New generation of a mobile primary frequency standard based on cold atoms

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Abstract. We have constructed a mobile primary frequency standard using intra-cavity cold cesium atoms and the results have shown the advantages of using this kind of system compared to cesium beam standards. Based on the first setup with an expanding cloud of atoms, we can plan the construction of a clock more compact since it has no strict size limitations. In order to assemble the new system even smaller, the development of a system containing lasers, microwave source and cavity in a single box has already begun. The mobile atomic standard based on cold atoms is a possible strategic product with a broad range of applications and an important contribution to a primary standard of high relevance.

1. Introduction

With exceptional accuracy, atomic clocks have applications in several fields of modern fundamental physics [1]. They allow not only to investigate the macroscopic scales theories like relativity or gravitation, but also to know better the microscopic world, in atomic scale, thanks to quantum mechanics. Two of the main applications are navigation and telecommunication systems, and atomic references are the heart of the most advanced navigation system, satellite constellations positioning like GPS, GLONASS, and Beidou [2].

Most of the high performance time standards require an extremely complex construction and operation, but the size of these systems makes them incompatible with some applications, which require a compromise between size and performance. These include space and industrial applications, such as telecommunication lines, mobile telephone networks or internet, calibration of instruments, dissemination of local time references with good quality, etc.

The Atomic Time and frequency Standard Program USP São Carlos [3] started a few years ago with the construction of a thermal beam atomic frequency standard, today our research is focused on the development of two frequency standards based on cold atoms: an atomic fountain [4] and a compact system based in a cold atomic cloud in free expansion [5]. Besides those experimental standards, our facility has commercial atomic clocks and a hydrogen maser.

The atomic frequency standards developed up to now provided us the theoretical and experimental knowledge for the development of a mobile atomic frequency standard with the same level of precision.
and stability of the previous setups. The new diode laser sources, microwave synthesizer, vacuum and control systems are being reduced in order to ensure the portability of the system.

2. Experimental setup and temporal sequence
The aim of this project is the construction of a cold atoms compact frequency standard that works in an innovative way, since the steps of the sequence occur in the same place, within a microwave cavity. For the physical package we use a cylindrical cavity, sculpted in a stainless steel vacuum chamber and resonant in 9.2 GHz. This operation mode allows us to design a much more compact system than a conventional cold atoms clock, where the various interactions are in different parts of the instrument. Therefore, the compactness of the clock is achieved through a sequence purely temporal. The most relevant steps can be seen in Figure 1.

![Figure 1. Temporal sequence of a clock cycle performed inside the microwave cavity.](image)

The temporal sequence of the compact frequency standard can be divided in four well defined steps (see figure 1), as follows:

**(Step 1) Trapping atoms in a magneto optical trap (MOT)**
In this stage is possible to capture $10^8$ atoms using magnetic field and three counter-propagating pairs of laser beams (MOT) [6]. This is important to catch up the atoms together in the same spatial region, forming a cold cloud, and to remove a huge portion of the cloud’s kinetic energy. In this step the atomic cloud attains very low temperatures and becomes more stable. The $5F_2^1 \rightarrow 4F_3^2$ cycling transition is used, and repumping is done using the $5F_2^1 \rightarrow 6P_{3/2}^1$ transition.

**(Step 2) Sub-Doppler Cooling and the Preparation**
After the first reduction of the kinetic energy, the system passes from MOT configuration to optical molasses by switching off the current supply of the magnetic field. Simultaneously, the atomic cloud is cooled even more, changing the intensity and detuning of the laser beams with acousto-optical modulators, reaching levels below $10 \mu$K. In order to prepare the atoms in their ground electronic state $6S_{1/2}^1 |F=3\rangle$, the repumping light is switched off 5 ms before shutting off the cooling light. During this interval, optical pumping efficiently transfers the atoms to the required ground state.

**(Step 3) The clock transition interrogation**
Now, the cold atoms are in a single initial state and after the total shutdown of the lasers beams, the cloud starts a free expansion. During the expansion the atoms are interrogated in a Ramsey sequence
[7], consisting of two coherent microwave pulses $\pi/2$ with 1 ms of duration and separated by 8 ms. These pulses excite the clock transition between the two hyperfine levels $6^5S_{1/2}|F = 3, m_F = 0\rangle \rightarrow 6^5S_{1/2}|F = 4, m_F = 0\rangle$.

(Step 4) The Detection

To detect the atoms that have transitioned to the $6^5S_{1/2}|F = 4\rangle$ level after the two microwave pulses, the light beams originally used as a cooling laser are turned back on for 40 ms, and the fluorescence signal is collected.

Once the resonance is observed, it can be used as a frequency discriminator. The transition probability difference of two successive measurement acts as an error signal used to control the local oscillator frequency.

3. Results

Figure 2 presents a typical scan of the microwave frequency across the clock resonance in our device [5]. Using the Ramsey fringe of Figure 2, we can scan around the central fringe to determine the linewidth with a theoretical fitting (Figure 3), obtaining a value of 47 Hz. The contrast is better than 80% (where the contrast is defined as a difference between resonance amplitude and background).

