**EE C247b/ME C218: Introduction to MEMS**

**Lecture 3m: Benefits of Scaling II**

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**EE C247B – ME C218**

**Introduction to MEMS Design**

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Lecture Module 2: Benefits of Scaling

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**3CC 3λ/4 Bridged μMechanical Filter**

**Performance:**

\[ f_s = 9\text{MHz}, \quad BW = 20\text{kHz}, \quad PBW = 0.2\% \]

\[ I.L. = 2.79\text{dB}, \quad Stop. \text{ Rej.} = 51\text{dB} \]

\[ 20\text{dB} \text{ S.F.} = 1.95, \quad 40\text{dB} \text{ S.F.} = 6.45 \]

**Design:**

\[ L_s = 40\mu\text{m}, \quad W = 6.5\mu\text{m}, \quad h_s = 2\mu\text{m} \]

\[ L_s = 3.5\mu\text{m}, \quad L_m = 1.6\mu\text{m}, \quad V_{P} = 10.47\text{V} \]

\[ P = 5\text{dBm}, \quad R_{in} = 12\Omega \]

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**Micromechanical Filter Circuit**

**Basic Concept: Scaling Guitar Strings**

- **μMechanical Resonator**
  - [Bannon 1996]
  - \( f_s = 8.5\text{MHz} \)
  - \( Q_m = 8,000 \)
  - \( Q_{vac} \approx 50 \)
  - \( m_r \approx 10^{-10} \text{kg} \)
  - \( W_s \approx 8\mu\text{m} \)
  - \( h_s = 2\mu\text{m} \)
  - \( d = 1000\text{Å} \)
  - \( V_{P} = 5\text{V} \)
  - \( \text{Press.} = 70\text{mTorr} \)

**Freq. Equation:**

\[ f_s = \frac{1}{2\pi} \sqrt{\frac{k_s}{m_r}} \]

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**Historical Notes:**

- **Scaling Guitar Strings**
  - \( k \rightarrow \frac{k}{L^4} \)
  - \( f \rightarrow \frac{f}{L^2} \)
  - \( Q \rightarrow \frac{Q}{L^2} \)

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**References:**

- Li, Nguyen, FCS
- Bannon 1996

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**Acknowledgments:**

- University of California at Berkeley
- Prof. Clark T.-C. Nguyen

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Below are images and tables related to MEMS design and RF front ends. The text discusses the benefits of scaling II, focusing on the design and performance of MEMS resonators and filters.

### 1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk Mechanical Resonator
- **Polysilicon Stem (Impedance Mismatched to Diamond Disk)**
- **CVD Diamond Mechanical Disk Resonator**
- **Growth Plane**

**Operated in the 2nd radial-contour mode**
- \( Q \approx 11,555 \) (vacuum)
- \( Q \approx 10,100 \) (air)
- **Below:** 20 \( \mu \)m diameter disk

**Resonant Frequency:**
- \( f = 1.51 \text{ GHz} \)
- \( Q = 11,555 \) (vacuum)
- \( Q = 10,100 \) (air)

**Design & Performance:**
- \( R = 10 \mu \Omega \), \( l = 2.2 \mu \Omega \), \( d = 800 \Omega \), \( V_p = 7 \text{V} \)
- \( f_0 = 1.51 \text{ GHz} \) (2nd mode), \( Q = 11,555 \)

### 163-MHz Differential Disk-Array Filter
- **Com. Array Couplers**
- **Filter Couplers**
- **Port1**
- **Port2**
- **Port3**
- **Port4**

**Design & Performance:**
- **Micromechanical resonators**
- **Filters for front-end frequency selection**
- **High Q and good linearity of micromechanical resonators**

### Miniaturization of RF Front Ends
- **Dual-Band Zero-IF Transistor Chip**
- **RF Power Amplifier**
- **RF SAW Filter**
- **26-MHz Xstal Oscillator**
- **Problem:** high-Q passives pose a bottleneck against miniaturization

**From TX to RXRF LO**
- **BPF**
- **LPF**
- **AGC**
- **Mixer I**
- **Mixers Q**
- **Osc**
- **Xstal**
- **RF PLL**
- **Diplexer**

