

Component-Level Demonstration of a Microfabricated Atomic Frequency Reference

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Abstract— We demonstrate component-level functionality of the three critical subsystems for a miniature atomic clock based on microfabrication techniques: the physics package, the local oscillator and the control electronics. In addition, we demonstrate that these three components operating together achieve a short-term frequency instability of $6 \times 10^{-10}/\sqrt{\tau}$, with a total volume below 10 cm^3 and a power dissipation below 200 mW.

I. INTRODUCTION

Over the last three years highly miniaturized atomic frequency references based on microfabricated physics packages have evolved rapidly from concept [1] to component demonstration [2] to subsystem demonstration [3] to prototype [4]. These unique devices differ from all other atomic frequency references in that their physics packages are strongly motivated by microelectromechanical systems (MEMS). The use of MEMS techniques allows for an unprecedented degree of miniaturization of the device and an associated, and perhaps more important, reduction in the power required to run it. Funded almost exclusively by the Defense Advanced Research Projects Agency (DARPA), these “chip-scale” frequency references are expected to attain a volume below 1 cm^3 , a power dissipation below 30 mW, and a fractional frequency instability of 10^{-11} at one hour of integration. If these goals are obtained, this would represent an improvement by a factor of 100 in volume and power over the current state-of-the-art, while retaining essentially all of the long-term stability that atomic clocks provide. This work has been motivated in large part by the needs of advanced military systems and technology [5, 6] but major commercial applications exist both in global navigation satellite systems (GNSS) [7-9] and in wireless telecommunications systems [10].

Two key innovations have been responsible in large part for the successful development of microfabricated atomic frequency references:

- The use of atomic excitation based on coherent population trapping (CPT) [11-13], particularly

when generated by light from a modulated diode laser [14, 15]

- The use of MEMS for confining the atoms and integrating the optical and electronic components, first proposed to our knowledge in [1, 16, 17].

CPT allows for considerable simplification of the overall physics package design, while MEMS allows for a highly compact, low-power implementation. From a technical viewpoint, these innovations are largely independent: MEMS-based atomic clock physics packages have been proposed that do not include CPT [18] and many CPT implementations do not use MEMS [19]. We believe, however, that the most powerful designs, the ones most likely to make a considerable impact to our daily lives, include both CPT and MEMS.

In a general sense, the miniaturization of atomic frequency references has been an active area of research throughout the last fifteen years. Compact lamp-pumped vapor cell standards have been designed and tested [20-27], culminating in several successful commercial implementations [28]. These frequency references had a volume near 100 cm^3 , dissipated several watts of power and were stable to about 10^{-11} at an integration time of one second. Encouraging progress has also been made on miniaturized vapor cell frequency references pumped by diode lasers, rather than lamps, for even smaller size and lower power consumption [29].

Frequency references based on alternative excitation and detection techniques also offer the potential for improved performance, smaller size and lower power dissipation. In particular, atomic clocks based on coherent population trapping currently appear to have significant advantages, when compared to more conventional lamp-pumped devices [30, 31]. Coherent population trapping with externally modulated light fields was used initially for the realization of atomic beam frequency standards [32-35]. In this

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configuration, the modulated light field replaced the microwave cavities in the Ramsey interrogation zones. CPT frequency references based on phase-locked or directly modulated diode lasers were more recently investigated [14, 15, 36-38]. In table-top experiments [39-41], fractional frequency instabilities as low as 1.4×10^{-12} at one second were obtained. Much theoretical work has also been carried out to elucidate the fundamental limits to the performance of these devices [30, 31, 42-47]. Physics packages for compact frequency references based on CPT have also been developed [48] and the scaling of this type of frequency reference with cell size was investigated [1]. Recently, a practical realization of a compact frequency reference based on CPT for commercial and military applications was announced [49]. While this pioneering prototype had a volume of 125 cm^3 , comparable to the current generation of commercial optically pumped compact frequency references [50], and its power requirement was not discussed, the prospects for further miniaturization and low-power operation appear good.

Advanced CPT techniques have also been developed, most with the goal of increasing the resonance contrast and thereby improving the short-term frequency stability. These techniques include the use of the D1 line to excite the resonance [51],[52], the use of “end” resonances that are unaffected by spin-exchange broadening [53], the use of optical pumping techniques [54-56], the detection of polarization rotation [14, 57] and the use of ‘N-resonances’ [58]. In addition, spatially separated [59] time-separated [60-62] Ramsey-type CPT interrogation has been demonstrated, and is advantageous particularly with regard to control of the light shift. Direct detection of the microwave signal emitted by the atoms under CPT excitation has also been observed [46, 63-68] and an opto-electronic oscillator locked to an atomic vapor cell has also been investigated [69]. Many of these are described in other papers in these proceedings.

