Vibrating RF MEMS for Low Power Wireless 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
  ➜ micromechanical C’s and L’s

• Power Savings Via High-Q MEMS
  ➜ trade Q (or selectivity) for power
  ➜ MEMS-based xceiver architecture

• Research Challenges

• Conclusions
Frequency Division Multiplexed Communications

- Information is transmitted in specific frequency channels within specific bands

Transmitted Power

Band

GSM Band

Adj. Band

DCS1800 Band

Frequency
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>
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Filter

Frequency
Frequency Division Multiplexed Communications

- Information is transmitted in specific frequency channels within specific bands

Transmitted Power

Band

GSM Band

Adj. Band

DCS1800 Band

Filter

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

$\triangleright$ heavy insertion loss for resonator $Q < 5,000$
**Need for High-Q: Oscillator Stability**

- **Main Function**: provide a stable output frequency
- **Difficulty**: superposed noise degrades frequency stability

**Ideal Sinusoid**: \[ v_o(t) = V_0 \sin(2\pi f_o t) \]

**Real Sinusoid**: \[ v_o(t) = (V_0 + \epsilon(t)) \sin(2\pi f_o t + \theta(t)) \]

- **Higher Q**: Tighter spectrum
- **Zero-Crossing Point**
An Ideal Receiver

Received Power

Pre-Select Filter

Desired Signal

Local Osc Power

Mixer

IF Power

Frequency

\( \omega_{IF} \)

\( \omega_{LO} \)

\( \omega_{RF} \)
An Ideal Receiver

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Desired Signal

Frequency

Local Osc Power

Mixer

IF Power
An Ideal Receiver

Desired Signal

Pre-Select Filter

Interfering Signal

Received Power

Local Osc Power

Mixer

Ideal Local Oscillator

IF Power

IF Filter

ω_{RF}  ω_{LO}  ω_{IF}  Frequency

ω_{RF}  ω_{LO}  ω_{IF}  Frequency

ω_{IF}  ω_{LO}  ω_{RF}  Frequency
An Ideal Receiver

- Received Power
- Pre-Select Filter
- Interfering Signal
- Desired Signal
- Local Osc Power
- Ideal Local Oscillator
- Mixer
- IF Power
- IF Filter

Frequency

\( \omega_{IF} \) \( \omega_{LO} \) \( \omega_{RF} \)
Impact of Phase Noise on Receivers

Received Power

Pre-Select Filter

Interfering Signal

Desired Signal

Local Osc Power

Local Oscillator With Phase Noise

Interference From Tail of Phase Noise Spectrum IF

Mixer

IF Filter

Signal Not Recoverable

Desired Signal

Interfering Signal

ω_{IF}  ω_{LO}  ω_{RF}

Frequency

ω_{IF}  ω_{LO}  ω_{RF}

Frequency
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+μMechanics Integration

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

• To allow the use of >600°C processing temperatures, tungsten (instead of aluminum) is used for metallization
**Target Application:** Integrated Transceivers

- Off-chip high-Q mechanical components present bottlenecks to miniaturization → replace them with μ-mechanical versions

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MEMS for Wireless Communications
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Vertically-Driven Micromechanical Resonator

• To date, most used design to achieve VHF frequencies

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

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

\( E = \text{Young's Modulus} \)
\( \rho = \text{density} \)

• Smaller mass \( \rightarrow \) higher frequency range and lower series
Fabricated HF $\mu$Mechanical Resonator

- Surface-micromachined, POCl$_3$-doped polycrystalline silicon
- $L_r=40.8 \ \mu m$, $W_r=8 \ \mu m$, $h=2 \ \mu m$, $d=0.1 \ \mu m$
- Extracted $Q = 8,000$ (vacuum)
- Freq. influenced by dc-bias and anchor effects
Desired Filter Characteristics

- Small shape factor generally preferred

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

Input Force $F_i$

Output Displacement $x_o$

Key Design Property: High Q
Desired Filter Characteristics

- Small shape factor generally preferred
Ideal Spring-Coupled μMechanical Filter

**Symmetric Mode**

**Anti-Symmetric Mode**

\[ \frac{X}{F_d} \]