**Frequency Selection Filters for front-end**
- **Mixed Amplitude [dB]**
Benefits of Scaling II

Multi-Band Wireless Handsets

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

All High-Q Passives on a Single Chip

Chip-Scale Atomic Clocks (CSAC)

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

Physics Package

Loses 1 sec every 30 million years!
Benefits of Accurate Portable Timing

Secure Communications

- Better Timing
- Networked Sensors
- More efficient spectrum utilization
- Larger networks with longer autonomy
- Longer autonomy periods
- Faster frequency hop rates
- Faster acquire of pseudorandom signals
- 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: 1 x 10⁻¹⁵
- Stab: 3.3 x 10⁻¹⁵/hr

- After 1 sec => Error: 10⁻¹⁵ sec
- Loses 1 sec every 30 million years!

1st Chip-Scale Atomic Physics Package

- NIST’s Chip-Scale Atomic Physics Package
- Total Volume: 9.5 mm³
- Cell Interior Vol: 0.6 mm³
- Stability: 2.4 x 10⁻¹⁶ @ 1s
- Power Cons: 75 mW

Tiny Physics Package Performance

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

- Stability Measurement:

  - Stability Measurement
  - Q = 1.3 x 10⁴
  - Sufficient to meet CSAC program goals
  - CSAC Goal

- Drift Issue
- CSAC Goal
- Integration Time, t [s]
Atomic Clock Fundamentals

Frequency determined by an atomic transition energy

Excite e⁻ to the next orbital

Energy Band Diagram

\[ \Delta E = 1.46 \text{ eV} \]
\[ \nu = \Delta E / h \]
\[ \nu = 352.11 \text{ THz} \]
\[ \Delta E = 0.000038 \text{ eV} \]
\[ \nu = \Delta E / h \]
\[ \nu = 9192631770 \text{ Hz} \]

Miniature Atomic Clock Design

Atoms become transparent to light at 852 nm

Hyperfine Splitting Freq.

Sidebands

Modulated Laser

4.6 GHz

Photo Detector

133Cs vapor at 10⁻⁷ torr

4.6 GHz

VCSEL

mod wave osc

1000X Volume Scaling

Surface / Volume

Chip-Scale Atomic Clock

MEMS and Photonic Technologies

Key Challenges:
- thermal isolation for low power
- cell design for maximum Q
- low power mod wave oscillator

Chip-Scale Atomic Clock

Vol: 1 cm³
Power: 30 mW
Stab: 1x10⁻¹¹

Challenge: Miniature Atomic Cell

Large Vapor Cell

1.000X Volume Scaling

Wall collision dephases atoms \( \Rightarrow \) lose coherent state

9.2 GHz

More wall collisions \( \Rightarrow \) stability gets worse

Lowest Q

Chip-Scale Atomic Clock

Laser 133Cs vapor at 10⁻⁷ torr Mod f

Atomic Resonance

Mod f

Surface Volume
**Challenge: Miniature Atomic Cell**

**Large Vapor Cell** vs. **Tiny Vapor Cell**

- **1,000X Volume Scaling**
- **Solution:** Add a buffer gas
- **Lower the mean free path of the atomic vapor**

**Micro-Scale Oven-Control Advantages**

**Macro-Scale**

- Atomic Cell @ 80°C
- Insulation
- Laser
- 3 cm

**Micro-Scale**

- 300x300x300 μm³ Atomic Cell @ 80°C
- Heater
- Laser
- 25°C

**Physics Package Power Diss. < 10 mW**

- Achieved via MEMS-based thermal isolation
- Only ~5 mW heating power needed to achieve 80°C cell temperature

**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**

- **Volume:** 1 cm³
- **Power:** 30 mW
- **Stability:** 1×10⁻¹³

**Polymer**

- 4.6 GHz
- VCSEL
- Frame Suspension
- Glass Detector Substrate
- Only ~5 mW needed to achieve 80°C cell temperature

**Power: 30 mW**

**Measured** vs. **Model**

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Power [mW]</th>
</tr>
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<tbody>
<tr>
<td>0</td>
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