

# MICROFABRICATED ATOMIC CLOCKS AT NIST

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## Abstract

*This paper presents the latest progress in the development, fabrication, and characterization of microfabricated atomic frequency references at NIST. With volumes below 10 mm<sup>3</sup> the physics packages contain the complete integrated assembly for probing the ground-state hyperfine splitting frequency of the alkali atoms by coherent population trapping (CPT). This technique allows for a simple and compact device containing a vertical-cavity surface-emitting laser (VCSEL), optics to shape the laser beam, a vapor cell containing the atoms, and a detector. We present an improved technique for microfabricating the miniature alkali vapor cells. When integrated into a CPT clock, a clear reduction of long-term frequency drifts is observed. This leads to a fractional frequency instability of less than 10<sup>-11</sup> at one hour of integration, a more than one order of magnitude improvement over previous results. We identify the remaining sensitivities of the clock frequency to environmental influences and propose ways to reduce them.*

## INTRODUCTION

The application of coherent population trapping (CPT) [1] to vapor-cell atomic frequency references has led to a simple and elegant way to fabricate miniature microwave atomic clocks. The small size of these frequency references allows for a huge reduction in power consumption when compared to conventional atomic clocks. Recently, the first chip-scale atomic-clock (CSAC) physics package was demonstrated with a volume below 10 mm<sup>3</sup> [2]. It achieved a fractional frequency instability of  $3 \times 10^{-10}$  at 1 s of integration. This could potentially lead to complete frequency references of volume 1 cm<sup>3</sup>, with stabilities of 10<sup>-11</sup> at 1 hour of integration and power consumptions of 30 mW. Furthermore, design methods borrowed from the field of micro-electromechanical systems (MEMS), could allow for wafer-level

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fabrication and integration of atomic clocks. Small size, in combination with low power consumption and reduced fabrication costs, could result in the integration of CSACs into a wide variety of portable devices. Applications could range from anti-jam global positioning system (GPS) receivers to the synchronization of telecommunication networks [3].

## PRINCIPLE OF OPERATION

The CSAC takes advantage of CPT to excite a microwave resonance in the alkali atoms inside the vapor cell. This technique uses two phase-coherent light fields that couple the two hyperfine components of the ground state to a common excited state. If the frequency difference between the light fields is equal to the ground-state hyperfine splitting, the atoms can be pumped into a so-called dark state in which they no longer interact with either of the light fields. As a result, the transmission of the light through the atomic vapor increases (Figure 1). To create the two phase-stable light fields, the signal of a local oscillator is used to modulate the injection current of a vertical-cavity surface-emitting laser (VCSEL) at half the frequency of the ground-state splitting. The laser wavelength is tuned such that both first-order modulation sidebands are resonant with the transitions from the  $S_{1/2}$  state to one of the P-states. When the local oscillator frequency is chosen such that its second harmonic is equal to the frequency of the ground-state hyperfine splitting of the atoms, the light transmitted through the cell increases. This signal is used to tune the local oscillator frequency and keep it resonant with the atoms. The local oscillator is locked to the atomic resonance and provides the frequency output of the clock.

