C. T.-C. Nguyen, “Micromechanical components for miniaturized low-power communications (invited plenary),” *Proceedings*, 1999 IEEE MTT-S International Microwave Symposium RF MEMS Workshop (on Microelectromechanical Devices for RF Systems: Their Construction, Reliability, and Application), Anaheim, California, June 18, 1999, pp. 48-77.

Microelectromechanical Components for Miniaturized Low-Power Communications

Clark T.-C. Nguyen

Center for Integrated Microsystems
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, Michigan 48109-2122

ABSTRACT

An overview of recent progress in the research and development of microelectromechanical devices for use in wireless communication sub-systems is presented. Among the specific devices described are tunable micromachined capacitors, integrated high-*Q* inductors, and micro-scale vibrating mechanical resonators with *Q*’s in the tens of thousands. Specific applications are reviewed for each of these components with emphasis on methods for miniaturization and performance enhancement of existing and future wireless transceivers.

1. INTRODUCTION

Vibrating mechanical tank components, such as crystal and SAW resonators, are widely used for frequency selection in communication sub-systems because of their high quality factor (*Q*’s in the tens of thousands) and exceptional stability against thermal variations and aging. In particular, the majority of heterodyning communication transceivers rely heavily upon the high *Q* of SAW and bulk acoustic mechanical resonators to achieve adequate frequency selection in their RF and IF filtering stages and to realize the required low phase noise and stability in their local oscillators. In addition, discrete inductors and variable capacitors are used to properly tune and couple the front end sense and power amplifiers, and to implement widely tunable voltage-controlled oscillators. At present, the aforementioned resonators and discrete elements are off-chip components, and so must interface with integrated electronics at the board level, often consuming a sizable portion of the total sub-system area. In this respect, these devices pose an important bottleneck against the ultimate miniaturization and portability of wireless transceivers. For this reason, many research efforts have been focused upon strategies for either miniaturizing these components [1-5] or eliminating the need for them altogether [6-8].

The rapid growth of IC-compatible micromachining technologies that yield micro-scale, high-*Q* tank components may now bring the first of the above strategies closer to reality. Specifically, the high-*Q* RF and IF filters, oscillators, and couplers, currently implemented via off-chip resonators and discrete passives may now potentially be realized on the micro-scale using micromachined equivalents based on a variety of novel devices, including high-*Q* on-chip vibrating mechanical resonators [10-12], voltage-tunable on-chip capacitors [13], isolated low-loss inductors [14-18], microwave/mm-wave medium-*Q* filters [19-22], structures for high frequency isolation packaging [23-24], and low loss micromechanical switches [25-27]. 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. For systems operating past X-Band, antennas can also be micromachined with potential cost savings and with additional capabilities attained via active antenna arrays (e.g., phased arrays, power combining, etc.) [28-30].

This abstract provides a prelude to the presentation material that follows. It begins with a brief introduction into the needs of wireless communication transceivers, identifying specific functions that could greatly benefit from micromechanical implementation, and describing methods for substantially reducing power consumption by using micromechanical devices in alternative transceiver architectures. The presentation material that follows then reviews several specific devices, with particular emphasis on frequency-selective microelectromechanical components for high-*Q* oscillators and filters. It concludes with suggestions on how this micro-scale technology can best be used to revolutionize wireless communications.

Additional author information:
Full Address: 2406 EECS Bldg., 1301 Beal Ave, University of Michigan, Ann Arbor, MI 48109-2122
Tel: (734)764-1220, FAX: (734)763-9324, email: ctnguyen@eecs.umich.edu, http://www.eecs.umich.edu/~ctnguyen

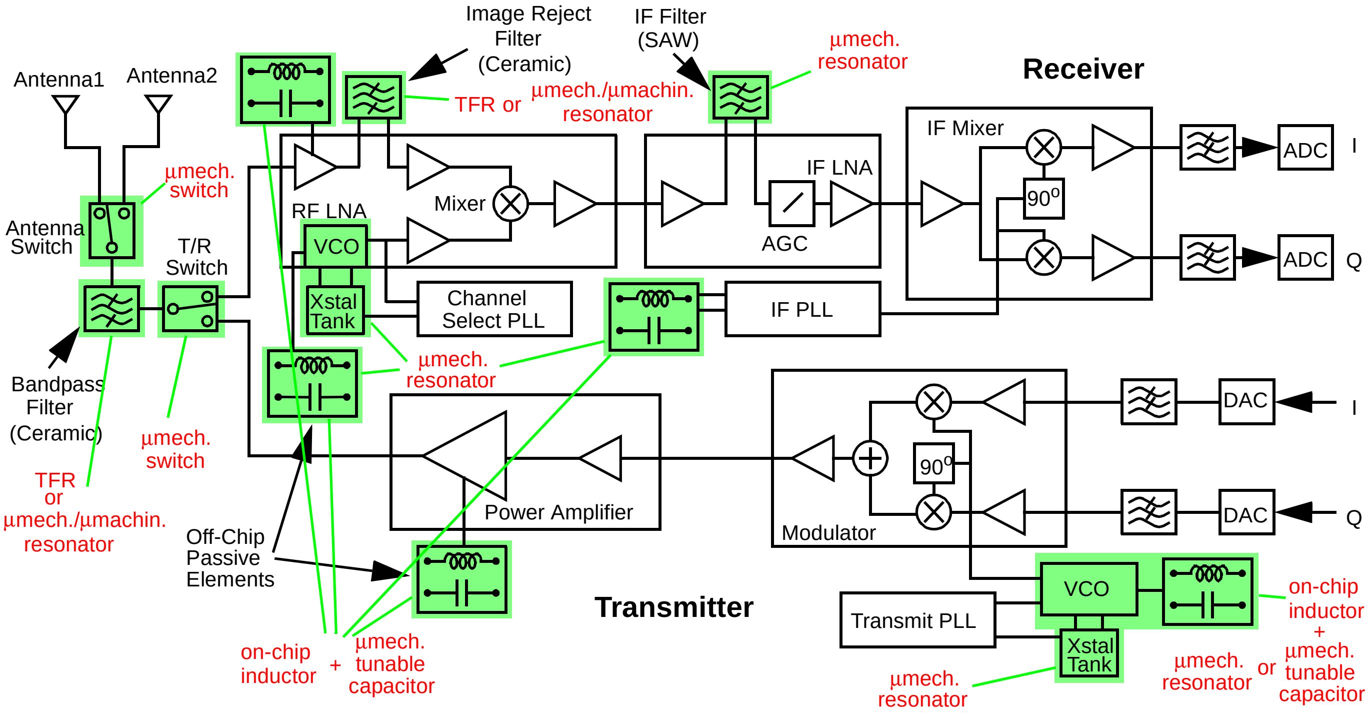


Fig. 1: System-level schematic detailing the front-end design for a typical wireless transceiver. The off-chip, high-*Q*, passive components targeted for replacement via micromechanical versions (suggestions in lighter ink) are indicated in the figure.

2. ADVANTAGES OF MEMS IN COMMUNICATION TRANSCEIVERS

To illustrate more concretely the specific transceiver functions that benefit from micromechanical implementation, Fig. 1 presents the system-level schematic for the front-end of a typical super-heterodyne wireless transceiver. As implied in the figure, several of the constituent components can already be miniaturized using integrated circuit transistor technologies. These include the low noise amplifiers (LNA's) in the receive path, the solid-state power amplifier (SSPA) in the transmit path, synthesizer phase-locked loop (PLL) electronics, mixers, and lower frequency digital circuits for baseband signal demodulation. Due to noise, power, and frequency considerations, the SSPA (and sometimes the LNA's) are often implemented using compound semiconductor technologies (i.e., GaAs). Thus, they often occupy their own chips, separate from the other mentioned transistor-based components, which are normally realized using silicon-based bipolar and CMOS technologies. However, given the rate of improvement of silicon technologies (silicon-germanium included [31]), it is not implausible that all of the above functions could be integrated onto a single-chip in the foreseeable future.

Unfortunately, placing all of the above functions onto a single chip does very little towards decreasing the overall super-heterodyne transceiver size, which is dominated not by transistor-based components, but by the numerous passive components indicated in Fig. 1. The presence of so many frequency-selective passive components is easily justified when considering that communication systems designed to service large numbers of users require numerous communication channels, which in many implementations (e.g., Time Division Multiple Access (TDMA)) must have small bandwidths and must be separable by transceiver devices used by the system. The requirement for small channel bandwidths results in a requirement for extremely selective filtering devices for channel selection and extremely stable (noise free) local oscillators for frequency translation. For the vast majority of cellular and cordless standards, the required selectivity and stability can only be achieved using high-*Q* components, such as discrete inductors, discrete tunable capacitors (i.e., varactors), and SAW and quartz crystal resonators, all of which interface with IC components at the board level. The needed performance cannot be achieved using conventional IC technologies, because such technologies lack the required *Q*. It is for this reason that virtually all commercially available cellular or cordless phones contain numerous passive SAW and crystal components.

The presentation that follows describes methods for reducing the size and power consumption of portable transceivers by first replacing high-*Q* passives by micromechanical versions, then extending their system-level presence by using them in large quantities. Among the components targeted for replacement in cellular and cordless applications are RF filters, including image reject filters, with center frequencies ranging from 800 MHz to 2.5 GHz; IF filters, with center frequencies ranging from

455 kHz to 254 MHz; high-Q, tunable, low phase noise oscillators, with frequency requirements in the 10 MHz to 2.5 GHz range; and switches for transmit/receive (T/R) selection, antenna selection, and multi-band configurability.

2.1. Miniaturization and IC-Compatibility

Reduced size constitutes the most obvious incentive for replacing SAWs, crystals, and other discrete passives by equivalent µmechanical devices. The substantial size difference between micromechanical components and their macroscopic counterparts is illustrated in Fig. 3, which compares a typical SAW resonator with a clamped-clamped beam micromechanical resonator of comparable frequency. The particular µresonator shown is excited electrostatically via parallel-plate capacitive transducers and designed to vibrate in a direction parallel to the substrate with a frequency determined by material properties, geometric dimensions, and stress in the material. Typical dimensions for a 100 MHz micromechanical resonator are $L \approx 12.9$ µm, $W = 2$ µm, and $h = 2$ µm. With electrodes and anchors, this device occupies an area of 420 µm^2 = 0.00042 mm^2. Compared with the several mm^2 required for a typical VHF range SAW resonator, this represents several orders of magnitude in size reduction.

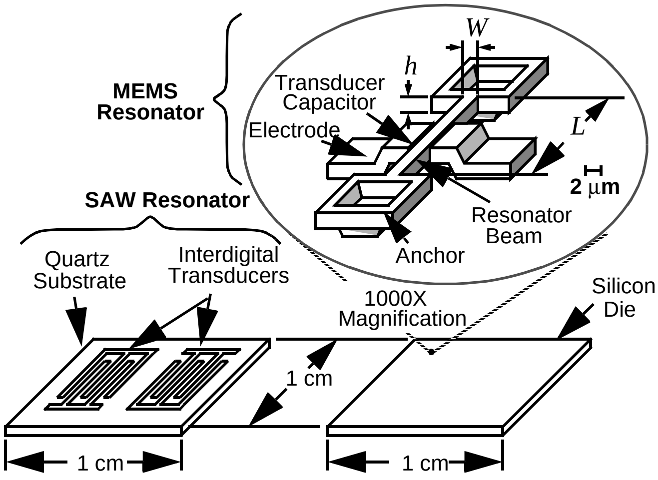


Fig. 2. (a) Simplified block diagram of a dual-conversion receiver. (b) Approximate physical implementation, emphasizing the board-level nature (many inductor and

A related incentive for the use of micromechanics is integrability. Micromechanical structures can be fabricated using the same planar process technologies used to manufacture integrated circuits. Several technologies demonstrating the merging of CMOS with surface micromachining have emerged in recent years [10,32-34], and one of these is now used for high volume production of commercial accelerometers [32]. Using similar technologies, complete systems containing integrated micromechanical filters and oscillator tanks, as well as amplification and frequency translation electronics, all on a single chip, are possible. This in turn makes possible high-performance, single-chip transceivers, with super-heterodyne architectures and all the communication link advantages associated with them. Other advantages inherent with integration are also obtained, such as elimination of board-level parasitics that could otherwise limit filter rejections and distort their passbands.