MEMS-based atomic clocks, utilizing CPT or otherwise, are a significant departure from conventional bulk-assembled designs. The use of lithography to define structural

geometries, wafer-level processing and assembly, and a high degree of integration of optical elements promises to allow unprecedented reductions in the size of atomic clocks. Since much of the power required to run an atomic frequency reference is used to heat the vapor cell to its operating temperature, small size also implies a low power dissipation.

The fabrication of MEMS-based vapor cells, a technology key to the implementation of a micromachined atomic frequency reference was demonstrated in 2003 at NIST [2, 70]. Other methods of fabricating highly compact MEMS-based vapor cells have also been successfully explored [71, 72]. Recently, the first physics package for a microfabricated (or chip-scale) atomic frequency reference was demonstrated [3]. This physics package had a volume of only 9.5 mm^3 , about a factor of 1000 smaller than the volume of the smallest physics packages previously described in the published literature [29].

Rather remarkably, this first physics package required only 75 mW to heat the cell to its operating temperature and run the laser diode (the power required to heat the laser was not included in the power budget since at that point, no attempt had been made to thermally isolate the laser from the surroundings). However, a detailed thermal analysis indicated that a more refined structure could dissipate under 15 mW of power at room temperature [73]. Another microfabricated atomic clock physics package, with a better thermal design based on polymer tethers, demonstrated operation on less 10 mW of power at room temperature [74].

II. CHIP-SCALE ATOMIC CLOCK COMPONENTS

A. Physics Package

The advanced physics package constructed at NIST over the last year and shown in Fig. 1, included several improvements over the device first demonstrated in 2004 [3]. The first of these improvements was the inclusion of a secondary baseplate on which the laser, and the rest of the device above it, was mounted. This secondary baseplate

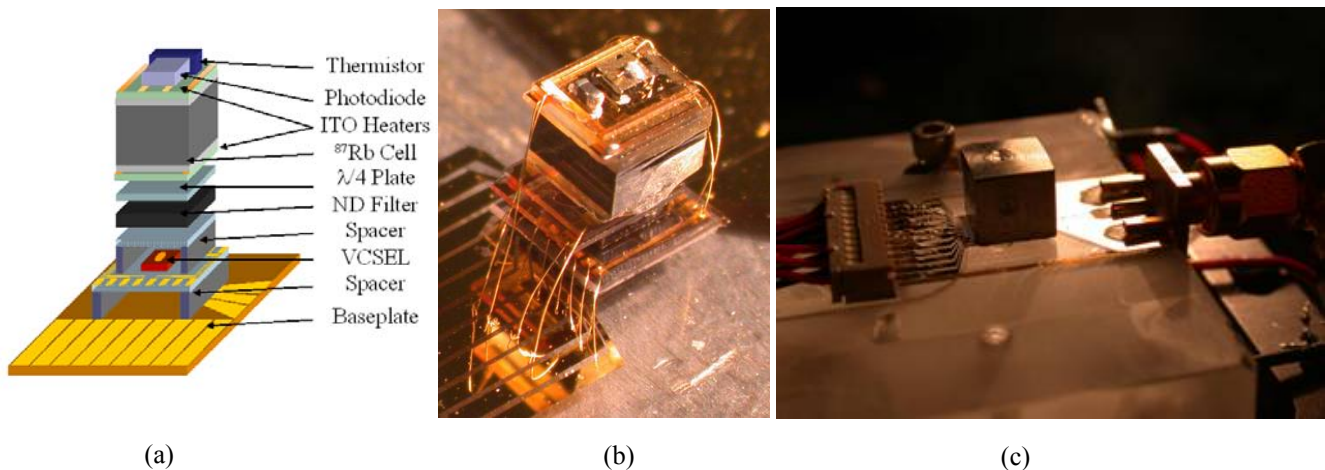


Figure 1. The NIST CSAC physics package. (a) Basic structure, (b) photograph and (c) packaged version with magnetic shield and B-field coils.

served to thermally isolate the laser from the primary baseplate, which was at room temperature, allowing the laser to be heated to its operating temperature (~ 75 °C) with less than 100 mW of power. Electrical connections from the rest of the physics package stack were wire-bonded to the secondary baseplate. These bonding pads were then connected via thin traces to a second set of bonding pads, which were connected to the primary baseplate.

