C. T.-C. Nguyen, “Communication architectures based on high-*Q* MEMS devices (invited),” *Workshop Notes*, Workshop on Microwave and Photonic Applications of MEMS at the 2000 IEEE MTT-S International Microwave Symposium, Anaheim, California, June 16, 2000.

# *Communication Architectures Based on High-Q MEMS Devices*

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The increasing demand for mobile wireless communications has stimulated interest in compact, low power, inexpensive transceivers. This, along with the current trend to implement complete systems on single silicon chips, makes desirable completely monolithic versions of such transceivers. To date, many of the proposed strategies for achieving single-chip transceivers have evolved from the premise that the off-chip high-*Q* RF and IF filters and oscillators used in heterodyning transceiver architectures cannot be miniaturized. Specifically, tank circuits with *Q*’s greater than 100 have not been achievable using conventional planar IC technologies in the frequency ranges of interest.

The rapid growth of IC-compatible micromachining technologies that yield micro-scale, high-*Q* tank components may now allow miniaturized, low-power transceivers based upon traditional super-heterodyne architectures. Specifically, the high-*Q* RF and IF filters and low phase noise oscillators currently implemented via off-chip resonators and discrete passives may now potentially be realized on the micro-scale using micromachined vibrating mechanical resonators with *Q*’s in the thousands, orders of magnitude smaller size, and the ability to be integrated alongside IC transistors. Once these miniaturized filters and oscillators become available, the fundamental bases upon which communication systems are developed may also evolve, giving rise to new system architectures with possible power and bandwidth efficiency advantages.

As an example, one of the more revolutionary potential uses of micromechanical resonator devices takes advantage of their tiny size and zero dc power consumption. Such features make possible the use of hundreds, perhaps thousands of them, to form banks of interlinked, on/off switchable micromechanical filters that can potentially serve as an RF channel-select filter bank•something presently unattainable with today’s macroscopic technologies. With RF channel-selection, adjacent channel interferers can be removed *before* they reach subsequent RF transistor electronics, allowing substantial reductions in the dynamic range and phase noise specifications in those electronics, leading in turn to substantial power savings. In effect, a paradigm-shift in receiver architectural design may be possible, where instead of minimizing the number of high-*Q* components in a given system, the use of such components is maximized in an attempt to harness the *Q* vs. power trade-off commonly seen in communications design. Cost reduction is also possible, since the above performance relaxations may also allow the realization of certain transceiver stages in less expensive transistor technologies (e.g., all silicon?).

In a broader sense, these ideas can be taken a step further by recognizing that the subject mechanical resonators are actually mechanical links that can be thought of as tiny circuit elements, much like resistors or individual transistors. Like a single transistor, a single mechanical link does not possess adequate processing power for most applications. However, again like transistors, when hooked up into larger (potentially, VLSI) circuits, the true power of micromechanical links can be unleashed, and signal processing functions previously inaccessible to transistor circuits may become feasible. (High-*Q* micromechanical filters, comprised of interlinked resonators, represent one simple example of this. Mixer-filter devices are yet another.)

This talk explores the above possibilities, first giving an overview of the micromechanical circuits useful for communications applications, then suggesting potential receiver architectures that utilize MEMS technology to greatly improve communication sub-system performance.

# Communication Architectures Based on High-*Q* MEMS Devices

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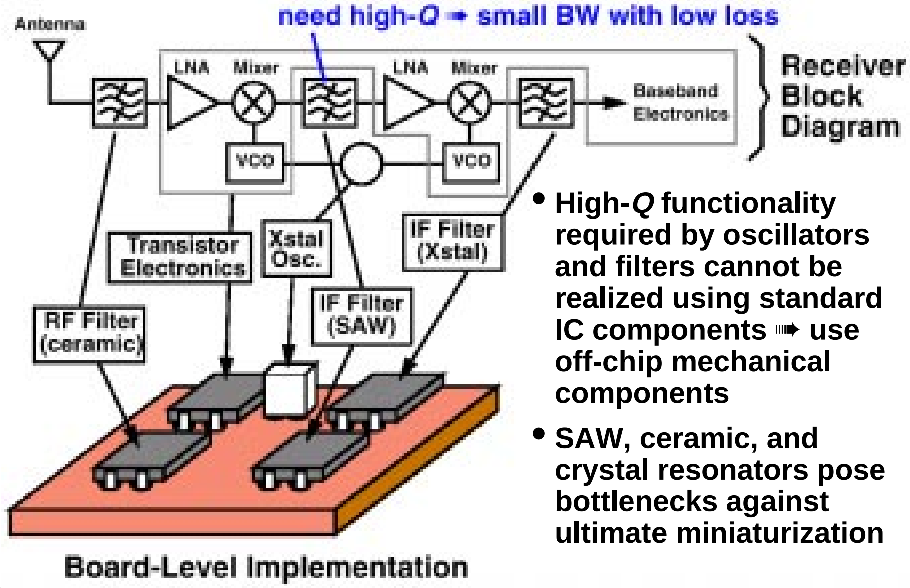
## Outline