2.2. Power Savings Via MEMS

Although certainly a significant advancement, miniaturization of transceivers only touches the surface of the true potential of this technology. MEMS technology may in fact make its most important impact not at the component level, but at the system level, by offering alternative transceiver architectures that emphasize selectivity over complexity to substantially reduce power consumption and enhance performance.

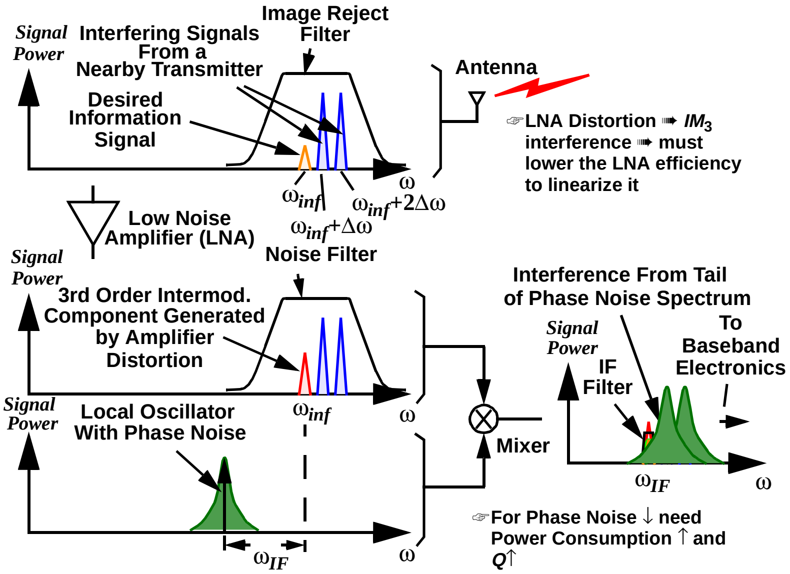


Fig. 4. Modified signal flow diagrams for a conventional receiver using wide-band RF filters.

The power savings advantages afforded by MEMS is perhaps best illustrated by comparison with recent attempts to reduce the cost and size of wireless transceivers via increased circuit complexity. Specifically, in these approaches higher levels of transistor integration and alternative architectures are used to reduce the need for the off-chip, high-Q passives used in present-day super-heterodyne transceivers, with obvious size advantages. Unfortunately, removal of off-chip passives often comes at the cost of increased power consumption in circuits preceding and including the analog-to-digital converter (ADC), which now must have higher dynamic ranges to avoid desensitization caused by larger adjacent channel interferers. A selectivity (or Q) versus power trade-off is clearly seen here.

To better convey this point, specific phenomena that give rise to receiver desensitization are illustrated in the diagram of Fig. 4, which depicts the signal flow for a desired signal at ω_{inf} with two adjacent interferers (offset $\Delta\omega$ and $2\Delta\omega$) from antenna to baseband in a conventional receiver architecture using *wideband* RF filters. As shown, due to nonlinearity in the low-noise amplifier (LNA) and phase noise in the local oscillator, the presence of interferers can potentially desensitize the receiver by (1) generating third-order intermodulation (IM_3) distortion components over the desired signal at the output of the LNA; and (2) aliasing superposed phase noise sidebands from the local oscillator onto the desired signal immediately after the mixer stage. In order to avoid such desensitization, the LNA must satisfy a strict linearity requirement, and the local oscillator a strict phase noise requirement, both of which demand significantly higher power consumption in these components. Similar increases in power consumption are also often necessary to maintain adequate dynamic range in subsequent stages (e.g., the A/D converter).

A method for eliminating such a waste of power becomes apparent upon the recognition that the above desensitization phenomena arise in conventional architectures only because such architectures allow interfering signals to pass through the RF filter and reach the LNA and mixer. If these signals were instead eliminated at the outset by a much more selective RF filter, then interference from IM_3 components and from phase noise sidebands would be greatly alleviated, as shown in Fig. 5, and specifications on linearity and phase noise could be greatly relaxed. The power savings afforded by such relaxations in specifications is potentially enormous, especially when considering the possibility of replacing conventional Class A or AB type amplifiers with more efficient topologies, such as Class E. The above discussion pertains to the receive path, but if channel-select filters with both sufficiently high Q and power handling capability are available and placed right before the transmitting antenna, similar power savings are possible for the *transmit* local oscillator and power amplifier, as well.

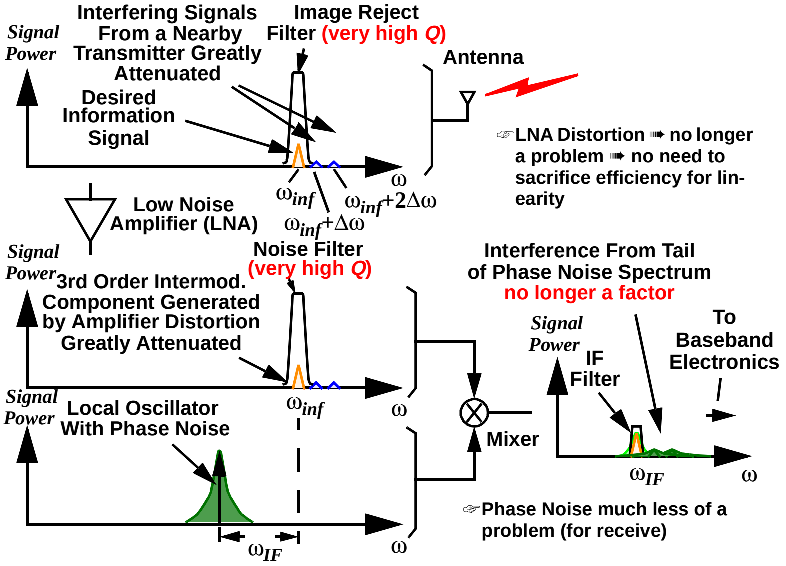


Fig. 5. Modified signal flow diagrams for an RF channel-select receiver.

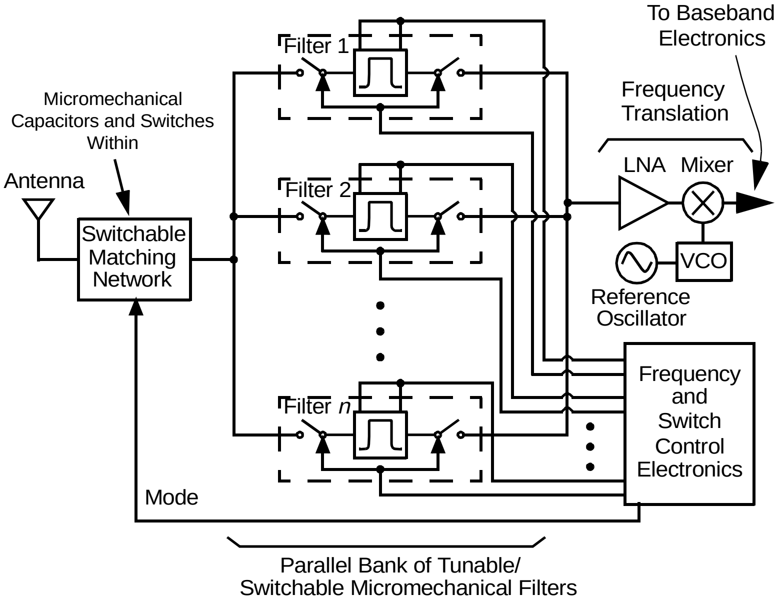


Fig. 6. Possible front-end receiver architecture utilizing a parallel bank of tunable/switchable micromechanical filters for a first stage of channel selection. Note that several micromechanical resonator devices can also be used within the frequency translation blocks as well.

An architecture such as shown in Fig. 5 requires a tunable, highly selective (i.e., high-Q) filter capable of operation at RF frequencies. Unfortunately, partially due to their own high stability, high-Q filters are generally very difficult to tune over large frequency ranges, and MEMS-based filters are no exception to this. Although µmechanical resonators can be tuned over larger frequency ranges than other high-Q tank technologies, with voltage-controllable tuning ranges of up to 5% depending on design, a single micromechanical filter still lacks the tuning range needed for some wide-band applications

Thanks to the tiny size of micromechanical filters, however, there no longer needs to be only one filter. One of the major advantages of micromechanical filters is that, because of their tiny size and zero dc power dissipation, many of them (perhaps hundreds or thousands) can be fabricated onto a smaller area than occupied by a single one of today's macroscopic filters. Thus, rather than use a single tunable filter to select one of several channels over a large frequency range, a massively parallel bank of switchable micromechanical filters can be utilized, in which desired frequency bands can be switched in, as needed. The simplified block diagram for such a front-end architecture is illustrated in Fig. 6, where each filter switch combination corresponds to a single micromechanical filter, with input and output switches activated by the mere application or removal of dc-bias voltages from the resonator elements [11]. By further exploiting the switching flexibility of such a system, some very resilient frequency-hopping spread spectrum transceiver architectures can be envisioned that take advantage of simultaneous switching of high-Q micromechanical filters and oscillators.

In effect, frequency-selective devices based on MEMS technologies can potentially enable substantial power savings by making possible paradigm-shifting transceiver architectures that, rather than eliminate high-Q passive components, attempt to maximize their role with the intention of harnessing the Q versus power trade-off often seen in transceiver design. The next sections now focus upon the subject micromechanical resonator devices.

3. REFERENCES

[1] E. Frian, S. Meszaros, M. Chuaci, and J. Wight, "Computer-aided design of square spiral transformers and inductors," *1989 IEEE MTT-S Dig.*, pp. 661-664.

[2] N. M. Nguyen and R. G. Meyer, "Si IC-compatible inductors and *LC* passive filters," *IEEE J. of Solid-State Circuits*, vol. SC-25, no. 4, pp. 1028-1031, Aug. 1990.

[3] N. M. Nguyen and R. G. Meyer, "A 1.8-GHz monolithic *LC* voltage-controlled oscillator," *IEEE J. of Solid-State Circuits*, vol. SC-27, no. 3, pp. 444-450.

[4] S. V. Krishnaswamy, J. Rosenbaum, S. Horwitz, C. Yale, and R. A. Moore, "Compact FBAR filters offer low-loss performance," Microwaves & RF, pp. 127-136, Sept. 1991.

[5] R. Ruby and P. Merchant, "Micromachined thin film bulk acoustic resonators," *Proceedings* of the 1994 IEEE International Frequency Control Symposium, Boston, MA, June 1-3, 1994, pp. 135-138.

[6] P. R. Gray and R. G. Meyer, "Future directions in silicon IC's for RF personal communications," *Proceedings*, 1995 IEEE Custom Integrated Circuits Conference, Santa Clara, CA, May 1-4, 1995, pp. 83-90.

[7] A. A. Abidi, "Direct-conversion radio transceivers for digital communications," *IEEE J. Solid-State Circuits*, vol. 30, No. 12, pp. 1399-1410, Dec. 1995.

[8] D. H. Shen, C.-M. Hwang, B. B. Lusignan, and B. A. Wooley, "A 900-MHz RF front-end with integrated discrete-time filtering," *IEEE J. of Solid-State Circuits*, vol. 31, no. 12, pp. 1945-1954, Dec. 1996.

[9] C. T.-C. Nguyen, L. P.B. Katehi, and G. M. Rebeiz, "Micromachined devices for wireless communications (invited)," *Proc. IEEE*, vol. 86, no. 8, pp. 1756-1768, Aug. 1998.

[10] C. T.-C. Nguyen and R. T. Howe, "An integrated CMOS micromechanical resonator high-Q oscillator," *IEEE J. Solid-State Circuits*, vol. 34, no. 4, pp. 440-445, April 1999.

