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School Lecture/Tutorial on

Micromechanical Signal Processors for Low-Power Communications

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Outline

• Miniaturization of Transceivers
  ➢ the need for high-Q

• High-Q Micromechanical Resonators

• Micromechanical Circuits
  ➢ micromechanical filters
  ➢ micromechanical mixer-filters
  ➢ micromechanical switches

• Using MEMS in Comm. Receivers
  ➢ direct replacement of passives
  ➢ trade Q (or selectivity) for power
  ➢ MEMS-based receiver architecture

• Research Issues

• Conclusions
Frequency Division Multiplexed Communications

- Information is transmitted in specific frequency channels within specific bands

Transmitted Power

<table>
<thead>
<tr>
<th>Band</th>
<th>GSM Band</th>
<th>Adj. Band</th>
<th>DCS1800 Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td></td>
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</table>

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Frequency Division Multiplexed Communications

- Information is transmitted in specific frequency channels within specific bands.
Frequency Division Multiplexed Communications

- Information is transmitted in specific frequency channels within specific bands

Transmitted Power

- **Need**: high frequency selectivity
  - need high-Q

GSM Band  Adj. Band  DCS1800 Band

Filter

Frequency
**Need for High-Q: Selective Low-Loss Filters**

In resonator-based filters: high tank $Q \leftrightarrow$ low insertion loss

*At right*: a 0.3% bandwidth filter @ 70 MHz (simulated)

⇒ heavy insertion loss for resonator $Q < 5,000$
Attaining High-Q

- **Problem**: IC’s cannot achieve Q’s in the thousands
  - transistors → consume too much power to get Q
  - on-chip spiral inductors → Q’s no higher than ~10
  - off-chip inductors → Q’s in the range of 100’s

- **Observation**: vibrating mechanical resonances → Q > 1,000

- **Example**: quartz crystal resonators (e.g., in wristwatches)
  - extremely high Q’s ~ 10,000 or higher (Q ~ 10^6 possible)
  - mechanically vibrates at a distinct frequency in a thickness-shear mode
Miniaturization of Transceivers

- High-Q functionality required by oscillators and filters cannot be realized using standard IC components → use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization
So Many Passive Components!

- The total area on a printed circuit board for a wireless phone is often dominated by passive components ⇒ passives pose a bottleneck on the ultimate miniaturization of transceivers.
Surface Micromachining

- Fabrication steps compatible with planar IC processing

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Post-CMOS Circuits+$\mu$Mechanics Integration

- Completely monolithic, low phase noise, high-Q oscillator (effectively, an integrated crystal oscillator) [Nguyen, Howe]

- To allow the use of $>600^\circ$C processing temperatures, tungsten (instead of aluminum) is used for metallization
Target Application: Integrated Transceivers

Board-Level Implementation

- Off-chip high-Q mechanical components present bottlenecks to miniaturization \( \Rightarrow \) replace them with \( \mu \)-mechanical versions
Micromechanical Resonators
Vertically-Driven Micromechanical Resonator

• To date, most used design to achieve VHF frequencies

Resonator Beam

Electrode

\[ f_o = \frac{1}{2\pi} \sqrt{\frac{k_r}{m_r}} = 1.03 \sqrt[3]{\frac{E}{\rho}} \frac{h}{L_r^2} \]

(e.g. \( m_r = 10^{-13} \text{kg} \))

\[ E = \text{Youngs Modulus} \]
\[ \rho = \text{density} \]

• Smaller mass \( \Rightarrow \) higher frequency range and lower series \( R_x \)

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HF μMechanical CC-Beam Resonator

- Surface-micromachined, POCl₃-doped polycrystalline silicon

- Extracted $Q = 8,000$ (vacuum)

- $L_r = 40.8 \, \mu m$, $W_r = 8 \, \mu m$, $h = 2 \, \mu m$, $d = 0.1 \, \mu m$

- Freq. and $Q$ influenced by dc-bias and anchor effects
Anchor Dissipation in Fixed-Fixed Beams

- **Frequency [MHz]**
  - Left: 8.48 to 8.52
  - Right: 71.0 to 73.0

- **Transmission [dB]**
  - Left: -25 to 0
  - Right: -68 to -56

- **Parameters**
  - Left: $L_f=40.8\,\mu m$, $W_f=8\,\mu m$, $h=2\,\mu m$, $d=1,000\,\AA$, $W_e=20\,\mu m$, $V_P=35V$
  - Right: $L_f=14\,\mu m$, $W_f=8\,\mu m$, $h=2\,\mu m$, $d=300\,\AA$, $W_e=7\,\mu m$, $V_P=35V$

