Chip-Scale, Microfabricated Atomic Clocks

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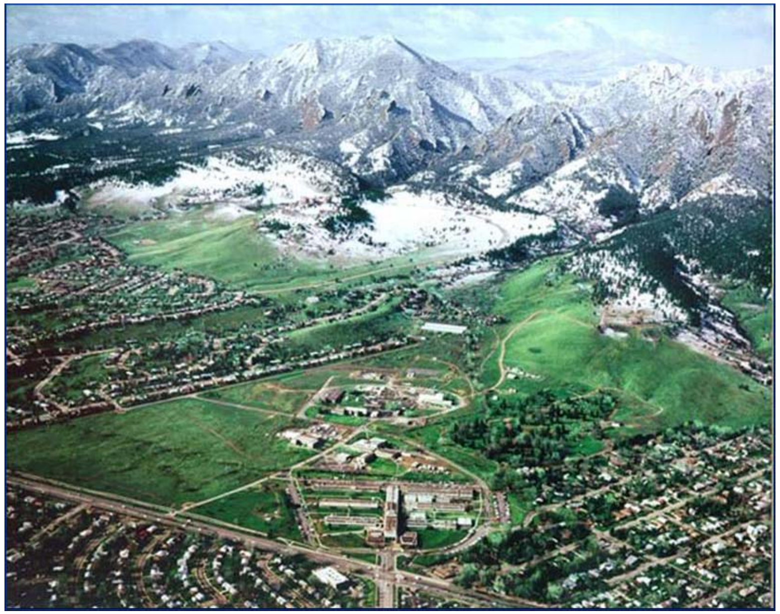


Outline

I. Introduction to Atomic Clocks
- Applications
- Basic description

II. Chip-Scale Atomic Clocks (CSACs)
- Basic science
- Examples of components (not an exhaustive review)

III. State of the Art from Industry**
- Status of performance
- Ongoing research and development

IV. Technology Spinoffs from Chip-Scale Atomic Clocks

** Products or companies named here neither constitute nor imply endorsement by NIST or by the US government.

Applications for higher-performance portable clocks

- Navigation.
- Security/encryption.
- RF/microwave broadcasts.
- Telecommunications network synchronization.
- Sensors (magnetic fields, gravity, etc.)
- Unpredicted applications.

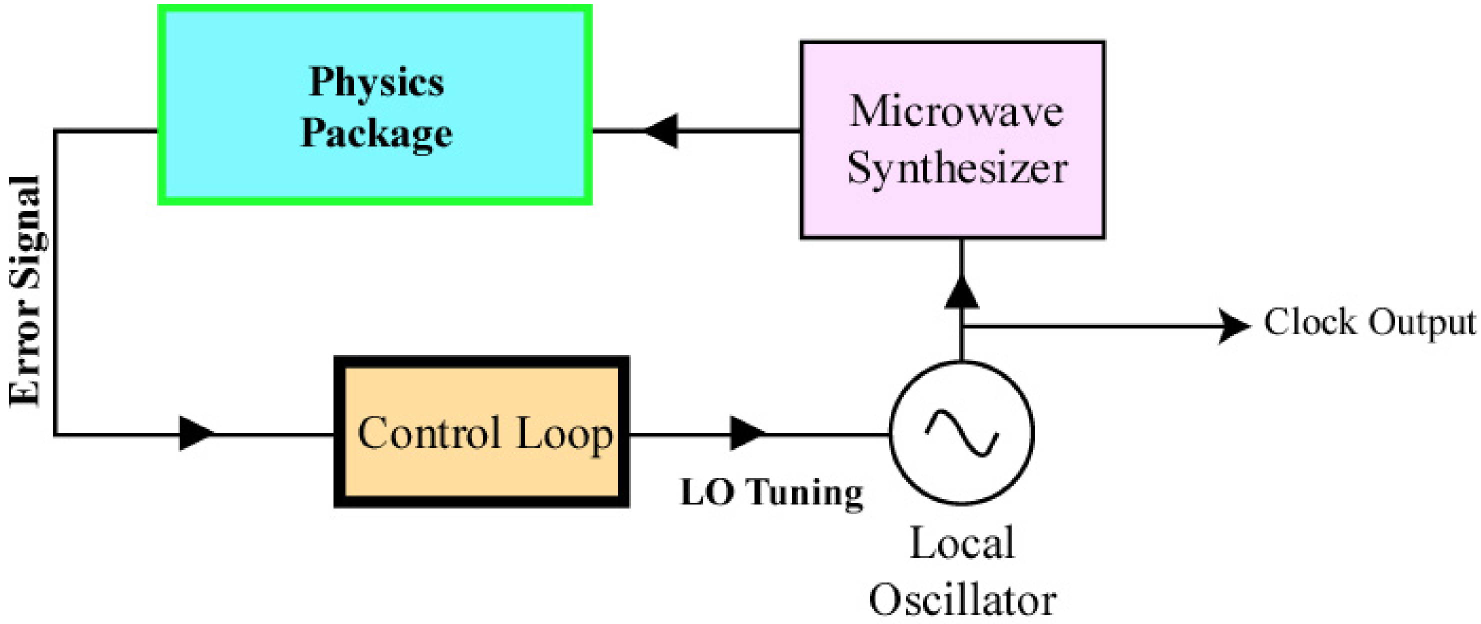
One Specific Application:

Telecommunication Networks

Synchronization to about
1 microsecond per day
for CDMA systems.

Chip-scale atomic clocks can now exceed this performance specification.

What is an atomic clock?

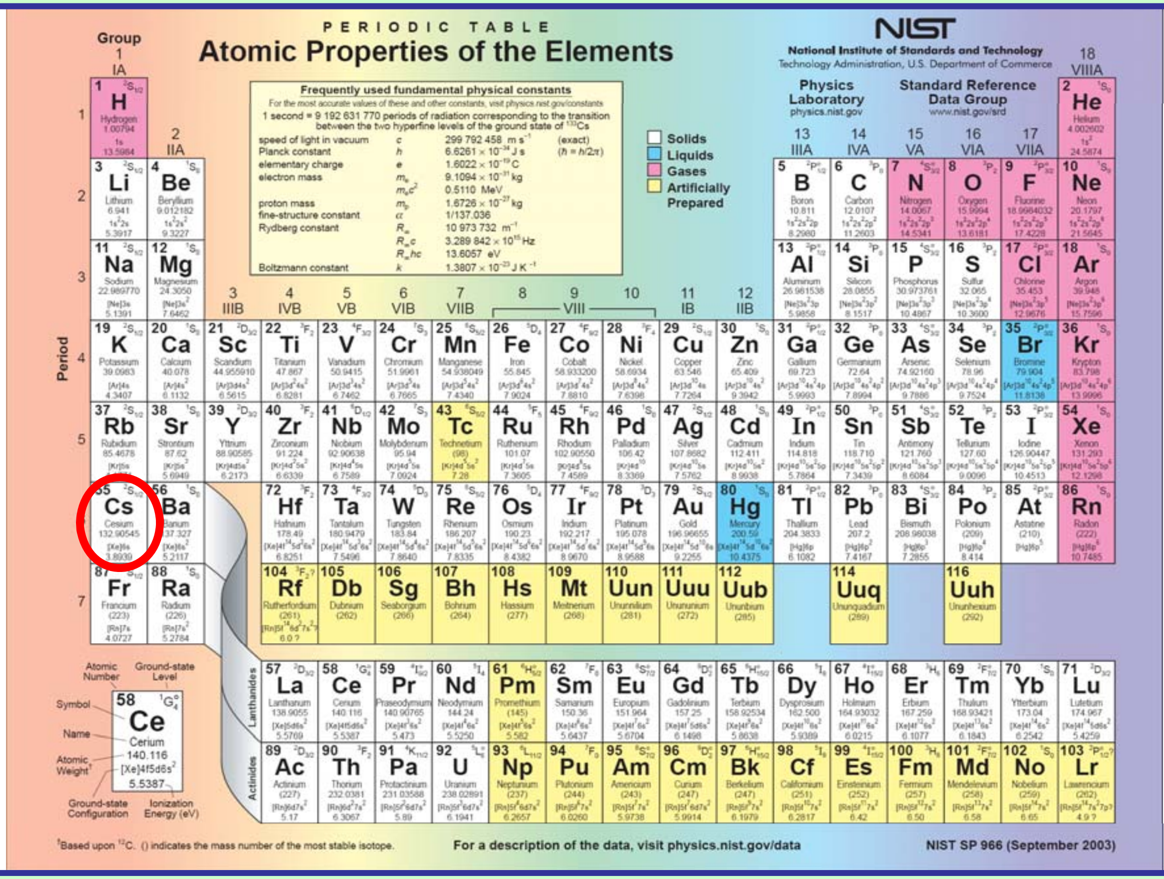


Atomic resonance is intrinsically more stable than quartz local oscillator.

"Natural" atomic microwave resonance frequency is synthesized from RF LO.
Control Loop continuously steers LO frequency to atomic resonance.
RF output *(10 MHz)* embodies stability of atomic resonance.

Courtesy of R. Lutwak *2008 FCS Tutorial*

Since 1967, the SI second has been defined by the frequency of a microwave transition in Cesium atoms.



Resonance frequencies of atomic transitions

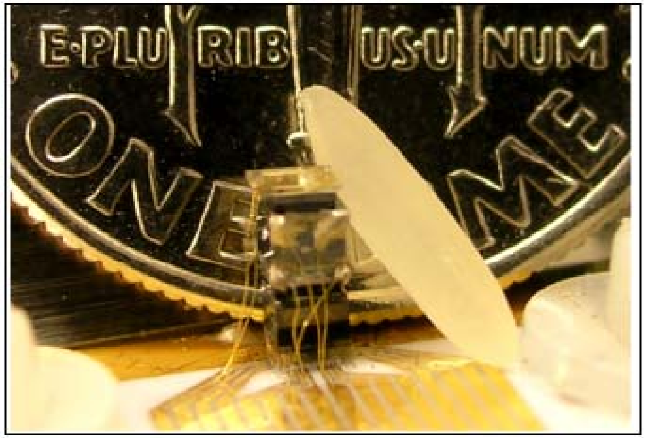
- Can be measured with high precision and accuracy
- Are relatively stable over time

Cesium Microwave Frequency Standards

NIST-F1:

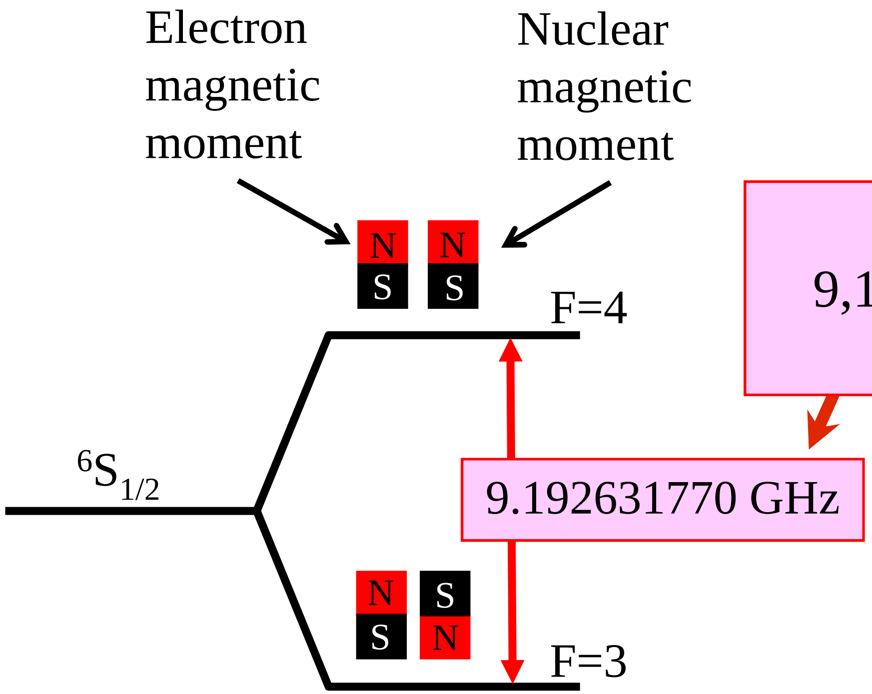
- 0.30×10^{-15} in house frequency uncertainty.
- 0.6×10^{-15} uncertainty reported to BIPM.
- Best in the world, in house and reported uncertainties.

