Chip Scale Atomic Clocks Sources: Working Principles and Applications

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Abstract

Chip Scale Atomic Clocks (CSACs) have emerged as compact and high-performance timing references, revolutionizing various applications where precise timekeeping is essential. This paper provides a comprehensive overview of the working principles and diverse applications of CSACs. Beginning with an introduction to the fundamental principles of atomic clocks, including the operation of the cesium and rubidium-based systems, this paper delves into the miniaturization and integration of these technologies onto semiconductor chips.

The discussion elaborates on the core components of CSACs, such as the miniature atomic vapor cell, laser systems for atomic excitation, and the interrogation and control electronics. The exceptional stability and accuracy of CSACs, often surpassing traditional quartz crystal oscillators, make them ideal for applications requiring precise timekeeping in challenging environments. These clocks exhibit long-term frequency stability on the order of parts per billion over extended periods, enhancing their utility in critical infrastructure, communication systems, aerospace, and defense applications.

Moreover, the compact size and low power consumption of CSACs enable their integration into a wide array of devices, including unmanned aerial vehicles (UAVs), satellites, and portable communication equipment. This paper explores specific use cases, such as satellite navigation systems where CSACs enhance Global Navigation Satellite System (GNSS) signals' accuracy and integrity. Furthermore, CSACs find applications in financial networks, where high-frequency trading relies on nanosecond-level precision.

In conclusion, the paper highlights the burgeoning role of Chip Scale Atomic Clocks in modern technology landscapes. Their miniature size, exceptional performance, and versatility make them pivotal in advancing fields requiring precise synchronization and timekeeping. As research continues to refine these systems, the potential for further integration into emerging technologies such as Internet of Things (IoT) devices and 5G networks becomes increasingly promising.

Introduction

The evolution of precise timekeeping has been instrumental in shaping modern technological landscapes, enabling a myriad of applications ranging from global navigation to financial transactions. Central to this advancement are atomic clocks, renowned for their unparalleled accuracy and stability. Among the latest innovations in this realm are Chip Scale Atomic Clocks (CSACs), compact devices that bring the precision of atomic clocks to a miniature form factor suitable for a diverse array of applications.

This paper serves as a comprehensive exploration of the working principles and multifaceted applications of CSACs. To appreciate the significance of CSACs, it is imperative to first understand the foundation of atomic clock technology. Atomic clocks operate on the principle of utilizing atomic transitions, such as those in cesium or rubidium atoms, to generate highly stable and precise time references. The transition between two energy states within these atoms forms the basis for a clock that can maintain time with extraordinary accuracy.

Traditionally, atomic clocks have been large and complex devices, often housed within laboratory settings or specialized equipment. However, the miniaturization of these systems onto semiconductor chips has led to the development of CSACs, marking a pivotal advancement in timekeeping technology. These compact devices retain the exceptional accuracy and stability of their larger counterparts while offering significant advantages in terms of size, power consumption, and portability.

The core components of CSACs include a miniature atomic vapor cell, which contains the atoms used for timekeeping, and a laser system for atomic excitation. The interrogation and control electronics are crucial for maintaining the stability of the clock and extracting precise time measurements. This integration onto a chip-scale platform has enabled CSACs to achieve remarkable performance metrics, boasting long-term frequency stability on the order of parts per billion over extended durations.

The applications of CSACs span a wide spectrum of industries and technologies, underscoring their versatility and utility. In aerospace and defense, CSACs provide critical timing references for navigation systems, communication equipment, and synchronization of distributed networks. Their com-

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pact size and low power consumption make them ideal for integration into unmanned aerial vehicles (UAVs), satellites, and portable communication terminals, where precise timing is paramount.

Furthermore, CSACs are finding increasing adoption in financial networks, where high-frequency trading operations rely on nanosecond-level synchronization for optimal performance. The stability and accuracy of CSACs ensure the integrity of timestamps and facilitate efficient transactions within milliseconds, contributing to the efficiency and reliability of global financial markets.