- **Frequencies and $Q$ Values**
  - 8.5 MHz, $Q=8,000$
  - 71.8 MHz, $Q=300$
**92 MHz Free-Free Beam \(\mu\text{Resonator}**

- Free-free beam \(\mu\text{mechanical resonator with non-intrusive supports} \Rightarrow \) reduce anchor dissipation \(\Rightarrow\) higher \(Q\)

**Design/Performance:**
- \(L_r=13.1\mu\text{m}, W_r=6\mu\text{m}\)
- \(h=2\mu\text{m}, d=1000\text{Å}\)
- \(V_p=28-76\text{V}, W_e=2.8\mu\text{m}\)
- \(f_0\sim 92.25\text{MHz}\)
- \(Q\sim 7,450 @ 10\text{mTorr}\)

[Wang, Yu, Nguyen 1998]

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92 MHz Free-Free Beam \( \mu \)Resonator

- Free-free beam \( \mu \)mechanical resonator with non-intrusive supports \( \Rightarrow \) reduce anchor dissipation \( \Rightarrow \) higher \( Q \)

**Design/Performance:**
- \( L_r = 13.1 \mu m, W_r = 6 \mu m \)
- \( h = 2 \mu m, d = 1000 \AA \)
- \( V_p = 28-76V, W_e = 2.8 \mu m \)
- \( f_0 \sim 92.25MHz \)
- \( Q \sim 7,450 @ 10mTorr \)

[Wang, Yu, Nguyen 1998]
70MHz Nano-Scale Bulk Si Resonators

- Magnetically driven
- $Q = 20,000$ @ $T=4.2K$

[Cleland and Roukes, 1996]
Scaling-Induced Performance Limitations

**Mass Loading Noise**

- Differences in rates of adsorption and desorption of contaminant molecules
  - mass fluctuations
  - frequency fluctuations

- Problem: If dimensions too small ⇒ phase noise significant!
- The smaller the resonator ⇒ smaller the power handling

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]

- Contaminant Molecules

**Temperature Fluctuation Noise**

- Absorption/emission of photons
  - temperature fluctuations
  - frequency fluctuations

- Photons

- Volume ~10^{-15} m^3

- Mass loading fluctuations

- Mass ~10^{-13} kg

[J. R. Vig, 1999]
156 MHz Radial Contour-Mode Disk μMechanical Resonator

- Below: Balanced radial-mode disk polysilicon mechanical resonator (34 μm diameter)

μmechanical Disk Resonator

Metal Electrode

Metal Electrode

Anchor

Design/Performance:

$R = 17 \mu m$, $t = 2 \mu m$, $d = 1000 \AA$, $V_P = 35 V$, $f_0 = 156.23 MHz$, $Q = 9400$

[Clark, Hsu, Nguyen IEDM’00]
Desired Filter Characteristics

- Small shape factor generally preferred

\[
\text{40dB Shape Factor} = \frac{\text{40dB Bandwidth}}{\text{3dB Bandwidth}}
\]
Micromechanical Circuits
Micromechanical Circuits

- A single mechanical beam can’t really do much on its own
- But use many mechanical beams attached together in a circuit, and attain a more complex, more useful function

Key Design Property: High Q
• Small shape factor generally preferred
**Micromechanical Filter Circuit**

- **Freq. Pulling Electrode**
- **Resonator**
- **Anchor**
- **Coupling Spring**
- **Output Electrode**

