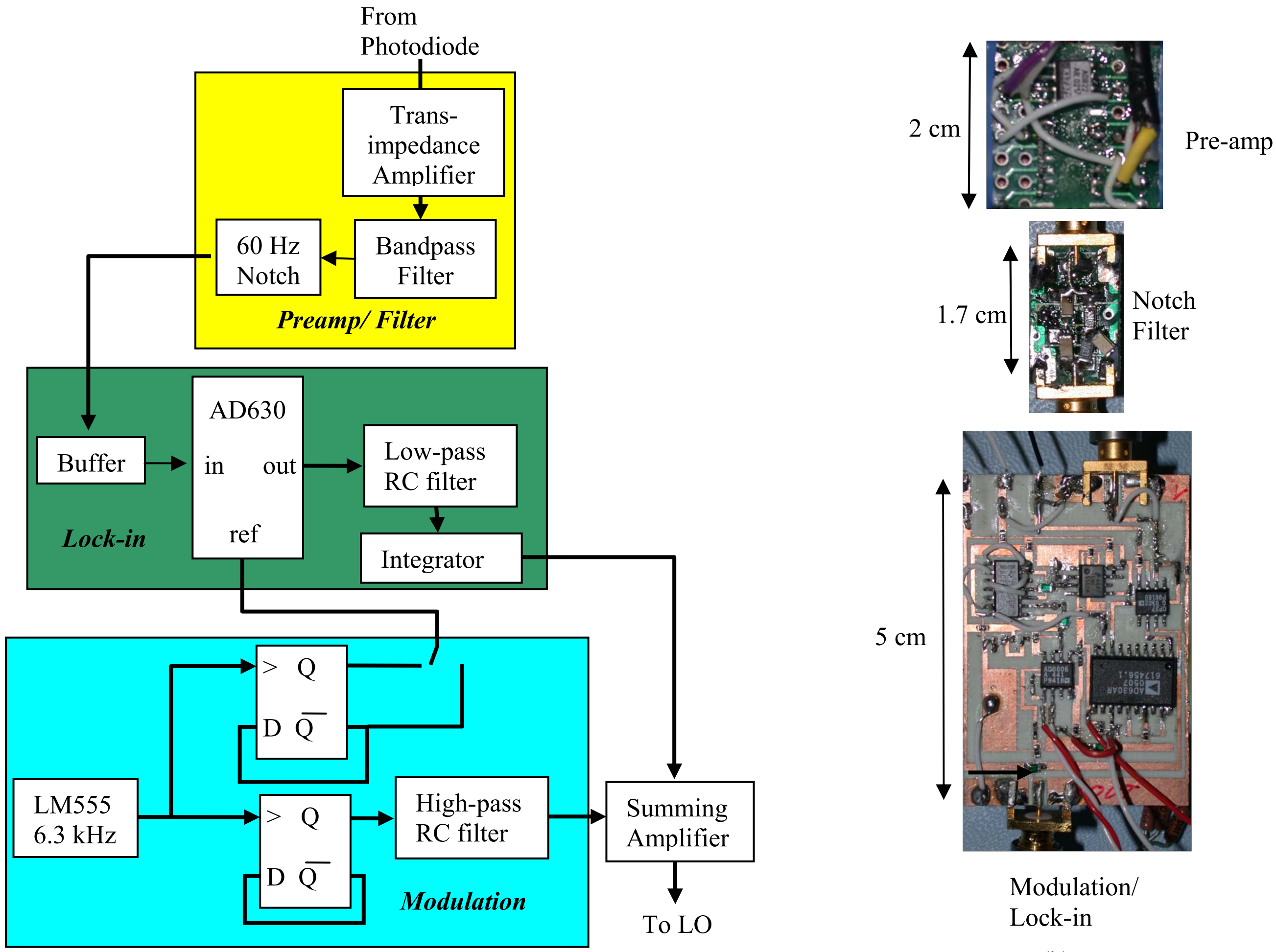
When free running, the LO had a fractional frequency instability of about 10^{-7} at an integration time of 1 second. When locked to a table-top physics package with large, rack-mounted electronics, this instability could be reduced to near 10^{-10} at 1 s, as shown in Figure 5b.