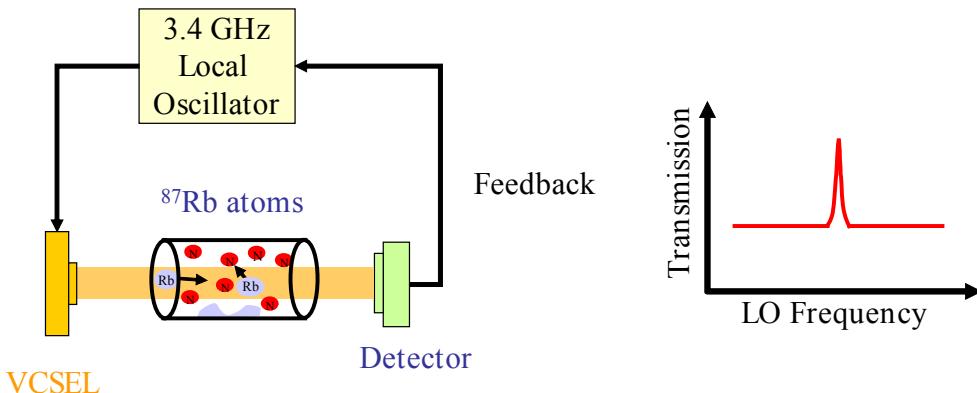


Figure 1. Principle of operation of a CPT Rb atomic clock. The current of a VCSEL is modulated at half the ground-state hyperfine splitting of the  $^{87}\text{Rb}$  atoms by use of a local oscillator. The emitted light transmitted through a vapor cell containing the Rb atoms is detected with a photodiode (left). When the frequency of the local oscillator is scanned, a CPT resonance can be detected in the transmitted light (right). The CPT signal can be used to lock the local oscillator to the atomic resonance.

## EXPERIMENTAL SETUP

A schematic and photograph of the clock physics package can be seen in Figure 2. At the bottom of the structure, a VCSEL is mounted onto a baseplate that provides the input for the DC laser current as well as the RF modulation current. In our first CSAC physics package based on the D<sub>2</sub> line of cesium, roughly 2 mA of DC current were required to tune the VCSEL to the atomic resonance at 852 nm wavelength at a temperature of 46°C. In order to transfer 60% of the light into the two first-order modulation sidebands, an RF power of 70 μW at 4.6 GHz was needed. This light was sent through a micro-optics assembly, mounted over the VCSEL onto a spacer unit. It consisted of two neutral-density filters, a micro-lens, and a quarter-wave plate. At its output was a roughly collimated beam of power 12 μW, of diameter 250 μm, and of circular polarization.

The light was transmitted through a vapor cell of interior volume 0.8 mm<sup>3</sup>, which contained the cesium atoms along with roughly 25 kPa of a mixture of nitrogen and argon. In order to increase the density of cesium atoms in the vapor to a point where roughly 30% of the light was absorbed, the cell was heated to 85°C. This was done with two transparent heaters, which were glued directly onto the windows of the vapor cell. When current was sent along a thin layer of indium-tin oxide (ITO) deposited onto a 125 μm thick piece of glass, heat was generated on the cell windows. Finally, the light transmitted through the cell was detected on a photodiode. The total volume of the physics package was 9.5 mm<sup>3</sup>.

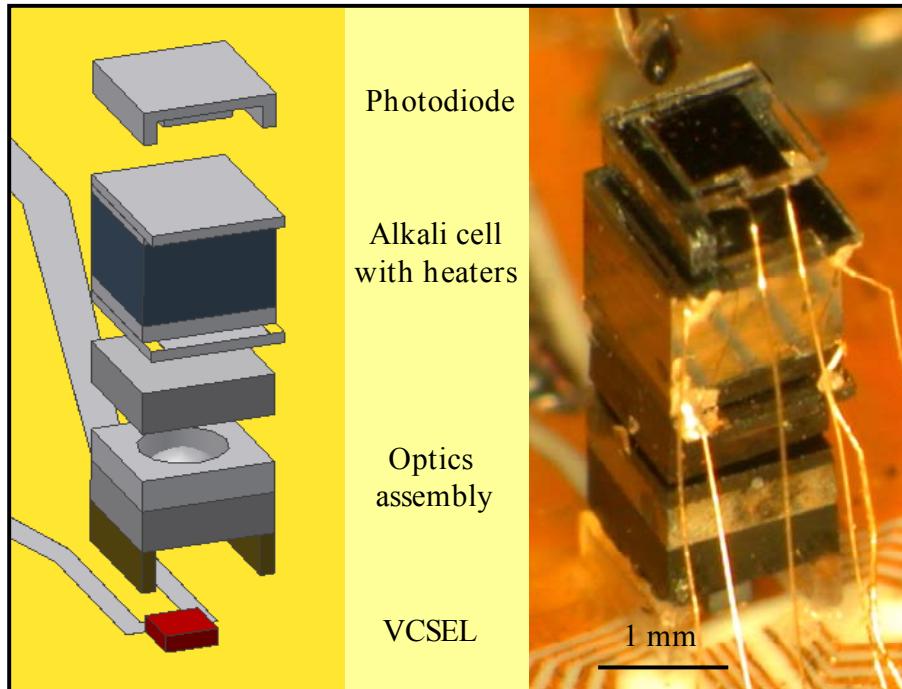


Figure 2. The chip-scale atomic-clock physics package has a total volume of 9.5 mm<sup>3</sup>. It consists of a VCSEL mounted onto a baseplate, a micro-optics assembly, a vapor cell with integrated ITO heaters, and a photodiode.