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

\[ m_r1 \quad k_{r1} \quad c_{r1} \]

\[ k_{s12} \]

\[ m_r2 \quad k_{r2} \quad c_{r2} \]
Micromechanical Filter Circuit

Freq. Pulling Electrode
Input Electrode
DC-Bias

Resonator
Anchor
Coupling Spring
Output Electrode

$\frac{v_o}{v_i}$
$\omega_0$

$R_{Q1}$
$R_{Q2}$

$V_1\Delta f$

$V_P$

$C_{o1}$
$C_{o2}$

$1:\eta_{e1}$
$1:\eta_{c1}$
$1:\eta_{e2}$

$1/k_r m_r$

$x$

$\eta_{c1}$
$\eta_{c2}$

$\eta_{e1}$
$\eta_{e2}$

$\omega$

$x$
$y$
$z$

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HF Spring-Coupled Micromechanical Filter

Electrode

Coupling Spring

Resonators

Electrodes

Anchor

$W_r$

$L_r$

$L_{12}$

20 μm

Performance

$f_o=7.81\text{MHz}$, $BW=15\text{kHz}$

Rej.=35dB, I.L.<2dB

2-Resonator HF (4th Order)

[Bannon, Clark, Nguyen 1996]
High-Order μMechanical Filter

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

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

[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

Replace with single μmechanical Mixer+Filters

[Wong, Nguyen 1998]
Micromechanical Switch

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

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

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

[C. Goldsmith, 1995]
Voltage-Tunable High-Q Capacitor

- Micromachined, movable, aluminum plate-to-plate capacitors
- Tuning range exceeding that of on-chip diode capacitors and on par with off-chip varactor diode capacitors

**Design/Performance:**

\[ C_{tot} = 2.2 \text{pF} \text{ for four plates in parallel} \]

16% tuning range for \( \Delta V_{tune} = 5.5 \text{V} \)

\( Q = 60 \)

-Challenges: microphonics, tuning range truncated by pull-in
Suspended, Stacked Spiral Inductor

- **Strategies for maximizing Q:**
  - $15\mu m$-thick, electroplated Cu windings → reduces series $R$
  - Suspended above the substrate → reduces substrate loss

**Performance:**
- $W_{\text{wind}}=30\mu m$
- $h_{\text{wind}}=15\mu m$
- Top: 3 turns
- Bot: 2.5 turns
- $L_{\text{tot}}=5\text{nH}$
- $Q=28$ @ 1.8 GHz

[J.-B. Yoon, et al., MTT-S’99]

- **Challenge:** microphonics
A large number of off-chip high-Q components replaceable with μmachined versions; e.g., using μmachined resonators, switches, capacitors, and inductors

[Cannon, Clark, Nguyen 1996]
[Young, Boser 1996]
[J.-B. Yoon, et al. 1999]
[Wang, Yu, Nguyen 1999]
[Yao 1997]
• Off-chip high-Q mechanical components present bottlenecks to miniaturization \( \rightarrow \) replace them with \( \mu \)mechanical versions
MEMS-Based Receiver Architecture

- **Most Direct Approach**: replace off-chip components (in orange) with mechanical versions (in green)
  
  \[ L_1 \approx 2\text{dB} \]
  \[ L_3 \approx 6\text{dB} \]
  \[ L_5 \approx 12\text{dB} \]

  - Ceramic RF Filter
  - SAW RF Filter
  - SAW IF Filter
  - IF Amp
  - Channel Select PLL
  - Quartz Xtal
  - VCO
  - Tunable Off-Chip LC Tank

  Replace with MEMS

  \[ L_1 \approx 0.3\text{dB} \]
  \[ L_3 \approx 0.5\text{dB} \]
  \[ L_5 \approx 1\text{dB} \]

  - \( \mu \text{Mech. RF Filter} \)
  - \( \mu \text{Mech. IF Filter} \)
  - IF Amp
  - \( \mu \text{Mech. Res.} \)
  - \( \mu \text{Mech. Res.} \)

  \[ \text{Antenna Diversity for resilience against fading} \]

  \[ \text{Higher} \ \ \ \text{Q} \rightarrow \]

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

- **Obvious Benefit**: substantial size reduction
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Power vs. Selectivity (or Q) Trade-Offs

- **Example:** power consumption as a function of front-end selectivity
  - case: wideband front-end filtering

![Diagram showing Received Power vs. Frequency with Antenna and RF Pre-Select Filter (Res. Q ~500) highlighting Desired Signal and Power Consumption as a function of front-end selectivity.]
**Power vs. Selectivity (or Q) Trade-Offs**

- **Example**: power consumption as a function of front-end selectivity
  - **Case**: wideband front-end filtering