- **Input Electrode**

- **Resonator1**

- **Resonator2**

- **Coupling Spring12**

- **DC-Bias**

- **$V_{1\Delta f}$**

- **$V_P$**

- **$v_i$**

- **$v_o$**

- **$R_{Q1}$**

- **$R_{Q2}$**

- **$x$**

- **$y$**

- **$z$**

- **$v_1$**

- **$v_2$**

- **$C_{o1}$**

- **$C_{o2}$**

- **$\eta_{e1}$**

- **$\eta_{c1}$**

- **$\eta_{c2}$**

- **$\eta_{e2}$**

- **$c_r$**

- **$m_r$**

- **$1/k_{s1}$**

- **$1/k_{s12}$**

- **$1/k_r$**

- **$\omega_0$**

- **$\omega$**
Ideal Spring-Coupled μMechanical Filter

Symmetric Mode

Anti-Symmetric Mode

\[ \text{BW} \sim \frac{k_{s12}}{k_r} \]

\[ \left| \frac{X}{F_d} \right| \]

\[ \omega_0 \]

\[ \omega \]
Micromechanical Filter Circuit

Freq. Pulling Electrode

Resonator

Anchor

Coupling Spring

Output Electrode

Input Electrode

$V_{1\Delta f}$

DC-Bias

$R_{Q1}$

$R_{Q2}$

$v_i$

$V_P$

$\frac{v_o}{v_i}$

$\omega_0$

$\omega$

$x$

$y$

$z$

Resonator 1

Resonator 2

Coupling Spring 1-2

$1: \eta_{c1}$

$1: \eta_{e1}$

$-\frac{1}{k_{s12}}$

$\frac{1}{k_{s12}}$

$\frac{1}{k_r} m_r$

$\frac{1}{k_r} m_r$

$C_{o1}$

$C_{o2}$

$v_1$

$v_2$

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HF Spring-Coupled Micromechanical Filter

2-Resonator HF (4th Order)  
[Bannon, Clark, Nguyen 1996]

Performance

\[ f_0 = 7.81 \text{MHz}, \quad BW = 15 \text{kHz} \]
\[ \text{Rej.} = 35 \text{dB}, \quad \text{I.L.} < 2 \text{dB} \]
High-Order $\mu$Mechanical Filter

3-Resonator MF
(6th Order, 1/5-Velocity Coupled)

- $f_0=340$ kHz
- $BW=403$ Hz
- $\%BW=0.09\%$
- $Stop.R.=64$ dB
- $I.L.<0.6$ dB

[Wang, Nguyen 1997]
Electromechanical Mixing

**Electrostatic Force:**

\[
F_i = -\frac{\partial E}{\partial x} = -\frac{\partial}{\partial x}\left(\frac{1}{2}C_{gap}V_{gap}^2\right) \\
= -\frac{1}{2}(V_P + v_{LO} - v_{RF})^2 \frac{\partial C_{gap}}{\partial x} \\
= \ldots + v_{LO}v_{RF} \frac{\partial C_{gap}}{\partial x} + \ldots
\]
Micromechanical Mixer-Filter

[Image showing a diagram of a micromechanical mixer-filter system, including components such as LNA, Mixer, VCO, and a bandpass filter.]

[Text: "RF Information Input: \( v_{RF} = |v_{RF}| \cos \omega_{RF} t \) \( R_{Qi} \) \( C_{Pi} \) \( v_{LO} = |v_{LO}| \cos \omega_{LO} t \) \( V_{P1} \) \( V_{P2} \) \( v_{IF} \) \( R_{Qo} \) \( C_{Po} \) \( L_{r1} \) \( L_{r2} \) \( W_{r2} \) \( h \) \( \text{Input Electrode} \) \( \text{Anchor} \) \( \text{Non-conductive Coupling Beam} \) \( \text{Output Electrode} \) \( \text{Down-Converted and Filtered Output} \) \( \text{Mixing Transducer} \) \( \text{Baseband Electronics} \) \( \text{Replace with single \( \mu \) mechanical Mixer+Filters} \)]

[Wong, Nguyen IEDM'98]
Micromechanical Switch

- Operate the micromechanical beam in an up/down binary fashion

Performance: $I.L. \sim 0.1\,\text{dB}$, $IIP3 \sim 66\,\text{dBm}$ (extremely linear)

Issues: switching voltage $\sim 20\,\text{V}$, switching time: $1-5\,\mu\text{s}$

[C. Goldsmith, 1995]
MEMS-Based Receivers
MEMS-Based Receiver Architecture

- **Most Direct Approach**: replace off-chip components (in orange) with mechanical versions (in green)

- **Obvious Benefit**: substantial size reduction

\[ L_1 \sim 2\text{dB} \]
\[ L_3 \sim 6\text{dB} \]
\[ L_5 \sim 12\text{dB} \]

- **Replace with MEMS**

\[ NF = 8.8\text{dB} \]
\[ NF = 2.8\text{dB} \]