To measure the frequency stability of the system it is necessary to lock the central resonance observed on figure 3 to the microwave chain (macroscopic oscillator). The microwave chain on the other hand is phase locked to the 5 MHz output of the Hydrogen Maser. The modulation of the frequency is controlled by a computer, which also register the introduced correction to keep the interrogation signal at its maximum.

The stability observed is $\sigma_f(\tau) = (5 \pm 0.5) \times 10^{-13}\tau^{-1/2}$, as presented in Figure 4, demonstrating that this compact cold atom frequency standard can reach performances better than commercial beam clocks, which typically have short time stabilities on the range of $10^{-11} - 10^{-12}$.

![Figure 2](image2.png)

**Figure 2.** Ramsey Fringes obtained by an interrogation performed in the cavity by two microwave pulses of 1 ms each and separated by 8 ms. The linewidth of the central fringe is 47 Hz.

![Figure 3](image3.png)

**Figure 3.** Scan over the central Ramsey fringe (figure 2) giving a 47 Hz linewith with 80% contrast.

The advantage of cold atoms in such compact system can be easily observed if compared with commercial thermal Cs beam clocks. The long term stability already surpasses the currently used commercial standards and the clock transition linewidth is on the order of 50 Hz for our system, meanwhile the same resolution can be achieved only with a thermal system that has some meters in the interrogation region (26 Hz for a 4 m long interrogation region [8]).
4. Reducing the system volume

We actually envisage a more compact system, mounting the apparatus in a single block. This should be done keeping all the necessary processes to produce a frequency standard signal.

4.1. The macroscopic oscillator

A fundamental piece of the atomic standard, it corresponds to the signal that generates the time reference. The feedback from the atoms interrogated with its signal closes the loop for the atomic frequency reference. It should be as small as possible, but still taking into account some parameters as temperature deviations [9, 10]. To achieve reliable performance, we will use PID (Proportional-Integral-Derivative) control and peltier elements as actuators.

4.2. Lasers Diode

The use of laser diodes is fundamental in the system. They should keep a very low effective linewidth, in order to not degrade the SNR of the clock transition. In the limit of high resolution spectroscopy, the laser noise can add a significant parcel to the overall budget of noise contributions.

4.3. General Control of the System

Careful control of all the steps of the clockwork (trap, sub-doppler cooling, interrogation and detection) is mandatory. In each cycle the microwave source is corrected, and the steps consist of well synchronized events, such as laser light frequency shifts, pulsing of the microwave signal, triggered signal detection and processing of the atomic fluorescence [11].

5. Conclusions

We have developed a compact system to be used as a mobile reference for frequency signals. We managed to cool $10^8$ atoms at 10 μK in a microwave cavity and after the Ramsey interrogation the detection by fluorescence is applied. The core idea is the use of cold atoms as a high performance and reliable clock source. We have been working in the reduction of volume to make an embeddable prototype, in order to maintain the high quality characteristics necessary for the operation of such device.

References

[1] Jespersen J and Fitz-Randolph J 1999 From sundials to atomic clocks (Mineola: Dover Publications)
[2] Ramsey N F 2002 *Application of atomic clocks* in: *Laser physics at the limits*, ed Figger H. *et al* (Berlin: Springer) p 3
[3] Ahmed M, Magalhães D V, Bebeachibuli A, Müller S T, Alves R F, Ortega T A, Weiner J and Bagnato V S 2008 The brazilian time and frequency atomic standards program *An Acad Bras Cienc* **80**, 2
[4] Magalhães D V 2004 Construção de uma fountain atômica para utilização como padrão primário de tempo *Doctorate thesis*
[5] Müller S T, Magalhães D V, Alves R F and Bagnato V S 2011 Compact Frequency Standard based on an Intracavity Sample of Cold Cesium Atoms *J. Opt. Soc. Am. B* **28** 11 p 2592
[6] Metcalf H and Van Der Straten P 2003 Laser cooling and trapping of atoms *J. Opt. Soc. Am. B* **20** p 887
[7] Vanier J, Audoin C 1989 *The quantum physics of atomic frequency standards* v2 (Adam Hilger)
[8] Glaze D J, Hellwig H, Allan D W and S. Jarvis 1977 NBS-4 and NBS-6: The NBS primary frequency standards *Metrologia* **13** p 17-28
[9] L. E. Schnurr 1967 The transient thermal characteristics of quartz resonators and their relation to temperature-frequency curve distortion *21st Annual Symposium on Frequency Control* (1967)
[10] Ji Wang, Yook-Kong Yong and Tsutomu Imai 1998 High-order plate theory based finite element analysis of the frequency-temperature relations of quartz crystal oscillators *Frequency Control Symposium* Proceedings of the 1998 IEEE International (1998)
[11] J. Levine 1999 *Introduction to time and frequency metrology* *Review of scientific instruments* **70**, 6