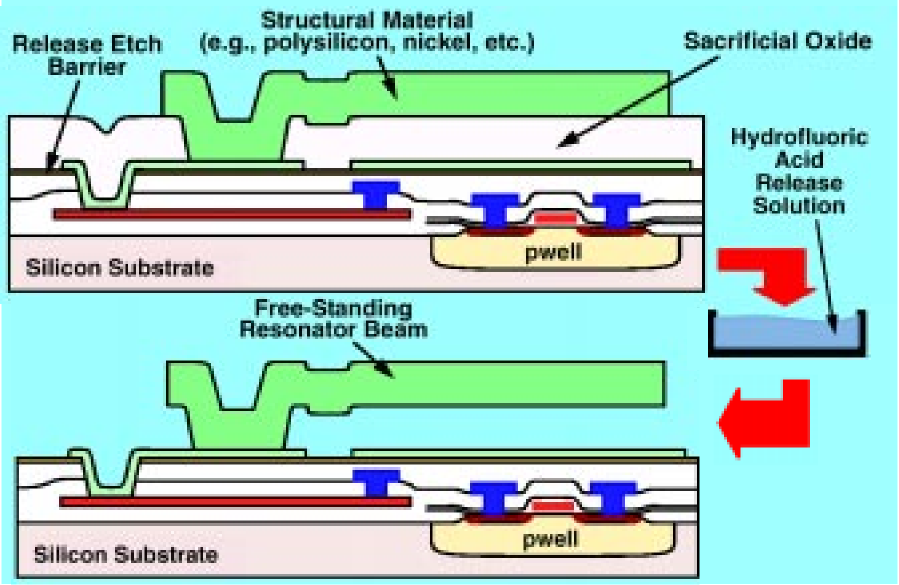
- **Miniaturization of Transceivers**
- **High-*Q* Micromechanical Resonators**
- **Micromechanical Circuits**
  - **micromechanical filters**
  - **micromechanical mixer-filters**
  - **micromechanical switches**
- **Power Savings Via High-*Q* MEMS**
  - **trade *Q* (or selectivity) for power**
- **MEMS-Based Transceiver Architecture**
- **Conclusions**

# Miniaturization of Transceivers



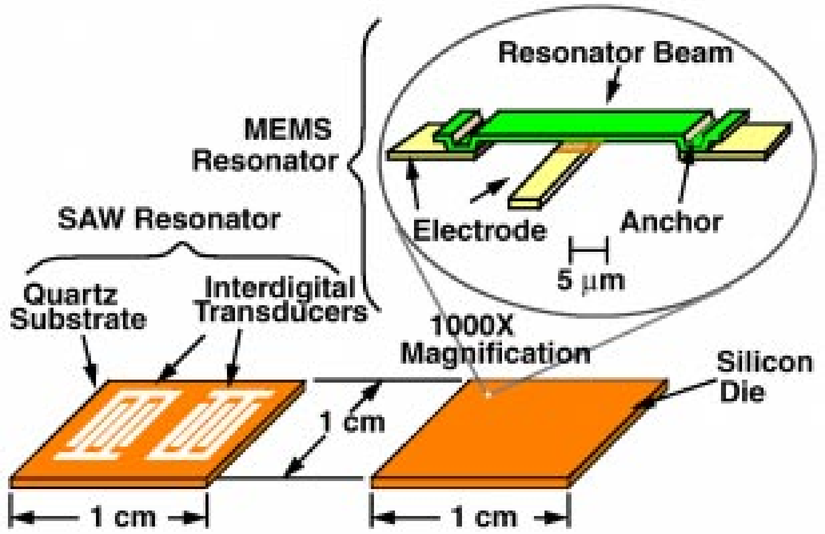
- High-*Q* functionality required by oscillators and filters cannot be realized using standard IC components ➠ use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization

# Surface Micromachining



- Fabrication steps compatible with planar IC processing

# MEMS vs. SAW Comparison



- **MEMS offers the same or better high-*Q* frequency selectivity with orders of magnitude smaller size**

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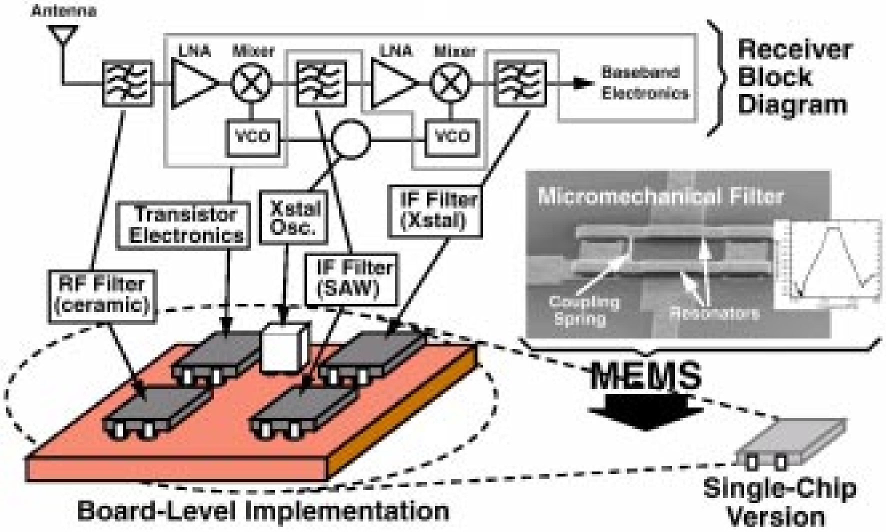
# ***<u>Target Application</u>*: Integrated Transceivers**



- **Off-chip high-*Q* mechanical components present bottlenecks to miniaturization ➟ replace them with μmechanical versions**

# Outline

- Miniaturization of Transceivers
- ☞ High-*Q* Micromechanical Resonators
- ☞ Micromechanical Circuits
  - micromechanical filters
  - micromechanical mixer-filters
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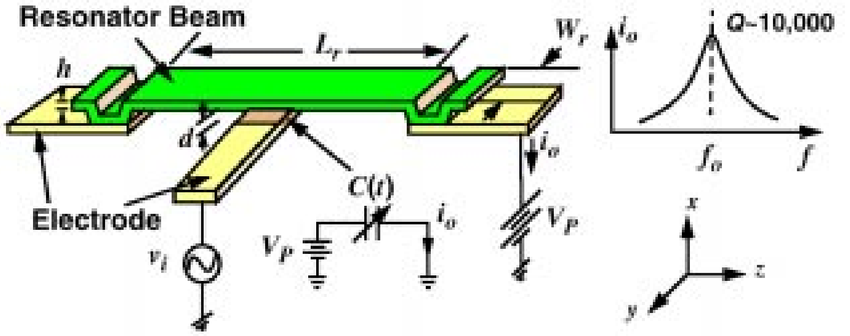
# Vertically-Driven Micromechanical Resonator