The control system was used to lock the frequency of the local oscillator to the atomic transition. The input to the control system was the output from the physics package photodetector. The output from the control system was the error (correction) signal that went to the frequency control port of the LO. In addition, the control system provided a 3 kHz square-wave modulation superimposed on the error signal that allowed the physics package resonance to be measured with lock-in detection. The lock-in detection served the dual purpose of (a) generating a dispersive correction signal to which the LO could be locked and (b) moving the signal away from baseband, where 1/f noise causes large frequency instability.

The LO correction servo is implemented with a compact, low-power analog lock-in amplifier system. This system is shown schematically in Figure 6(a). The modulation for the LO and also for the reference of the lock-in was generated by a LM555 chip in a self-oscillation configuration. Each signal was sent to a flip-flop (74AC74) that cleaned up the signal, divided the frequency by 2 and allowed for a 180° phase shift for the lock-in reference. The output from the flip-flop in the LO channel was sent to a high-pass RC filter which eliminated the DC component. The remaining AC signal was sent to one channel of a summing amplifier (OP284) and then to the LO input port.

The detected photocurrent from the physics package photodiode was amplified with a transimpedance amplifier, and the signal was then filtered with a band-pass filter around 3 kHz. The resulting AC signal was sent to the input port of a phase-sensitive detector (AD630), which took the original 3 kHz modulation (with the variable phase shift) as its reference. The output of the AD630, a phase-sensitive signal near DC, was filtered with a low-pass RC filter to eliminate the original modulation component and then integrated to provide the LO correction signal. This correction signal was sent to the summing amplifier, to correct the LO frequency.

All components of this locking system, shown in Figure 6(b), are implemented as surface-mount devices on printed circuit boards. The three boards have a volume of 6.3 cm^3, and all components together dissipate a total of 70 mW.



(a) (b)

Figure 6 (a) Schematic and (b) Photographs of control electronics used to lock the frequency of the local oscillator to the atomic transition resonance generated by the physics package.

In the future, we plan to implement a digital system that will control four major parameters critical to the operation of the frequency reference: the laser temperature, the cell temperature, the laser wavelength and the LO frequency. These four servos will be implemented in a low-power microprocessor, connected to the physics package and local oscillator with an analog interface circuit. This system is currently under development and is expected to be operational within one year; a schematic is shown in Figure 7.

PERFORMANCE

With all subsystems running together, the stability of the locked LO is $6\times10^{-10}/\sqrt{\tau}$, $0 < \tau < 100$ s, as shown in Figure 8. Since the physics package performed at $1\times10^{-10}/\sqrt{\tau}$ when operated with a large-scale LO and control electronics, the degradation to $6\times10^{-10}/\tau$ was likely caused by phase noise on the LO aliased down to low frequencies by the lock implementation. At longer integration times, the frequency of the system drifted due to temperature variations of the laser current.

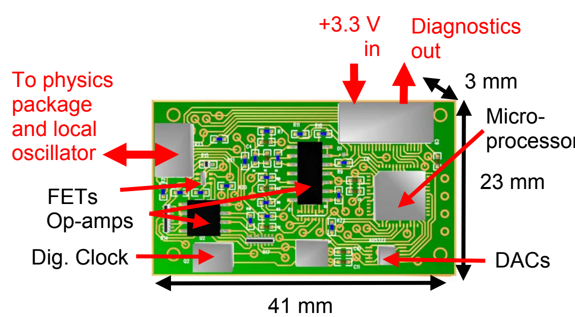


Figure 7 Digital control system under development to replace the analog system shown in Figure 6.

