A chip-scale atomic clock based on ^{87}Rb with improved frequency stability

S. Knappe, P.D.D. Schwindt, V. Shah[†], L. Hollberg, and J. Kitching

Time and Frequency Division, National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

[†] *also with: Physics Department, University of Colorado, Boulder, CO 80309, USA*
knappe@boulder.nist.gov

http://www.boulder.nist.gov/timefreq/ofm/smallclock/

L. Liew and J. Moreland

Electromagnetics Division, National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

Abstract: We demonstrate a microfabricated atomic clock physics package based on coherent population trapping (CPT) on the D_1 line of ^{87}Rb atoms. The package occupies a volume of 12 mm^3 and requires 195 mW of power to operate at an ambient temperature of 200 °C. Compared to a previous microfabricated clock exciting the D_2 transition in Cs [1], this ^{87}Rb clock shows significantly improved short- and long-term stability. The instability at short times is $4 \times 10^{-11} / \tau^{1/2}$ and the improvement over the Cs device is due mainly to an increase in resonance amplitude. At longer times ($\tau > 50$ s), the improvement results from the reduction of a slow drift to $-5 \times 10^{-9} /$ day. The drift is most likely caused by a chemical reaction of nitrogen and barium inside the cell. When probing the atoms on the D_1 line, spin-exchange collisions between Rb atoms and optical pumping appear to have increased importance compared to the D_2 line.

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1. Introduction

Battery-operated clocks with frequency instabilities in the 10^{-11} range for time intervals of up to a day, and in a package not larger than 1 cm^3, could find widespread use in portable electronic devices. Certain military [2,3] and civilian [4] applications, such as jam-resistant global positioning systems and synchronization of mobile communication and navigation networks, demand timing precision that cannot be reached with low-power quartz crystal technology over time intervals of more than a few minutes. Atomic clocks can provide these stabilities, but state-of-the-art atomic clocks are large (~ 100 cm^3) and consume several watts of power, making them unusable for portable applications. Chip-scale atomic clocks (CSACs) could bridge this gap. Recently, the first CSAC physics package was demonstrated [1].

2. The chip-scale atomic clock

The microfabricated frequency references being developed at the National Institute of Standards and Technology (NIST) are based on miniature cells containing an alkali atom vapor fabricated by use of etched Si wafers bonded to glass windows [5,6]. The miniature cells used in the devices described here were filled with ^{87}Rb by reacting BaN_6 and ^{87}RbCl in a controlled environment. The reaction produces alkali atoms, Ba, Cl, and N_2 in addition to the ^{87}Rb. Before sealing the cell by anodic bonding [7], most of the nitrogen produced in the reaction was pumped off, and the vacuum chamber, including the interior of the cell, was
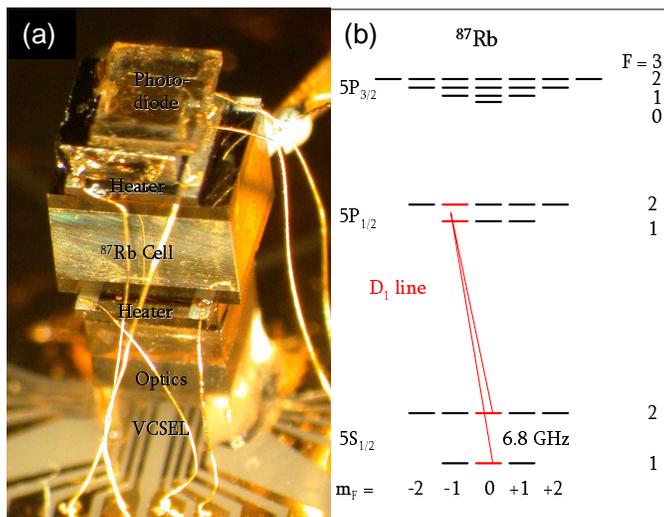

Fig. 1. (a) Picture of the ^{87}Rb D_1 CSAC physics package. (b) Level diagram of ^{87}Rb.

backfilled with 24 kPa of neon and 11 kPa of argon. The interior volume of the cell was 1 mm^3. The cell was integrated with heaters, an optics assembly, a vertical-cavity surface-emitting laser (VCSEL) light source, and a photodetector to form a functional physics package for an atomic clock of volume 12 mm^3, consuming 195 mW of power at an ambient temperature of 22 °C (Fig. 1a). The power to run the electronics and the synthesizer are not

part of the 195 mW of power dissipation at present. In a final design, it should be possible to reduce the total power required to operate the complete system to below 50 mW.