- To date, most used design to achieve VHF frequencies



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

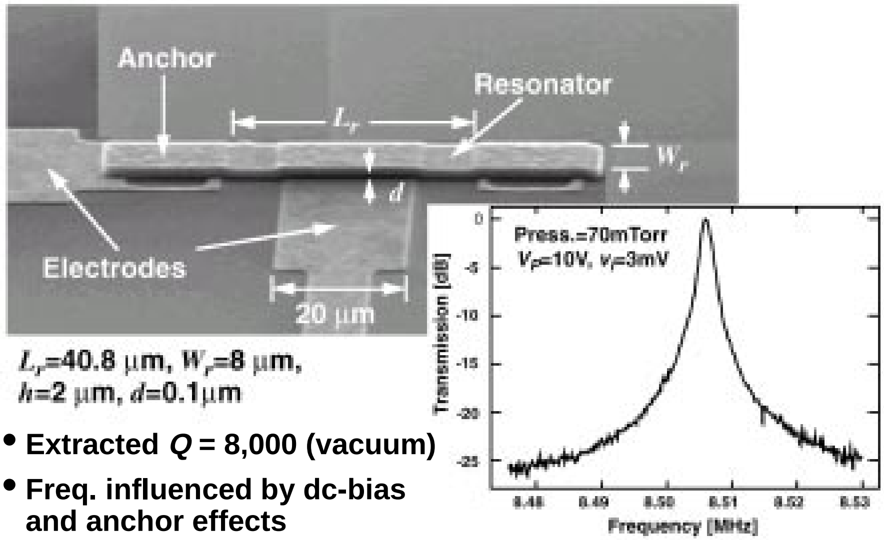
(e.g. $m_r = 10^{-13}$kg)

$E$ = Youngs Modulus
$\rho$=density

- Smaller mass ➠ higher frequency range and lower series $R_x$

# Fabricated HF μMechanical Resonator

- **Surface-micromachined, $POCl_3$-doped polycrystalline silicon**



- **Extracted $Q$ = 8,000 (vacuum)**
- **Freq. influenced by dc-bias and anchor effects**

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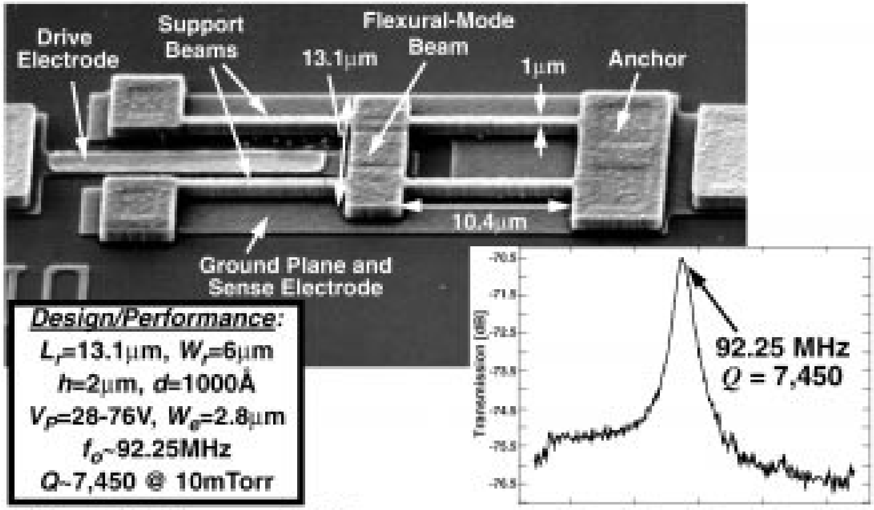
# 92 MHz Free-Free Beam μResonator

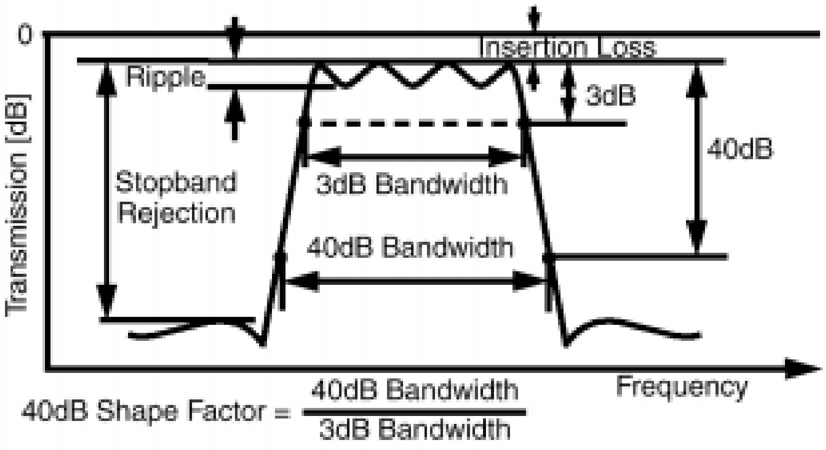
- **Free-free beam μmechanical resonator with non-intrusive supports ➠ reduce anchor dissipation ➠ higher $Q$**



**Design/Performance:**
$L_r$=13.1μm, $W_r$=6μm
$h$=2μm, $d$=1000Å
$V_P$=28-76V, $W_e$=2.8μm
$f_o$~92.25MHz
$Q$~7,450 @ 10mTorr

[Wang, Yu, Nguyen 1998]