Chip Scale Atomic Clock = CSAC



- Lower performance
- <u>MUCH</u> lower power
- <u>MUCH</u> smaller size

^{133}Cs Energy Levels



To realize one SI second, count 9,192,631,770 cycles of the radiation absorbed by this transition.

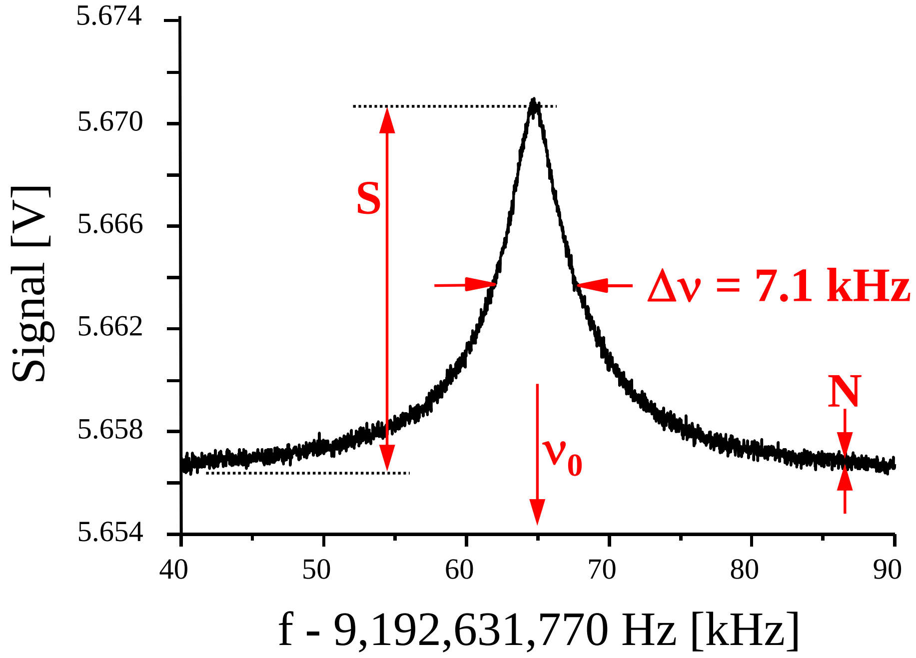
Transition is between hyperfine ground state energy levels

States correspond to different relative orientations of the valence electron and nuclear spins

Magnetic-field dependent substructure of energy levels has to be accounted for

Clock Stability:

Set by the properties of the atomic resonance



$$Q = \frac{\nu_0}{\Delta \nu}$$

$$\sigma(\tau) \approx \frac{1}{(S/N)_\tau \cdot Q}$$

- $(S/N)_\tau$ is the signal-to-noise ratio at an averaging time of τ.
- ν_0 is the center frequency of the atomic resonance
- $\Delta\nu$ is the width of the atomic resonance
- A clock's precision improves with lower values of stability

Miniaturized Atomic Frequency References

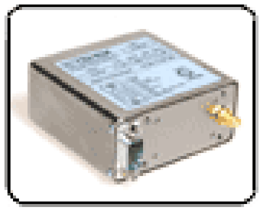
- Small size, low power dissipation BUT retain long-term frequency stability typical of atomic standards
  - Portability, battery operation

DATUM/Symmetricom

- State-of-the-art (as of very recently):
  - $V \sim 100\ cm^3$
  - $P \sim 5\ W$
  - Stability $\sim 10^{-11}$ @ 1 sec. $\rightarrow$ 1 day

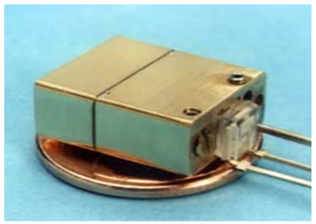
Kernco

Frequency Electronics

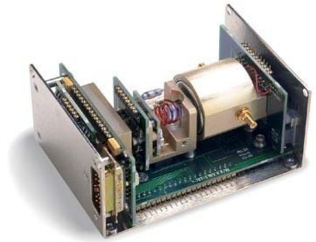


Temex

Accubeat



Northrop-Grumman Physics Package



Stanford Research Systems

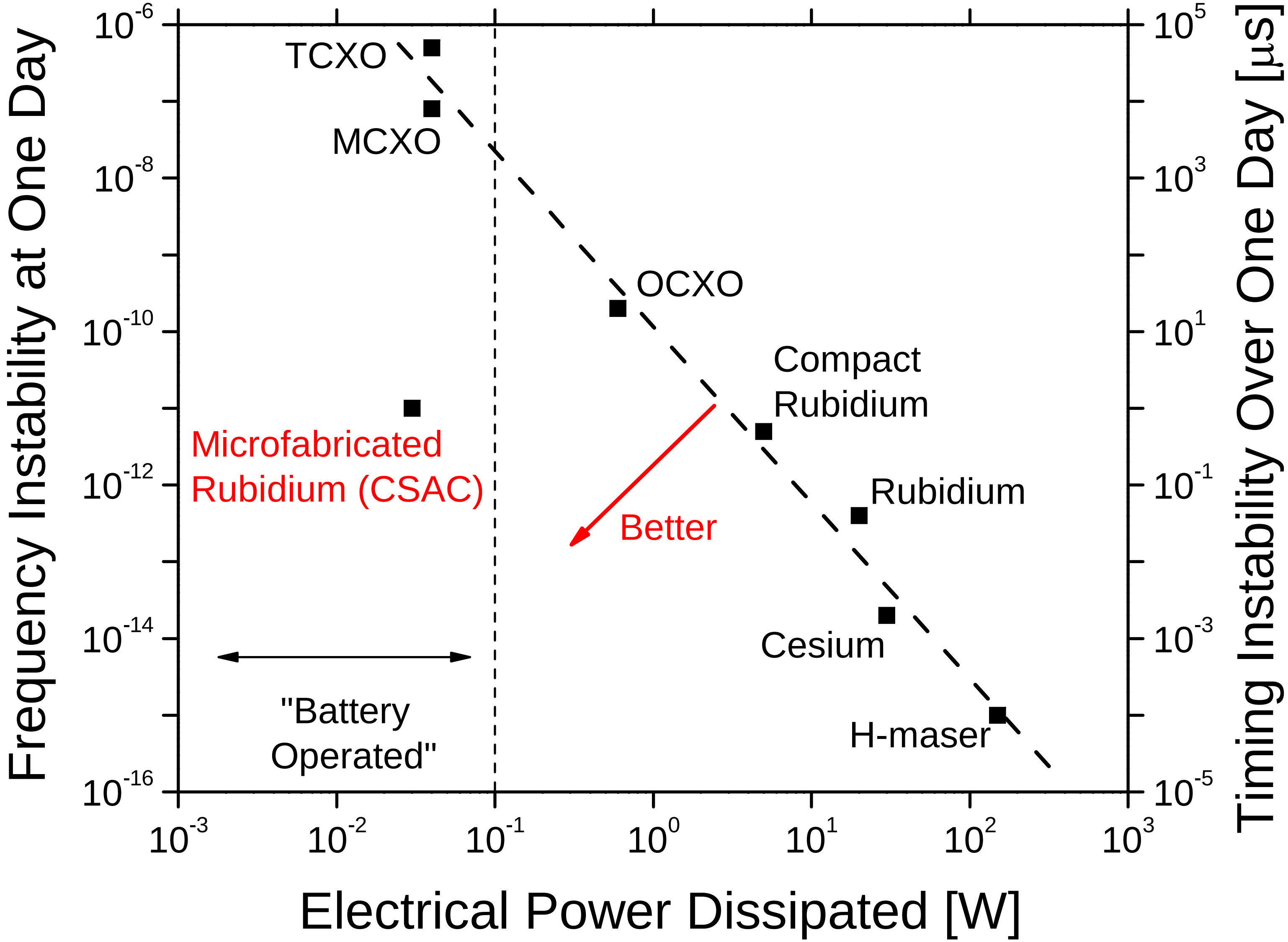
Standard Portable Clock Technology Size/Power Limitations :

- Size
  - Microwave cavity (~ 1 cm^3)
  - Control electronics (~ 10's cm^3)
  - Local oscillator/synthesizer
- Power
  - Lamp (watts)
  - Cell heating (100's mW)
  - Local oscillator/synthesizer

Chip-Scale Atomic Clocks (CSACs)

- DARPA-funded effort to produce accurate timing sources for portable instruments
  - Began in 2001. Initially funded:
    - NIST/U. of Colorado
    - Symmetricom/Draper/Sandia
    - Teledyne Scientific/Rockwell Collins/Agilent
    - Honeywell
    - Sarnoff/Princeton/Frequency Electronics
  - Still ongoing with industry participants (Symmetricom & Teledyne)
- Key Specifications
  - Device Volume: $< 1\text{cm}^3$
  - Total Power Consumption: < 30 mW
  - Stability: $\sigma_y(\tau = 1\,\text{hr}) < 1 \times 10^{-11}$
- 100× smaller and lower power than current atomic clock technology.

