**Basic Concept: Scaling Guitar Strings**

- **Guitar String**
  - **Freo.** vs. **Vib. Amplitude**
  - Low Q, High Q
  - String (110 Hz)

- **Freq. Equation:**
  \( f_s = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \)

- **Performance:**
  \( f_s = 8.5 \text{MHz} \)
  \( Q_{\text{res}} = 8.000 \)
  \( Q_{\text{m}} = 50 \)

- **[Bannon 1996]**

**μMechanical Resonator**

- **Metallized Electrode**
- **Polysilicon Clamped-Clamped Beam**
- **Anchor**

**3CC 3\( \lambda/4 \) Bridged μMechanical Filter**

- **Performance:**
  \( f_{\text{c}} = 9\text{MHz} \)
  \( BW = 20\text{kHz} \)
  \( PBW = 0.2\% \)
  \( L = 2.79\text{dB} \)
  \( Stop.\ Rej = 51\text{dB} \)
  \( 20\text{dB} \text{ S.F.} = 1.95, \ 40\text{dB} \text{ S.F.} = 6.45 \)

- **Design:**
  \( L = 40\text{µm} \)
  \( W_r = 6.5\text{µm} \)
  \( h_r = 2\text{µm} \)
  \( L_c = 3.5\text{µm} \)
  \( L = 18.6\text{µm} \)
  \( V_i = 10.47\text{V} \)
  \( P_s = 0\text{dBm} \)
  \( R_o = R_{\text{in}} = 12\text{kΩ} \)

**Micromechanical Filter Circuit**

- **R \( \text{O} \) Input**
- **V \( \text{P} \) Output**

**1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator**

- **Impedance-mismatched stem for reduced anchor dissipation**
- **Operated in the 2\text{nd} radial-contour mode**
- **Q = 11,555 (vacuum): Q = 10,100 (air)**
- **Below: 20 µm diameter disk**

**Design/Performance:**

- **P = 10\text{µm}, \ m = 2.2\text{µm}, \ d = 800\text{Å}, \ V_i = 7\text{V} \)
- **f_{\text{c}} = 1.51\text{GHz} (2\text{nd} mode), Q = 11,555 \)

- **Polyisilicon Stem**
  - (Impedance Mismatched to Diamond Disk)

- **CVD Diamond μMechanical Disk Resonator**

- **Ground Plane**

**Mixed Amplitude [dB]**

- **Q = 10,100 (air)**

- **Wang, Butler, Nguyen MEMS'04**
163-MHz Differential Disk-Array Filter

Com. Array Couplers
Filter Coupler

Port1
$\lambda/2$

$V_p$

Port3
$\lambda/2$

$V_p$

Port2
Diff. Array Couplers

Port4
$\lambda/4$

$V_o$

$V_o$

$V_o$

[Li, Nguyen Trans '07]

Linear MEMS in Wireless Comms

High Q and good linearity of micromechanical resonators

Filters for front-end frequency selection

Micromechanical Bandpass Filter

Wireless Phone

Antenna

Diplexer

Mixer I

LPF

LNA

RXRF LO

Xstal

Osc

I

Q

AGC

LNA

RF BPF

Mixer Q

LPF

AGC

From TX

RF PLL

Problem: high-Q passives pose a bottleneck against miniaturization

Minimization of RF Front Ends

RF Power Amplifier

Diplexer

925-960MHz RF SAW Filter

1805-1880MHz RF SAW Filter

26-MHz Xstal Oscillator

Wireless Phone

Antenna

Diplexer

RF BPF

LNA

From TX

RF BPF

Mixer I

LNA

RXRF LO

Xstal

Osc

I

Q

AGC

LNA

From TX

RF BPF

GSM 900

CDMA

DCS 1900

PCS 1900

WCDMA

Multi-Band Wireless Handsets

* The number of off-chip high-Q passives increases dramatically

* Need: on-chip high-Q passives

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All High-Q Passives on a Single Chip

- CDMA RF Filters (869-894 MHz)
- GSM 900 RF Filter (935-960 MHz)
- PCS 1900 RF Filter (1930-1990 MHz)
- DCS 1800 RF Filter (1805-1990 MHz)
- CDMA-2000 RF Filters (1850-1990 MHz)
- WCDMA RF Filters (2110-2170 MHz)

Chip-Scale Atomic Clocks (CSAC)

NIST F1 Fountain Atomic Clock

- Vol: ~3.7 m^3
- Power: ~500 W
- Acc: 1 \times 10^{-15}
- Stab: 3.3 \times 10^{-15}/hr

After 1 sec 
Error: 10^{-15} sec

Loses 1 sec every 30 million years!