Antenna Diversity for resilience against fading

Higher Q \rightarrow L_1 \sim 0.3\text{dB} \quad L_3 \sim 0.5\text{dB} \quad L_5 \sim 1\text{dB}
MEMS-Based Receiver Front-End

Received Power

Desired Signal

Conventional RF Filter $\Rightarrow Q_{\text{res}} \sim 400$

Frequency

$\omega_{\text{LO}}$  $\omega_{\text{RF}}$

Conventional RF Filter

Antenna

Ceramic RF Filter  LNA  SAW RF Filter

Mixer

SAW IF Filter

IF Amp

$90^\circ$

IQ Osc.

Quartz Xstal

Tunable Off-Chip LC Tank

VCO

Quartz Xstal

Channel Select PLL

I  Q
MEMS-Based Receiver Front-End

\[ \omega_{RF} \]

\[ \omega_{LO} \]

\[ Q_{res} \approx 400 \]

Conventional RF Filter

Out-of-Band Interferers Removed

\[ \text{Received Power} \]

Desired Signal

\[ \text{Conventional RF Filter} \rightarrow Q_{res} \approx 400 \]

\[ \text{Out-of-Band Interferers Removed} \]

\[ \text{Desired Signal} \]

\[ \text{Conventional RF Filter} \]

\[ \text{Out-of-Band Interferers Removed} \]

\[ \text{Desired Signal} \]

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\[ \text{Out-of-Band Interferers Removed} \]

\[ \text{Desired Signal} \]

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\[ \text{Desired Signal} \]

\[ \text{Conventional RF Filter} \]

\[ \text{Out-of-Band Interferers Removed} \]

\[ \text{Desired Signal} \]

\[ \text{Conventional RF Filter} \]

\[ \text{Out-of-Band Interferers Removed} \]
**MEMS-Based Receiver Front-End**

- **Received Power**: Described in terms of frequency and mechanical RF filter performance.

- **RF Filter**:
  - $Q_{res} \sim 400$
  - $Q_{res} \sim 10,000$

- **Block Diagram**:
  - Antenna
  - LNA
  - Mixer
  - IF Filter
  - IF Amp
  - 90° phase shifter
  - IQ Osc.
  - Quartz Xtal
  - Tunable Off-Chip LC Tank
  - Quartz Xtal
  - Channel Select PLL

- **Frequency Response**:
  - $\omega_{LO}$
  - $\omega_{RF}$

**Notes**:
- MEMS for Wireless Communications
- C. T.-C. Nguyen
MEMS-Based Receiver Front-End

Provides robustness against jammers and extends battery lifetime

\[ \omega_{LO} \]

\[ \omega_{RF} \]

\[ \mu \text{Mechanical RF Filter} \]

\[ Q_{\text{res}} \approx 400 \quad \Rightarrow \]

\[ Q_{\text{res}} \approx 10,000 \quad \Rightarrow \]

All Interferers Removed
MEMS-Based Receiver Front-End

Provides robustness against jammers and extends battery lifetime

Reduces loss and removes power consumption by active devices

Eliminates active phase-locking ckt. power consumption

Miniaturization
MEMS-Based Receiver Front-End

Low Loss  Eliminate the RF LNA?

- If possible, could
  - enhance robustness
  - substantially reduce RF front-end power

[Nguyen, Top. Mtg. on Si IC’s in RF Systems 2001]
Research Issues
Research Issues: Frequency Extension

• Needed diameters to achieve UHF fundamental-mode resonance frequencies using a 2μm-thick disk resonator

<table>
<thead>
<tr>
<th>Frequency, $f_0$</th>
<th>Diameter</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>polysilicon</td>
</tr>
<tr>
<td>500 MHz</td>
<td>11 μm</td>
</tr>
<tr>
<td>800 MHz</td>
<td>6.8 μm</td>
</tr>
<tr>
<td>1 GHz</td>
<td>5.4 μm</td>
</tr>
<tr>
<td>2 GHz</td>
<td>2.8 μm</td>
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</table>
38.8 kHz CVD Polydiamond Folded-Beam μMechanical Resonator

- In situ-doped polydiamond deposited via a microwave plasma reactor (methane and diborane reactants) at 540°C
- 80% higher resonance frequency than polysilicon version