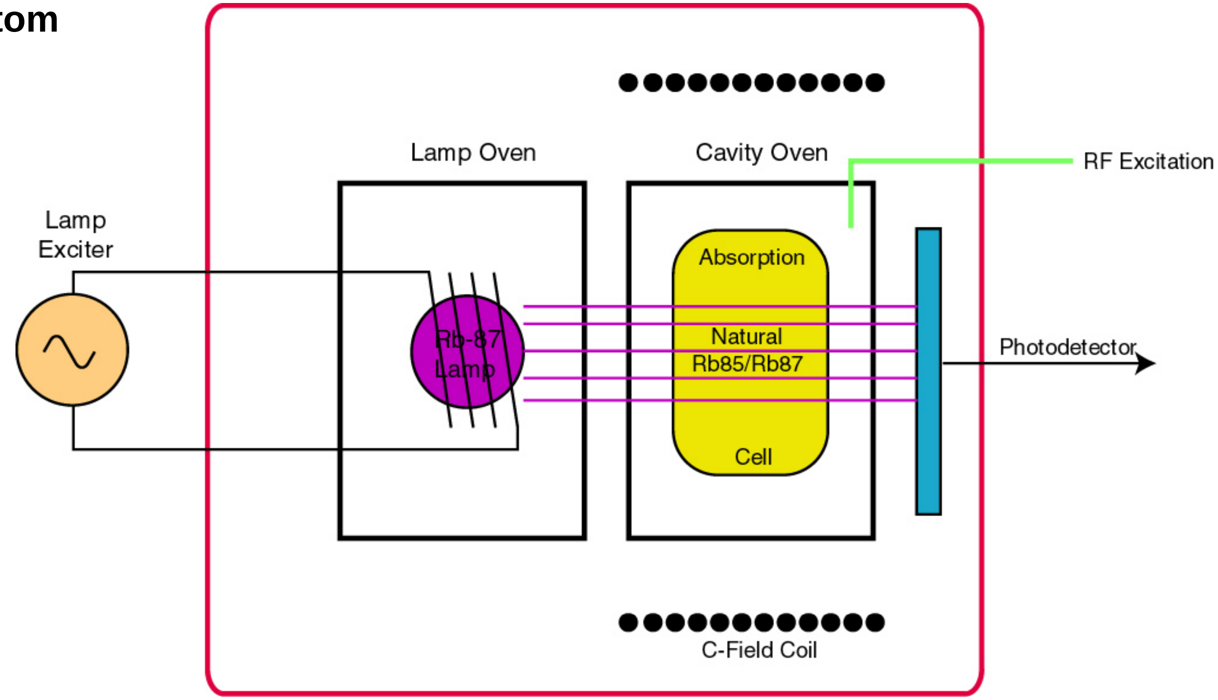
(A Very Rough) Oscillator Comparison



Adapted from figure by M. Garvey, Symmetricom

“Classical” Compact Frequency Standards

E. Jechart, Efratom early 1970s

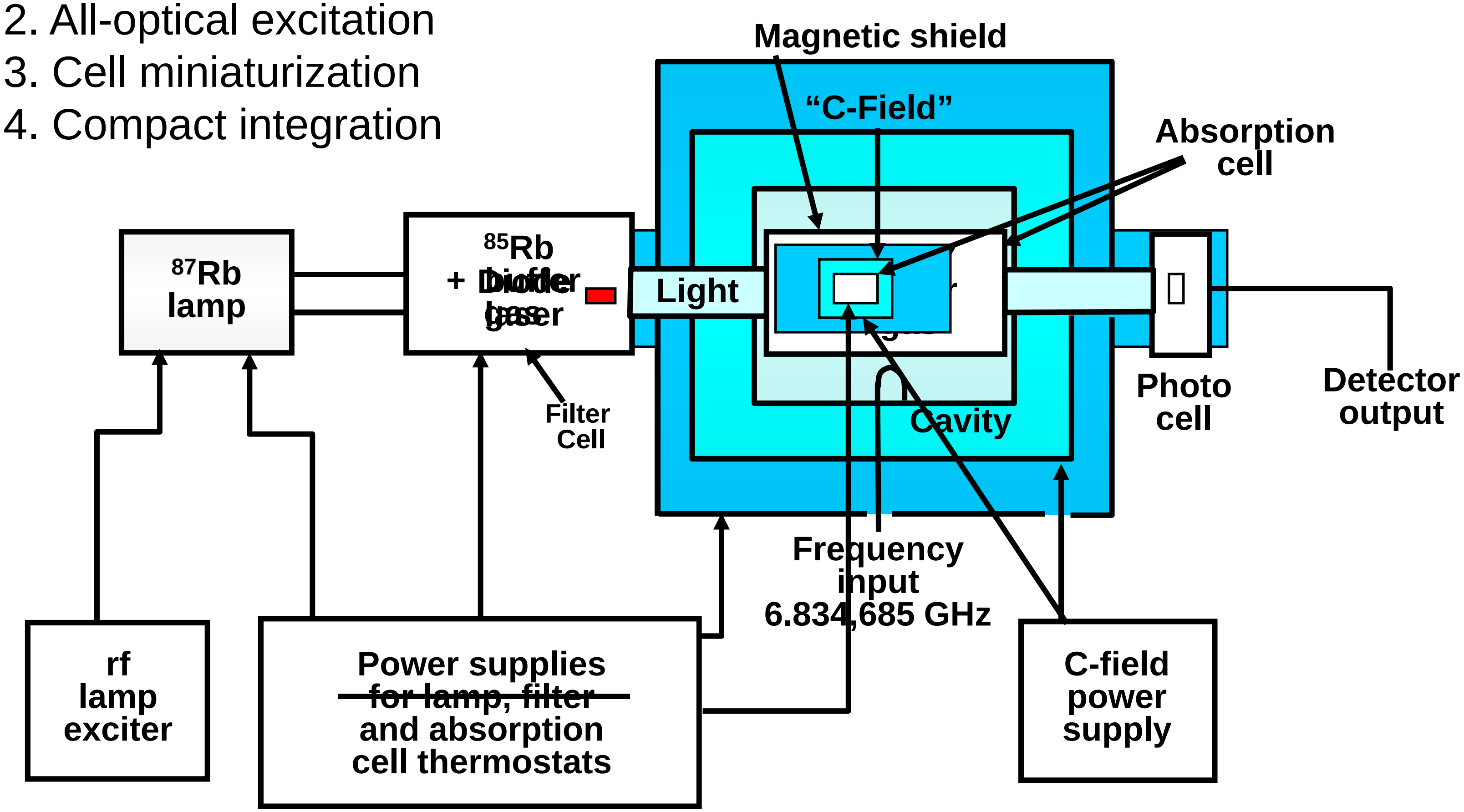


- Smaller, lower power, lower cost than previously available clocks

Figure courtesy of R. Lutwak

Rubidium Miniaturization: Philosophy

1. Lamp → laser
2. All-optical excitation
3. Cell miniaturization
4. Compact integration



Adapted from figure by John Vig, Tom Parker

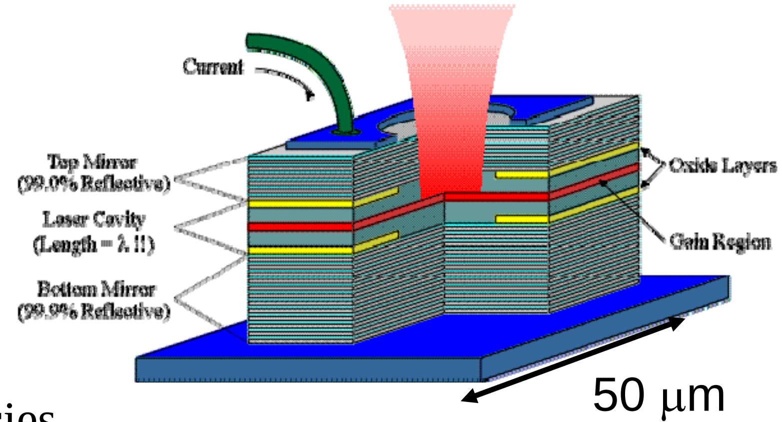
Laser Technology

Replaces Lamp for small size, low power

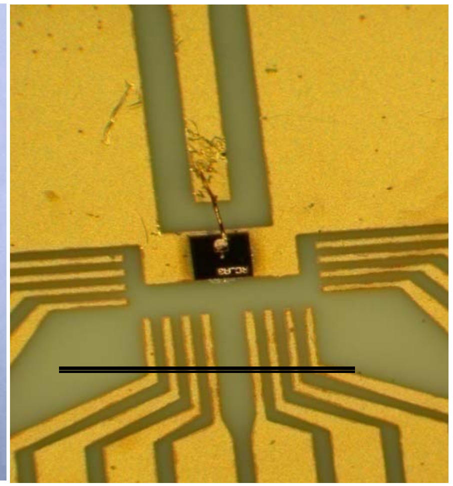
- Requirements:
  - Single-frequency operation
  - Wavelengths:

    Rb – D2: 780 nm, D1: 795 nm

    Cs - D2: 850 nm, D1: 894 nm
  - Low-power operation
  - High modulation efficiency at GHz frequencies

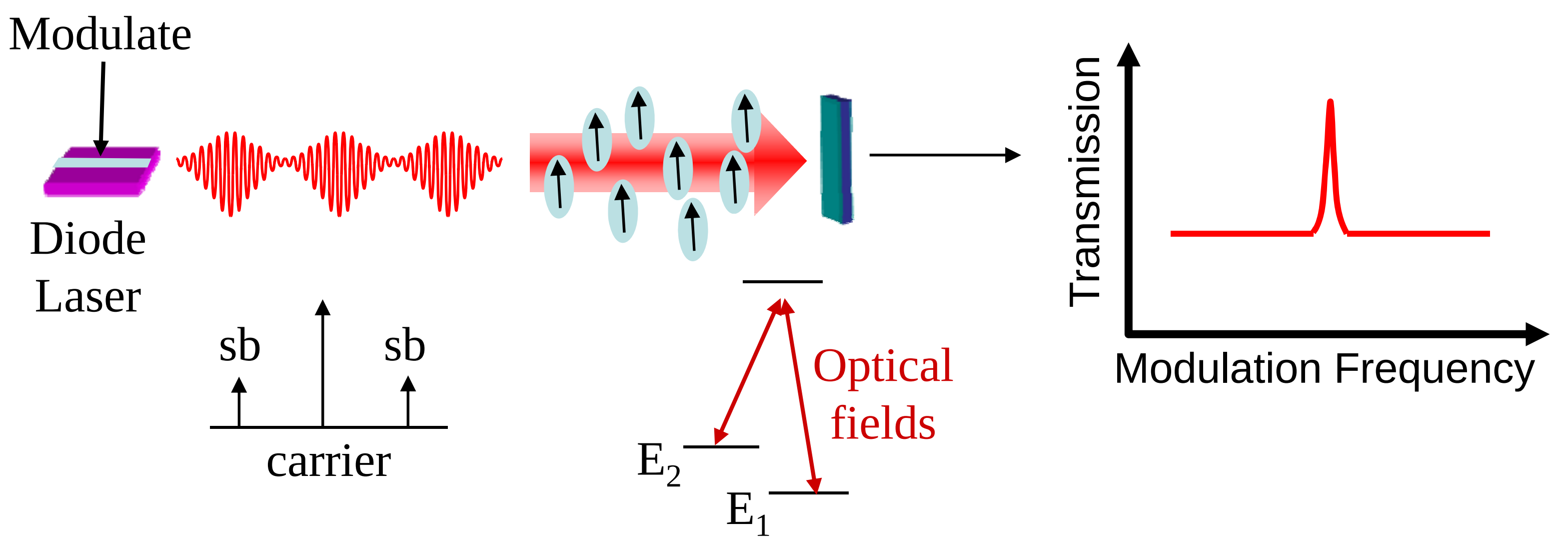


- Vertical-cavity, surface-emitting lasers (VCSELs)
  - Typical i_{th} < 1 mA; P_{op} ~ 4 mW
  - Modulation bandwidth > 5 GHz
  - Highly reliable



All-Optical (CPT) Excitation

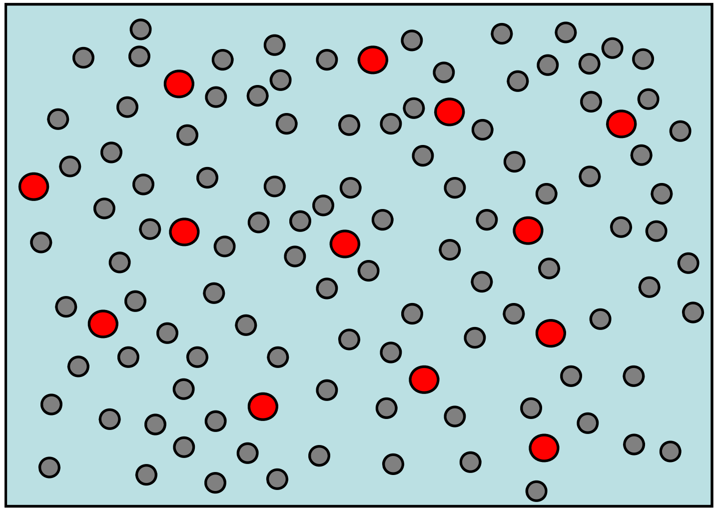
Cyr, Tetu, and Breton, IEEE Trans. Instrum. Meas. 42, 640 (1993)



- Non-linear process in atoms drives hyperfine oscillation at difference frequency between optical fields
- Absorption of light drops when modulation frequency equals half of the hyperfine splitting
- Advantage: *no microwave cavity required*

Buffer Gas Cells

R.H. Dicke, Physical Review 89, 472 (1953)