Second, a small heater was included directly under the laser to provide highly localized heat to the laser die and further avoid conduction losses from this component. The heater was implemented with a lithographically defined resistive element etched in a tungsten film deposited on the (secondary) baseplate. By running current through the resistive element, the laser temperature could be controlled.

Third, two chip thermistors were mounted onto the structure, one placed near the laser and the second near the photodiode on the very top of the structure, which monitored the temperature of the cell. Because of the thermal isolation between the upper part of the structure and the secondary baseplate, the cell temperature and laser temperature could be controlled independently, and so the laser wavelength could be tuned to the appropriate frequency while simultaneously setting the cell temperature to produce an optimal optical thickness.

The physics package was based on D1 excitation of ^{87}Rb and achieved a fractional frequency instability of 1×10^{-10} at one second of integration, when operated with a large-scale control system and local oscillator. This physics package thus implemented ran on 110 mW of power at an ambient temperature of 25 °C. When placed in an evacuated environment the power dissipation dropped to 73 mW. The total volume of the packaged device, complete with magnetic shield and magnetic field coils, was 0.7 cm^3 .

Because of minor damage to the structure during the course of the integration experiments, the physics package had to be repaired. The rebuilt device, which was used in all subsequent experiments, had a somewhat higher power dissipation at room temperature, 195 mW. All other properties of this new physics package remained unchanged.

B. Local Oscillator

A compact voltage-controlled local oscillator (LO) [75] provided the 3.4 GHz modulation necessary for exciting the CPT resonance. The oscillator, shown photographed in Fig. 2(a), used a micro-coaxial resonator capacitively coupled in a series-resonant feedback topology. The loaded quality factor (Q) was measured to be 125, from which the unloaded Q was estimated to be 250. A loosely-coupled varactor diode provided a tuning range large enough to compensate for part tolerances and temperature-induced shifts, and small enough to achieve a precision lock to the atoms. This oscillator design was optimized for a minimal number of readily-available, surface-mount components for low cost and small size ($< 0.1 \text{ cm}^3$).

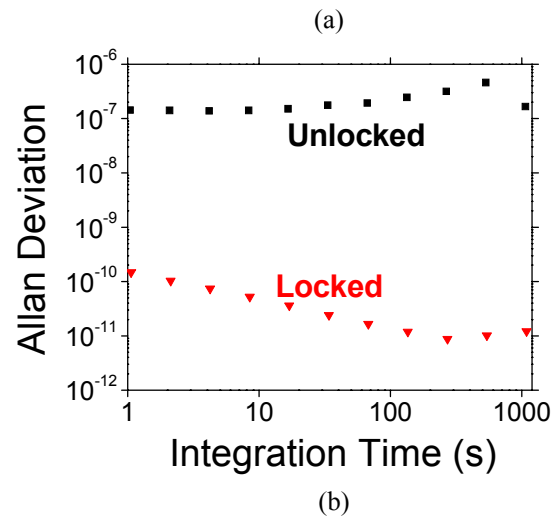
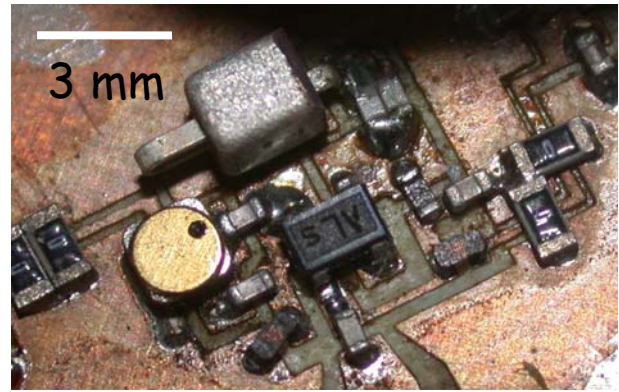


Figure 2. The local oscillation subsystem of the NIST chip-scale atomic clock. (a) Photograph of the LO, which is based on a micro-coaxial resonator at 3.4 GHz. (b) The fractional frequency stability of the LO running both unlocked and locked to a large-scale CPT physics package with large control electronics.

The LO output power was optimized for modulating the diode laser of the physics package. The LO generated 0.25 mW of RF power while consuming only 2.5mW of DC power. The measured single-sideband phase noise was -92dBc/Hz at a 10kHz offset and -33dBc/Hz at a 100Hz offset. When locked to a large-scale CPT physics package, the LO attained a fractional frequency instability below 2×10^{-10} at one second of integration [Fig. 2(b)].