The atomic hyperfine resonance was excited by use of coherent population trapping spectroscopy (CPT) [8] on the D_1 lines of ^{87}Rb (Fig. 1(b)). The two phase-stable circularly polarized light fields were produced by modulating the current of the VCSEL at half the frequency of the ground-state hyperfine splitting, creating two first-order sidebands on the optical carrier separated by the full atomic hyperfine splitting of 6.8 GHz. The laser wavelength of 795 nm was then tuned so that these two sidebands were resonant with the transitions from the two ground states to the excited $5P_{1/2}$ state. A longitudinal magnetic field was applied to lift the degeneracy of the Zeeman sub-states. The modulation frequency was tuned such that the CPT resonance associated with the two first-order magnetically-insensitive components $m_F = 0$ was excited. The resonance was detected by measuring the transmitted optical power by use of phase-sensitive detection with a lock-in amplifier. A feedback loop stabilized the modulation frequency of 3.4 GHz onto the center of the CPT resonance.

3. Experimental results

3.1 Short-term frequency stability

The red dots in Fig. 2 show the Allan deviation versus averaging time for the clock described above. The cell was heated to 120 °C to increase the vapor pressure to the point where the optical absorption through the cell was 25 %. The measured short-term stability of 4×10^{-11} / $\tau^{1/2}$ was consistent with an estimate based on the width and amplitude of the dark line
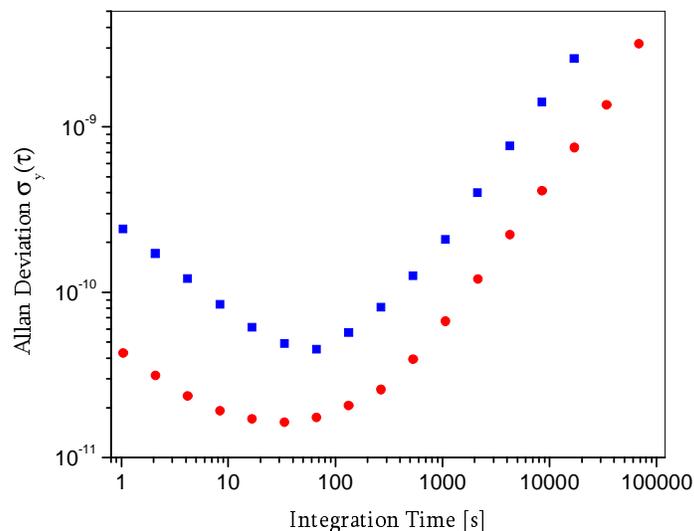

Fig. 2. Measured Allan deviation for the ^{87}Rb D_1 CSAC (red dots). It shows a clear improvement in stability over the first CSAC [1], which was based on the Cs D_2 line (blue squares).

resonance and the detection noise. Since the detection noise was within a factor of two of the shot-noise level, the properties of the dark line resonance had the largest and most direct impact on the stability of the clock. The fractional reduction in absorption of the laser light due to the CPT was 4.6 %. The improvement of the short-term stability over the first CSAC physics package developed by our group at NIST using the D_2 line of cesium (blue squares in Fig. 2) was due mainly to the increase in resonance contrast, which is caused by the following differences: Firstly, ^{87}Rb has eight ground-state Zeeman components, half the number of Cs, so when the atomic population is distributed equally among the levels ¼ of the atoms are

found in the $m_F = 0$ states. Secondly, selection rules allow single-photon transitions out of the dark state to the excited $P_{3/2}$ state, but not to the $P_{1/2}$ state. The longer lifetime of the dark state using the D_1 line [9,10] results in a larger resonance amplitude and thus a better short-term stability of the clock. Finally, the two Λ-systems formed by the 0–0 ground states and the m_F = −1 states of the two excited state hyperfine components can have a "coherent dark state" simultaneously [9], which is not the case for Λ-systems formed by the corresponding levels connected with the D_2 lines. Nevertheless, the normalized CPT resonance amplitude is still lower than the one measured in centimeter-sized cells containing [87]Rb. This is due most likely to off-resonant excitation to the strongly homogeneously broadened $P_{1/2}$ state by the carrier and second-order sidebands of the laser field.

The CPT linewidth was measured to be 9.3 kHz. Nearly one third of this width is a result of power broadening from the 125 μm diameter laser beam of power 3.5 μW. The remaining linewidth is dominated by spin-exchange collisions between the Rb atoms, while contributions due to collisions of the Rb atoms with the cell walls and the buffer gas atoms play a minor role.

3.2 Long-term frequency stability

From Fig. 2 it is also apparent that the rubidium CSAC physics package also had a much improved long-term stability as compared to its Cs predecessor. The clock frequency is
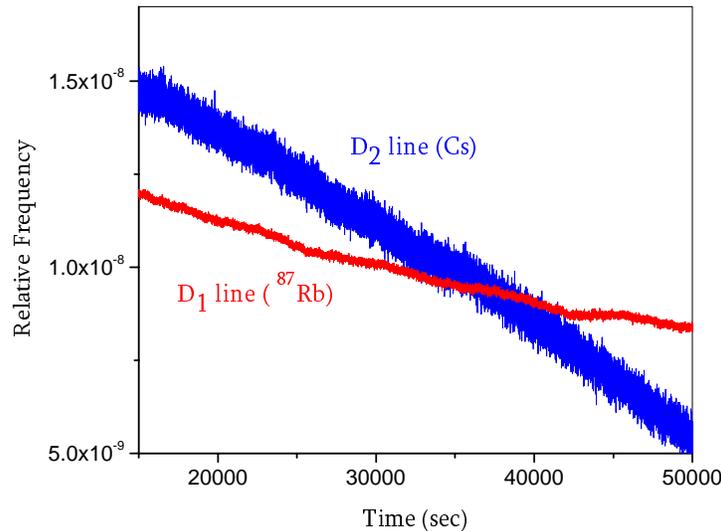