[11] C. T.-C. Nguyen, "Frequency-selective MEMS for miniaturized low-power communication devices," to be published in *IEEE Trans. Microwave Theory Tech.*, May 1999, 18 pages.

[12] K. M. Lakin, G. R. Kline, and K. T. McCarron, "Development of miniature filters for wireless applications," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 12, pp. 2933-2939, Dec. 1995.

[13] D. J. Young and B. E. Boser, "A micromachined variable capacitor for monolithic low-noise VCOs," Technical Digest, 1996 Solid-State Sensor and Actuator Workshop, Hilton Head Island, South Carolina, June 3-6, 1996, pp. 86-89.

[14] D. J. Young, V. Malba, J.-J. Ou, A. F. Bernhardt, and B. E. Boser, "Monolithic high-performance three-dimensional coil inductors for wireless communication applications," *Technical Digest*, IEEE International Electron Devices Meeting, Washington, D. C., Dec. 8-11, 1997, pp. 67-70.

[15] M. G. Allen, "Micromachined intermediate and high frequency inductors," 1997 IEEE International Symposium on Circuits and Systems, Hong Kong, June 9-12, 1997, pp. 2829-2832.

[16] C. H. Ahn, Y. J. Kim, and M. G. Allen, "A fully integrated micromachined toroidal inductor with nickel-iron magnetic core (the switched DC/DC boost converter application)," *Digest of Technical Papers*, the 7th International Conference on Solid-State Sensors and Actuators (Transducers'93), Yokohama, Japan, June 7-10, 1993, pp. 70-73.

[17] B. Ziaie, N. K. Kocaman, and K. Najafi, "A generic micromachined silicon platform for low-power, low-loss miniature transceivers," *Digest of Technical Papers*, 1997 International Conference on Solid-State Sensors and Actuators (Transducers'97), Chicago, Illinois, June 16-19, 1997, pp. 257-260.

[18] C. Y. Chi and G. M. Rebeiz, ``Planar microwave and millimeter-wave lumped elements and coupled-line filters using micro-machining techniques," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-43, pp. 730-738, April 1995.

[19] T. M. Weller, L. P. Katehi and G. M. Rebeiz, "High performance microshield line components," *IEEE Trans. Microwave*

Theory Tech., vol. MTT-43, pp. 534-543, March 1995.

[20] S. V. Robertson, L. P. Katehi and G. M. Rebeiz, “Micromachined W-band filters,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, pp. 598-606, April 1996.

[21] C. Y. Chi and G. M. Rebeiz, “Conductor-loss limited stripline resonators and filters,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, pp. 626-630, April 1996.

[22] T. M. Weller, L. P. Katehi and G. M. Rebeiz, “A 250~GHz microshield band-pass filter,” *IEEE Microwave Guided Wave Lett.*, vol. MGWL-5, pp. 153-155, May 1995.

[23] R. F. Drayton, R. M. Henderson, and L. P. B. Katehi, “Advanced monolithic packaging concepts for high performance circuits and antennas,” 1996 IEEE MTT-S Digest, pp. 1615-1618, June 1996.

[24] A. R. Brown and G. M. Rebeiz, “Micromachined micropackaged filter banks”, *Microwave and Guided Wave Letters*, vol. 8, March 1998.

[25] C. Goldsmith, J. Randall, S. Eshelman, T. H. Lin, D. Denniston, S. Chen and B. Norvell, “Characteristics of micromachined switches at microwave frequencies,” IEEE MTT-S Digest, pp. 1141-1144, June, 1996

[26] J. Yao and M. F. Chang, “A surface micromachined miniature switch for telecommunications applications with signal frequencies from DC to 4 GHz,” 8th Int. Conf. on Solid-State Sensors and Actuators, Transducers, pp. 384-387, June 1995.

[27] S. Pacheco, C. T.-C. Nguyen, and L. P. B. Katehi, “Micromechanical Electrostatic K-Band Switches”, IEEE MTT-S International Microwave Symposium, June 1998.

[28] G. P. Gauthier, A. Courtay, and G. M. Rebeiz, “Microstrip antennas on synthesized low dielectric constant substrates,” *IEEE Trans. Antennas Propag.*, vol. AP-45, pp. 1310-1314, Aug. 1997.

[29] J. Papapolymerou, R. F. Drayton, and L. Katehi, “Micromachined patch antennas”, *IEEE Trans. on Antennas and Propag.*, vol. AP-46, pp. 275-283, Feb. 1998.

[30] M. Stotz, G. Gottwald, and H. Haspeklo, “Planar millimeter-wave antennas using SiNx-membranes on GaAs,” *IEEE Trans. Microwave Theory Techn.*, vol. 44, pp. 1593-1595, Sept. 1996.

[31] J. D. Cressler, et al., “Silicon-germanium heterojunction bipolar technology: the next leap for silicon?” *Digest of Technical Papers*, 1994 ISSCC, San Francisco, CA, February, 1994.

[32] T. A. Core, W. K. Tsang, S. J. Sherman, “Fabrication technology for an integrated surface-micromachined sensor,” *Solid State Technology*, pp. 39-47, Oct. 1993.

[33] R. D. Nasby, *et al.*, “Application of chemical-mechanical polishing to planarization of surface-micromachined devices,” *Technical Digest*, 1996 Solid-State Sensor and Actuator Workshop, Hilton Head, SC, pp. 48-53, June 3-6, 1996.

[34] J. M. Bustillo, G. K. Fedder, C. T.-C. Nguyen, and R. T. Howe, “Process technology for the modular integration of CMOS and polysilicon microstructures,” *Microsystem Technologies*, **1** (1994), pp. 30-41.

Presentation material now follows.

Microelectromechanical Components for Miniaturized Low-Power Communications

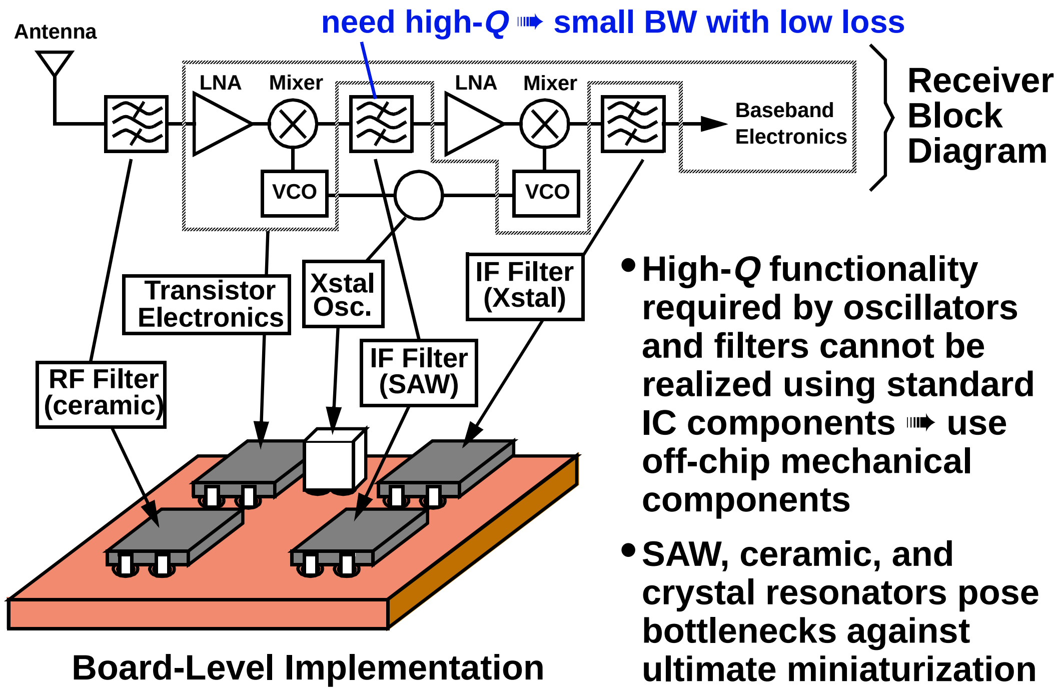
Clark T.-C. Nguyen

Center for Integrated Microsystems
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, Michigan 48109-2122

Outline

- Background: Target Application
  — need for high-*Q*
- Medium *Q* Passives: VCO
  — micromechanical capacitors
  — micromachined inductors
- High *Q* Passives: IF and RF Filters
  — micromechanical resonators
  — micromechanical filters
  — frequency extension
- Conclusions