# Desired Filter Characteristics



- **Small shape factor generally preferred**

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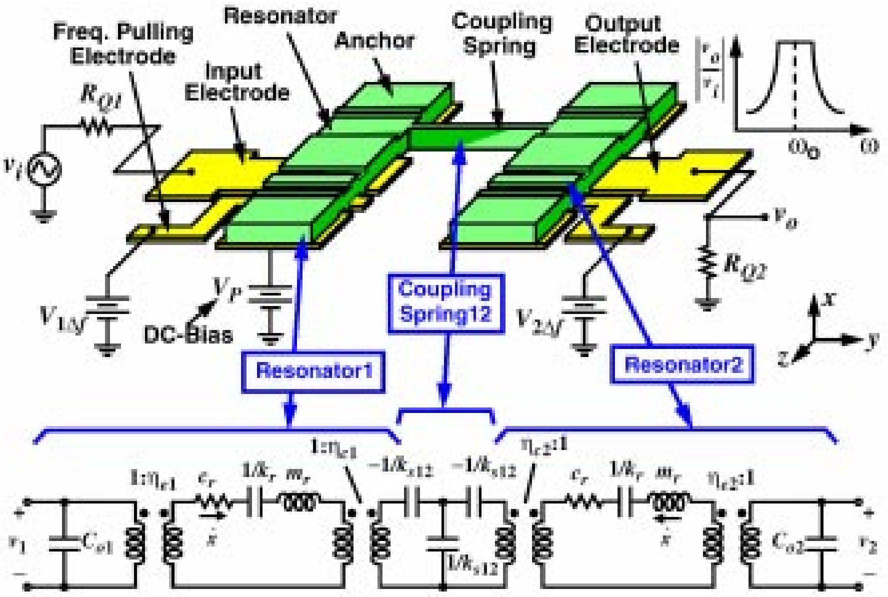
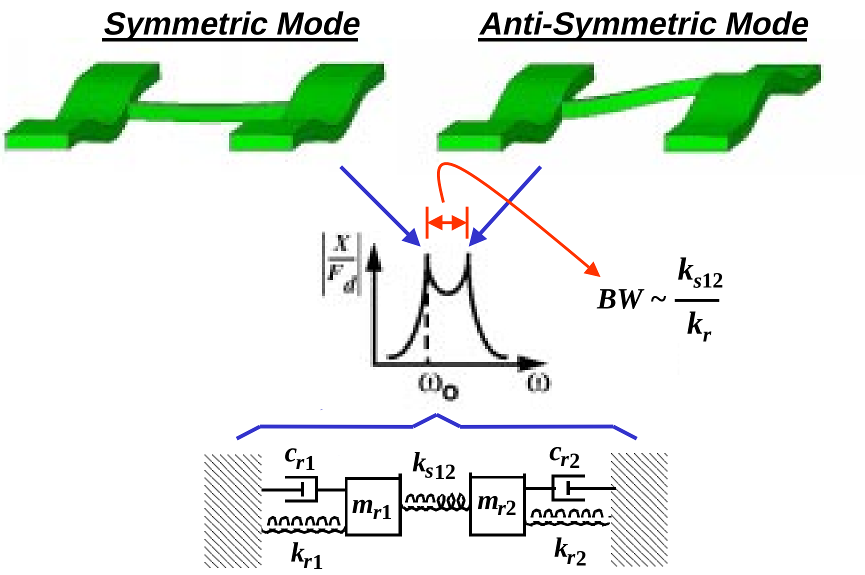
# Micromechanical Filter Circuit



# Ideal Spring-Coupled μMechanical Filter



$$BW \sim \frac{k_{s12}}{k_r}$$

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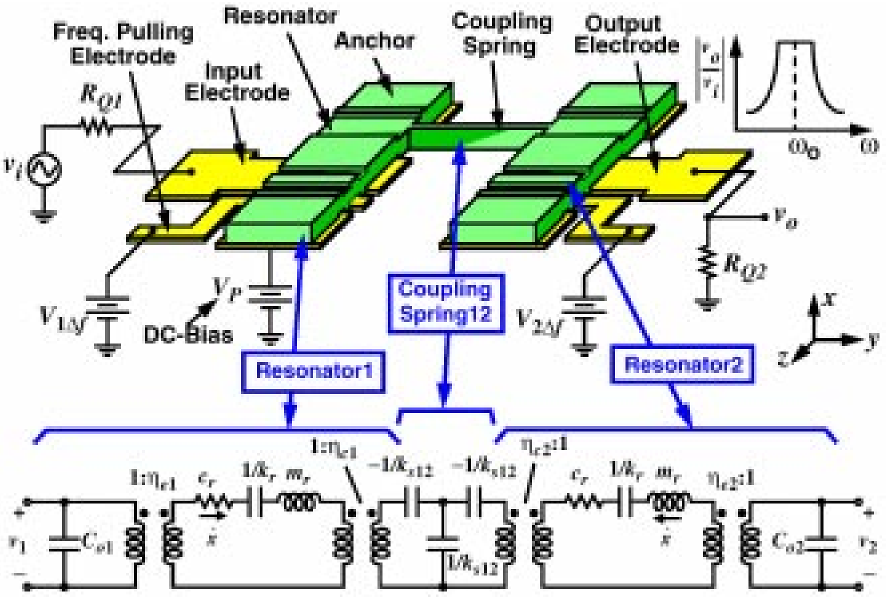
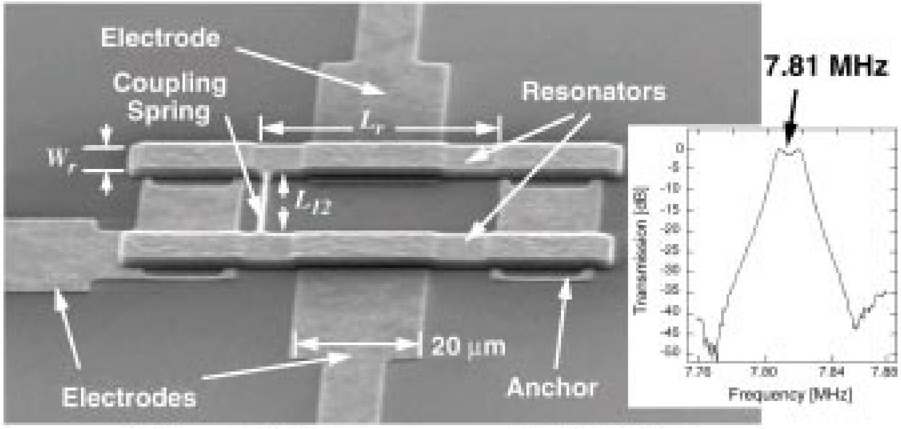
# Micromechanical Filter Circuit