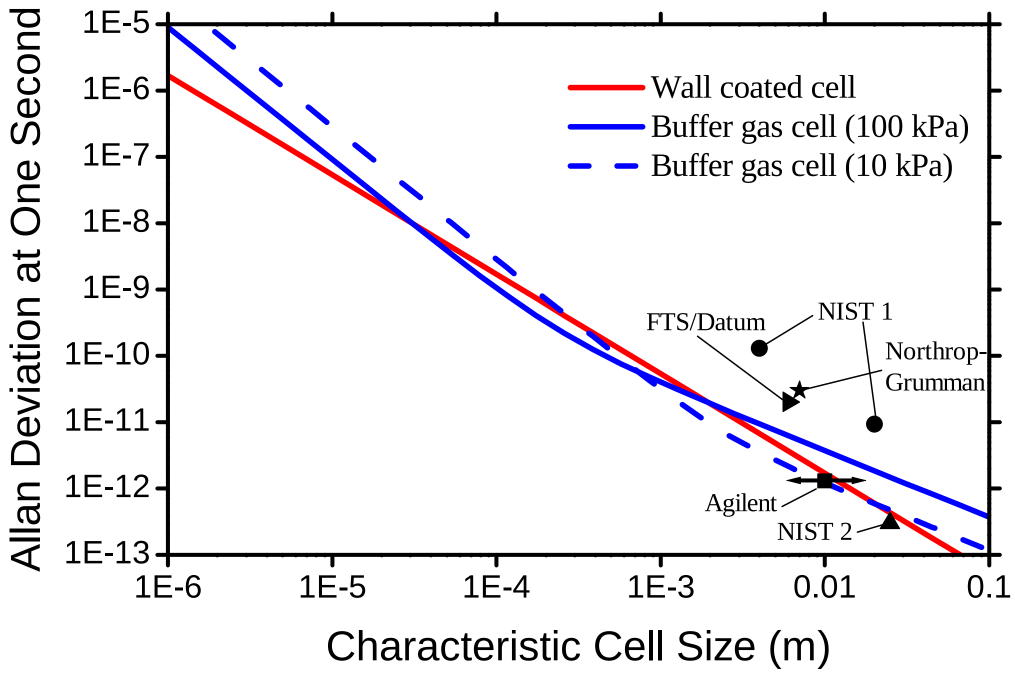
- Buffer Gas (N_2, Ne, Ar, …)
- Alkali Atom (Cs, Rb, …)

- Buffer gas
  - confines Cs atoms to small volumes away from the cell walls and each other
  - Eliminates first order Doppler Shift

Scaling of Clock Stability with Size

Kitching, Knappe, & Hollberg, Appl. Phys. Lett. **81**, 553 (2002)

- Allan deviation: $$\sigma_y(\tau) \approx \frac{1}{Q \cdot (S/N)_\tau}$$
- Both Q and S/N are functions of cell size
  - Q-factor: collisions of atoms with walls of cell
  - S/N: smaller size ⇒ smaller optical power ⇒ shot noise

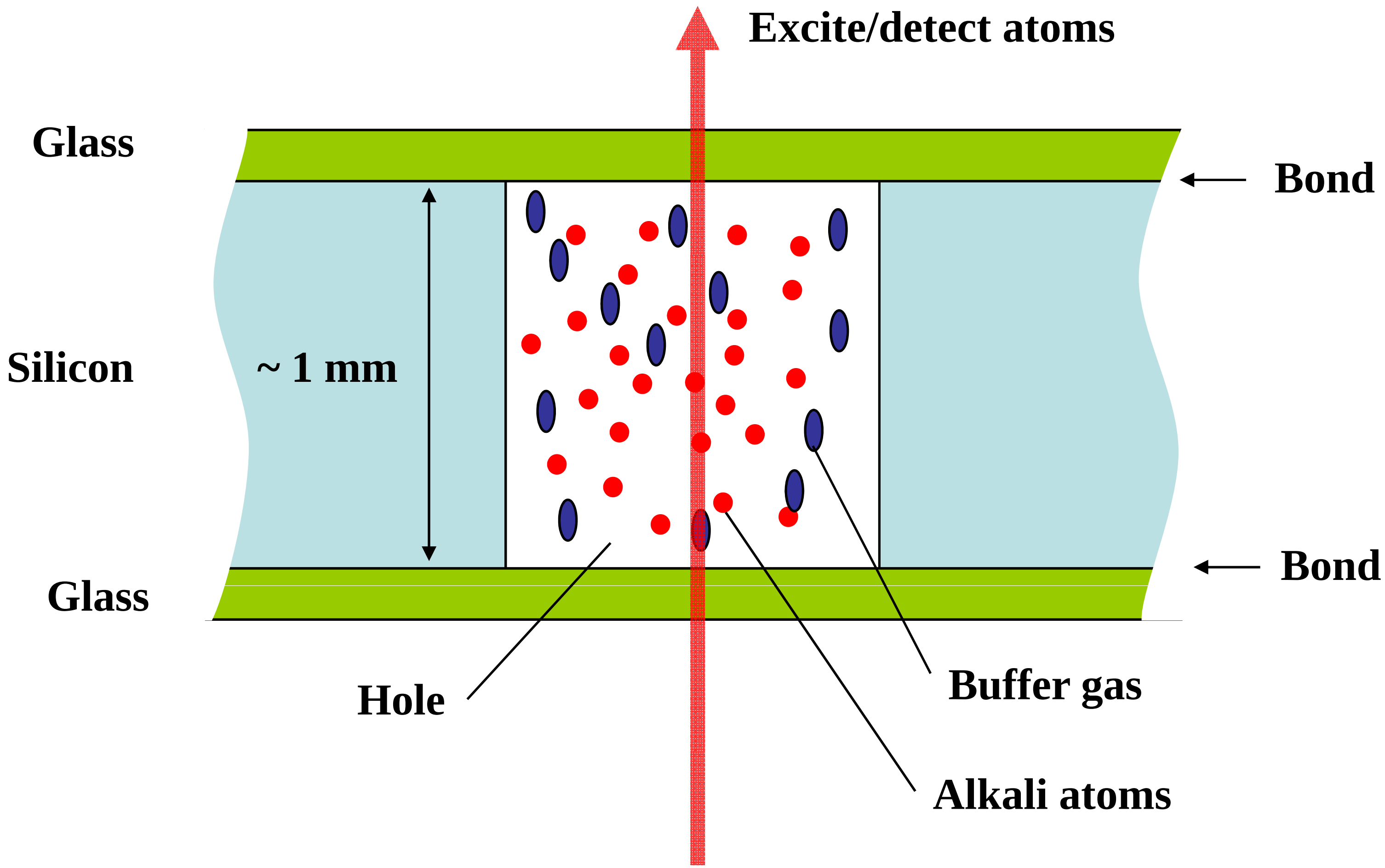


Smaller size ⇒ worse performance

BUT

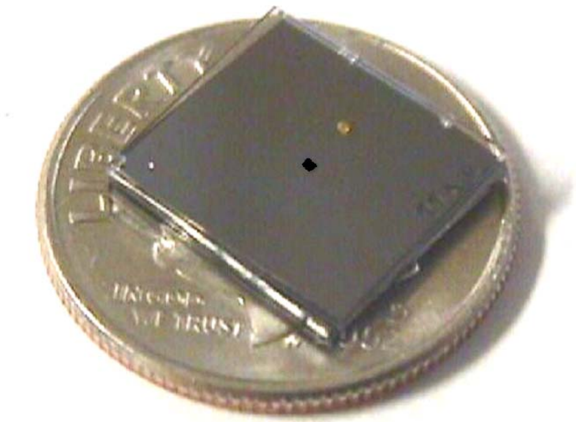
σ_y (1 sec) ~ 3×10^{-11} for 1 mm cell

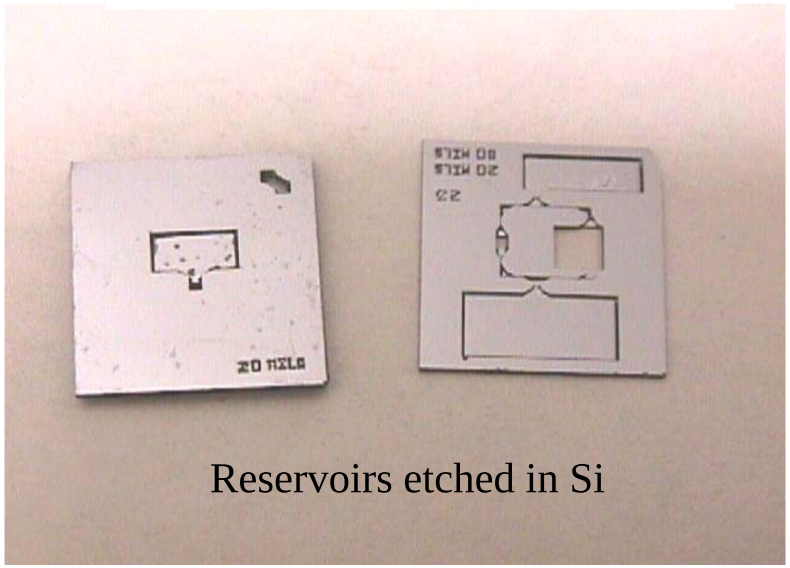
Cell Fabrication: Basic Structure



Cell Fabrication: Micromachining Process

- <100> Si wafer DSP
- LPCVD nitride dep
- PR spin on
- PR exposure
- CF4 plasma etch
- PR strip
- Anisotropic KOH etch
- Nitride strip
- Glass bonding

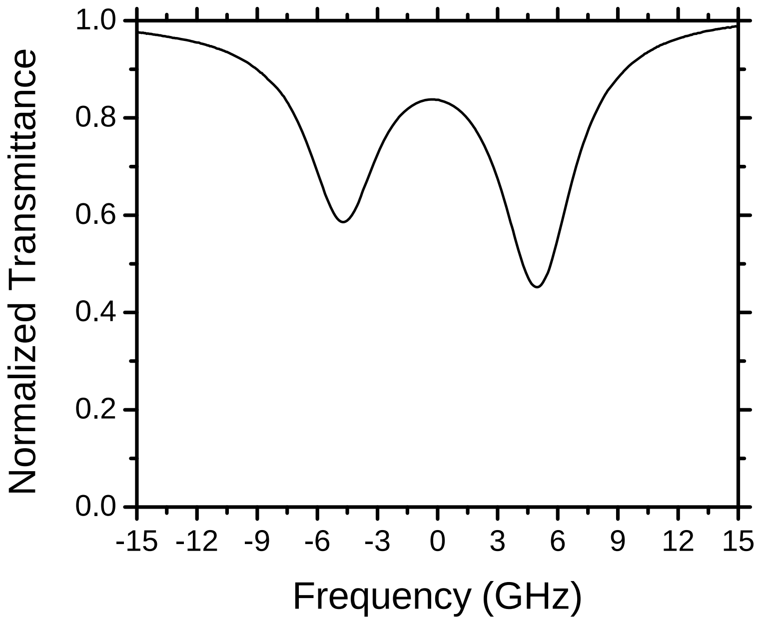


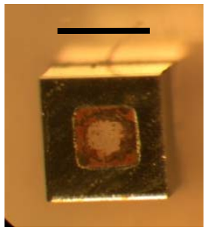


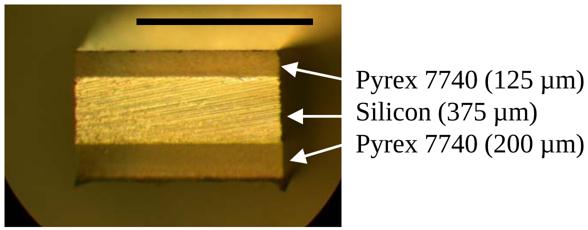
Reservoirs etched in Si

Cell Fabrication: Anodic Bonding

- Preform created by KOH etching or DRIE of Si
- Pyrex bonded on one side with anodic bonding
- Cell preform filled with Cs
  - $BaN_6 + CsCl \rightarrow BaCl + Cs + 3N_2$ @ 150 ºC
- Diced cells made at NIST using the anodic bonding technique
  - Interior: 1 mm x ∅ 0.9 mm
  - Exterior: 1.33 mm x (1.45 mm)^2