Miniaturization of Transceivers



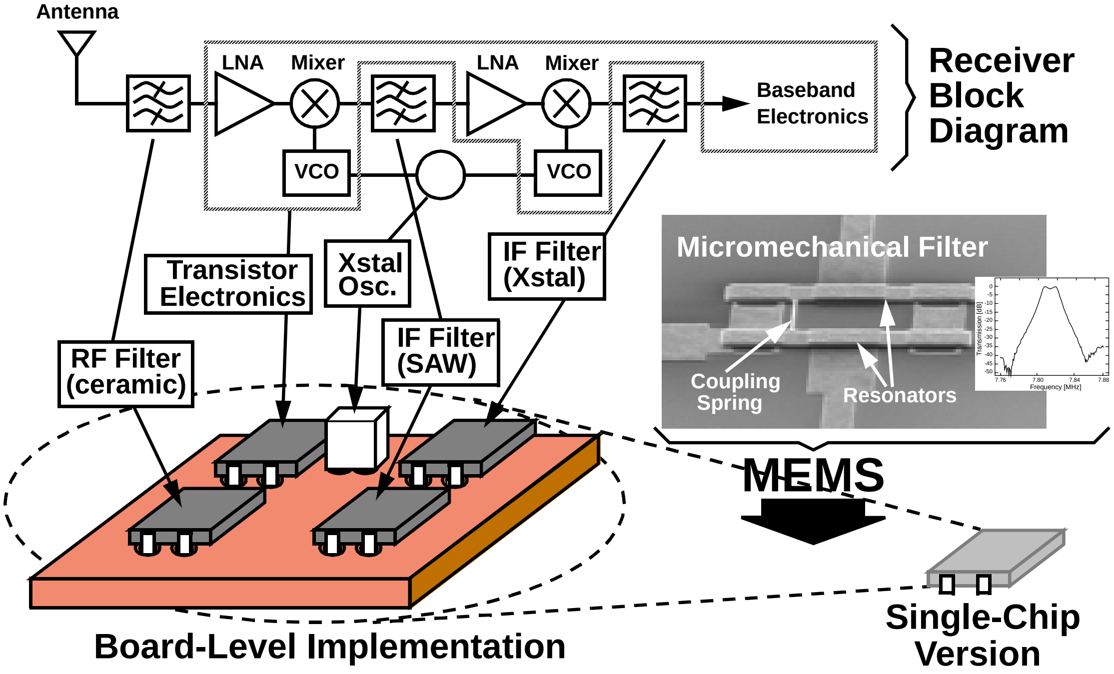
need high-*Q* ➠ small BW with low loss

Board-Level Implementation

- 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

---

Target Application: Integrated Transceivers

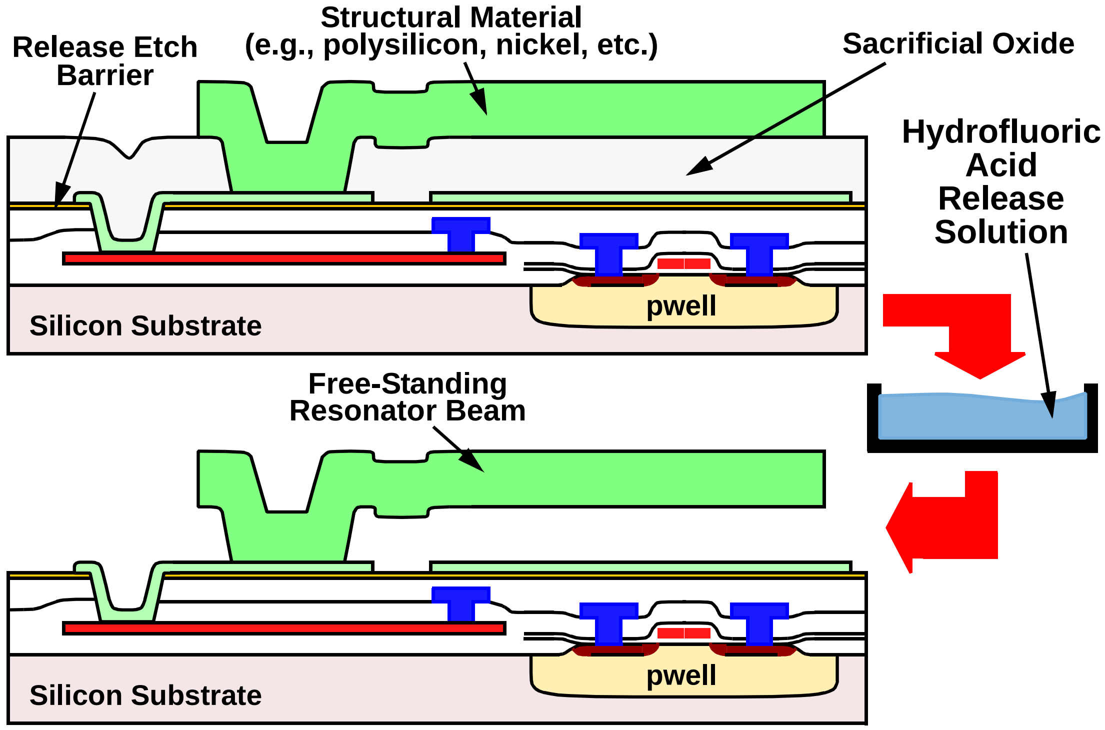


Board-Level Implementation

Single-Chip Version

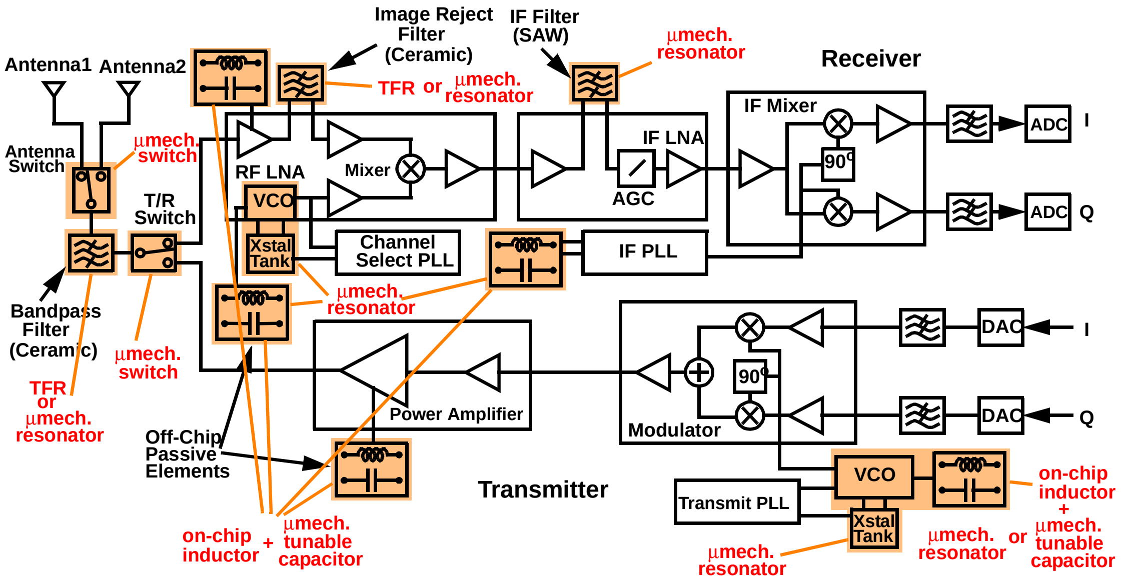
- Off-chip high-*Q* mechanical components present bottlenecks to miniaturization ➠ replace them with μmechanical versions

Surface Micromachining



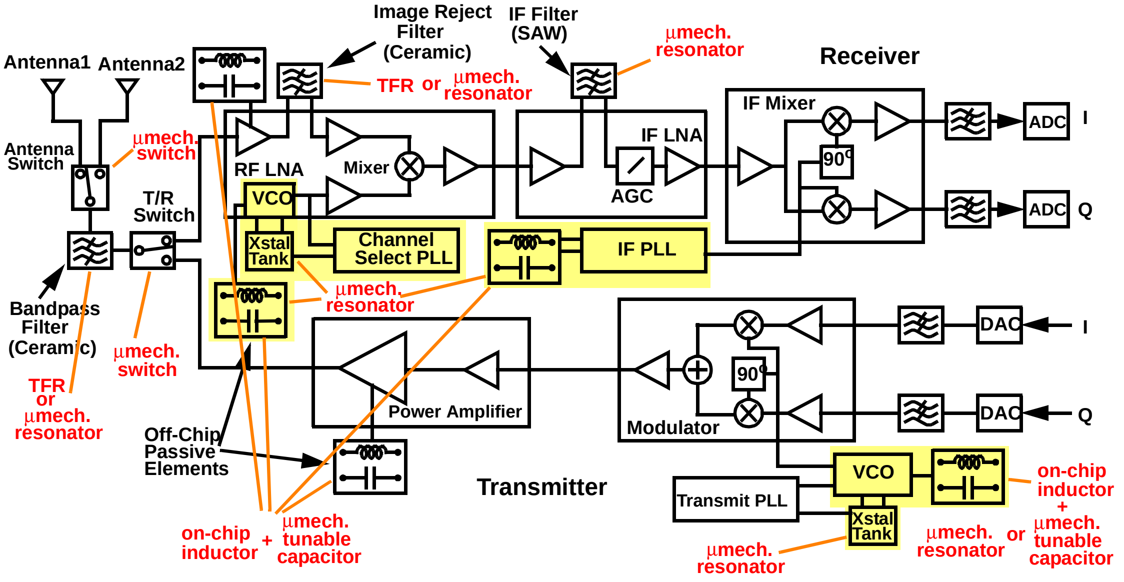
- Fabrication steps compatible with planar IC processing

MEMS-Replaceable Transceiver Components



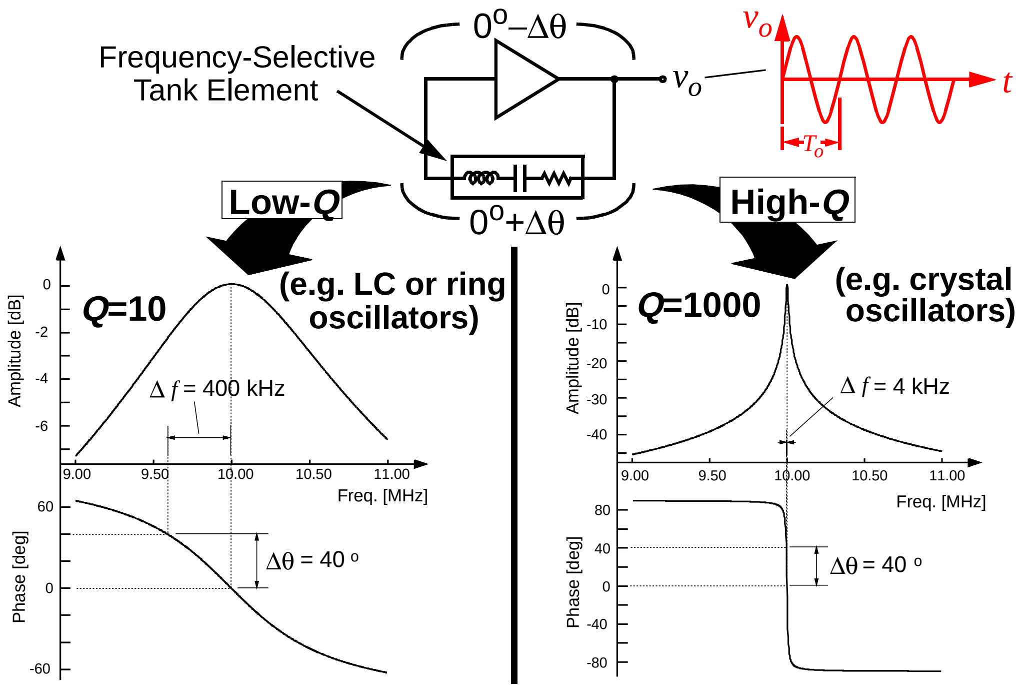
- A large number of off-chip high-Q components replaceable with μmachined versions; e.g., using μmachined resonators, switches, capacitors, and inductors

Synthesizer Oscillators Within Transceivers



- Synthesizers indicated in yellow

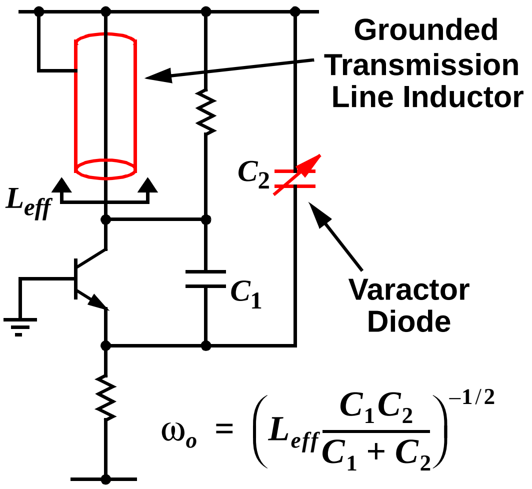
Achieving High Oscillator Stability



- High tank *Q* ➠ high frequency stability

Voltage-Controlled Oscillators (VCOs)

Off-Chip Implementation



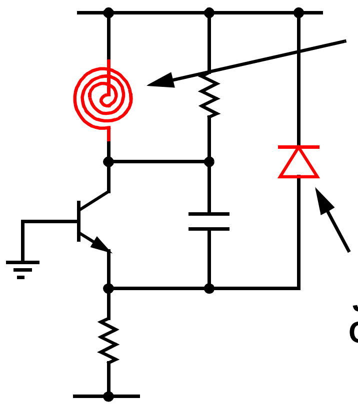
Grounded Transmission Line Inductor

Varactor Diode

$$\omega_o = \left(L_{eff}\frac{C_1C_2}{C_1+C_2}\right)^{-1/2}$$

- Off-chip inductor ➠ Q~100’s
- Tunable Varactor Diode Capacitor ➠ Q~60

On-Chip Implementation



On-chip Spiral Inductor

Silicon Diode Junction Capacitor

- Spiral (shown) or bond-wire inductor ➠ Q: 3 to 10
- Tunable reverse-biased diode capacitor ➠ high series R
- ***Problem***: capacitor lacks sufficient Q and tuning range

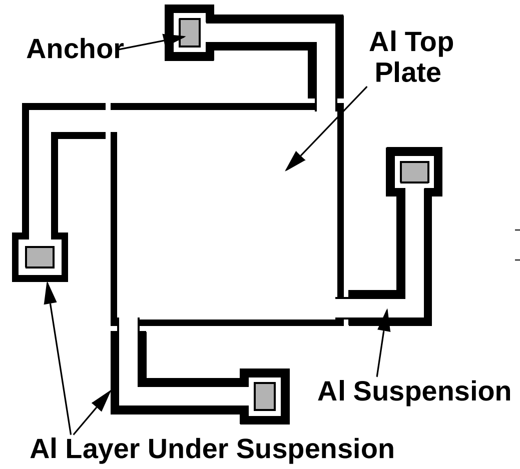
---

Outline

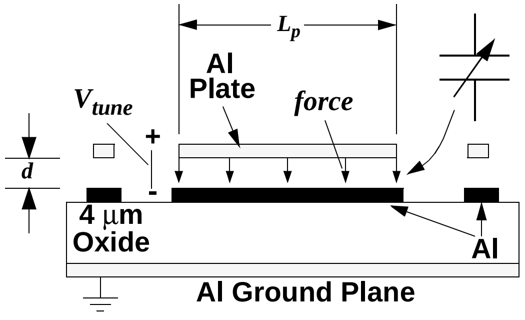
- Background: Target Application
  — need for high-*Q*
- ☞ Medium *Q* Passives: VCO
  — micromechanical capacitors
  — micromachined inductors
- High *Q* Passives: IF and RF Filters
  — micromechanical resonators
  — micromechanical filters
  — frequency extension
- Conclusions

