Chip Scale Atomic Clocks Sources

Working principles

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March 20, 2024

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Acronyms

API Application Programming Interface

LAN Local Area Network

ASCII American Standard Code for Information Interchange

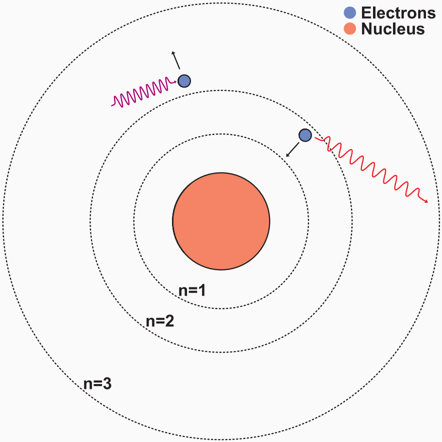
Toolbox

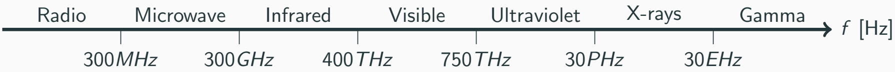
Energy quantization

Energy is a quantized quantity. The energy of a photon is given by the **Planck's relation**:

$$e = hf \tag{1}$$

Unit of energy: electron-volt (eV) or Joule (J).

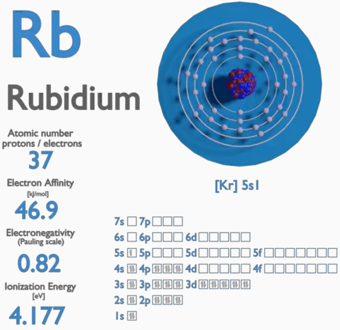


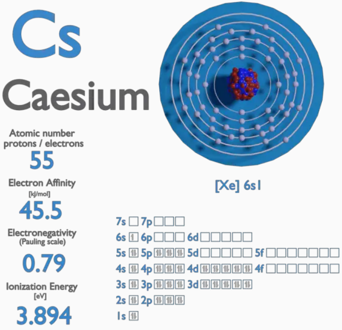


Rubidium and Cesium

We will deal with Rubidium (isotopes ^{85}Rb & ^{87}Rb) and Cesium (^{133}Cs).

- They are both alkali metals with a single valence electron.
- Their first ionization energy is low.





Quantum levels

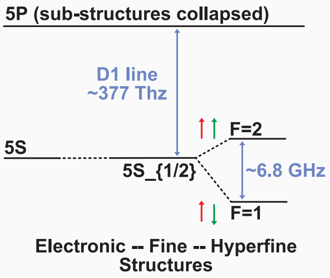


Figure 1: ^{87}Rb quantum levels.

Elementary energy level ($n = 1, 2, 3, \ldots$), can further be split.[1]

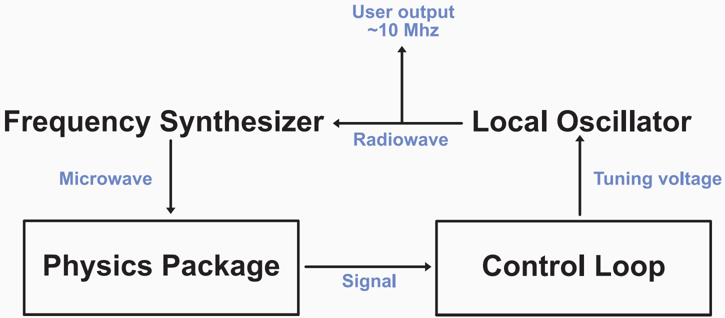
Substructures are due to various quantum phenomena acting inside the atom domain.

- Electronic: classical orbital levels.
- Fine: electronic spin-orbit coupling.
- Hyperfine: nuclear spin-electron spin coupling.

[1] For the purpose of the CSACs, we can consider the sub-$5P$ structures as collapsed into a single one.

CSAC Block Diagram

Block diagram of a generic CSAC



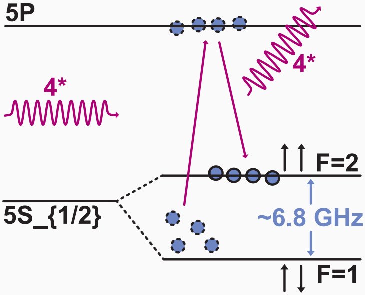
In the following slides, we are going to see:

- Physics Package
  - Based on Microwave Optical Double-Resonance (MODR)
  - Based on Coherent Population Trapping (CPT)
- Control loop
- Local Oscillator

Physics Package based on Microwave Optical Double-Resonance (MODR)

^{87}Rb Reference Cell

At the heart of a MODR based CSAC, we find a ^{87}Rb reference cell.



We can distinguish 3 phases:

1. Optical Pumping (Population Inversion)

Ground state population $F = |1\rangle$ gets pumped to $F = |2\rangle$.

^{87}Rb Reference Cell

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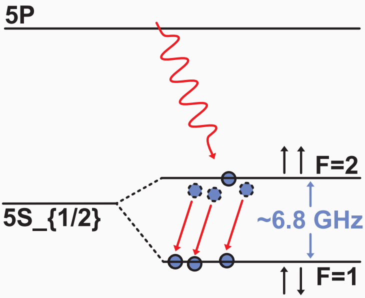


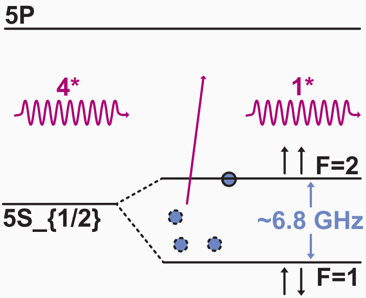
We can distinguish 3 phases:

1. Optical Pumping (Population Inversion)
2. Microwave Excitation

Microwave tuned at the atomic resonance frequency ($\approx$ 6.8 GHz) brings part of the population back to $F = |1\rangle$.