# HF Spring-Coupled Micromechanical Filter

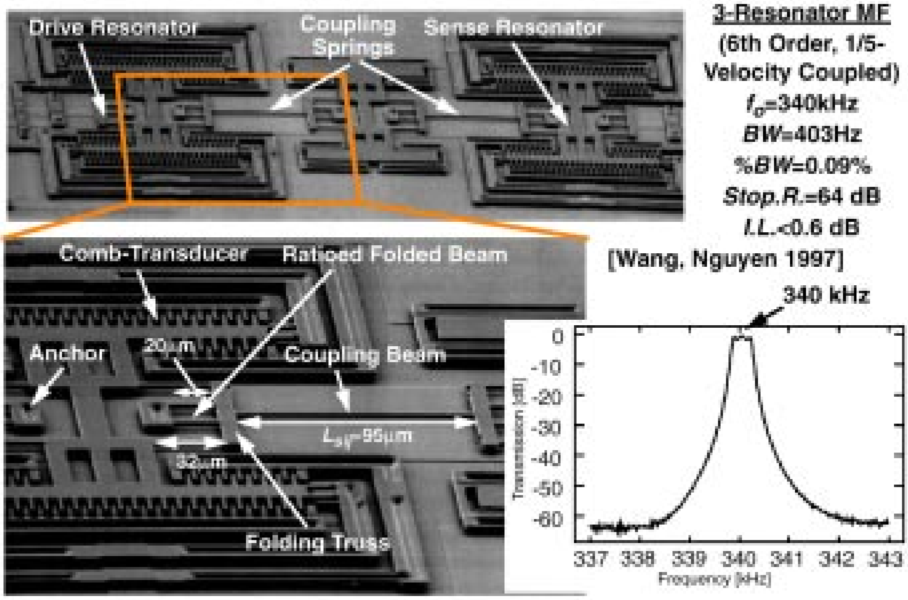


**2-Resonator HF**
(4th Order)
[Bannon, Clark,
Nguyen 1996]

**Performance**
$f_o$=7.81MHz, $BW$=15kHz
Rej.=35dB, I.L.<2dB

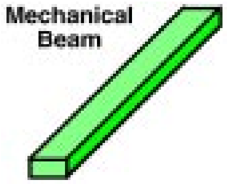
# High-Order μMechanical Filter

**3-Resonator MF**
(6th Order, 1/5-
Velocity Coupled)
$f_o$=340kHz
$BW$=403Hz
%$BW$=0.09%
$Stop.R.$=64 dB
$I.L.$<0.6 dB
[Wang, Nguyen 1997]



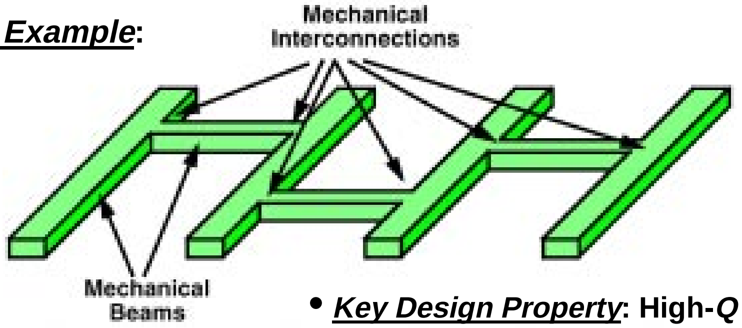
# Micromechanical Circuits

***Fundamental Building Block***:



***Equivalent Building Block Ckt.***:

***Circuit Example***:



- ***Key Design Property***: **High-$Q$**

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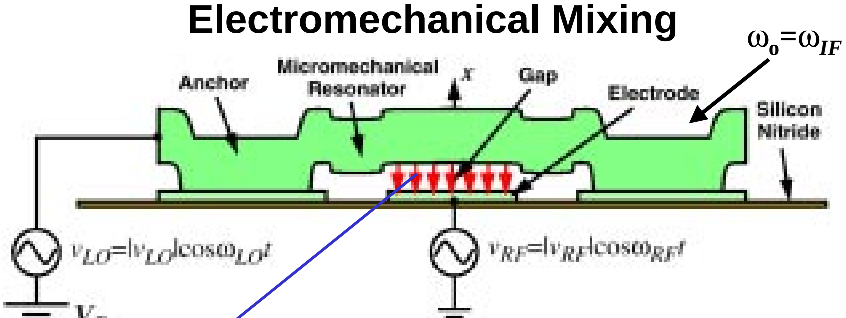
# Electromechanical Mixing