Voltage-Tunable High-*Q* Capacitor

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



Top View



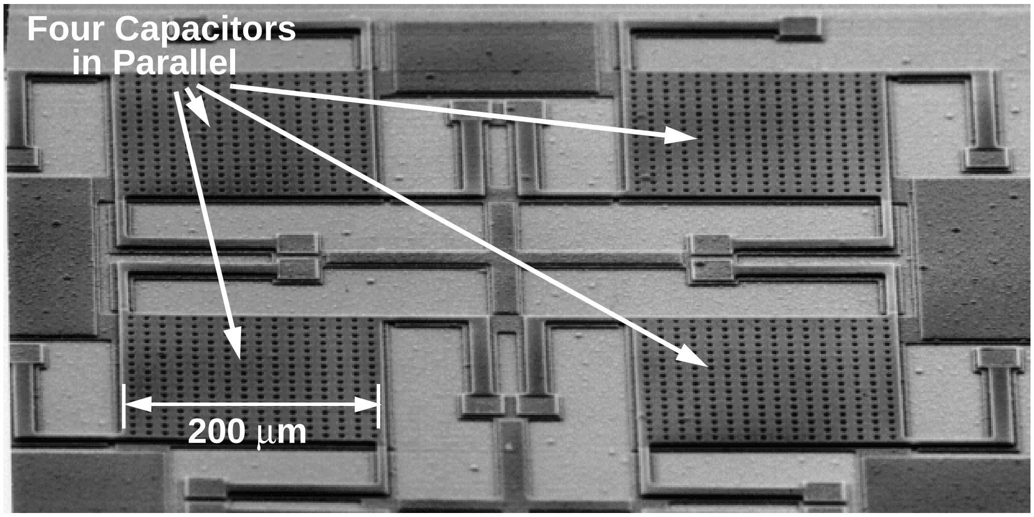
Cross-Section

[Young, Boser 1996]

- ***Challenges*: microphonics, tuning range truncated by pull-in**

Fabricated Voltage-Tunable High-*Q* Capacitor

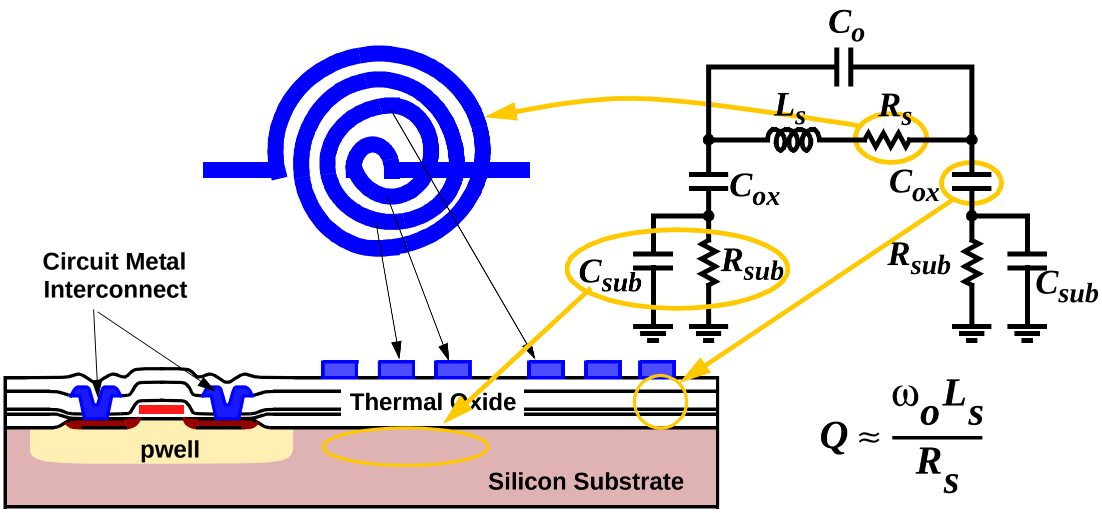
- **Surface micromachined in sputtered aluminum**



[Young, Boser 1996]

- **C_{tot}=2.2pF; 16% tuning range for ΔV_{tune}=5.5V; Q~60**
- ***Challenge*: contact and support line resistance ➠ degrades *Q***

Spiral Inductor Deficiencies

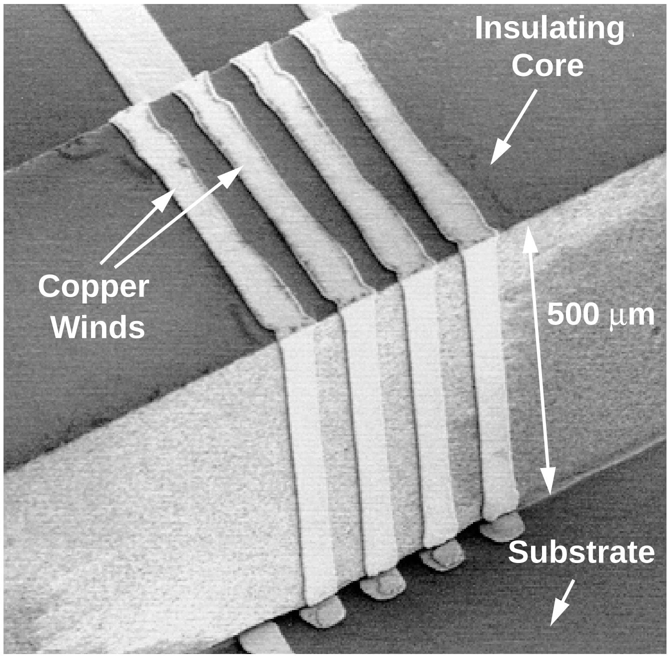


$$Q \approx \frac{\omega_o L_s}{R_s}$$

- Series R_s ➠ degrades Q
  — ***soln**s*: increase L per unit length; use thicker metal
- Parasitic C_o, C_{ox}, C_{sub} and R_{sub} ➠ self-resonance, degrades Q
  — ***soln***: isolate from substrate

Three-Dimensional Coil Inductor

- Electroplated copper winds achieved using maskless, 3-D, direct-write laser lithography to pattern resist mold

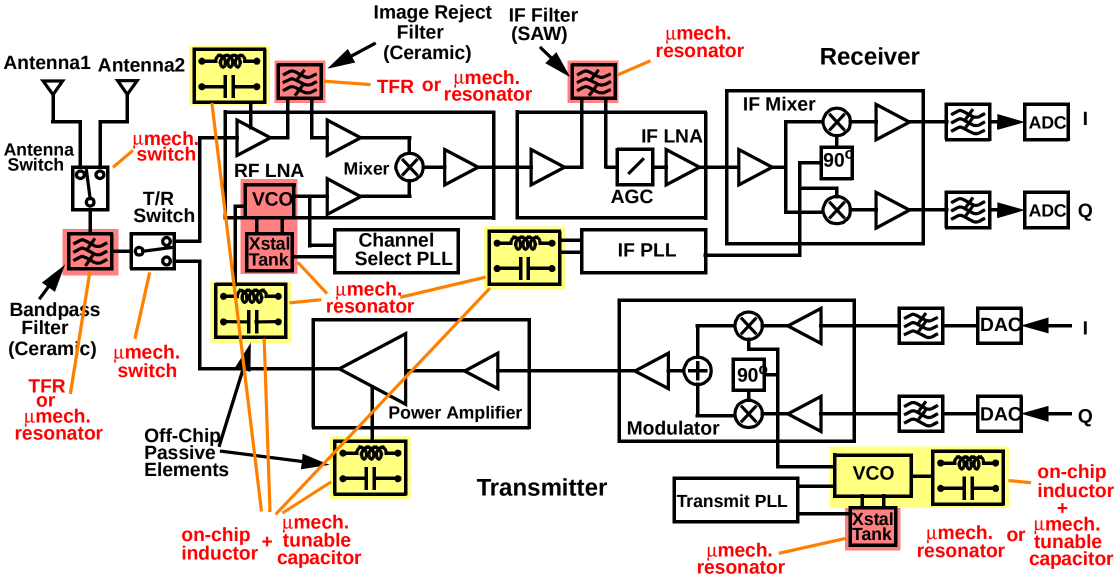


- 3-D structure ➠ minimizes substrate coupling and eddy current loss
- Thick copper ➠ reduces series R

Performance:
W_{wind}=50µm
h_{wind}=5µm
for 1 turn:
L_{tot}=4.8nH
Q=30 @ 1 GHz

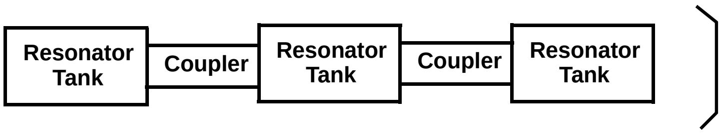
[Young, Boser IEDM'97]

LC-Tank Transceiver Components



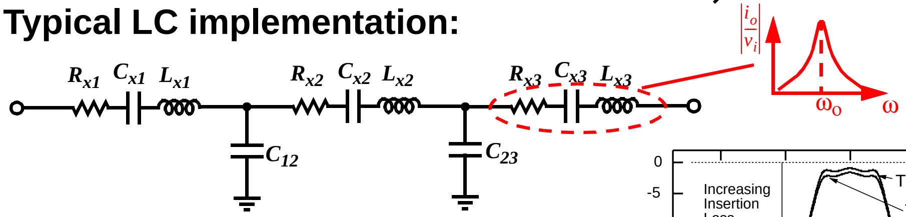
- Yellow: replaceable LC tanks (low to medium *Q* required)
- **Red**: very high-*Q* tanks required (*Q* > 1,000)

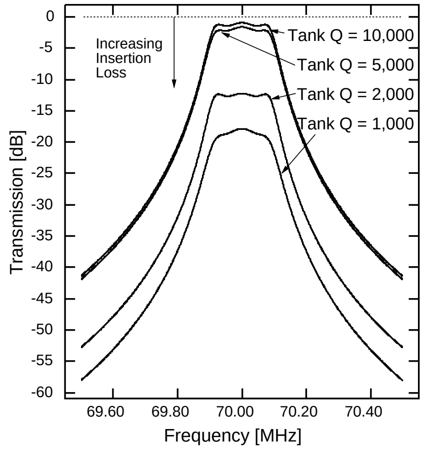
Selective Low Loss Filters: Need High-*Q*



General BPF Implementation

Typical LC implementation:





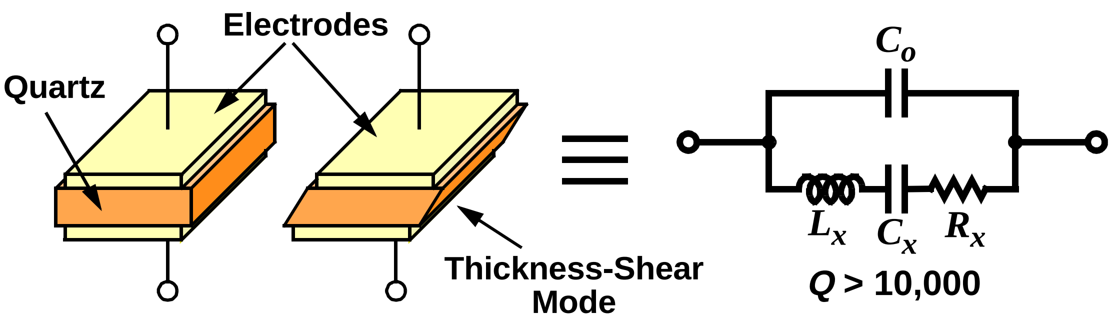
- In resonator-based filters: high tank *Q* ⇔ low insertion loss
- At right: a 0.3% bandwidth filter @ 70 MHz (simulated) — heavy insertion loss for resonator *Q* < 5,000