^{87}Rb Reference Cell

At the heart of a MODR based CSAC, we find a ^{87}Rb reference cell.



We can distinguish 3 phases:

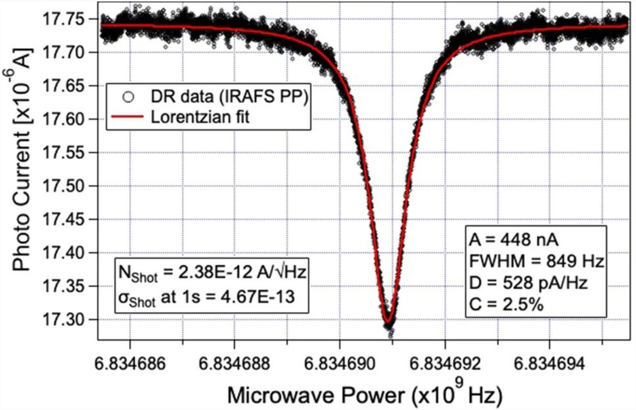
1. Optical Pumping (Population Inversion)
2. Microwave Excitation
3. Optical Pumping (Interrogation)

Depending on the intensity of the transmitted radiation, **we can infer if the microwave frequency was on resonance or not**.

In this case, given that one photon was able to go through the cell, we can infer that the microwave frequency was not in resonance.

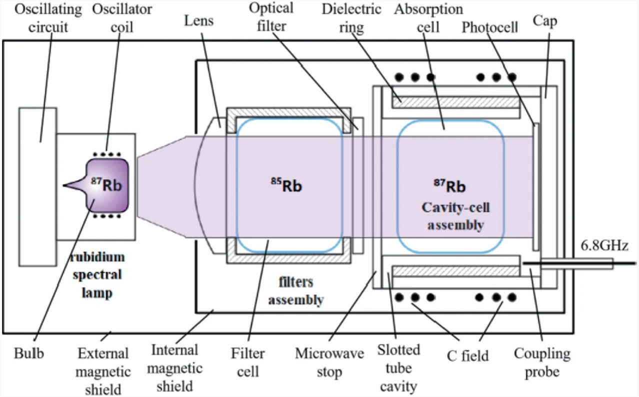
Photodetection

At the end of the cell, a photodiode is used to measure the intensity of the transmitted radiation.



Our target is to stay at the dip of the transmission curve.

Complete physics package for a MODR-based CSAC



Other notable components are:

- ^{87}Rb Bulb: high frequency radiation source.
- ^{85}Rb Filter cell: because of overlapping hyperfine levels, it filters out the unwanted transitions frequencies from the lamp.
- Microwave cavity: enhances the interaction between radiation and atoms.

Design bottleneck

...goal of developing an ultra-miniaturized, low-power, atomic time and frequency reference units...

In case of a MODR-based CSAC, we can recognize multiple problematic areas:

- Power consumption: each component inside the physics package is usually oven controlled (70% of the total power consumption).
- Size: microwave cavity imposes a low limit ($L_{min} = \frac{c}{2f_{transition}} \approx 2.2cm$).
- Optical instabilities[1]: Stark shifts, Zeeman effects, internal wall gas collision.

[1] More on this in the "Extra slides" section.

Physics Package based on Coherent Population Trapping (CPT)

Control loop

Control loop

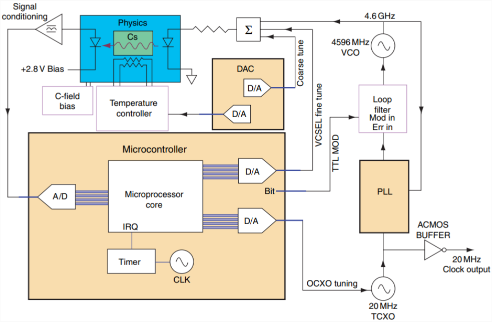


Figure 2: Control loop block diagram.

Close-loop control approach. Usually multiple PI controllers are used to operate a series of servo loops.

Indispensable targets:

- Laser temperature
- Cell temperature
- Laser frequency
- LO frequency

Electronics

Here are some possible problematic areas:

- Stability in the voltage and current provided to VCO and VCSEL (highly sensitive components)
- Cross-talk between the various control loops
- Noise from the electronics
- Power consumption

Local Oscillator

Local Oscillator

Normally, the local oscillator in a CSAC is a quartz crystal oscillator (XO).

There exist many versions of the XO, differentiated based on the environmental correction type applied to enhance stability:

- TCXO: Temperature Compensated Crystal Oscillator
- MCXO: Microcomputer Compensated Crystal Oscillator
- OCXO: Oven Controlled Crystal Oscillator

Quarter Crystal Oscillator

At short time scales, the quartz crystal oscillator is the main source of instability in a CSAC due to its phase noise.

Here are some other problematic areas:

- High temperature sensitivity
- Power consumption (in case of temperature compensation or oven control)
- Aging and frequency drift

In the end, the choice of a local oscillator is a trade-off between stability and power consumption.

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Questions?

Thank you!