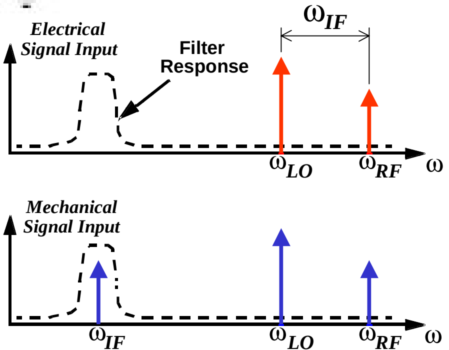


***Electrostatic Force***:

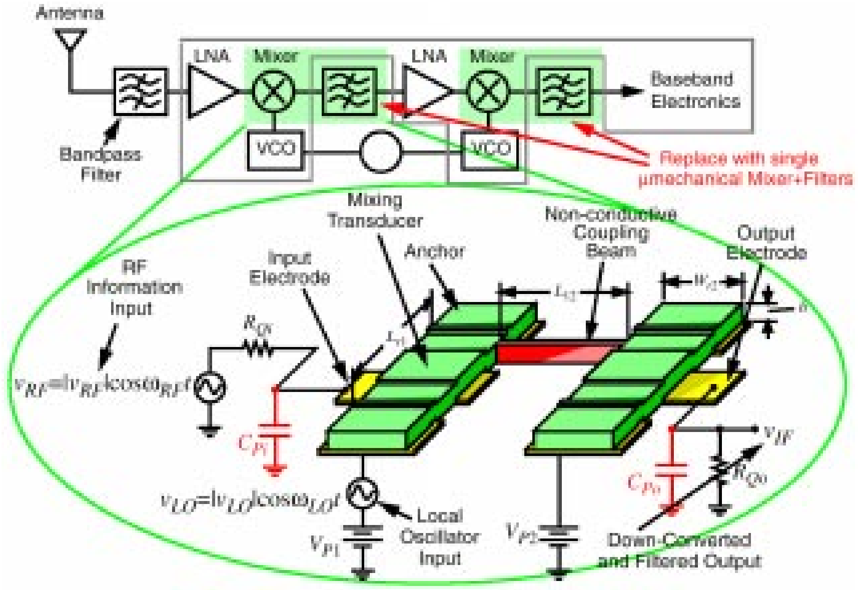
$$F_i = -\frac{\partial E}{\partial x} = -\frac{\partial}{\partial x}\left(\frac{1}{2}C_{gap}V_{gap}^2\right)$$

$$= -\frac{1}{2}(V_P + v_{LO} - v_{RF})^2\frac{\partial C_{gap}}{\partial x}$$

$$= \ldots + v_{LO}v_{RF}\frac{\partial C_{gap}}{\partial x} + \ldots$$

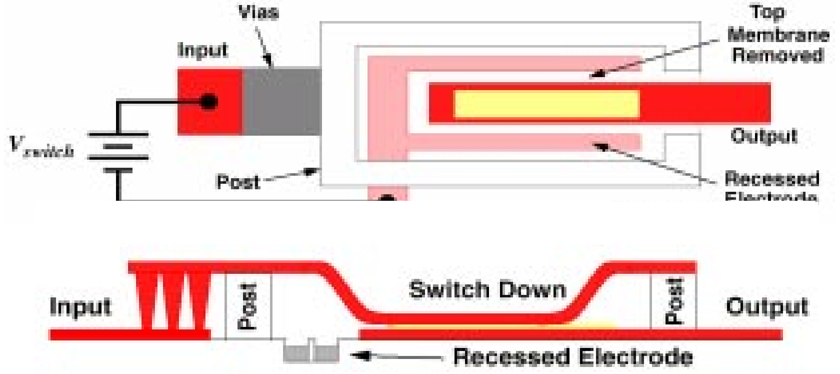


## Micromechanical Mixer-Filter



## Micromechanical Switch

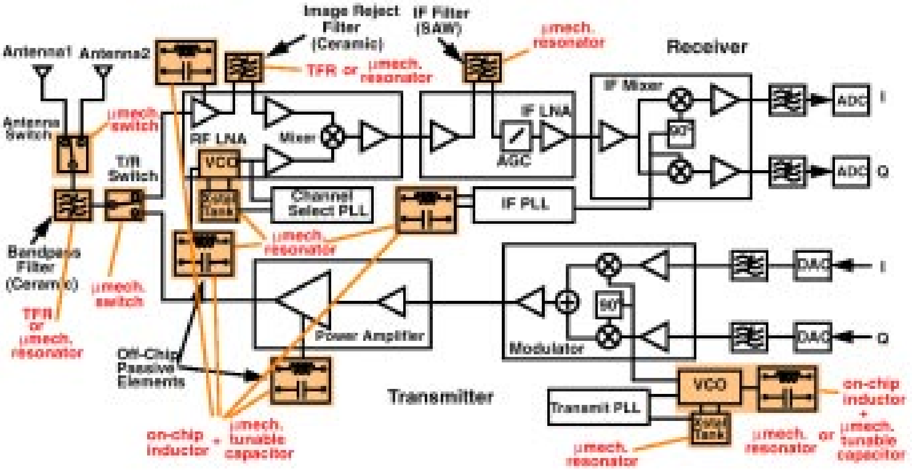
- **Operate the micromechanical beam in an up/down binary fashion**



**[C. Goldsmith, 1995]**

- ***Performance*: *I.L.*~0.1dB, *IIP3* ~ 66dBm (extremely linear)**
- ***Issues*: switching voltage ~ 20V, switching time: 10-100μs**

# MEMS-Replaceable Transceiver Components



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

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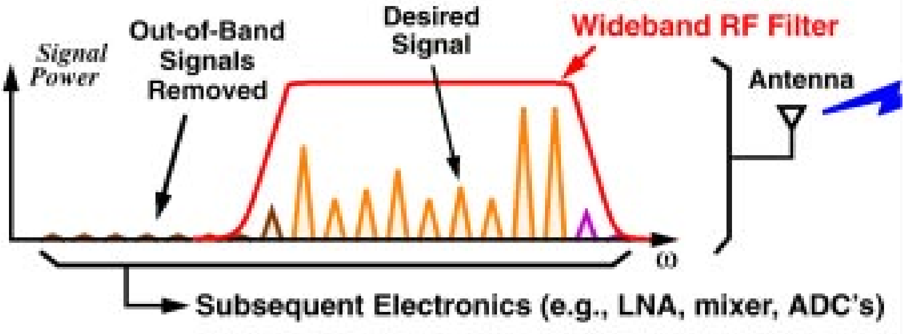
# Power Versus Selectivity (or *Q*) Trade-Offs