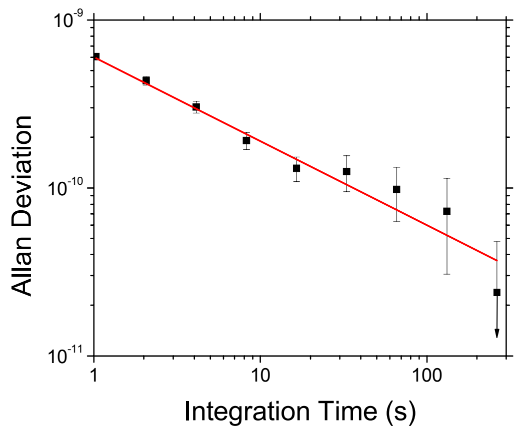


Figure 8 Allan deviation of low-power LO when locked with the compact control electronics to the MEMS physics package. A fractional frequency stability of $6\times10^{-10}/\sqrt{\tau}$ is obtained for $0 < \tau < 100$ s.

APPLICATIONS TO GNSS

As has been previously established [17] small, low-power atomic clocks could enhance the performance of GNSS receivers in a number of important ways. Perhaps the most significant of these at present is the enhanced code acquisition capability that precise long-term timing allows. In order to acquire a generic GNSS code, the receiver must do a search in both frequency and time and determine the unique receiver frequency and time that gives a high correlation between the receiver-generated code and the code received from the satellite. If the uncertainties in the receiver frequency and time are large, this search can require considerable processing power, particularly when the received signal is weak or when the code is long, as in the case of the P(Y) code.

For example, in indoor environments where the signals from the satellites are attenuated by building material, the reduced signal-to-noise implies a longer integration time is required to determine the correlation function for each time-frequency search bin. This in itself results in a longer code acquisition time. In addition, a longer integration time means that each frequency search bin is narrower, and therefore that more searches are required to determine the correct receiver frequency offset. A precise knowledge of both frequency and time would enable the receiver to narrow the search window over both quantities and therefore acquire the code in a shorter time.

Similar considerations apply for acquisition of the P(Y) code, even under normal signal strength conditions, and these have implications with regard to sensitivity of the receiver to jamming and interference. Normally P(Y) acquisition is done by first acquiring the C/A code, which has a much shorter code length, determining the time from this signal, and then using this time information to acquire the P(Y) code. While this acquisition process works well under many circumstances, it is considerably disadvantageous in a jamming environment, since the C/A code is broadcast over a much narrower bandwidth than the P(Y) code and is therefore much more sensitive to jamming. If a small clock is available to the receiver and timing to within 1 ms can be achieved over long periods, acquisition of the C/A code is not required. A quantitative analysis of the effect of a stable clock on P(Y) code acquisition was presented in [18].

Another advantage of precise time knowledge to GNSS receivers is that position can in principle be determined when fewer than four satellites are in view [19]. Since the receiver time is a known variable, only three unknowns remain in the position-time solution and therefore only three independent pieces of information are required to triangulate. This might be particularly important in urban environments, where buildings and other obstacles regularly impede the receiver's view of satellites.

Finally, a precise clock can allow a receiver on the earth's surface to better determine altitude [17]. Normally, the vertical component of the position solution is the least well known because of the effect of geometric dilution of precision. Since the receiver cannot see satellites below the horizon, the time uncertainty in the receiver is more tightly connected with the vertical uncertainty in position than it is with the horizontal uncertainty.

CONCLUSIONS

We have discussed ongoing work at NIST and the University of Colorado, Boulder to develop highly compact, low-power atomic frequency standards for use in portable, battery-operated devices. These devices are projected to have a volume below 1 cm^3, a power dissipation below 30 mW, and a fractional frequency instability at one hour of integration of 10^{-11}. This will allow microsecond-level timing over one day of operation, which could be used to considerable advantage in GNSS receivers.

The critical advance that allows such a small size for an atomic clock is the use of MEMS fabrication techniques. At present, the three critical subsystems that make up the frequency reference have been demonstrated. Together, they achieve a fractional frequency instability of $6\text{x}10^{-10}/\sqrt{\tau}$ for $\tau < 100$s, dissipate below 200 mW and have a total volume under 10 cm^3. It is anticipated that many improvements both in performance and size reduction will be achieved as this work progresses.

ACKNOWLEDGMENTS

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