C. Control Electronics

The control electronics subsystem performed the critical task of locking the local oscillator to the atomic CPT resonance by use of phase-sensitive detection. Phase-sensitive detection is required to a) lock the LO to the peak of the physics package resonance and b) reduce the effects of the excess electronic noise that exists at low frequencies. A rough schematic outlining the functionality of the control electronics is shown in Fig. 3.

In its most complex form, the control electronics should not only correct the LO frequency but also temperature stabilize the laser and absorption cell, as well as lock the wavelength of the laser to the absorption resonance. However, we have found that these three additional servo systems are not required in order to obtain significant short-term frequency stability results. Hence, we do not implement these servos here. The currents for the laser and cell heaters as well as the laser bias are considered simple power supply inputs. No active correction was applied to any of these parameters.

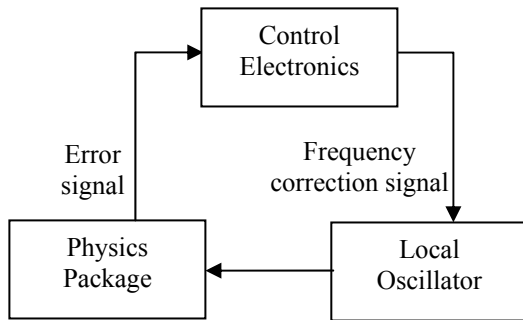


Figure 3. Schematic indicating functionality of control electronics with regard to LO and physics package.

The LO correction servo was implemented with a compact, low-power analog lock-in amplifier system. This system was shown schematically in Fig. 4(a). The modulation for the LO and also for the reference of the lock-in was generated by a LM555 [76] chip in a self-oscillation configuration. Each signal was sent to a flip-flop (74AC74 [76]) 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 is 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 [76]) 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 [76]), 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 were