As this paper unfolds, we will delve deeper into the working principles of CSACs, elucidating their unique features and advantages over traditional timing sources. Additionally, specific applications and use cases will be explored, highlighting the pivotal role of CSACs in advancing fields such as satellite navigation, communications, and financial technologies. Through this comprehensive examination, we aim to provide a thorough understanding of CSACs and their profound impact on modern technological advancements.

Working Principles

Commercial atomic clocks

We use the alkaline metal to use the single valence electron that exhibit a microwave transition (microwave frequency $300 MHz \rightarrow 300 GHz$). Because of this, we have the following properties:

- Ground state hyperfine splitting of the order of GHz so that we can use RF electronics.
- Simple electronic structure that allow a large optical absorption and possible use of optical detection.

Double optical-microwave resonance Every things happens on the reference cell rubidium inside the microwave cavity.

This is the technique used in the Rubidium atomic clock (table scale at least).

Here we have a first discharge lamp that excites the Rb^{87} atoms. In particular, we are here working between the $5^2S_{1/2}$ and the 5^2P fine states. The $5^2S_{1/2}$ state is split into two hyperfine states, $F = 1$ and $F = 2$ (where 1 indicate the lower of the two hyperfine states). From the initial situation, we want to move every electron to the $F = 2$ state. To do so, we use a first lamp that emit exactly at the energy difference between the 5^2P and the $5^2S_{1/2}$ states. This is a circularly polarized photo σ^+, and it will induce a population inversion between the two hyperfine states, so that we have more atoms in the $F = 2$ state.

Once we have the population inversion, we can go through a microwave cavity that will induce a transition between the two hyperfine states. In particular, our aim is to have a wave that is exactly at the frequency of the transition between the two hyperfine states of the $5^2S_{1/2}$ fine state. If we succeed, we will have a resonance, and all the electrons will switch back to the $F = 1$ state (ground state). By doing so, we end up with basically the starting situation and our initial beam of circularly polarized light will be absorbed again by the atoms.

If this happens, than if we use a photodetector that give us a signal of how much light is absorbed, we will have a peak in the signal when the microwave frequency is exactly the one of the transition between the two hyperfine states. Or similarly, a dip if we use a photodetector that give us a signal of how much light is transmitted (it's absorbed at that frequency).
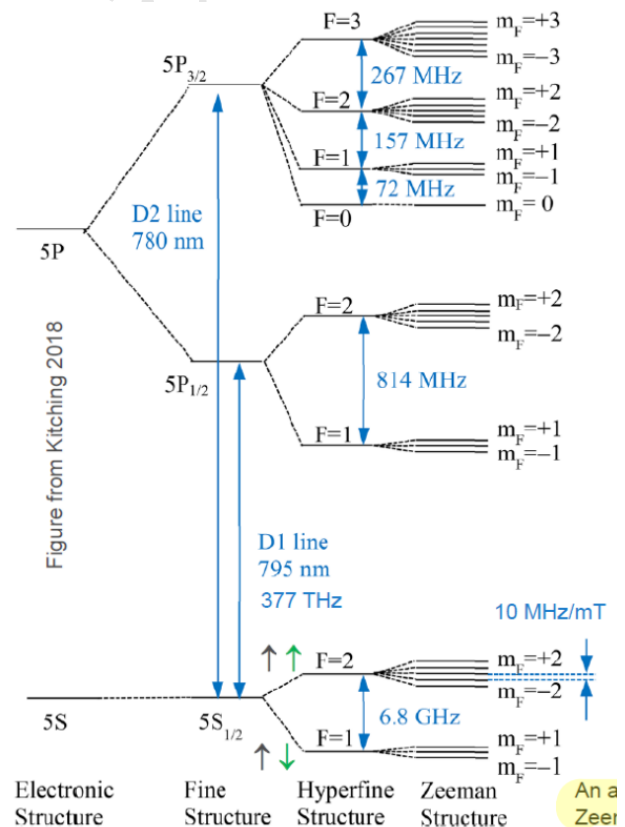

Figure 1: *Rubidium 87 electronic structure (external energy levels)*

More in depth Dipole transition selection rules:

- Excitation by a circularly polarized light σ^+: $\Delta m_f = +1$
- Spontaneous emission: $\Delta m_f = 0, \pm 1$, but on average $\Delta m_f = 0$

In the end, we are sure that pumping will force population inversion generating excess in the $F = 2$ state.