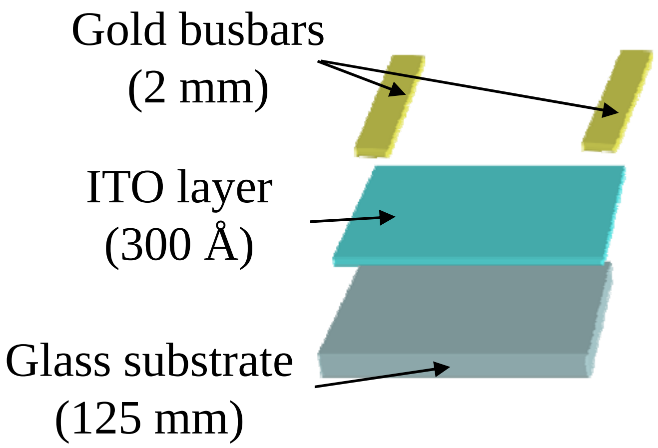




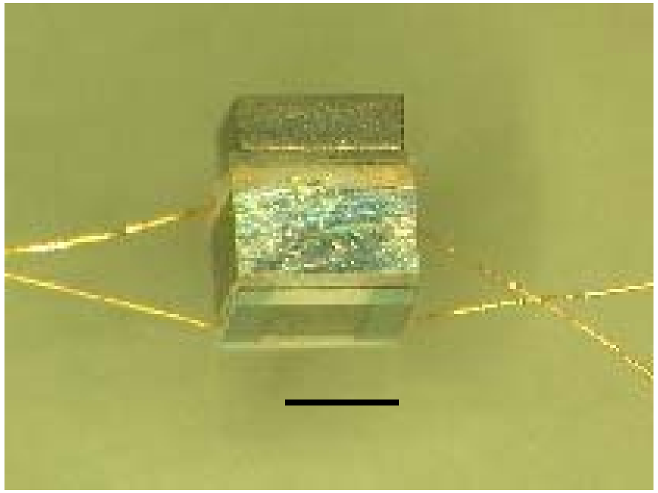


Integration: Heater Fabrication

Heaters fabricated by depositing a thin layer of Indium-Tin-Oxide onto glass

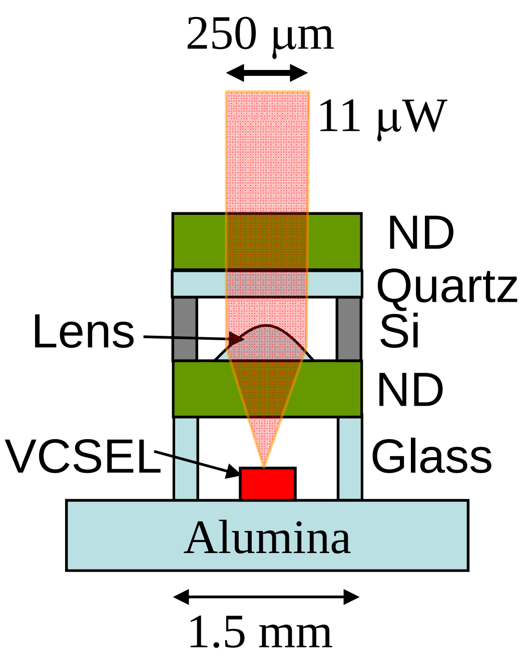


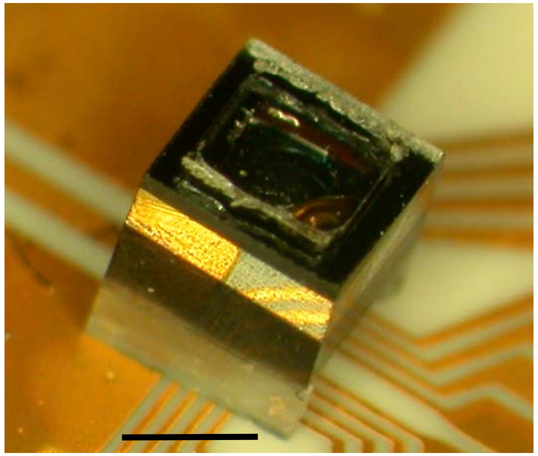
- ITO: transparent, conductive material
- Uniform heating of windows
- Reduces solid alkali buildup
- Gold contacts deposited via e-beam evaporation enable wire-bonds

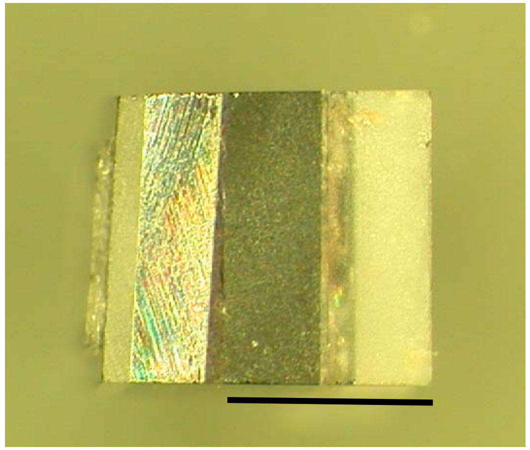


Integration: Optics Assembly

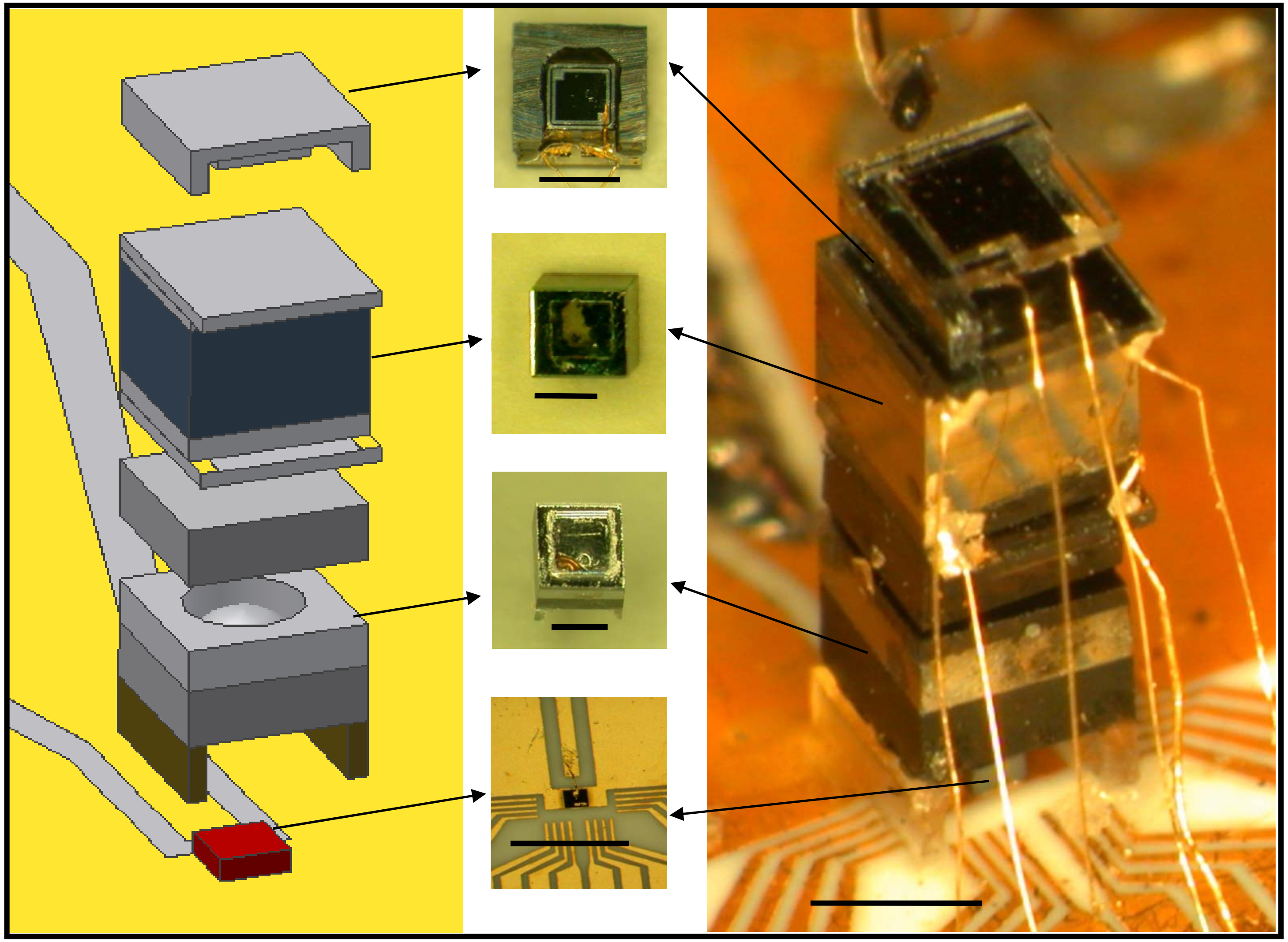
- Micro-refractive lens
  - Inkjet deposition of optical epoxy
  - Commercially available in arrays
- ND filters (opaque glass):
  - Total thickness = 1 mm
  - Total OD = 1.66
- Spacers
  - For light collimation, thermal isolation
  - Glass or SU-8
- Waveplate
  - Quartz 70 μm thick $\Rightarrow \lambda/4$ @ 850 nm







NIST Chip-Scale Atomic Clock



Volume:
9.5 mm^3

Cell volume:
0.81 mm^3

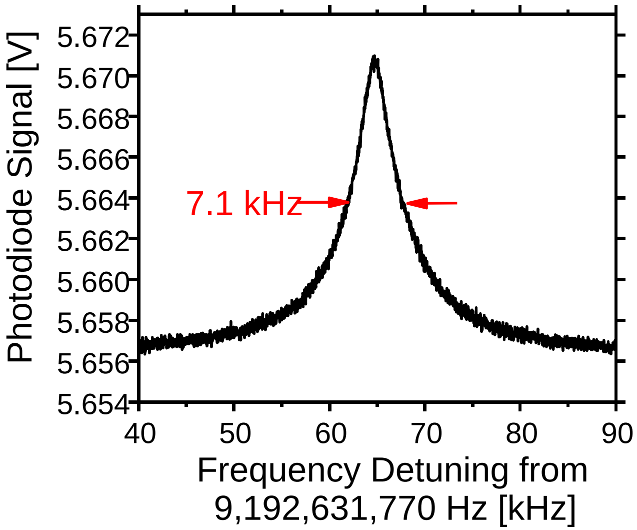
Power:
75 mW
(Physics Package)