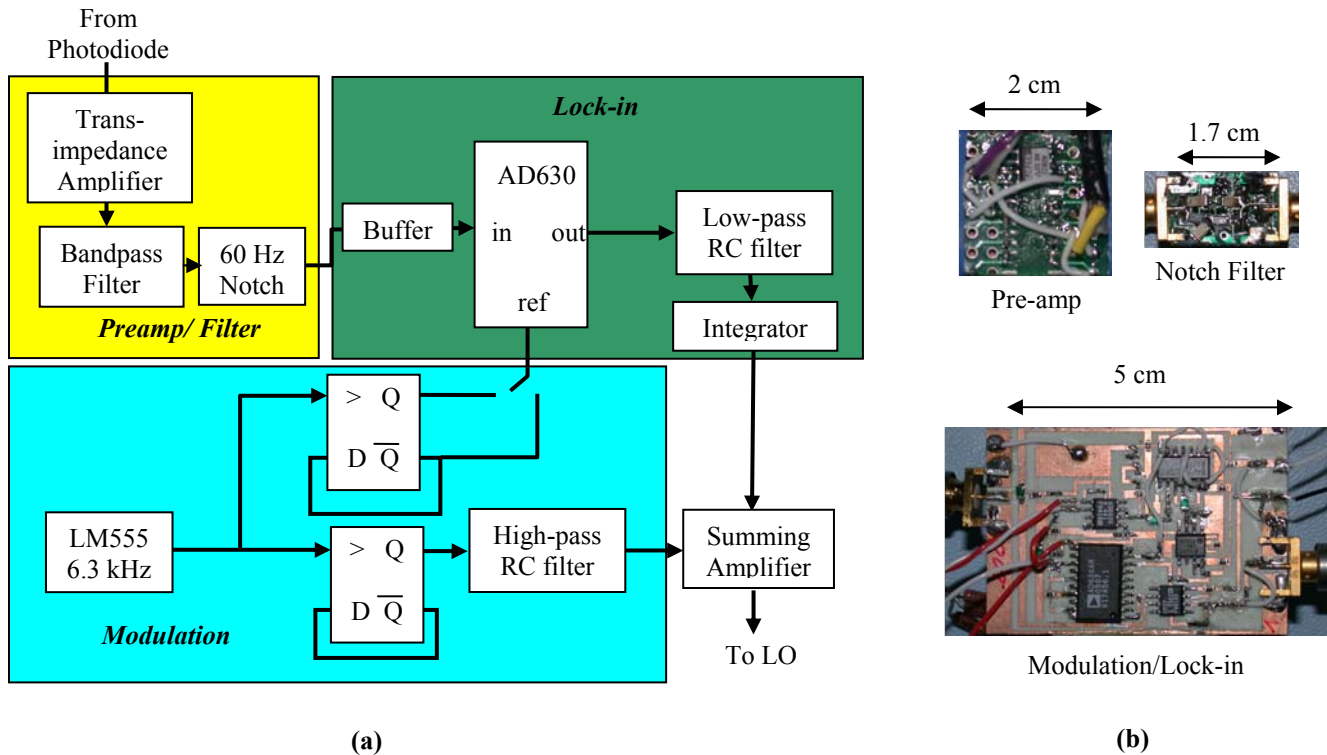


Figure 4. (a) Schematic of lock-in amplifier system and (b) Photograph of compact unit implemented on a printed circuit board. The system uses one phase-sensitive detector (AD630), one clock oscillator (LM555), dual flip-flops (74AC74), dual FET-input op-amps (AD8606), a low-noise op-amp (OP27), dual low-voltage-noise op-amps (OP284) and a number of discrete passive components. The total volume of the compact unit is 6.3 cm³ and the power required to run all components is 70 mW.

implemented as surface-mount devices on printed circuit boards. The three boards had a volume of 6.3 cm^3 and all components together dissipated a total of 70 mW.

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. We note that compact digital control systems for atomic frequency references have been described in [4, 49].

D. Integrated performance:

With all subsystems running together, the stability of the locked LO was $6 \times 10^{-10}/\sqrt{\tau}$, $0 < \tau < 100 \text{ s}$, as shown in Fig. 5. Since the physics package performed at $1 \times 10^{-10}/\sqrt{\tau}$ when operated with a large-scale LO and control electronics, the degradation to $6 \times 10^{-10}/\tau$ was likely caused by phase noise on the LO aliased down to low frequencies by the lock implementation [77]. At longer integration times, the frequency of the system drifted due to temperature variations of the laser current. The power dissipation of all subsystems is outlined in Table 1.

III. CONCLUSION

In conclusion, we have demonstrated functionality of the three main subsystems of a complete atomic frequency reference. These subsystems occupied a combined volume of 10 cm^3 and dissipated under 200 mW of power. The fractional frequency instability of the clock at one second of integration was 6×10^{-10} and was limited in large part by the

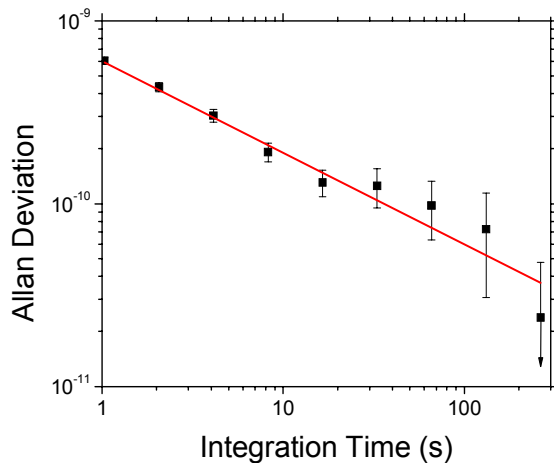


Figure 5. Allan deviation of low-power LO when locked with the compact control electronics to the MEMS physics package. A fractional frequency stability of $6 \times 10^{-10}/\sqrt{\tau}$ is obtained for $0 < \tau < 100 \text{ s}$.

TABLE 1 POWER BUDGET FOR THE NIST CHIP-SCALE ATOMIC CLOCK (CSAC).

Subsystem	Power Dissipated (mW)		Volume (cm^3)
<i>Physics Package (25 °C)</i>	<i>Best CSAC:</i> 110	<i>CSAC here:</i> 195	0.7^a
Cell heating	52	135	
Laser heating	55	57	
Laser DC current	2.5	2.8	
Magnetic field coils	0.1	0.1	
<i>Control electronics</i>	70^a		6.3^a
AD630	34		
AD8606	8		
74AC74	< 1		
OP284	11		
OP27	8		
LM555	< 1		
Biases	~ 10		
<i>Local Oscillator</i>	2.6^a		0.1^a
TOTAL	182.6 mW (measured, 25 °C)		7.1 cm^3

a. Measured value

performance of the control electronics and LO. Further improvements in stability are expected to be obtained with more refined control electronics and the use of a resonator with a higher Q-factor in the local oscillator.

We also expect to be able to integrate all three subsystems into a single compact package with a similar volume and power dissipation. Because of the small size of our physics package and local oscillator, prospects are excellent for further size reduction to near 1 cm; miniaturization of the electronics would be straightforward by using die electronics or an application specific integrated circuit (ASIC).

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