- **Problem**: helpful, but does not go far enough
  - Subsequent electronics must still have more dynamic range than really necessary ↭ power wasted
Power vs. Selectivity (or Q) Trade-Offs

• **Example:** power consumption as a function of front-end selectivity
  ➜ **better approach:** narrowband front-end filtering

Subsequent Electronics (e.g., LNA, mixer, ADC’s)
**Power vs. Selectivity (or Q) Trade-Offs**

- **Example:** power consumption as a function of front-end selectivity
  - better approach: narrowband front-end filtering

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![Diagram](image-url)

- Received Power
- Desired Signal
- RF Channel-Select Filter (Q ~500)
- RF Channel-Select Filter (Q ~10,000)
- Subsequent Electronics (e.g., LNA, mixer, ADC’s)
- Frequency
- Antenna
Power vs. Selectivity (or Q) Trade-Offs

• **Example**: power consumption as a function of front-end selectivity
  ➤ **better approach**: narrowband front-end filtering

• **Result**: substantial power savings in subsequent circuits
  ➤ relaxed dynamic range requirements
  ➤ relaxed oscillator phase noise requirements

---

Received Power vs. Selectivity (or $Q$) Trade-Offs

- Example: power consumption as a function of front-end selectivity
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  ➤ relaxed oscillator phase noise requirements
Front-End Channel Selector

• **Power Saving Strategy:** select channels right up at RF

• **One Approach:** Use a highly selective low-loss filter that is tunable from channel to channel:

  - **Problem:** high filter selectivity (i.e., high $Q$) often precludes tunability
Voltage-Controllable Center Frequency

- Quadrature force → voltage-controllable electrical stiffness:

\[ k_e = \frac{\varepsilon_0 A_0}{d^3} V^2 P \]

- Frequency expression:

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

- Graph showing an 1.1% change in frequency with a DC-Bias of 18 V.

- Anchor, Micromechanical Resonator, Electrode, Silicon Nitride, Isolation Oxide, Silicon Substrate.

- Area \( A_0 = 88 \mu m^2 \), gap \( d = 1000 \AA \).
Front-End Channel Selector

• **Solution**: rather than cover the band by tuning, cover with a bank of switchable filters

• **Problem**: macroscopic high-Q filters are too big

• **Requirement**: tiny filters $\rightarrow \mu$mecanical high-Q filters present a good solution
MEMS vs. SAW Comparison

- MEMS offers the same or better high-Q frequency selectivity with orders of magnitude smaller size.
Micromechanical RF Pre-Selector

- Use a massively parallel array of tunable, switchable filters
- Tiny size and zero dc power consumption of μmechanical filters allows this

![Diagram of Micromechanical RF Pre-Selector](image-url)

- Parallel Bank of Tunable/Switchable Micromechanical Filters
- Relaxed linearity and phase noise specifications
- Substantial power savings
MEMS-Based Transceiver Architecture

- Use numerous filters in a switchable bank to allow front-end channel selection
- Allows more efficient PA and lower dynamic range LNA and mixer

Micromechanical Filter

- Micromechanics are shaded in green
- Use numerous filters in a switchable bank to allow front-end channel selection
- Allows more efficient PA and lower dynamic range LNA and mixer

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MEMS-Based Transceiver Architecture

- Micromechanics are shaded in green
- When replace FET switch: I.L. goes from 2dB to 0.1dB
- Save 280mW when transmitting 500mW

Micromechanical Switch

Antenna

μMech. RF Channel Selector

μMech. T/R Switch

μMech. Mixer

Highly Efficient PA

Switchable μMech. Res. Oscillator

Mixer-Filter-Gain Stage

LNA

IQ Mixer to Baseband

Up-Conversion
MEMS-Based Transceiver Architecture

- Use transducer nonlinearity to obtain a mixer function, followed by a filter
- Eliminate active mixer power

Micromechanics are shaded in green

- Micromechanics are shaded in green

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MEMS-Based Transceiver Architecture

- Substantial power savings if resonator Q > 1,000
- Another example of Q versus power trade-off

Micromechanical Resonator Oscillator

Micromechanics are shaded in green

• Micromechanics are shaded in green
MEMS-Based Transceiver Architecture

Low Loss

Eliminate the RF LNA?