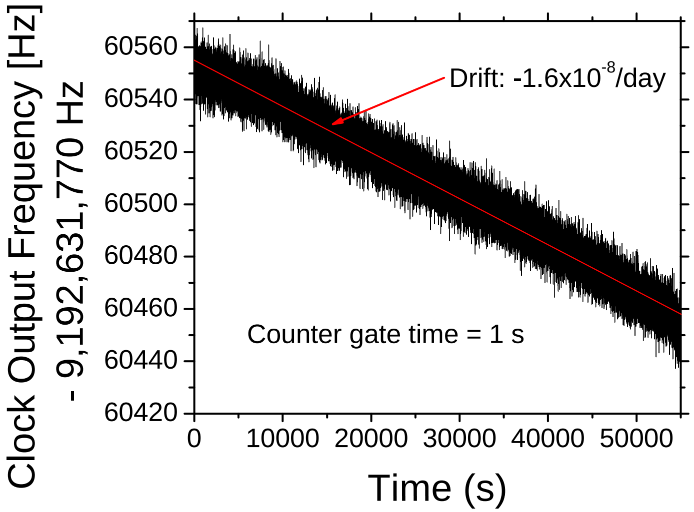
Stability:
σ_y(1 sec.) = 3×10^{-10}

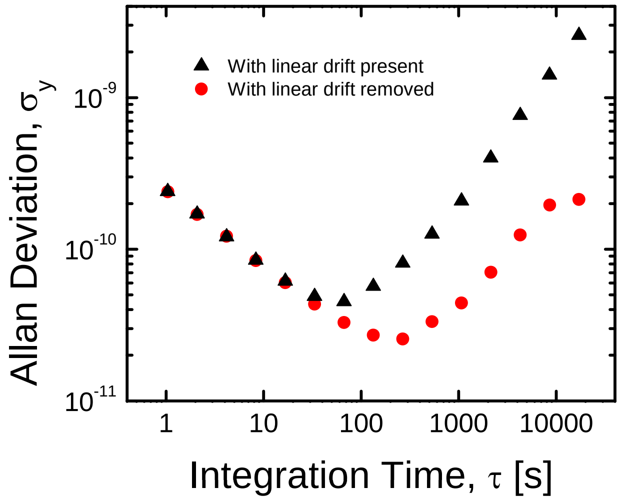
S. Knappe et al., App. Phys. Lett. 85, 1460 (2004)

CPT Resonance and Frequency Instability

- Short term instability:
  - Shot noise, laser AM noise, FM-AM conversion
- Long-term instability:
  - Drift, temperature fluctuations of cell

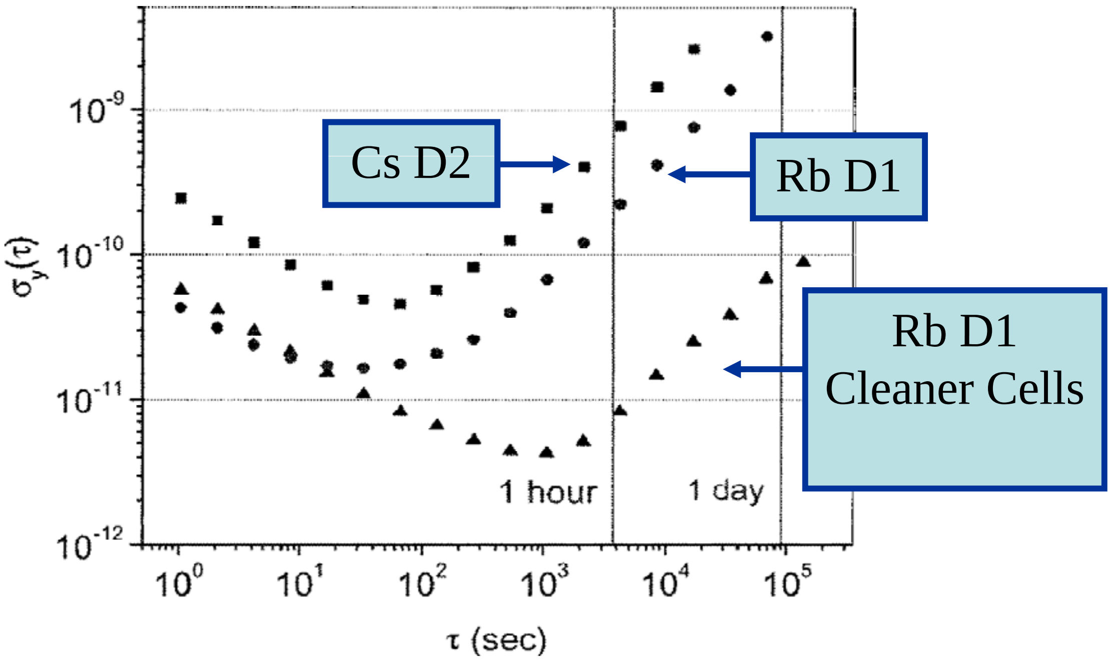






Improvements on Initial Performance

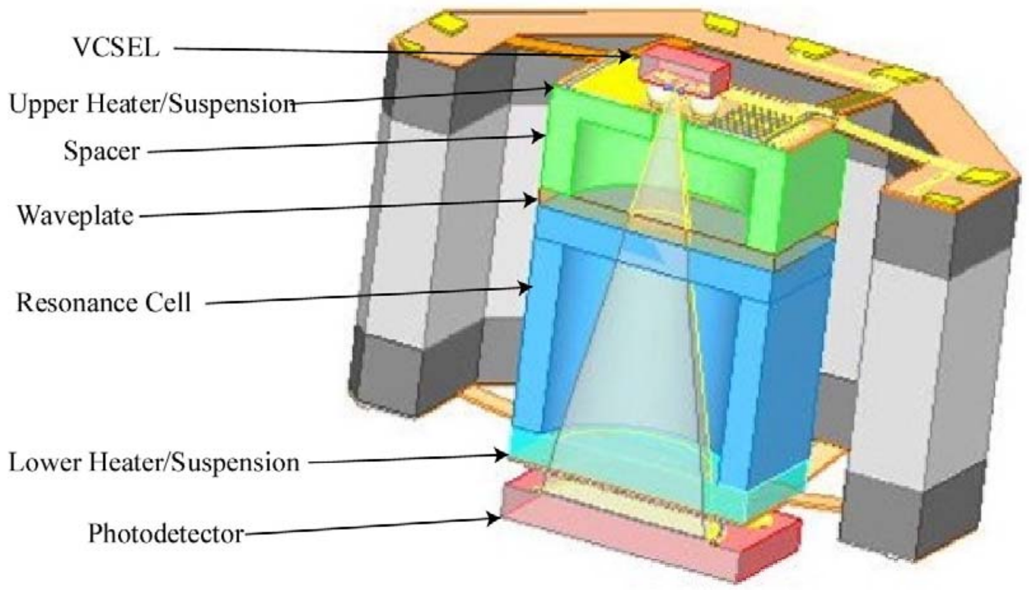
- Change from D2 to D1 laser excitation
  - Switch to Rb atoms because of laser wavelength availability
  - >3× improvement in line contrast – 5× improvement in clock stability
  - S. Knappe, et al., Opt. Exp. 13, 1249, (2005).
- Improve cell filling techniques to reduce drift from contamination
  - Alkali beam filling: S. Knappe et al., Opt. Lett. 30, 2351 (2005)
  - Cesiated cell walls: F. Gong et al., Rev. Sci. Instrum. 77, 076101 (2006)

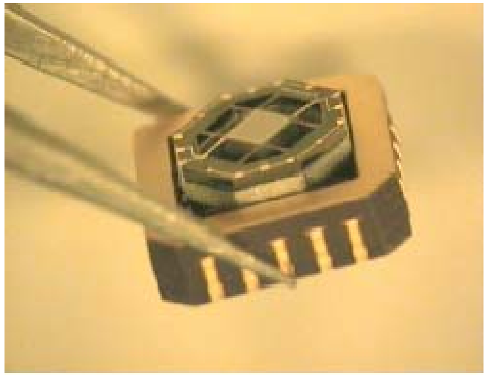


Commercial Chip-Scale Atomic Clocks

Symmetricom Physics Package

Mescher, Lutwak, & Vargese., IEEE Solid-State Sensors and Actuators (2005)





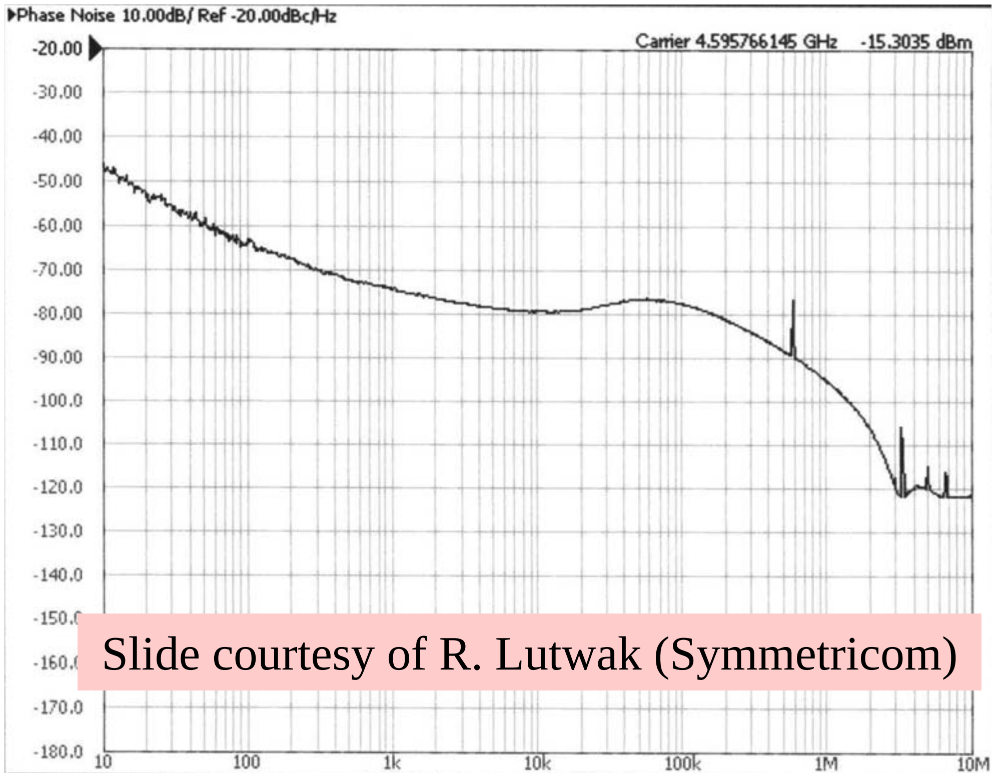
P_{diss} < 10 mW
T_{cell} ~ 80 °C, T_{amb} ~ 25 °C
Radiation dominated

Excellent thermal isolation

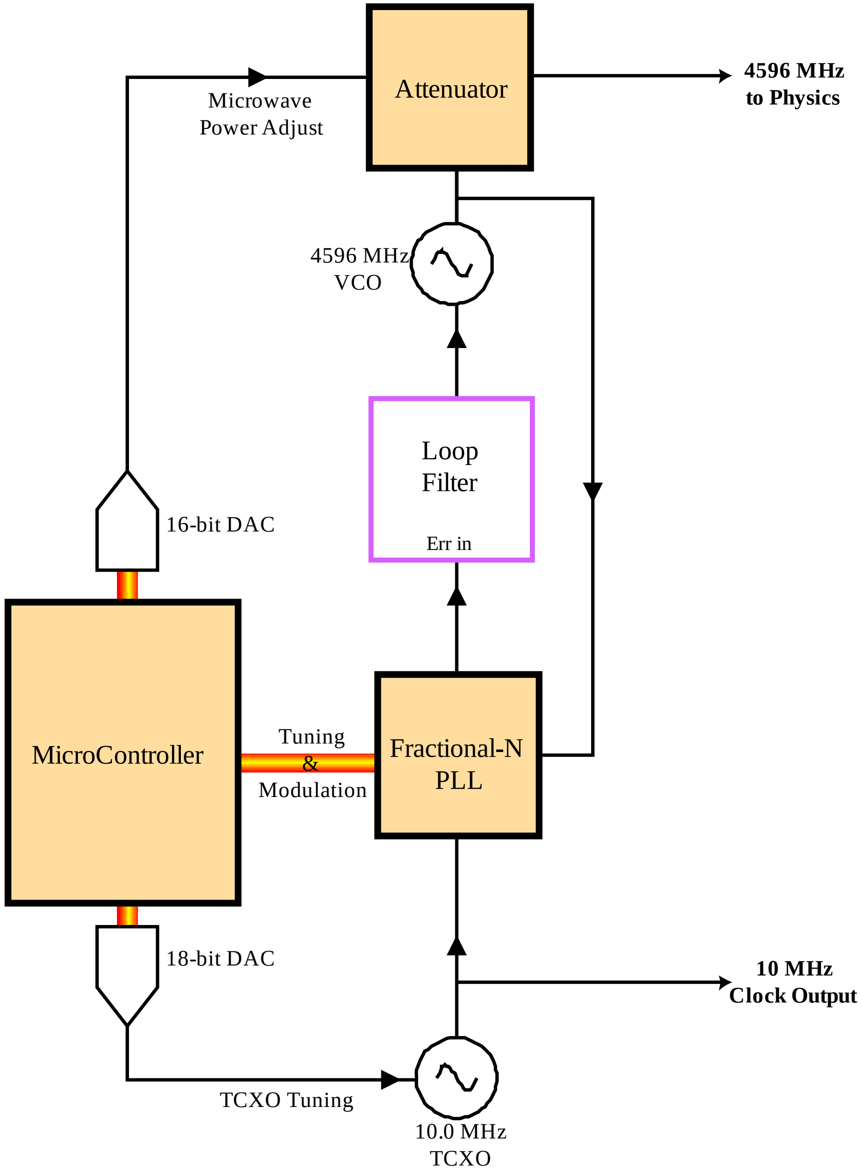
- Tensioned polyimide suspension
  - Excellent thermal & mechanical properties
- Vacuum-packaged to eliminate convection/conduction