## IMPROVED CELL FILLING TECHNIQUE

One of the most challenging tasks in the development of the physics package is the fabrication of the vapor cell. We developed a method based on anodic bonding of silicon to Pyrex [4] that allowed us to confine the alkali atoms inside a cavity of volume 1 mm<sup>3</sup> that is surrounded by a material that does not react with the atoms, has transparent windows, and can be heated to more than 100°C. Holes were etched into a silicon wafer of thickness 1 mm using KOH etching. A piece of a Pyrex wafer was anodically bonded to one side of a silicon wafer at a temperature of 300°C and an applied voltage of 1000 V. This produced a preform with a cavity of size 1 mm<sup>3</sup> into which the alkali atoms could be deposited.

In the first chip-scale cells [4], the alkali atoms were reduced from alkali chloride directly inside the cell cavity. This was done by inserting a mixture of barium azide and alkali chloride, which is stable under air, into the cell cavity. The filled cell preform was placed inside a high vacuum chamber. At about 200°C barium azide decomposes. The free nitrogen was pumped off. As the barium reduced the alkali chloride, a residue of barium chloride remained inside the cell. The vacuum chamber was then filled with the buffer gases desired inside the cell. The cell was finally closed by attaching a piece of Pyrex wafer to the top of the silicon wafer at 300°C and roughly 250 V by anodic bonding. Finally, the chips were diced into individual cells with sides 1.4 mm.

A cesium cell made in this way, containing roughly 25 kPa of a mixture of N<sub>2</sub> and Ar in addition to the Cs, was built in to a CSAC physics package [2]. The Allan deviation, a measure of the fractional frequency instability versus integration time, is shown as the black squares in Figure 4. It can be seen that the clock experiences a frequency drift that becomes apparent at averaging times longer than 100 s. This drift was found to be the result of a temperature coefficient of the cell of +160 Hz / K and an underlying frequency drift of  $-2 \times 10^{-8}$  / day. We believe that both effects are caused primarily by the remaining barium residue inside the cell. At the operating temperature of 85°C, a slow reverse reaction seems to take place, where the nitrogen buffer gas reacts with the barium residue, depleting the pressure of buffer gas inside the cell. The change in buffer gas pressure shifts the clock frequency. We believe that this reaction depends on the temperature of the cell, which adds to the large temperature coefficient. Attempts to use mixtures of noble gases such as argon and neon as buffer gases, which do not react with barium, were of only limited success: reducing the slow frequency drift to  $-5 \times 10^{-9}$  per day. Since it is very difficult to eliminate nitrogen from the cell, that is, to make sure the reaction is completed, some frequency drift always results from the nitrogen that remains trapped inside the cell.

To reduce the frequency drift caused by the barium residue, we developed a new cell filling technique [5]. Here, the mixture of barium azide and alkali chloride was deposited into a small glass ampoule with a long narrow opening on one side, forming a nozzle of about 700 μm diameter (see Figure 3). The tip of the nozzle was small enough to be lowered into the cavity of the cell preform. Inside the vacuum system at pressures below 10<sup>-5</sup> kPa, the glass ampoule was heated to 200°C, where the barium azide decomposed. The nitrogen was pumped away until the pressure inside the vacuum chamber again reached a value below 10<sup>-4</sup> kPa. After the alkali chloride was reduced by the barium, the alkali atoms were diffused through the nozzle of the ampoule into the cell preform. The vacuum chamber was filled with 3.5 kPa of argon and 6 kPa of neon. A piece of a Pyrex wafer was fused to the top of the silicon wafer at 300°C and 200 V by anodic bonding.

