**Basic Concept: Scaling Guitar Strings**

- **Guitar String**
  - Vibrating “A” String (110 Hz)
  - Frequency vs. Amplitude
  - Freq. vs. Mass

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

**Performance**:
- \( f_c = 8.5 \text{MHz} \)
- \( Q_{eq} = 8,000 \)
- \( Q_{eq} < 50 \)

**Micromechanical Filter Circuit**

**Design/Performance**:
- Design:
  - \( L_r = 40 \mu \text{m} \)
  - \( W_r = 6.5 \mu \text{m} \)
  - \( h_r = 2 \mu \text{m} \)
  - \( L_c = 3.5 \mu \text{m} \)
  - \( L_i = 1.6 \mu \text{m} \)
  - \( V_p = 10.47 \text{V} \)
  - \( P_s = 5 \text{dBm} \)
  - \( R_o = R_{o0} = 12k\Omega \)

**3CC 3\( \lambda \)/4 Bridged \( \mu \)Mechanical Filter**

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

**1.51-GHz, \( Q = 11,555 \) Nanocrystalline Diamond Disk \( \mu \)Mechanical Resonator**

- Impedance-mismatched stem for reduced anchor dissipation
- Operated in the 2nd radial-contour mode
- \( Q \approx 11,555 \) (vacuum)
- \( Q \approx 10,100 \) (air)
- Below: 20 \( \mu \)m diameter disk
**163-MHz Differential Disk-Array Filter**

- Com. Array Couplers
- Filter Coupler
- Port 1
- Port 2
- Port 3
- Port 4
- Diff. Array Couplers

[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

---

**Miniaturization of RF Front Ends**

- RF Power Amplifier
- Diplexer
- 897.5±17.5MHz RF SAW Filter
- 925-960MHz RF SAW Filter
- 1805-1880MHz RF SAW Filter
- 26-MHz Xstal Oscillator
- 3420-3840MHz VCO
- Dual-Band Zero-IF Transistor Chip

**Problem**: high-Q passives pose a bottleneck against miniaturization

---

**Multi-Band Wireless Handsets**

- CDMA
- GSM 900
- DCS 1800
- PCS 1900
- WCDMA

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

---

[Image of wireless phone and circuit diagrams]
**All High-Q Passives on a Single Chip**

- Vibrating Resonator 1.5-GHz, Q~12,000
- CDMA RF Filters (869-894 MHz)
- GSM 900 RF Filter (935-960 MHz)
- PCS 1900 RF Filter (1930-1990 MHz)
- DCS 1800 RF Filter (1805-1880 MHz)
- CDMA-2000 RF Filters (1850-1990 MHz)
- WCDMA RF Filters (2110-2170 MHz)
- Optional RF Oscillator Ultra-High Q Tanks
- Low Freq. Reference Oscillator Ultra-High Q Tank

**Chip-Scale Atomic Clocks (CSAC)**

**NIST F1 Fountain Atomic Clock**

- Vol: ~3.7 m³
- Power: ~500 W
- Acc: 1×10⁻¹⁵
- Stab: 3.3×10⁻¹⁵/hr

- After 1 sec \( \Rightarrow \) Error: 10⁻¹⁵ sec
- Loses 1 sec every 30 million years!

**Benefits of Accurate Portable Timing**

- Secure Communications
  - Faster frequency hop rates
  - Faster acquire of pseudorandom signals
  - Superior resilience against jamming or interception

- Networked Sensors
  - More efficient spectrum utilization
  - Longer autonomy periods
  - Fewer satellites needed
  - Higher jamming margin
  - Faster GPS acquire

- GPS
  - Larger networks with longer autonomy
**NIST F1 Fountain Atomic Clock**

- **Vol:** \( \sim 3.7 \text{ m}^3 \)
- **Power:** \( \sim 500 \text{ W} \)
- **Acc:** \( 1 \times 10^{-15} \)
- **Stab:** \( 3.3 \times 10^{-15}/\text{hr} \)

- **After 1 sec \( \Rightarrow \) Error:** \( 10^{-15} \text{ sec} \)

- **Loses 1 sec every 30 million years!**

---

**1st Chip-Scale Atomic Physics Package**

- **Total Volume:** 9.5 mm\(^3\)
- **Stability:** \( 2.4 \times 10^{-10} @ 1s \)
- **Cell Interior Vol:** 0.6 mm\(^3\)
- **Power Cons:** 75 mW

---

**Tiny Physics Package Performance**

- **Experimental Conditions:**
  - Cs D2 Excitation
  - External (large) Magnetic Shielding
  - External Electronics & LO
  - Cell Temperature: \( \sim 80 ^\circ \text{C} \)
  - Cell Heater Power: 69 mW
  - Laser Current/Voltage: 2mA / 2V
  - RF Laser Mod Power: 70 mW

- **Open Loop Resonance:**
  - Drift to Be Removed
  - Sufficient to meet CSAC program goals

- **Stability Measurement:**
  - **Q = 1.3 \times 10^6**
  - **565 kHz**
  - **Contrast:** 0.03%

- **Energy Band Diagram**

  - **\( \Delta E = 1.46 \text{ eV} \)**
  - \( \nu = \Delta E/\hbar \)
  - \( = 352 \text{ THz} \)
  - \( = 852.11 \text{ nm} \)

  - **\( \Delta E = 0.00038 \text{ eV} \)**
  - \( \nu = \Delta E/\hbar \)
  - \( = 9,192,631,770 \text{ Hz} \)

---

**Atomic Clock Fundamentals**

- **Frequency determined by an atomic transition energy**

---

Copyright © 2020 Regents of the University of California
Miniature Atomic Clock Design

- Atoms become transparent to light at 852 nm
- 133Cs vapor at 10^7 torr
- Laser
- Modulated Laser
- VCXO μwave osc
- Close feedback loop to lock

Chip-Scale Atomic Clock

- VCSEL
- Cs or Rb 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
- Tiny Vapor Cell
- 1,000X Volume Scaling

- Surface Volume ↑
- Atomic Resonance lowest Q
- Wall collision dephases atoms ⇒ lose coherent state
- More wall collisions ⇒ stability gets worse

- Intensity Mod f 9.2 GHz

Solution:
- Add a buffer gas
- Lower the mean free path of the atomic vapor

- Buffer Gas
- 1.000X Volume Scaling
- Lower the mean free path of the atomic vapor
- Return to higher Q
Chip-Scale Atomic Clock

**MEMS and Photonic Technologies**

- **Key Challenges:**
  - Thermal isolation for low power
  - Cell design for maximum Q
  - Low power microwave oscillator

**Chip-Scale Atomic Clock**

- Vol: 1 cm³
- Power: 30 mW
- Stab: 1 x 10⁻¹¹

---

**Micro-Scale Oven-Control Advantages**

**Macro-Scale**

- Macro-Oven (containing heater and T sensor)
- Atomic Cell @ 80°C

**Micro-Scale**

- 300x300x300 μm³ Atomic Cell @ 80°C
- Long, Thin Polysilicon Tethers

**Thermally Isolating Feet**

**Laser**

**25°C**

- T = P x Rₘₜ
- Rₘₜ ~ support length
- X-section area
- Cₘₜ ~ volume

- **P (@ 80°C) = 1.5 W**
  - 550x lower power
  - Warm Up, τ = 16 min.
  - 7,300x faster warm up

- **P (@ 80°C) = 2.6 mW**
  - Warm Up, τ = 0.1 s