Design/Performance:

\[ L_b = 160 \mu m, \ W_b = 2 \mu m, \ h = 2 \mu m, \ d = 2 \mu m, \ V_P = 25V, \ f_0 = 38.8 kHz, \ Q = 19,500 \]

\[ f_0 = 38.8 kHz, \ Q = 19,500 \]
Research Issues: Frequency Extension

• Needed diameters to achieve UHF fundamental-mode resonance frequencies using a 2 μm-thick disk resonator

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<tr>
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<tr>
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<td>20.8 μm</td>
</tr>
<tr>
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<td>6.8 μm</td>
<td>13 μm</td>
</tr>
<tr>
<td>1 GHz</td>
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<td>10.4 μm</td>
</tr>
<tr>
<td>2 GHz</td>
<td>2.8 μm</td>
<td>5.2 μm</td>
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• Problem: geometry not the only consideration; other important factors include:
  - impedance vs. linearity/power handling
  - manufacturing issues: trimming, vacuum encapsulation, MEMS/transistor integration
  - thermal and aging stability
**Research Issue: Termination Resistance**

- Need to minimize $R_Q$ for impedance matching → want:
  - $V_P$ = large
  - $A_o$ = large
  - $d$ = small

**Equation for $R_Q$**

$$R_Q = \frac{\sqrt{km}}{Q_{res} V_P^2 \left( C_o/d \right)^2 \left( \frac{Q_{res}}{q_i Q_{fltr}} - 1 \right)} \propto \frac{d^4}{V_P^2 A_o^2}$$

**Diagram Details**

- Input Electrode
- Anchor
- Resonator Electrode
- Output Electrode
- Electrode-to-Resonator Gap
- Electrode-to-Resonator Static Capacitance
- Filter $Q$
- Resonator dc-bias Voltage
- Electrode-to-Resonator Overlap Area
Small Electrode-to-Resonator Gaps

- For a 2 μm-thick, 70 MHz, 0.1% bandwidth filter, with $V_P=6V$:

<table>
<thead>
<tr>
<th>Termination $R_Q$</th>
<th>Resonator $R_x$</th>
<th>Gap $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000 Ω</td>
<td>516 Ω</td>
<td>250 Å</td>
</tr>
<tr>
<td>500 Ω</td>
<td>140 Ω</td>
<td>180 Å</td>
</tr>
<tr>
<td>100 Ω</td>
<td>28 Ω</td>
<td>120 Å</td>
</tr>
</tbody>
</table>
Design Issue: Process Tolerances

- Process variations can lead to distortion in the filter passband
μMechanical Filter Passband Correction

- **Problems**: too many interconnect leads, $\Delta f$ small at VHF
- **Need**: a permanent frequency trimming technique

[Wang, Nguyen, 1999]
**Research Issue: Frequency Trimming**

- For banks of filters or resonators → need automated trimming on a massive scale, preferably voltage-activated

- **Localized Annealing:**
  - Current through structure heats it like a filament
  - Extremely fast thermal time constants allow for ultra-rapid annealing
  - 16 ppm $f_o$ shift per anneal pulse

[Wang, Wong, Hsu, Nguyen Transducers’97]
Research Issue: Thermal Stability

- Need temperature compensation or control methods

[Wang, Yu, Nguyen 2000]

Temperature [°C]

Fractional Frequency Change [ppm]

Free-Free Beam

Clamped-Clamped Beam

Condensed Contaminant

Polysilicon Free-Free Beam

Polysilicon Clamped-Clamped Beam

$TC_f = 12.5$ ppm/°C

$TC_f = 16.7$ ppm/°C

2,800 ppm

3,750 ppm
Vacuum Encapsulation

- **Below**: localized heated bonding to seal a vacuum cap over a released micromechanical resonator

Schematic of the Bonding Encapsulation Procedure

![Schematic of the Bonding Encapsulation Procedure](image)

- Glass Cap
- Microcavity
- Broken Glass Cap
- V_{anneal}
- μHeater and Aluminum Solder

Graph: 80 weeks at 25 mTorr

[Cheng, Hsu, Lin, Nguyen, Najafi MEMS 2000]

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Thermal Stability Comparison

- Thermal stability of poly-Si micromechanical resonator is 10X worse than the worst case of AT-cut quartz crystal.
Geometric-Stress Compensation

- Use a temperature dependent mechanical stiffness to null frequency shifts due to Young’s modulus thermal dep.