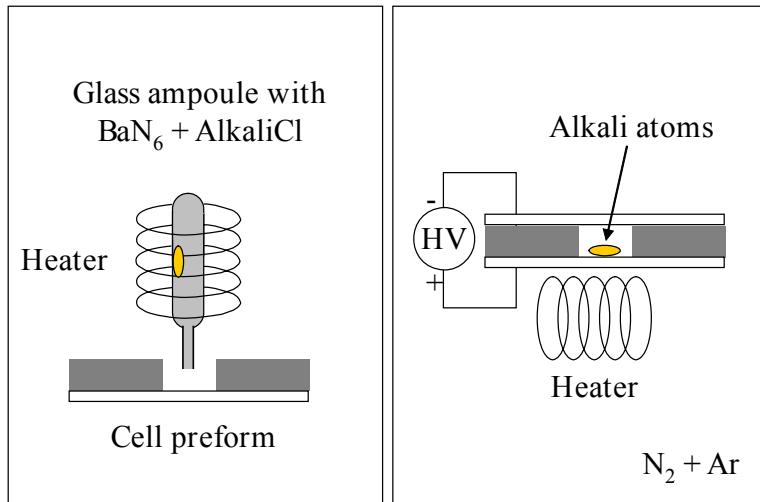


Figure 3. Novel filling method for chip-scale alkali cells. The alkali atoms are produced during a chemical reaction inside a glass ampoule. Afterwards, they are diffused through the nozzle of the ampoule into the cavity of the cell preform inside a vacuum chamber (left). Finally, the cell is closed using anodic bonding of a glass window onto the silicon wafer preform at 300°C and 250 V. The bonding is performed in an atmosphere of buffer gases desired inside the cell (right).

## EXPERIMENTAL RESULTS

A vapor cell produced by diffusion of  $^{87}\text{Rb}$  atoms in the way described in the previous paragraph was placed into a table-top CPT spectroscopy setup. The light was generated by a VCSEL emitting at 795 nm wavelength and was transmitted through a micro-optics package described in the previous section. Since the laser beam was still diverging after exiting the micro-optics package, it was collimated by an external lens and the polarization was readjusted to be circular. The cell was wedged between two aluminum heater plates. The plates were heated by a current sent through a twisted wire wrapped around them. The cell and heaters were placed at the center of a long coil inside a magnetic shield. Since the heaters produced a transverse magnetic field, an external longitudinal magnetic field of roughly 42  $\mu\text{T}$  was applied in order to lift the degeneracy of the Zeeman states and to ensure that the total magnetic field at the position of the cell was roughly parallel to the light beam, even when significant current flowed in the heater coils. The light transmitted through the cell was detected with a photodiode. A quartz crystal oscillator at 5 MHz serving as the frequency reference for a synthesizer at 3.4 GHz, half the ground-state splitting frequency of the  $^{78}\text{Rb}$  atoms, was then locked onto the CPT resonance, as described above. The output frequency of the CPT clock was measured against a more stable reference. The Allan deviation versus integration time measured in this way is plotted in Figure 4 (blue triangles). It can be seen that a fractional frequency instability of  $6 \times 10^{-11}$  was measured at 1 s of integration, averaging down to  $4 \times 10^{-12}$  at 1000 s. At 1 hour the instability was  $8 \times 10^{-12}$ , or below the goal set for the CSAC.