Outline

- Background: Target Application
  - — need for high-Q
- Medium Q Passives: VCO
  - — micromechanical capacitors
  - — micromachined inductors
- ☞ High Q Passives: IF and RF Filters
  - — micromechanical resonators
  - — micromechanical filters
  - — frequency extension
- Conclusions

Attaining High-Q

- ***Problem***: *LC* tanks cannot achieve *Q*'s in the thousands
  - — 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
  - — extremely high *Q*'s ~ 10,000 or higher ($Q \sim 10^6$ possible)
  - — mechanically vibrates at a distinct frequency in a thickness-shear mode



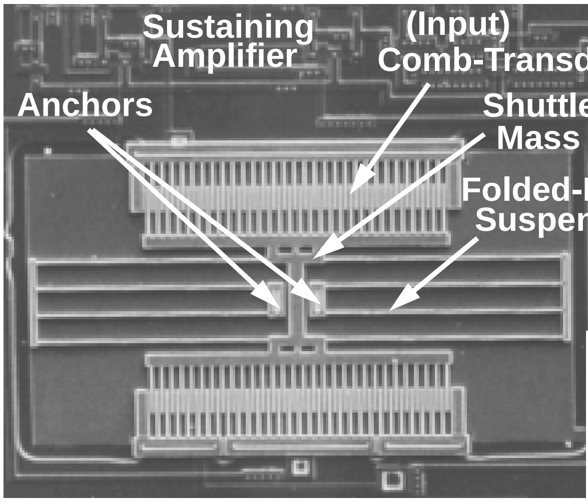
- ***Solution***: use vibrating *micro*mechanical resonators

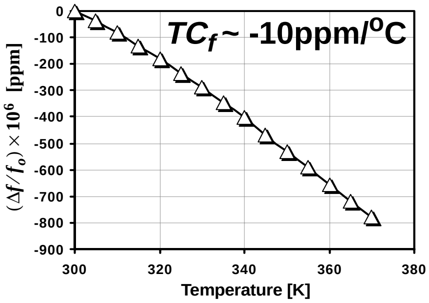
Outline

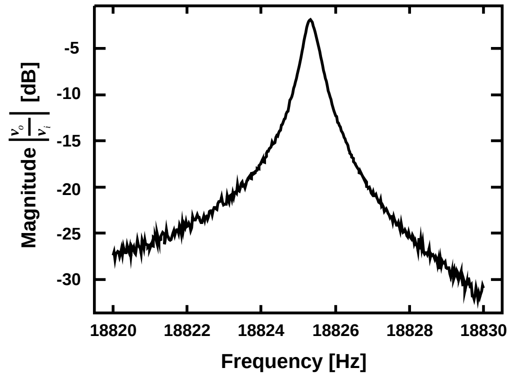
- Background: Target Application
  - — need for high-*Q*
- Medium *Q* Passives: VCO
  - — micromechanical capacitors
  - — micromachined inductors
- High *Q* Passives: IF and RF Filters
  - ☞ — micromechanical resonators
  - ☞ — micromechanical filters
  - — frequency extension
- Conclusions

Comb-Transduced Folded-Beam μResonator

- Micromachined from *in situ* phosphorous-doped polysilicon



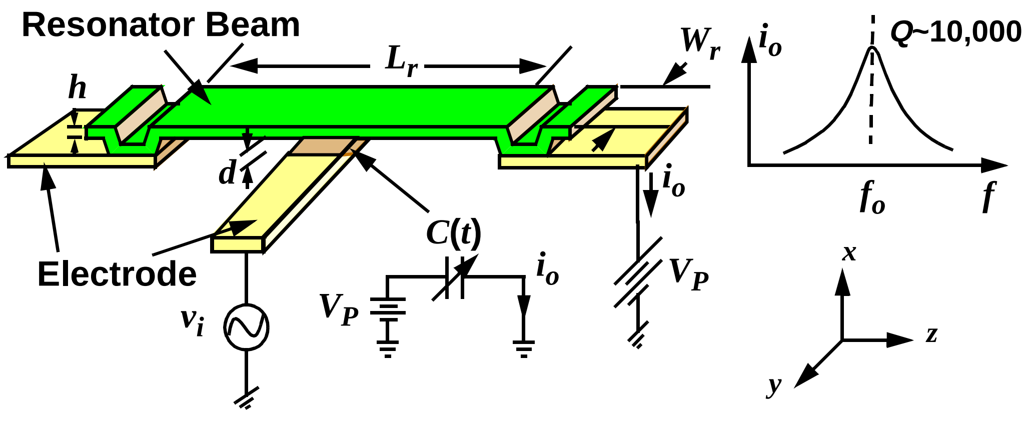




- <u>At right</u>: *Q* = 50,000 measured at 20 mTorr pressure
- (*Q* = 27 at atmospheric pressure)
- <u>Problems</u>: large mass ➠ limited to low frequencies; low coupling

Vertically-Driven Micromechanical Resonator

- To date, most used design to achieve VHF frequencies



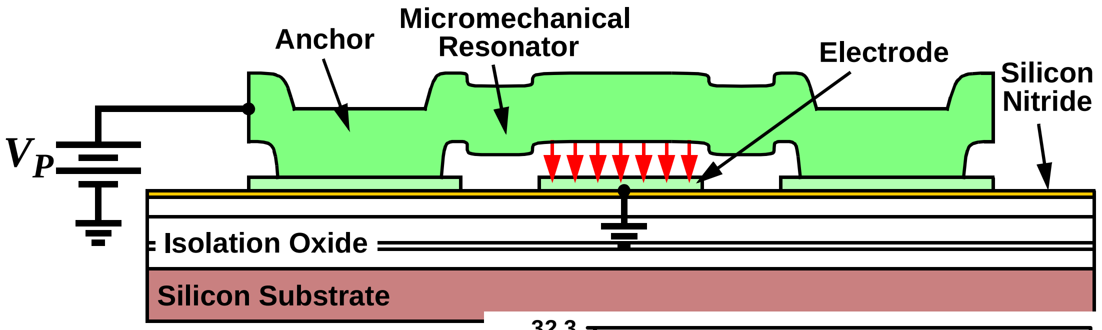
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}} = 1.03\sqrt{\frac{E}{\rho}}\frac{h}{L_r^2}$$

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

E = Youngs Modulus
ρ=density

- Smaller mass ➠ higher frequency range and lower series R_x

Voltage-Controllable Center Frequency



- Quadrature force ➠ voltage-controllable electrical stiffness:

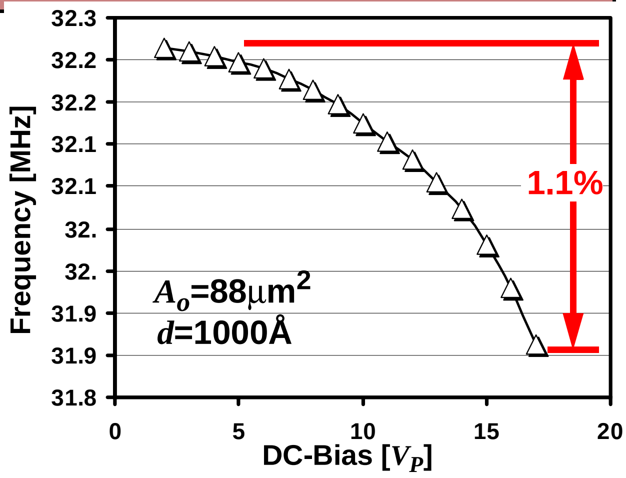
$$k_e = \frac{\varepsilon_o A_o}{d^3} V_P^2$$

Electrode Overlap Area

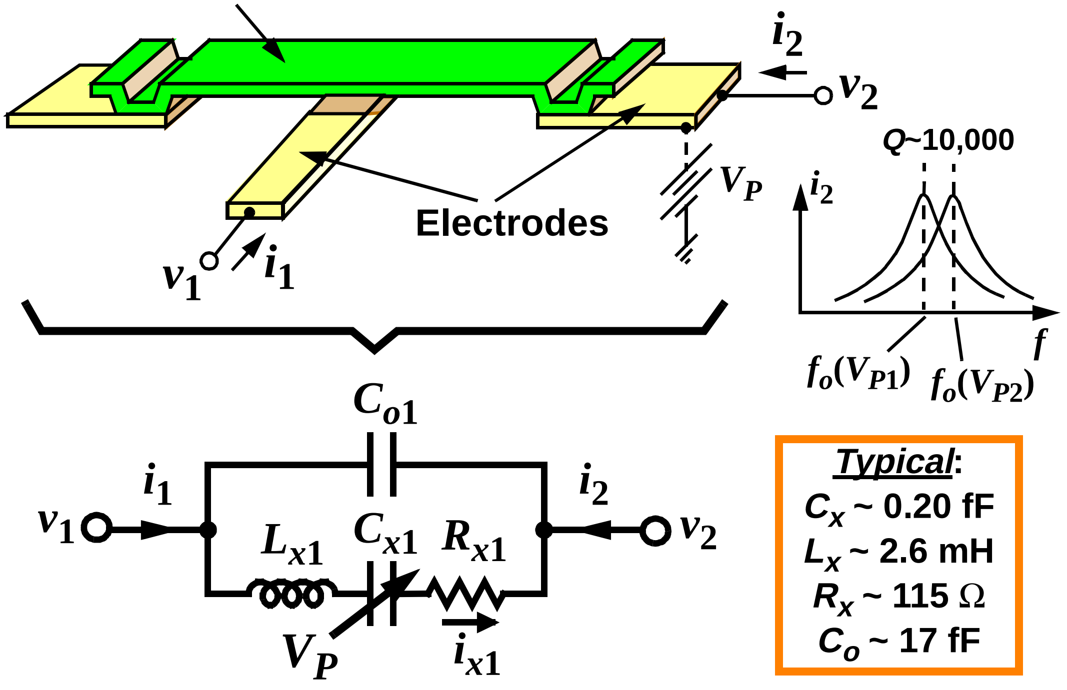
Finger Gap

⬇

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_m - k_e}{m_r}}$$



Micromechanical Resonator Equivalent Circuit



Typical:

C_x ~ 0.20 fF

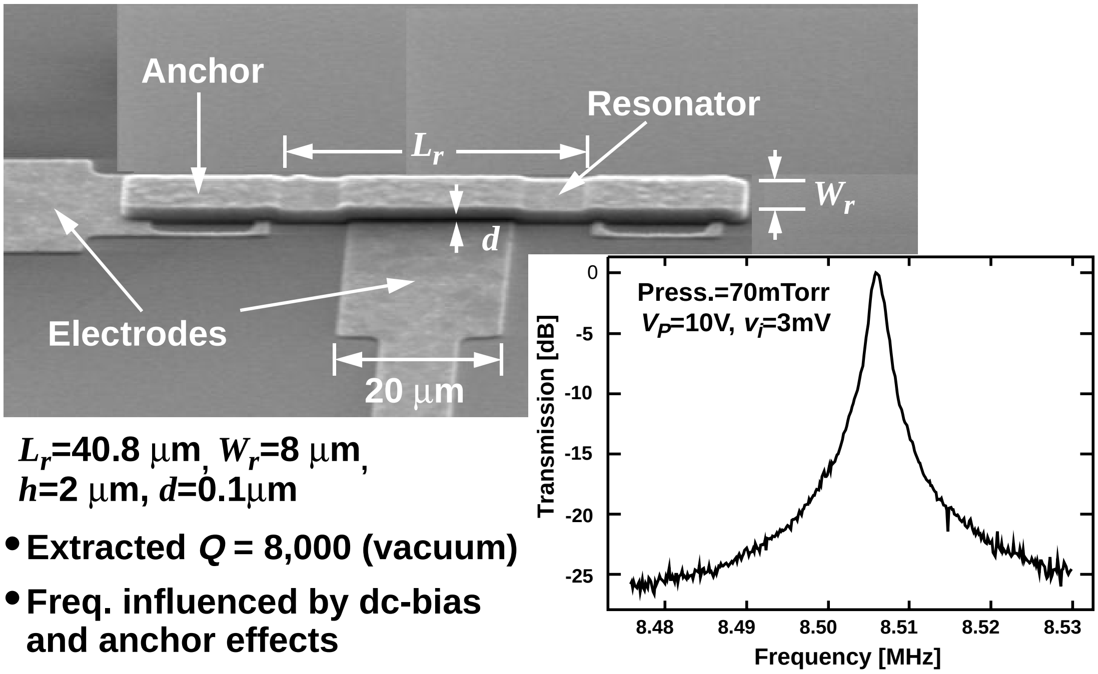
L_x ~ 2.6 mH

R_x ~ 115 Ω

C_o ~ 17 fF

Fabricated HF μMechanical Resonator

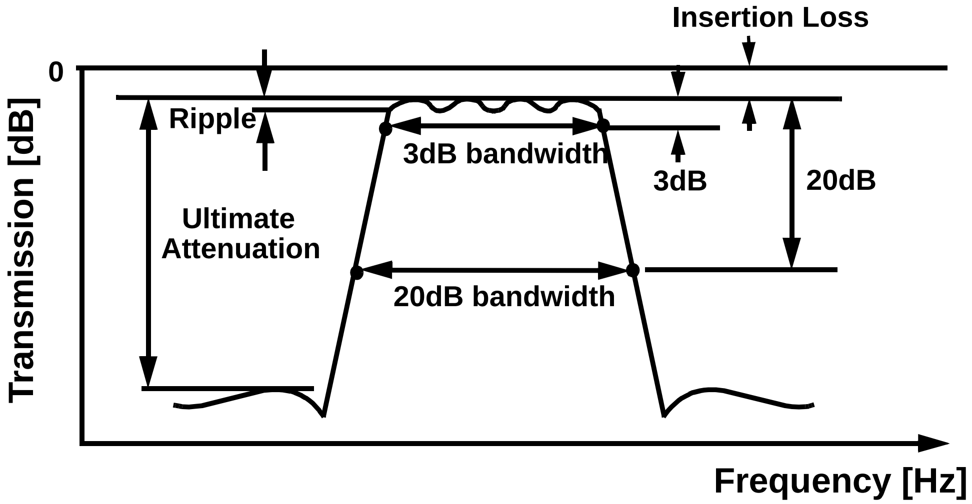
- Surface-micromachined, $POCl_3$-doped polycrystalline silicon



L_r=40.8 μm, W_r=8 μm,
h=2 μm, d=0.1μm

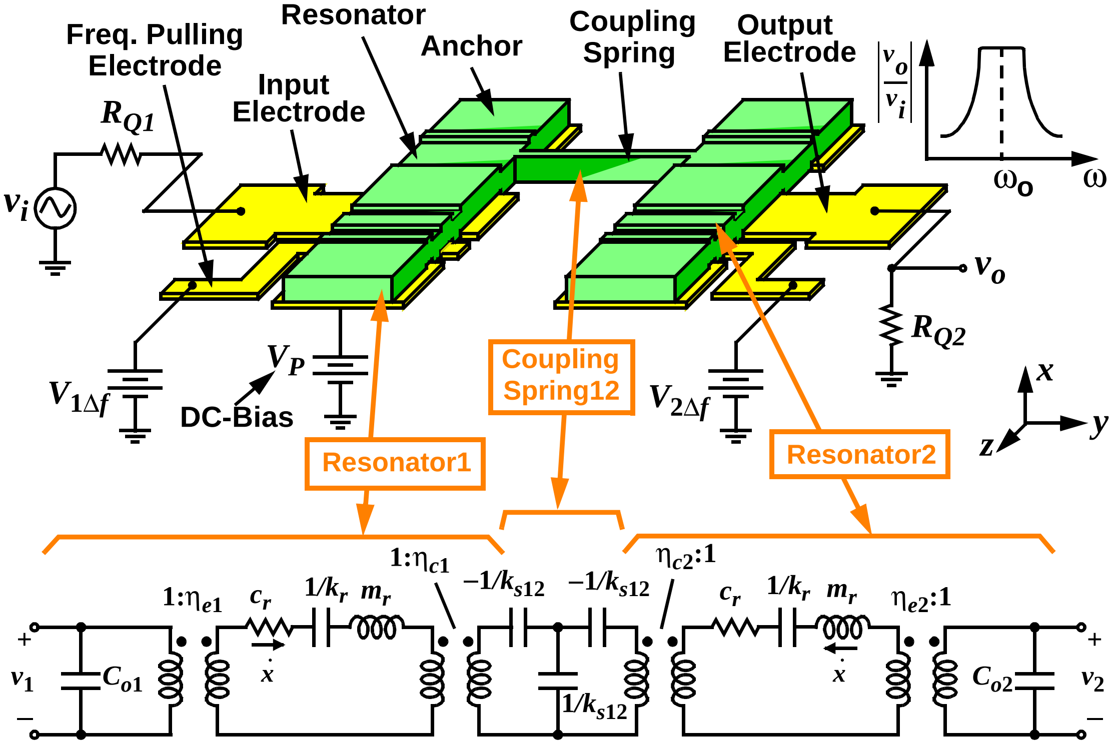
- Extracted Q = 8,000 (vacuum)
- Freq. influenced by dc-bias and anchor effects

Desired Filter Characteristics

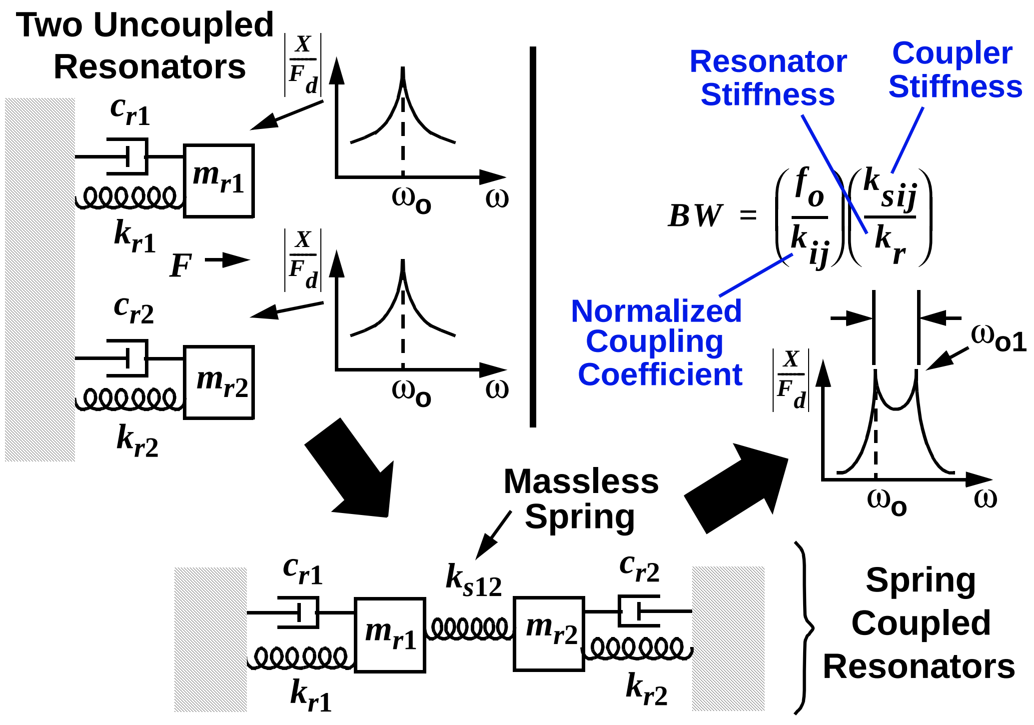


- 20 dB-down Shape Factor $= \dfrac{\text{20 dB-down Bandwidth}}{\text{3 dB-down Bandwidth}}$
- Small shape factor is preferred ➠ better selectivity

High-Frequency μMechanical Filters



Ideal Spring Coupled Filter



Two Uncoupled Resonators

Resonator Stiffness

Coupler Stiffness

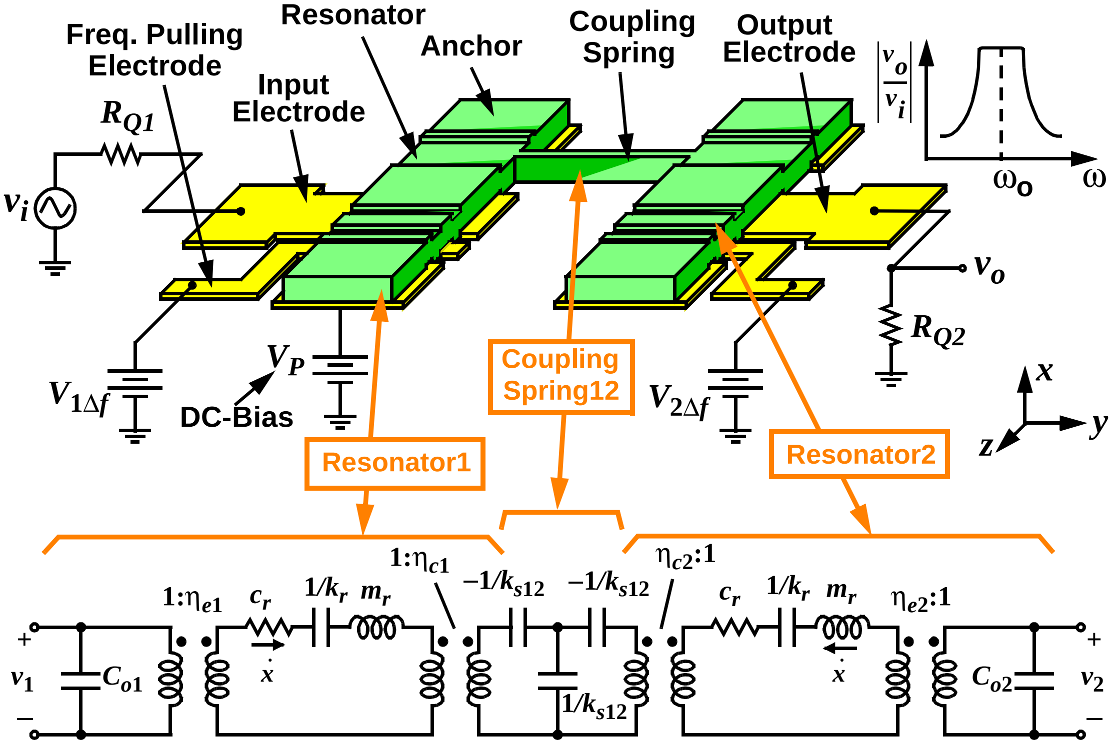
$$BW = \left(\frac{f_o}{k_{ij}}\right)\left(\frac{k_{sij}}{k_r}\right)$$