Fig. 3. Measured clock frequency normalized to the hyperfine frequency as a function of time for the [87]Rb D_1 CSAC (red). It can be seen that the slow frequency drift is reduced compared to the first Cs D_2 CSAC (blue).

plotted as a function of time in Fig. 3. From the red line in Fig. 3 a linear drift of -5×10^{-9} / day was measured. It appears likely that the chemical reaction that produced the Rb generated some nitrogen gas that was not completely pumped away before the cell was sealed. The barium residue that remained on the cell walls after the initial chemicals have reacted could then have recombined with the residual N_2, decreasing the N_2 pressure over time and causing a drift in the CPT frequency. Since barium does not react with noble gases, the Ne and Ar buffer gases also contained in the cell should not contribute to the slow frequency drift. Nevertheless, this clock demonstrated a substantial improvement over the long-term stability of the first cesium clock (blue line in Fig. 3), for which nitrogen was one of the primary buffer

gases contained in the cell. To reduce the instability at long times to the 10^{-11} range, we must eliminate the slow reaction and improve our control over the cell temperature. Thermal isolation of the cell by vacuum packaging and an advanced package design, as well as a better temperature sensor, are important future improvements to be considered.

3.3 Optical pumping

The temperature of 120 °C at which the cell had to be operated to achieve 25 % absorption is higher than expected from the vapor pressure and absorption cross-section. We believe that a reason for this can be found in the existence of a trapping state that exists for left-hand circularly polarized light in a longitudinal magnetic field on the D_1 line: atoms can accumulate in the "stretched state" $|5S_{1/2}, F = 2, m_F = -2\rangle$, since they cannot be excited by the light field from there. Note, that this state is not the coherent dark state used for the clock interrogation, but a single Zeeman state which cannot interact with the light fields. Furthermore, the circularly polarized light pumps atoms towards that state. Buffer gas collisions, on the other hand, depolarize the excited $P_{1/2}$ state, counteracting the optical pumping towards the "stretched state". But even for complete depolarization in the excited state, a substantial fraction of atoms would still get trapped in the "stretched state" for D_1 excitation [11]. At a buffer gas pressure of 32 kPa we estimate a depolarizing collision to happen roughly every 4 ns for atoms in the excited $P_{1/2}$ state, an order of magnitude less frequently than for atoms in the $P_{3/2}$ excited state [12]. Since this rate is close to the excited state lifetime of 28 ns, additional optical pumping towards the "stretched state" may be significant. Some evidence of this can be found when comparing the CPT resonances that couple the magnetically sensitive states with the same magnetic quantum number. The amplitude of the $(-1; -1)$ resonance is twice as high as the $(+1;+1)$ resonance using the laser power at which the CSAC is operated. For very low light intensities however, we find a ratio of the amplitudes of roughly 1.3. This indicates that the population in the $m_F = -1$ Zeeman-states is higher and optical pumping toward the "stretched state" takes place.

The "stretched state" is dark for the circularly polarized laser light and therefore these atoms contribute neither to the CPT resonance nor to the Doppler-broadened background absorption. But they do affect the performance of the clock because they can collide with the alkali atoms in the dark state, thereby broadening the CPT resonance. In fact, we estimate the broadening of the CPT resonance due to spin-exchange collisions to be the dominant broadening mechanism for the Rb D_1 CSAC. Furthermore, since the alkali density has to be several times higher on the D_1 line than on the D_2 line to achieve the same absorption, the vapor cell has to be heated to a higher temperature and therefore a clock based on D_1 excitation might in principle require more power to operate.

4. Conclusion

The first ^{87}Rb-based CSAC physics package has been demonstrated in a volume of 12 mm^3, dissipating 195 mW of power at an ambient temperature of 22 °C. Excited using light resonant with the D_1 line, it exhibited a much better short-term stability than CSACs operating on the D_2 line of cesium. A fractional frequency instability of $4 \times 10^{-11} / \tau^{1/2}$ was achieved for integration times between 1 s and 10 s. Using noble gases of neon or argon, a residual long-term drift of $-5 \times 10^{-9} /$ day was measured. When using the D_1 line, optical Zeeman pumping and the existence of a dark trapping state cause atoms to accumulate in the "stretched state". As a result of this a higher cell temperature is required, which increases the power consumption of the CSAC as well as the broadening due to spin-exchange collisions.