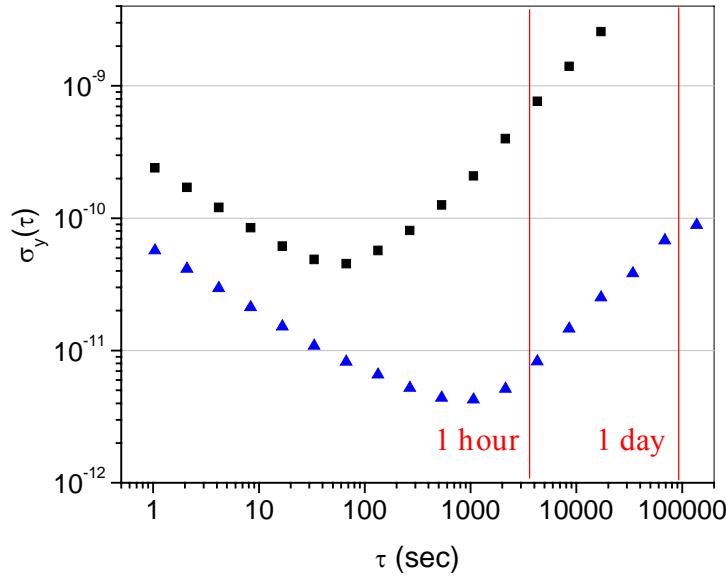


Figure 4. Allan deviation measured for the first CSAC physics package operating on the  $D_2$  line of Cs (squares) and a CPT clock operating on the  $D_1$  line of  $^{87}\text{Rb}$  with a chip-cell fabricated with the diffusion method (triangles).

It can be seen that the frequency stability at short integration times was improved by nearly an order of magnitude compared to that of the first CSAC. The reason for this is due mainly to more favorable selection rules when operating on the  $D_1$  line compared to the  $D_2$  line [6]. Some improvement is also found when using  $^{87}\text{Rb}$  instead of Cs, because it has half the number of ground-state Zeeman components compared to Cs. The major disadvantage with Rb is its lower vapor pressure. The rubidium vapor cells have to be operated at a temperature approximately 15 K higher than the cesium cells to achieve the same alkali density.

Figure 4 shows as well that frequency drifts become apparent at integration times longer than 1000 s. These drifts are caused mostly by fluctuations of the room temperature. For the clock, we measure a frequency shift of + 14.4 (5) Hz / K with respective changes of the temperature of the vapor cell. The temperature coefficient connected with the cell temperature is the result of the presence of buffer gases inside the cell [7]. As the temperature rises, the alkali and buffer gas atoms collide more frequently and with higher average velocity. This causes the buffer gas shift to depend on temperature. However, heavier buffer gas atoms shift the hyperfine components closer together, while lighter buffer gas atoms shift them apart. It is a well-known technique to use a mixture of light and heavy buffer gas atoms to compensate the temperature coefficient of the cell to a large degree. Therefore, by choosing the “magic” mixture of nitrogen and argon, it should be possible to reduce the temperature dependence of the cell by at least one order of magnitude.

Furthermore, the clock frequency was found to shift with laser temperature at a rate of + 14.4 (3) Hz / K. As the laser temperature drifts, the frequency lock of the laser changes the laser current, in order to keep the wavelength constantly on resonance. Operating at a different laser current alters the total laser power as well as the power of the modulation sidebands. The total AC Stark shift of the CPT resonance depends on the power in all laser fields present and, thus, depends on both the RF modulation index and the total

laser power. Since all the sidebands have a different detuning from the two atomic transitions, some of the light shifts cancel each other. By choosing a favorable RF modulation index, the optical power in the sidebands can be adjusted such that the frequency shift due to a change in total laser power and the frequency shift due to a change in the modulation index cancel each other to a large degree [8]. This can be seen in Figure 5, where the clock frequency is plotted as a function of laser temperature for three different modulation indexes. With this technique, it is possible to reduce the temperature coefficient due to changes in laser temperature to 0.2 (6) Hz/K. Operating the clock at this RF modulation index degrades the short-term frequency stability of the clock, by a factor of roughly 1.3.