Benefits of Accurate Portable Timing

- Better Timing
- Secure Communications
  - More efficient spectrum utilization
  - Longer autonomy periods
  - Faster frequency hop rates
  - Faster acquire of pseudorandom signals
- Networked Sensors
  - Larger networks with longer autonomy
- GPS
  - Fewer satellites needed
  - Superior resilience against jamming or interception
  - Higher jamming margin
  - Faster GPS acquire
NIST F1 Fountain Atomic Clock

Vol: ~3.7 m³
Power: ~500 W
Acc: 1x10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

After 1 sec ⇒ Error: 10⁻¹⁵ sec

Loses 1 sec every 30 million years!

Open Loop Resonance

1st Chip-Scale Atomic Physics Package

Total Volume: 9.5 mm³
Stability: 2.4 x 10⁻¹⁰ @ 1s
Power Cons: 75 mW

Cs D2 Excitation
External (large) Magnetic Shielding
External Electronics & LO
Cell Temperature: ~80 °C
Cell Heater Power: 69 mW
Laser Current/Voltage: 2 mA / 2 V
RF Laser Mod Power: 70 μW

Stability Measurement:

Frequency drift from 9,192,631,770 Hz

Experimental Conditions:

Tiny Physics Package Performance

Dime

NIST’s Chip-Scale Atomic Physics Package

Open Loop Resonance:

Stability: 0.91%

Volume: 0.6 mm³

Electronic Clocks: Introduction to MEMS Design
Lecture 3-4m: Benefits of Scaling II

Atomic Clock Fundamentals

ΔE = 1.46 eV
ν = ΔE/h
= 352 THz
≈ 852.11 nm

ΔE = 0.00038 eV
ν = ΔE/h
= 9 192 631 770 Hz

Sufficient to meet CSAC program goals

Energy Band Diagram

Excite e- to the next orbital

133Cs

Opposite e-spins

m = 0
f = 4

1 hour

1 day

10⁻¹²
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²

Integration Time, τ [s]

CSAC Goal

Energy

Δf = 4

Δf = 3

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**Miniature Atomic Clock Design**

- **Atoms become transparent to light at 852 nm**
- **Modulated Laser**
- **VCXO**
- **Photo Detector**
- **Close feedback loop to lock**

**Chip-Scale Atomic Clock**

- **Laser**
- **WCXO**
- **Photo Detector**
- **VCSEL**
- **Glass Detector Substrate**
- **MEMS and Photonic Technologies**
  - **Key Challenges**:
    - Thermal isolation for low power
    - Cell design for maximum Q
    - Low power μwave oscillator

**Challenge: Miniature Atomic Cell**

- **Large Vapor Cell**
  - 1,000X Volume Scaling
  - Surface Volume ↑
  - More wall collisions ⇔ stability gets worse
  - Wall collision dephases atoms ⇒ lose coherent state

- **Tiny Vapor Cell**
  - 1,000X Volume Scaling
  - Buffer Gas
  - Soln: Add a buffer gas
  - Lower the mean free path of the atomic vapor
  - Return to higher Q

**Atomic Clock Concept**

- **Cs or Rb**
- **3 GHz**
- **3 GHz**
- **Resonator in Vacuum**
- **Vol: 1 cm³**
- **Power: 30 mW**
- **Stab: 1×10⁻¹¹**
Chip-Scale Atomic Clock

Key Challenges:
- Thermal isolation for low power
- Cell design for maximum Q
- Low power \( \mu \) wave oscillator

MEMS and Photonic Technologies

Micro-Scale Oven-Control Advantages

Macro-Scale
- 300x300x300 \( \mu \)m\(^3\)
- Atomic Cell @ 80°C
- Heater
- Laser
- Insulation
- 3 cm
- \( R_{th} = 38 \text{ K/W} \)
- \( C_{th} = 22 \text{ J/K} \)

Micro-Scale
- 550x lower power
- 7,300x faster warm up
- \( P \) (@ 80°C) = 2.6 mW
- Warm Up, \( \tau = 0.1 \)

Chip-Scale Atomic Clock
- Vol: 1 cm\(^3\)
- Power: 30 mW
- Stab: \( 1 \times 10^{-11} \)

Micro-Scale Oven
- 3 cm
- \( R_{th} \sim \) support length
- \( C_{th} \sim \) volume
- \( T = P \times R_{th} \)

Micro-Scale Advantages
- 7,300x faster warm up
- Warm Up, \( \tau = 16 \text{ min.} \)