The microwave cavity on the other hand (if in complete resonance with the transition between the two hyperfine states) will induce a transition so that the population will be inverted again.

This result in the possibility for the reference cell to absorb again the circularly polarized light, and the trasmissibility of the light will be at a minimum.

Filter cell of Rb^{85} Since as pumping device we use a rubidium lamp, we will have both the photons coming from the $5^2P \rightarrow 5^2S_{1/2}F = 1$ (the one that we are interested in) and the photons coming from the $5^2P \rightarrow 5^2S_{1/2}F = 2$ (the one that we want to avoid since their effect is the one that must be provided by the microwave cavity).

To eliminate those photons, we add a filter cell of Rb^{85} that will absorb the photons coming from the $5^2P \rightarrow 5^2S_{1/2}F = 2$ transition given that the energy difference between the two its transitions $5^2P \rightarrow 5^2S_{1/2}F = 3$ is almost exactly the same as the one of the $5^2P \rightarrow 5^2S_{1/2}F = 2$ transition of Rb^{87}. Ate the same time, Rb^{85} will not absorb the photons coming from the $5^2P \rightarrow 5^2S_{1/2}F = 1$ transition of Rb^{87}.
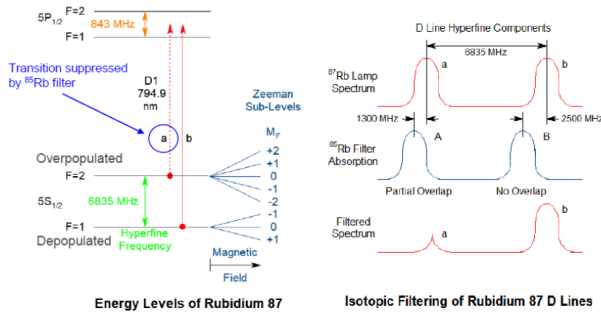

Figure 2: *Overlap of the two transitions of Rb^{85} and Rb^{87}*

Cesium atomic clock   For the cesium atomic clock unfortunately we cannot use the same technique. So in the end, the option is only to use a different source for the light, and in particular a very stable and accurate single-mode narrow-linewidth laser. In the end, this approach is less reliable than the combination of the Rb^{87} lamp and the Rb^{85} filter.

Problem so far with the double resonance approach - Power consumption   All components described so far has to be kept at a constant temperature and pressure to avoid any shift in the frequency of the transition. This means that our system must include stabilization in temperature driven by a oven controlled sensor and heater. The power consumption of this system is distributed as follows:

- 10%: Lamp Exciter
- 10%: RF Excitation
- 10%: Electronics
- 70%: Thermal stabilization oven

It's clear how the oven and the thermal stability is the most power consuming part of the entire system.

Problem so far with the double resonance approach - Size   Another problem is given by the minimum theoretical size of the system. The RF cavity must be at least half the wavelength of the microwave frequency. This means that for a microwave frequency of $6.8GHz$ we need a cavity of at least $L_{min} = \frac{\lambda}{2} = \frac{c}{2f} = \frac{3 \cdot 10^8}{2 \cdot 6.8 \cdot 10^9} = 22mm$.

Problem so far with the double resonance approach - Stark shift   Because of possible electric field, the energy levels of the atoms can be shifted (broadened). This means that even if our microwave frequency is exactly the one of the transition, the energy levels of the atoms can be shifted so that the resonance is not perfect and the absorption of the light is not at a minimum. Basically, the position of the dip in the transmissivity is shifted.

CSAC - Chip Scale Atomic Clock

Coherent population trapping (CPT)   CPT is based on the principle of trapping the population of the atoms in a coherent superposition of the ground states.