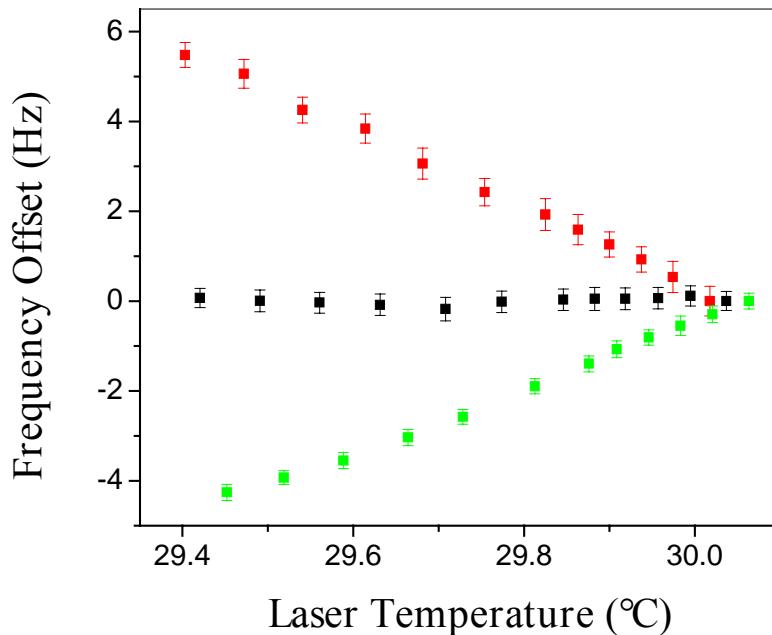


Figure 5. Frequency offset of the CPT clock frequency measured with a chip-cell of interior volume  $1 \text{ mm}^3$  for three different RF modulation indexes. The red squares correspond to a low, the black squares to a medium and the green squares to a high modulation index. It can be seen that the modulation index can be chosen such that the sensitivity of the clock frequency onto laser temperature is cancelled to a large extent. The frequencies are offset from different values for the three different graphs.

## SUMMARY

We introduce a new vapor-cell filling technique that eliminates the frequency drift of the chip-scale vapor cells to a large extent. Cells made with this method of diffusing the alkali atoms into the cell cavity apparently have no significant residues of other chemicals inside. A frequency reference using one of these cells with an interior volume of  $1 \text{ mm}^3$  in a coherent-population trapping setup shows improved long-term frequency stability compared to previous chip-scale atomic clocks. A fractional frequency instability of  $6 \times 10^{-11} / \tau^{1/2}$ , averaging down to  $4 \times 10^{-12}$  at 1000 s, was measured. The remaining frequency drifts can be attributed to fluctuations in the temperatures of the vapor cell and the laser. Finally, we propose a method to reduce these sensitivities, which might further improve the frequency

stability of chip-scale CPT clocks at long averaging times.

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## QUESTIONS AND ANSWERS

**ROBERT LUTWAK (Symmetricom):** Your data in which you reduce the light shift by adjusting your sideband balance, I would like to know what species and transition is that? And, also, what is your stability when you are running at that RF power?

**SVENJA KNAPPE:** Okay, it was done in the rubidium 87 on the D<sub>1</sub> line. But basically, I don't think it is limited to the D<sub>1</sub> line of rubidium, that you will find it on the other lines too. On the D1 line at least.

On the D<sub>2</sub> line, the light shift in general is bigger. And so you have a harder time to compensate the overall light shift.

The short-term stability we have run at that optimum is, I think,  $8 \times 10^{-11}$  instead of  $6 \times 10^{-11}$ . So it is a still a fairly favorable RF power we can run that at.

**JIM CAMPARO (The Aerospace Corporation):** In going to neon and argon, it seems like you're not worried about any kind of radiation trapping from fluorescence. Is that just because of the small volume that you figure that the photons just get out?

**KNAPPE:** That is a thing we have been discussing a lot. But I have not any good answer why we cannot see any effect of radiation trapping. It could be the small volume, but then we are operating in a very high density. So there are a lot of atoms.

**CAMPARO:** Are you aware of Krause? Krause, up in Canada, was doing sensitized fluorescence, and he measured increases in the lifetime of the excited state. That is when they were looking at trapping. Do you know of that work?

**KNAPPE:** No.

**CAMPARO:** If you do not, I will send you the references. I will give you my card, or I will get your card, and I will send you those references. Maybe that would help you explain what the depth might be for the temperatures and maybe the photons are just coming out. And you do not need to worry about it.

**KNAPPE:** Yes, the other thing is that once we move to the diffusion cells, we can go back to nitrogen. So we can get rid of the trapping that way, if we think we are limited by it.