Symmetricom Synthesizer

- Modulation via digital control of PLL
- Tuning via digital control of PLL
- Output is 10.0 MHz
- Power adjust 0 to -10 dBm
- Good phase noise (-75 dBc @ 1 kHz)
- High Power (≈ 50 mW)

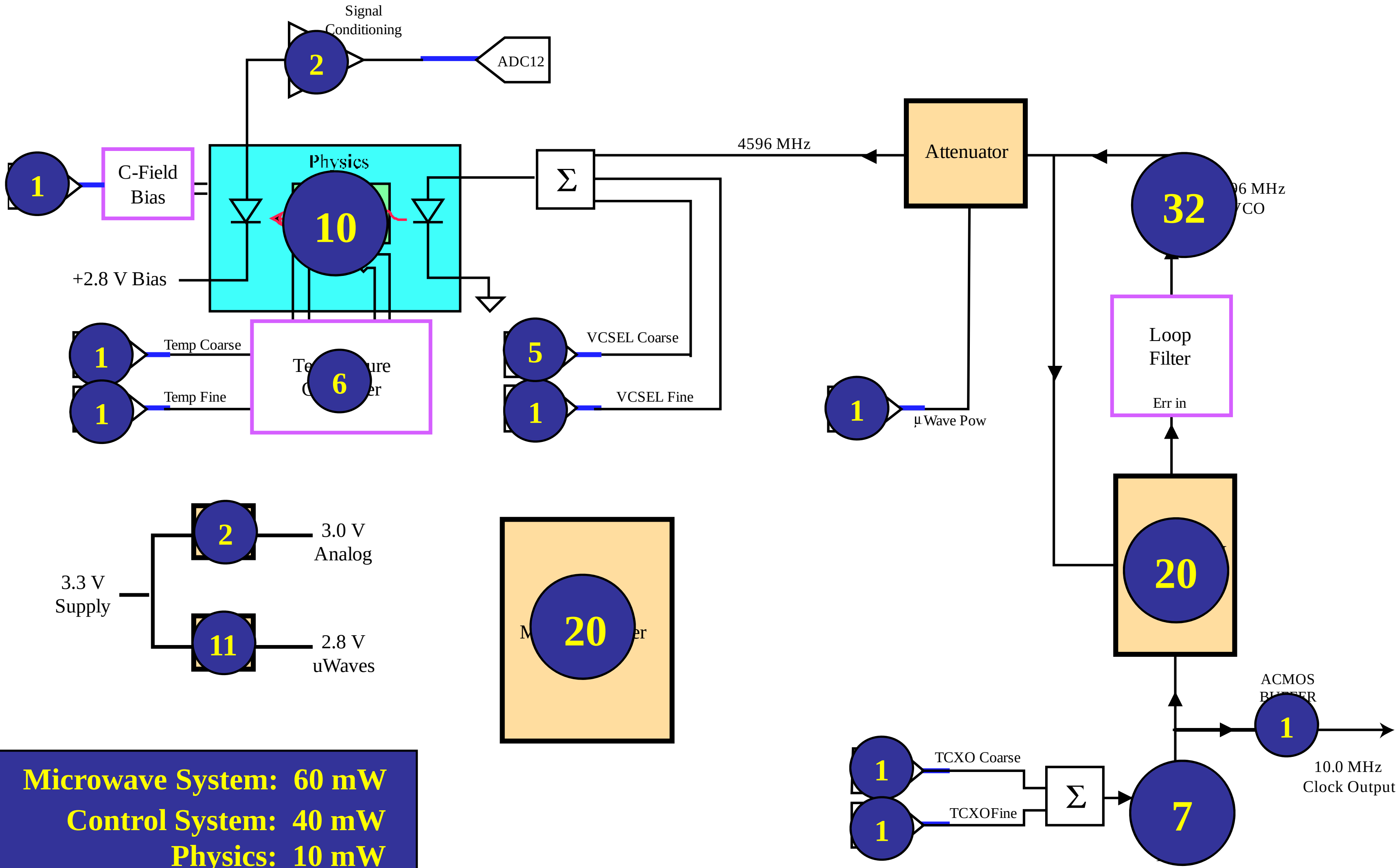


Slide courtesy of R. Lutwak (Symmetricom)



Electronics Block Diagram

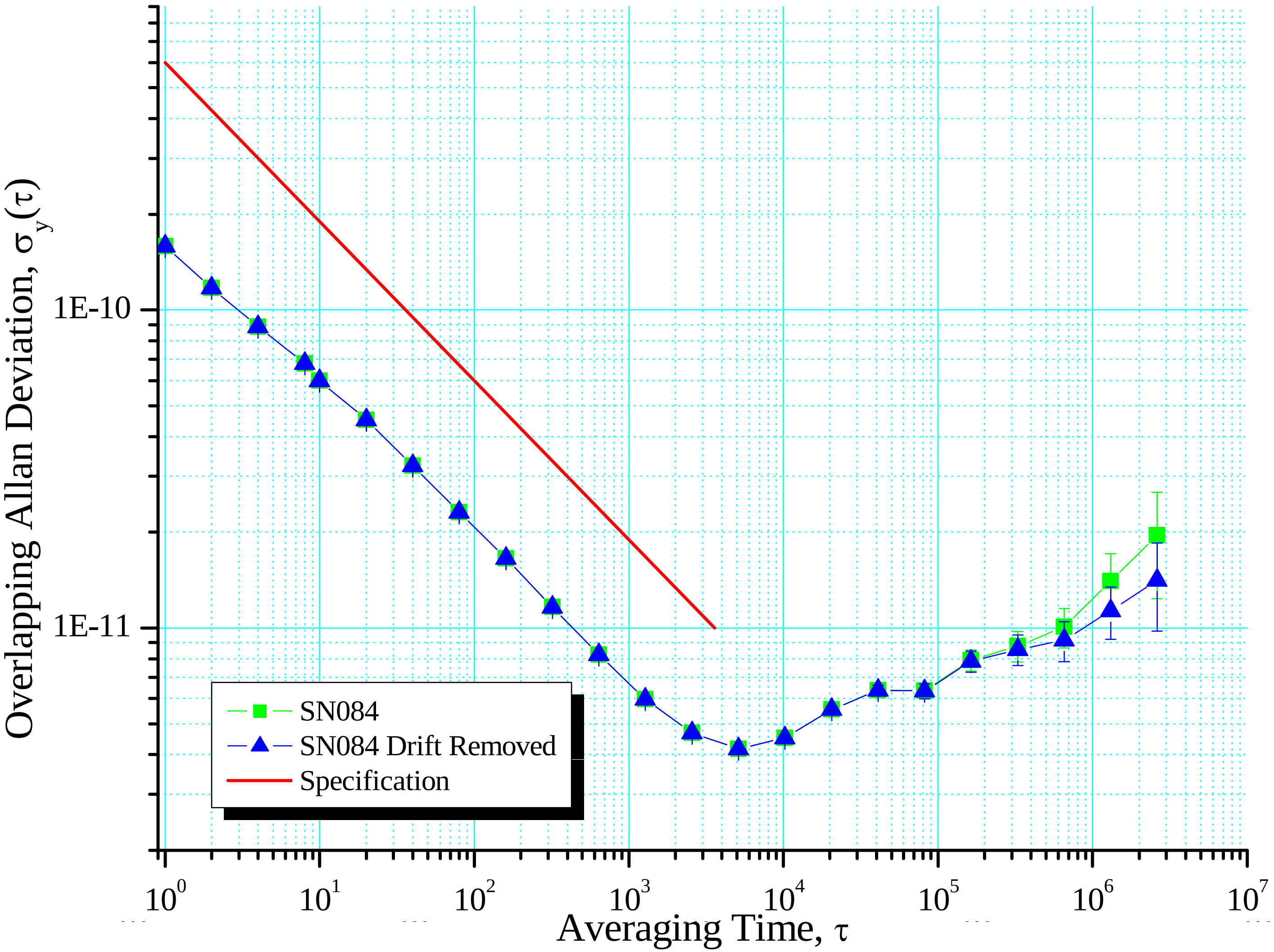
R Lutwak et al., Proc. 2007 Joint EFTF Frequency Control Symposium (Symmetricom & Draper Labs)



Microwave System:	**60 mW**
Control System:	**40 mW**
Physics:	**10 mW**
Regulators & Passives:	**15 mW**
Total:	**125 mW**