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



- ***Problem***: subsequent electronics must have sufficient dynamic range to handle all in-band signals → must consume power to attain the needed dynamic range

# Power Versus Selectivity (or *Q*) Trade-Offs

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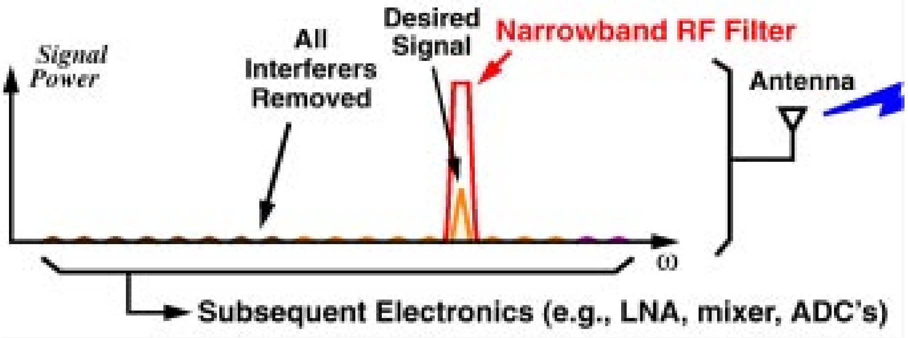
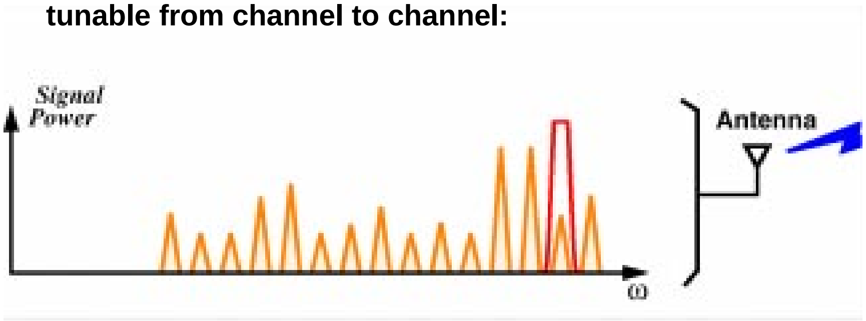
  - ↳ ***case***: narrowband front-end filtering



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

# Front-End Channel Selection

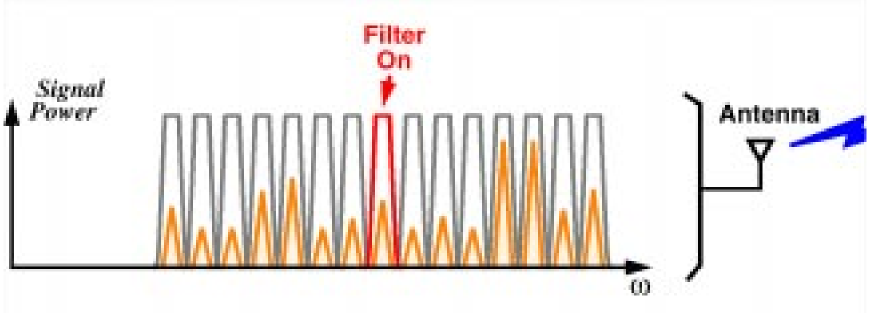
- ***Power Saving Strategy***: select channels right up at RF
- ***Approach:*** Use a highly selective low-loss filter that is tunable from channel to channel:



- ***Problem***: high filter selectivity (i.e., high *Q*) often precludes tunability

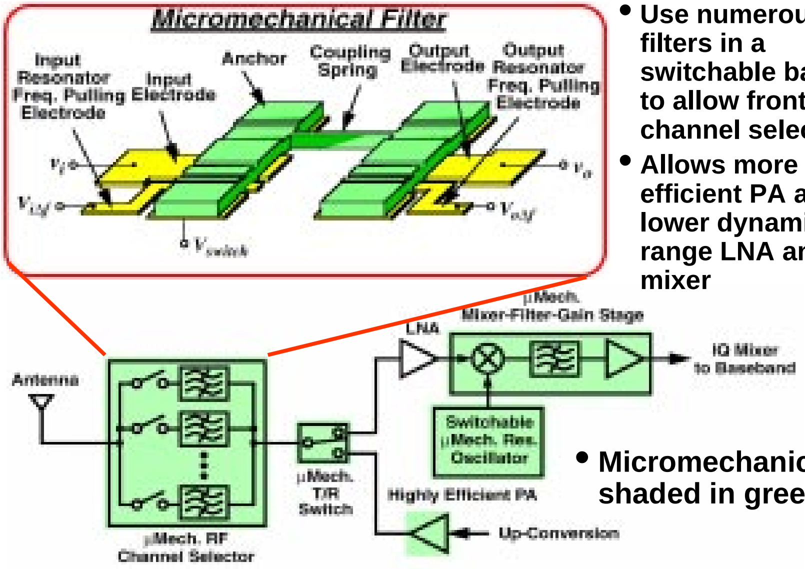
# Parallel Bank of Switchable Filters

- 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 ➟ micromechanical high-*Q* filters present a good solution