• Problems:
  - stress relaxation
  - compromised design flexibility

[Hsu and Nguyen, IEDM’00]

[Q = 10,317]

[frequency [MHz]]

[Amplitude [dB]]

[Fractional Frequency Change [ppm]]

[Temperature [K]]

[–2.5 ppm/°C]

[C. T.-C. Nguyen]
Displacement-dependent $E$ fields generate motional force in quadrature with the input force $\rightarrow$ electrical stiffness

Effective electrical stiffness subtracts from mechanical stiffness, causing frequency shift

\[ F_{90^\circ} = -\left( \frac{V_p^2 \varepsilon_0 W_e h}{d^3} \right) |x| \]

\[ k_e = \frac{V_p^2 \varepsilon_0 W_e h}{d^3} \]

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{k_r}{m_r}} = \frac{1}{2\pi} \sqrt{\frac{k_m - k_e}{m_r}} \]
Operation of Stiffness Compensation

• To implement stiffness compensation:
  ⇓ add a top electrode of a material with a larger thermal expansion coefficient than resonator material
  ⇓ design such that the top electrode-to-resonator gap spacing increases with increasing temperature

• T increase → gap increase → freq. increase → counteract freq. decrease caused by Young's modulus

\[ TC_f = \frac{\alpha_{Er} + \alpha_r}{2} + \frac{3}{2} \left( \frac{V_p - V_C}{d_{o2}^4 k_{r1}} \right)^2 \varepsilon_o A_{o2} (\alpha_e - \alpha_r) h_{be} \]

[Hsu, Nguyen MEMS’02]
SEM of 10MHz Stiffness-Compensated Resonator with Slitted Top Electrode

[Hsu, Nguyen MEMS’02]
Measured $\Delta f/f$ vs. Temperature for Electrical Stiffness-Compensated $\mu$Resonators

Design/Performance:

- $f_o = 10\text{MHz}$, $Q = 4,000$
- $V_P = 8\text{V}$, $h_e = 4\mu\text{m}$
- $d_o = 1000\AA$, $h = 2\mu\text{m}$
- $W_r = 8\mu\text{m}$, $L_r = 40\mu\text{m}$

[Hsu, Nguyen MEMS’02]

- Slits help to release the stress generated by lateral thermal expansion $\Rightarrow$ linear $TC_f$ curves $\Rightarrow -0.24\text{ppm/°C}$!!!
Summary of $\mu$Resonator $TC_f$’s

- With more accurate $V_C$, it may be possible to completely null the $TC_f$ using electrical stiffness compensation.

- Elect.-Stiffness Compensation $-0.24$ ppm/$^\circ$C
- Geom.-Stress Compensation $-2.5$ ppm/$^\circ$C
- AT-Cut Quartz Crystal at various angles
Conclusions

• Via enhanced selectivity on a massive scale, micromechanical circuits using high-Q elements have the potential for shifting communication transceiver design paradigms, greatly enhancing their capabilities

• **Advantages of Micromechanical Circuits:**
  - orders of magnitude smaller size than present mechanical resonator devices
  - better performance than other single-chip solutions
  - potentially large reduction in power consumption
  - alternative transceiver architectures that maximize the use of high-Q, frequency selective devices for improved performance

• **For more information:** http://www.eecs.umich.edu/~ctnguyen
Conclusions

• Compelling parallels between MEMS and integrated transistor signal processor technologies:
  ➡ **Before 1960**: discrete transistor circuits wired on boards with limited functionality
  ➡ **After IC’s**: VLSI CPU’s and memory circuits have revolutionized the way things are done
  ➡ **Today**: discrete mechanical circuits coupled by welded wires with limited functionality
  ➡ **With VLSI Micromechanical Signal Processors**: functions never before possible now realizable via a combination of transistor and mechanical circuits? a functional and system architectural revolution reminiscent of the IC revolution?

... potential for true revolution? ...

... but there is much work yet to be done ...
Acknowledgments

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• Former and present graduate students, especially Kun Wang, Frank Bannon III, and Ark-Chew Wong, who are largely responsible for the micromechanical filter work, and Wan-Thai Hsu and Mustafa Demirci, who are largely responsible for the resonator work

• My government funding sources: mainly DARPA and an NSF Engineering Research Center
Selected Readings


Selected Readings (cont.)


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