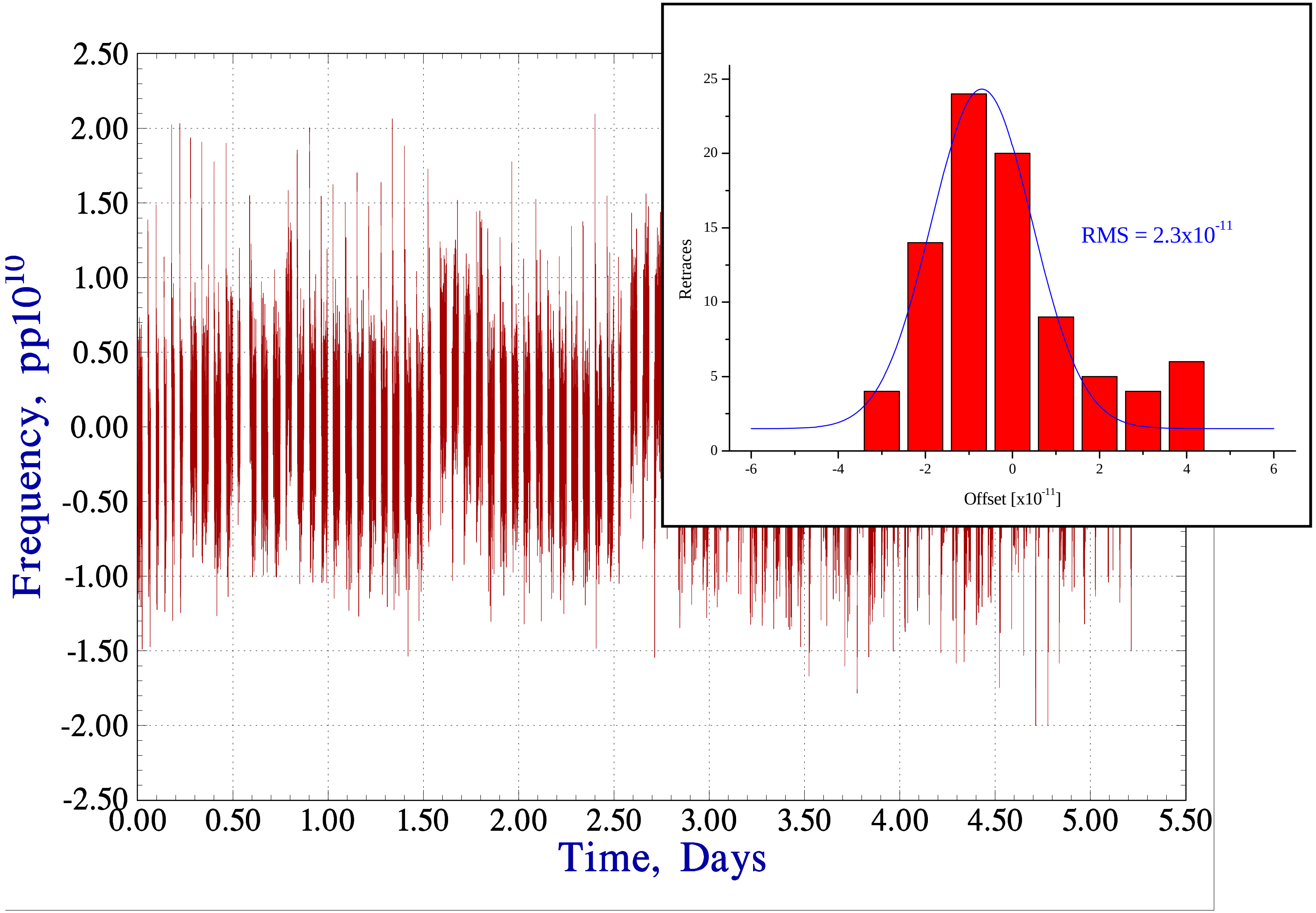
Slide courtesy of R. Lutwak (Symmetricom)

Symmetricom Clock Stability



R. Lutwak et al., Proceedings of the 2007 PTTI Conference

Symmetricom Retrace



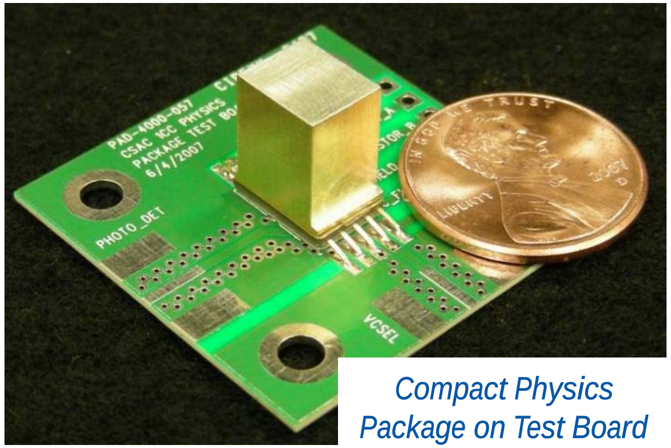
Courtesy of R. Lutwak *2008 FCS Tutorial*

CSAC Activities at Teledyne Scientific

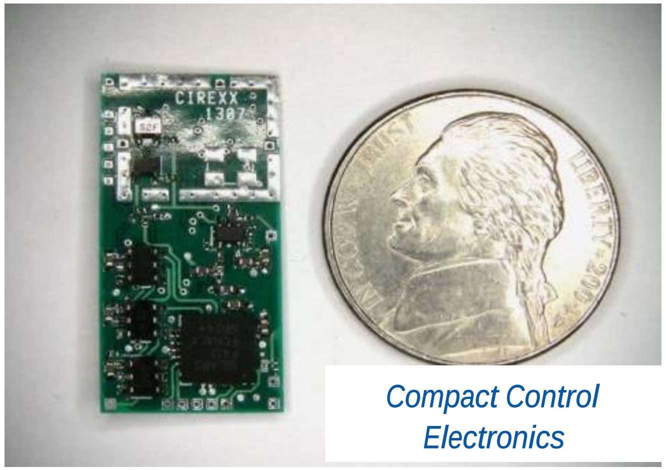
J.F. DeNatale et al., PLANS 2008, IEEE/ION (2008)

Under Phase III of CSAC program, achieved DARPA's program goals

- **Size** reduced to 1cc (0.7cc physics package and 0.3 cc electronics
- **Power** of physics package measured below 30 mW
- **Stability** of Phase-III physics package measured < 1x10^{-11} at 1 hour



Compact Physics Package on Test Board



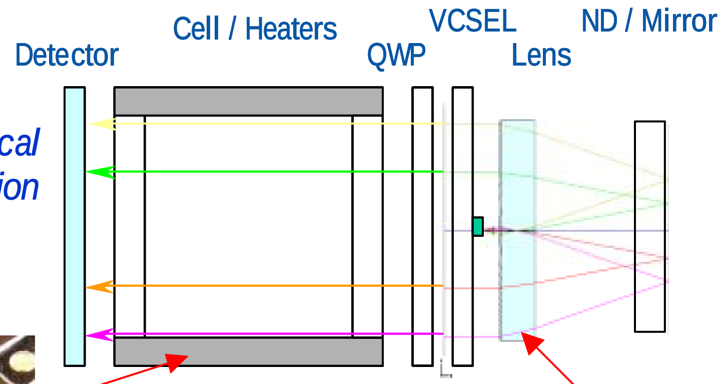
Compact Control Electronics

Photo of Fully Integrated 1cc CSAC with compact control electronics

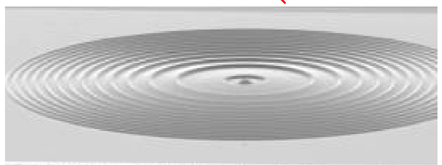
Teledyne Physics Package Features

J.F. DeNatale et al., PLANS 2008, IEEE/ION (2008)

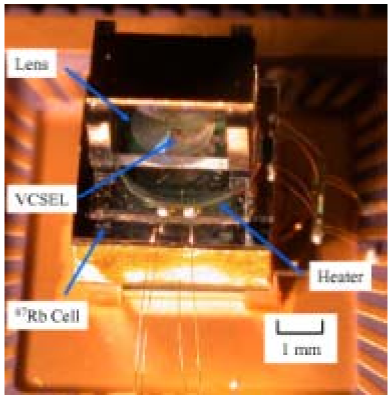
Dual-pass optical configuration



Compact Vapor Cells



Microfabricated Optics

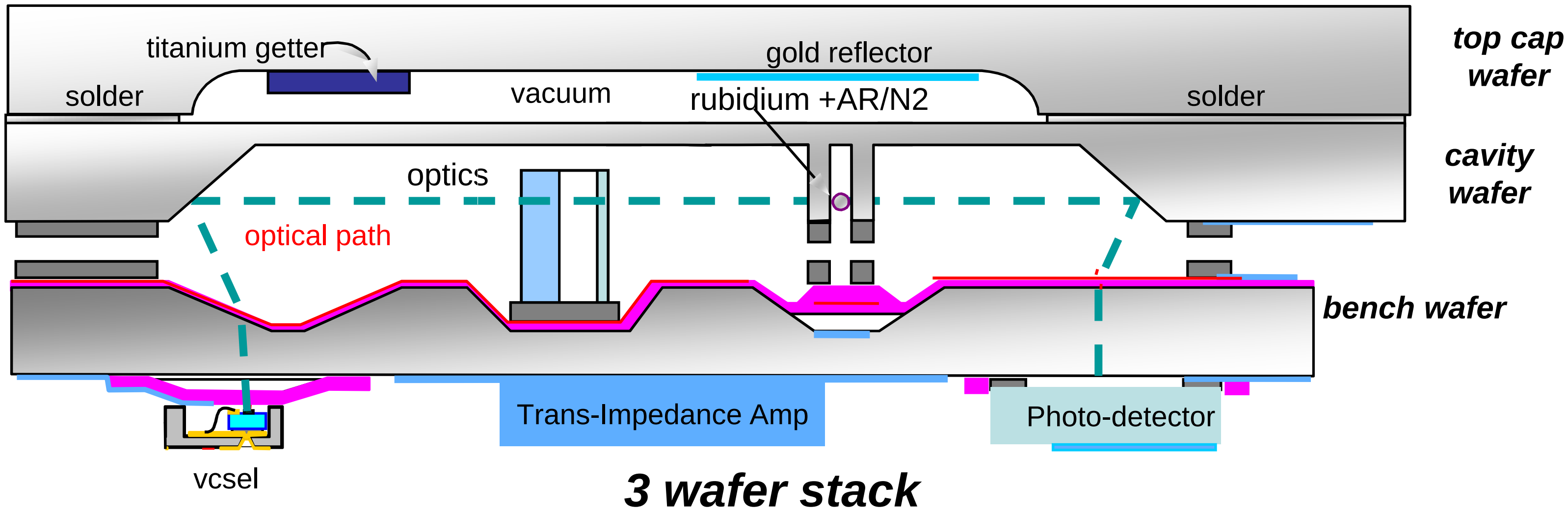


Phase-III Physics Package

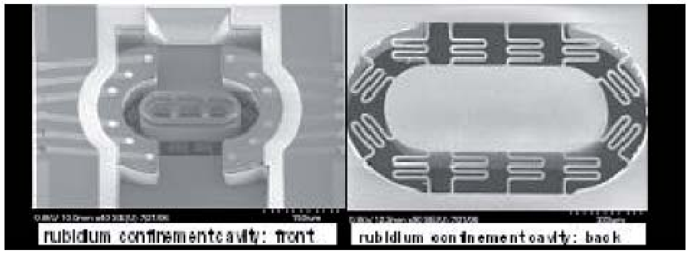
reduce size, power and improve robustness / assembly

Honeywell CSAC Physics Package

D.W. Youngner, et. al., Transducers & Eurosensors, 2007.



3 wafer stack



"Honeywell has attempted to differentiate itself … by making clocks that are easy to assemble and package."

- more integration and critical alignment at the wafer level, and less at the package level.

Current Status of DARPA-Funded CSAC Research

- Currently in Phase IV of DARPA CSAC program.
  - Funds Symmetricom and Teledyne Scientific
- The main Phase-IV objective: **"Demonstrate compliant functionality in a relevant military environment."**
  - Deliver a quantity of units (currently 35) to the U.S. Army
  - Power will be roughly 100 mW
  - Units will be tested over the full military range of temperature, shock, vibration, humidity, EM susceptibility, etc.

Evolution of CSAC Technology

Kitching et al., Proc. 2007 IEEE Intl. Freq. Cont. Symp.

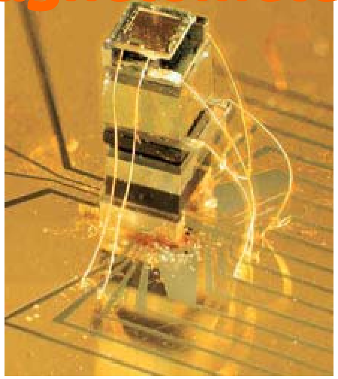
Spin-Off

Spin-Off

Integrated
Micro
Primary
Atomic
Clock
Technology

MTO MEMS

Chip Scale Atomic Magnetometers



One of the 10 emerging technologies most likely to change the way we live.
- MIT Technology Review (2008)

NMR Gyroscopes
- Add spin-polarized noble-gas nuclei to the cell

Biomedical Applications
- Magnetocardiography
- Magnetoencephalography
- Low-field MRI
- etc…

Other Sensors
- Magnetic Anomaly
- Geophysical
- etc…

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