# 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
- Micromechanics are shaded in green

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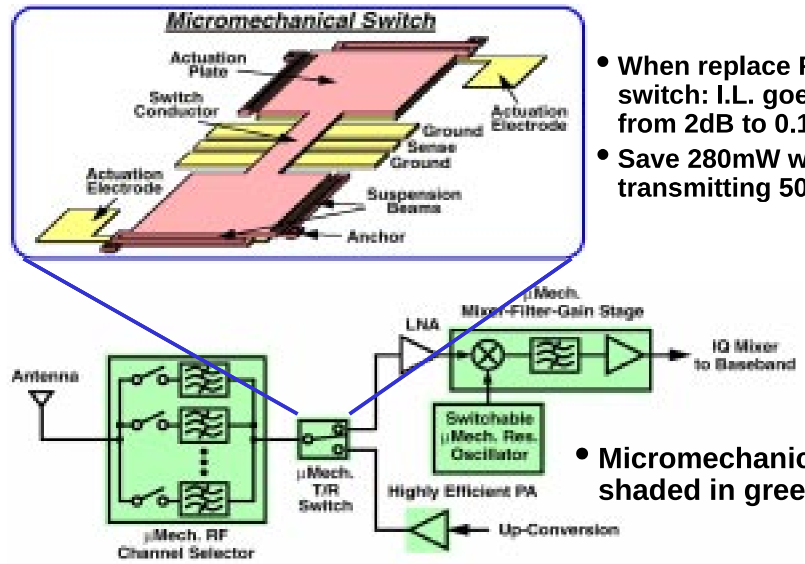
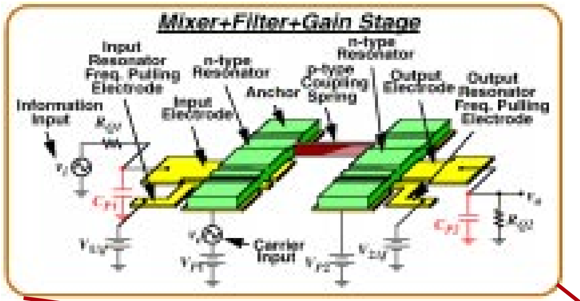
# MEMS-Based Transceiver Architecture

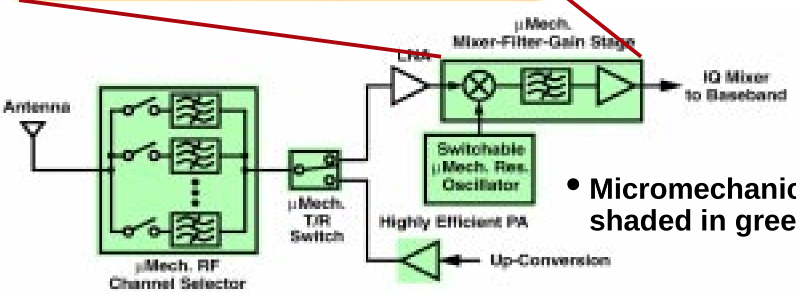


- When replace FET switch: I.L. goes from 2dB to 0.1dB
- Save 280mW when transmitting 500mW
- Micromechanics are shaded in green

# MEMS-Based Transceiver Architecture



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



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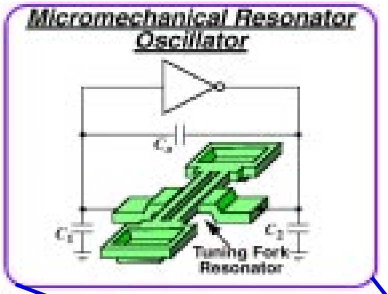
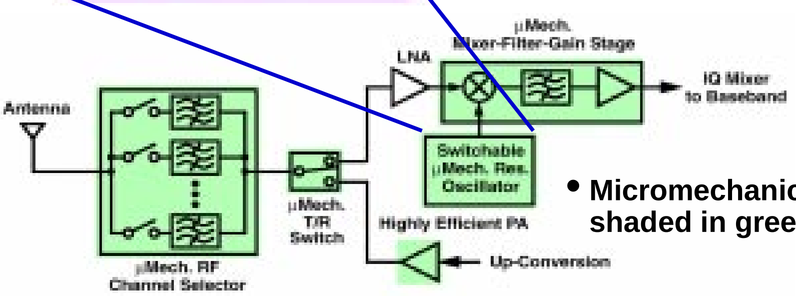
# MEMS-Based Transceiver Architecture

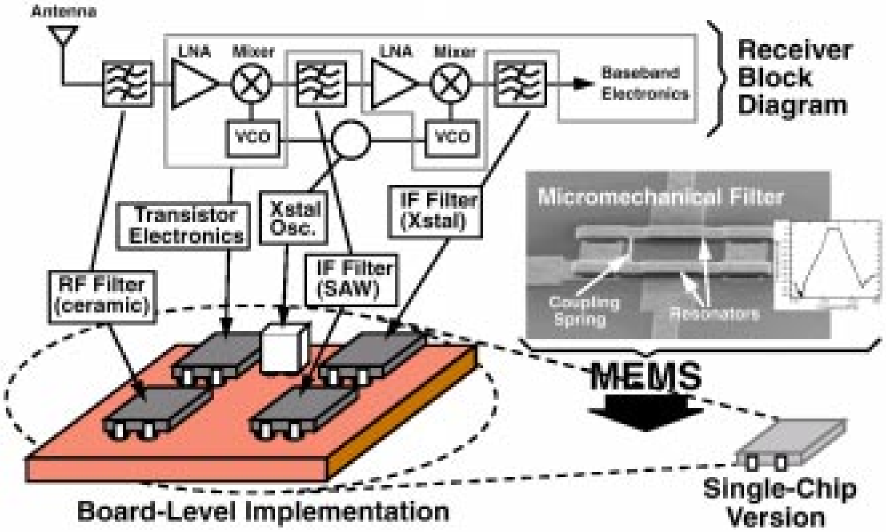


- Substantial power savings if resonator *Q*>1,000
- Another example of *Q* versus power trade-off



- Micromechanics are shaded in green

# ***Target Application***: Integrated Transceivers



- **Off-chip high-*Q* mechanical components present bottlenecks to miniaturization ➠ replace them with µmechanical versions**

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# 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 is much work yet to be done ...**

# Acknowledgments

- 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, Michael McCorquodale, and Mustafa Demirci, who are largely responsible for the resonator work
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