We are now interest in apply exactly the energy level corresponding to $\frac{5^2S_{1/2}F=1+5^2P_{3/2}F=2}{2}$. If we succeed in apply this energy level, we will have that our electron will most probably finish in the middle of the two hyperfine states. This will cause the atom to be impossibilities to absorb the light because of destructive interference between the ac and bc transition probability amplitudes. Given so, if we observe the spectrum of the light transmitted through the atoms, we will have a peak in the transmissivity at the frequency of the transition (where the CPT happens, and the atoms are not absorbing the light).

If our system is based on Rubidium as the principal element, then our target in frequency of the oscillator is $6.8/2GHz = 3.4GHz$, while if our system is based on Cesium, then our target in frequency of the oscillator is $9.2/2GHz = 4.6GHz$.

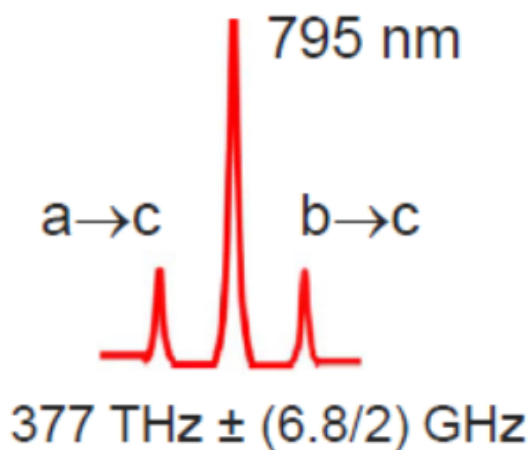CPT is visible from a transmissivity(frequency) plot like in Figure 3.

795 nm

a→c   b→c

377 THz ± (6.8/2) GHz

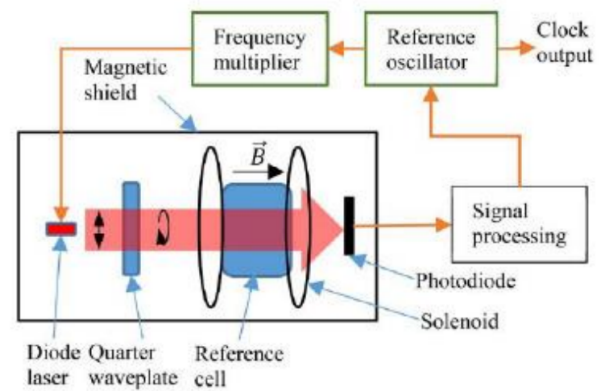**Figure 3:** *Transmissivity(frequency) plot of a CPT system*

Figure 5: *CPT*

Role of buffer gas mixture   The buffer gas mixture is used to increase the lifetime of the atoms in the excited state.

Benefits of CPT over double resonance   By using the CPT technique, we can avoid the use of the microwave cavity and the filter cell of Rb^{85}. This means that we can avoid the power consumption of the oven and the thermal stabilization, and we can avoid the size of the microwave cavity. In the end, we can have a system that is much smaller and with a much lower power consumption.

The only problem here is that our system must be able to generate a very stable and accurate single-mode narrow-linewidth laser. The less precise the laser, the less precise the peak in the transmissivity plot (and possible shifted to the wrong frequency). However, once we have the laser, we can also think of using more than one just element. In fact, we should opt to pick an element with higher frequency of the transition, so that we can have a more precise peak in the transmissivity plot (as Cesium for example).
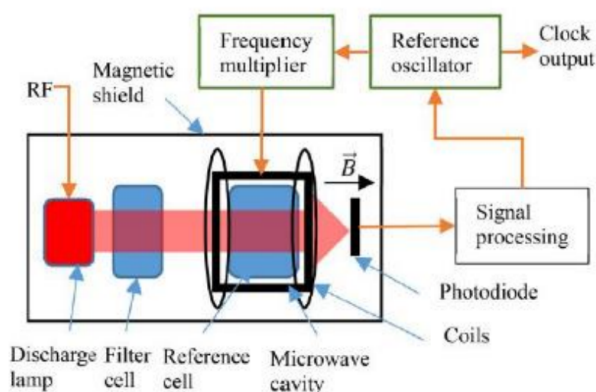
Here follows the two systems.

Figure 4: *Double resonance system*