• If possible, could substantially reduce RF front-end power

• Micromechanics are shaded in green

- Eliminate the RF LNA?
- If possible, could substantially reduce RF front-end power
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  MEMS-based receiver architecture

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**Research Issue: Frequency Extension**

- To extend the frequency range
  - shrink beam dimensions
  - must shrink gap $d$ dimensions, as well

\[ f_o = \frac{1}{2\pi\sqrt{\frac{k_r}{m_r}}} \]

870 MHz: $L_r=4.38$ μm, $W_r=2$ μm, $h=2$ μm, $d=300$Å (2\textsuperscript{nd} mode)

- **Possible Problem**: $Q$ reduction with frequency
  - material and anchor loss mechanisms
  - **solution**: defensive mechanical design, materials engineering
Anchor Dissipation in Fixed-Fixed Beams

- 8.5 MHz, $Q=8,000$
- 71.8 MHz, $Q=300$

$L_f=40.8 \mu m, W_f=8 \mu m, h=2 \mu m, d=1,000 \AA, W_e=20 \mu m, V_p=35 V$

$L_f=14 \mu m, W_f=8 \mu m, h=2 \mu m, d=300 \AA, W_e=7 \mu m, V_p=35 V$
92 MHz Free-Free Beam μResonator

- Free-free beam μmechanical resonator with non-intrusive supports → reduce anchor dissipation → higher $Q$

**Design/Performance:**

$L_f=13.1\mu m$, $W_f=6\mu m$
$h=2\mu m$, $d=1000\text{Å}$
$V_p=28-76V$, $W_e=2.8\mu m$
$f_o\approx 92.25\text{MHz}$
$Q\approx 7,450 \ @ \ 10\text{mTorr}$

[Wang, Yu, Nguyen 1998]

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92 MHz Free-Free Beam $\mu$Resonator

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  - material and anchor loss mechanisms
  - \textit{solution}: defensive mechanical design, materials engineering

- Possible Problem: size vs. power handling trade-offs
  - may limit the degree of size reduction allowable
  - \textit{solution}: transducer design, other vibration modes
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

$R = 17 \mu m$, $t = 2 \mu m$, $d = 1,000 \AA$, $V_P = 35V$

$f_0 = 156 MHz$, $Q = 9,400$

[Clark, Hsu, Nguyen IEDM’00]
1000Å Lateral Electrode-to-Disk Gaps

- Achieved via a fabrication process that combines polysilicon surface micromachining, metal electroplating, and sidwall spacer technologies

[Clark, Hsu, Nguyen IEDM’00]
Other ResearchIssues:
µMechanical Filter Passband Correction

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

[Wang, Nguyen, 1997]
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 $f_0$ shift per anneal pulse

[Wang, Wong, Hsu, Nguyen 1997]
Research Issue: Thermal Stability

- Need temperature compensation or control methods

[Wang, Yu, Nguyen 2000]
Geometric-Stress Temperature Compensation

- Geometrically generate a stress vs. temperature function that compensates Young’s modulus thermal variation.
**Fabricated Temp.-Insensitive μResonator**

- **Design/Performance:**
  - \( L_1 = 39 \mu m, L_2 = 39 \mu m, d = 1038 \AA \)
  - \( W_1 = 2.5 \mu m, W_2 = 20 \mu m, t = 2 \mu m \)
  - \( V_P = 16V, f_0 = 13.495 MHz, Q = 10,317 \)

Hsu, Clark, Nguyen IEDM’00
Demonstration of Geometric-Stress Temperature Compensation

- Below: polysilicon structure, silicon substrate

Less than 200 ppm $f_0$ variation over 80° C for $L_2/L_1=60/40$

[Hsu, Clark, Nguyen 2000]
Research Issue: Thermal Stability

- Need temperature compensation or control methods

[Wang, Yu, Nguyen 2000]
Research Issue: Contamination Sensitivity

• Contamination fluctuations $\rightarrow f_0$ and $Q$ fluctuations

• Typical $\mu$ resonator mass: $10^{-13}$ kg

• Larger frequency fluctuations for micro-sized resonators than for more massive quartz crystals

• Factors influencing contamination-derived instabilities
  - contaminant molecule size and weight
  - pressure and temperature

• Need encapsulation for contamination protection
**Research Issue: Vacuum Encapsulation**

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

Schematic of the Bonding Encapsulation Procedure

- 0005 10KV X190 100µm WD48

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

40 weeks at 25 mTorr
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

  … but there’s much more to it than just the above …
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

• Numerous authors referenced throughout

• 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