Normalized Coupling Coefficient

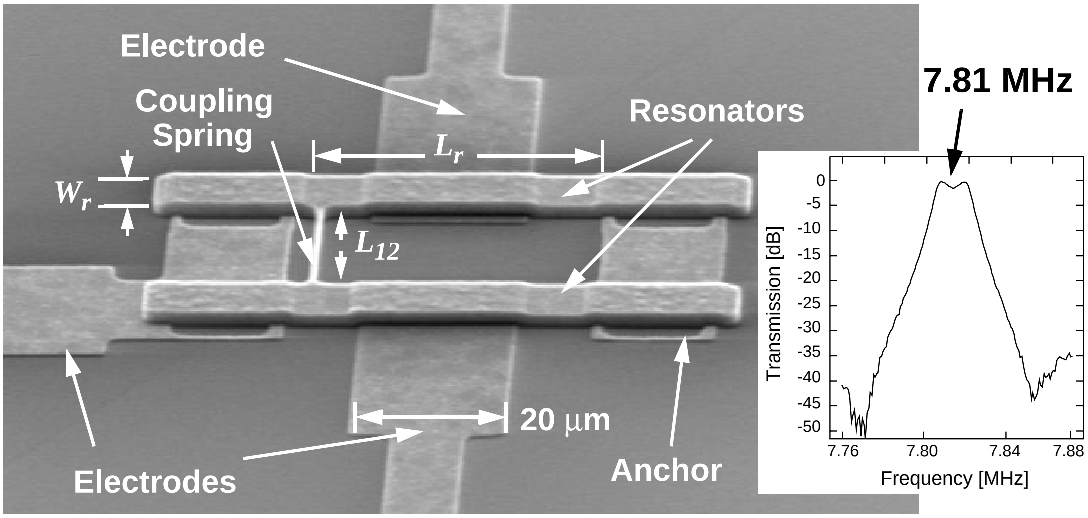
Massless Spring

Spring Coupled Resonators

High-Frequency μMechanical Filters



HF Spring-Coupled Micromechanical Filter



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

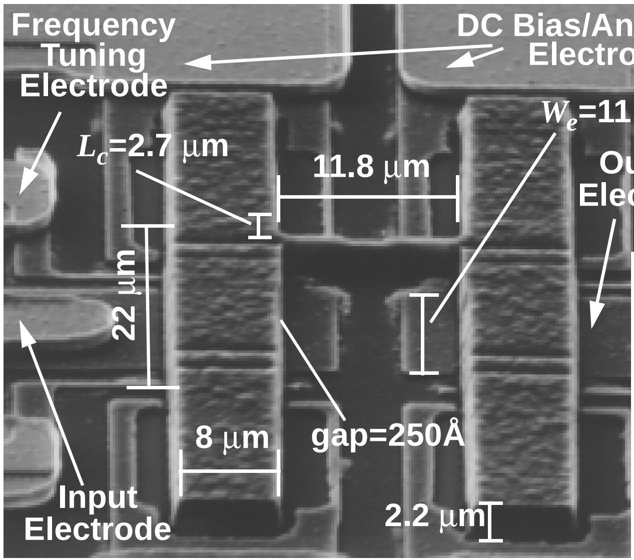
➡

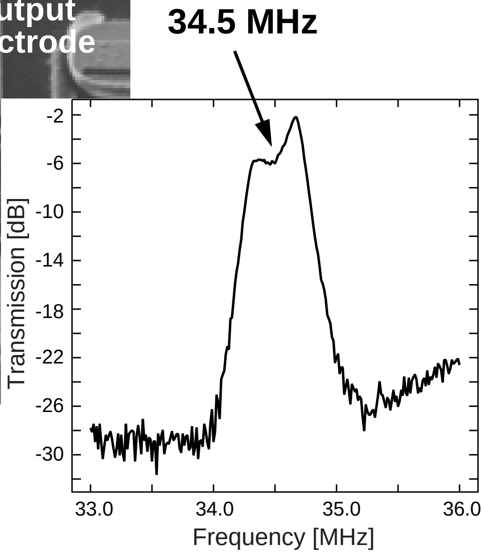
Performance

f_o=7.81MHz, *BW*=15kHz

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

VHF Spring-Coupled Micromechanical Filter





***Performance*:**

V_P~15V, R_Q~2kΩ

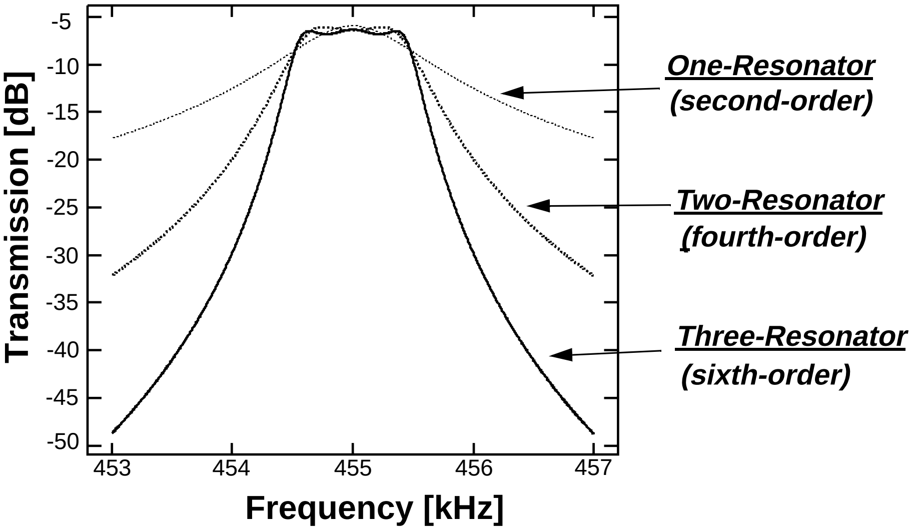
f_o~34.5MHz, *BW*~1.3%

Rej.=25dB, I.L.<6dB

[Wong, Ding, Nguyen 1998]

Attaining Better Performance

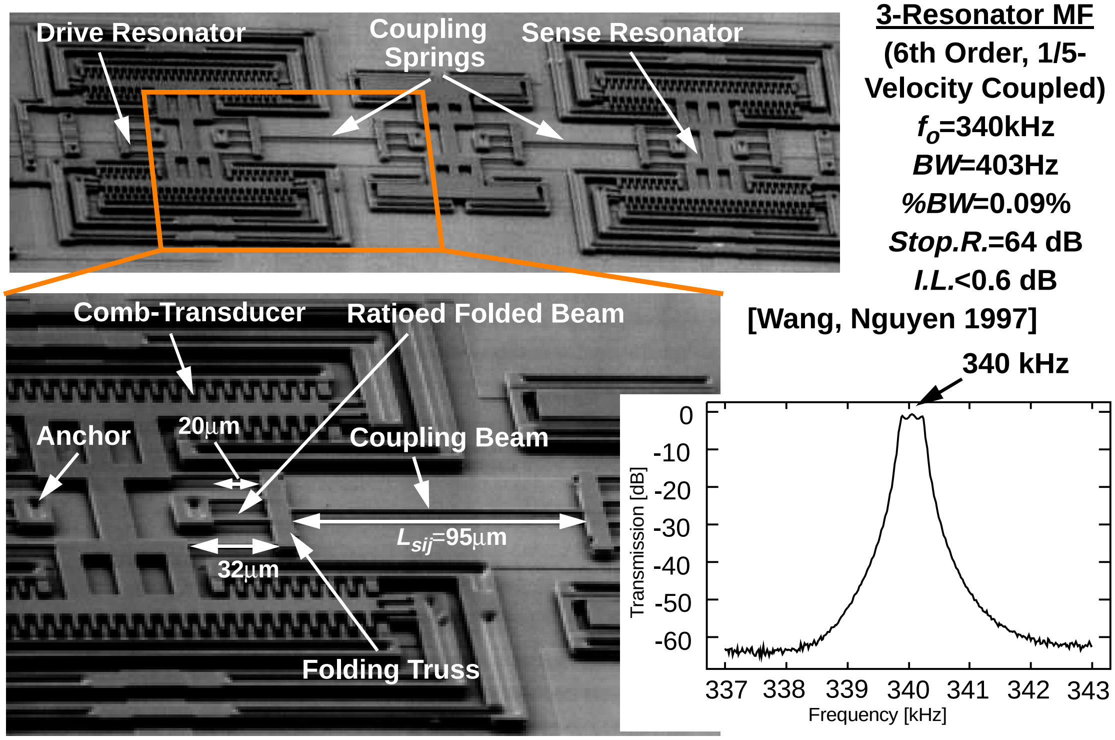
- Use more resonators to attain higher order
- Filter Order = 2 x (# of resonators)



- Higher order ➠ sharper roll-off ➠ better stopband rejection

---

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**

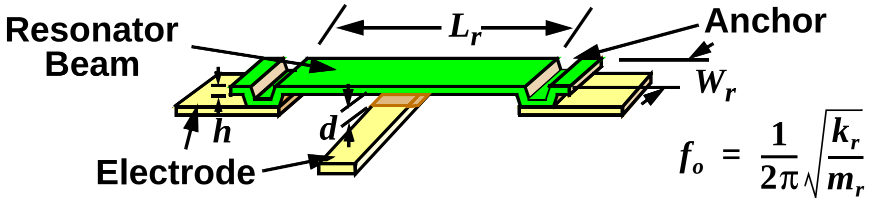
[Wang, Nguyen 1997]

Outline

- Background: Target Application
  - need for high-*Q*
- Medium *Q* Passives: VCO
  - micromechanical capacitors
  - micromachined inductors
- High *Q* Passives: IF and RF Filters
  - micromechanical resonators
  - micromechanical filters
  - ☞ frequency extension
- Conclusions

Extending the Frequency Range

- To obtain even higher frequency:
  - Shrink beam dimensions
  - Must shrink gap d dimensions, as well

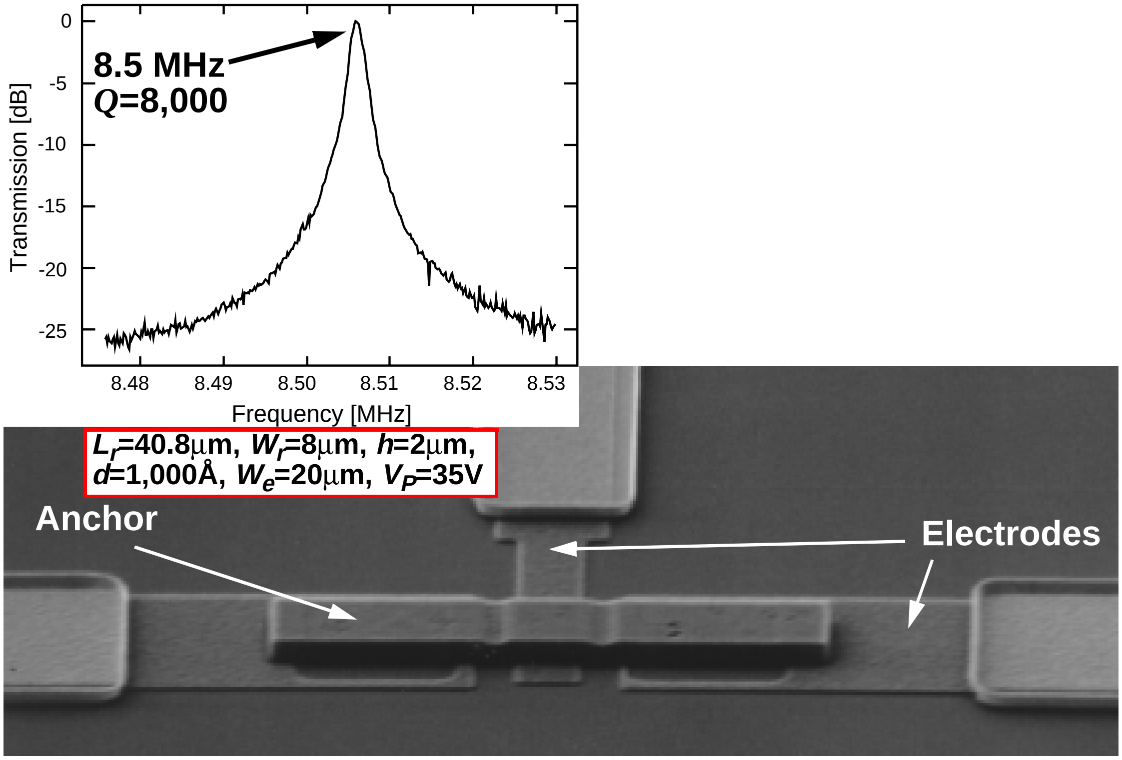


$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

<u>100 MHz</u>: L_r=11.8 μm, W_r=8 μm, h=2 μm, d=400Å

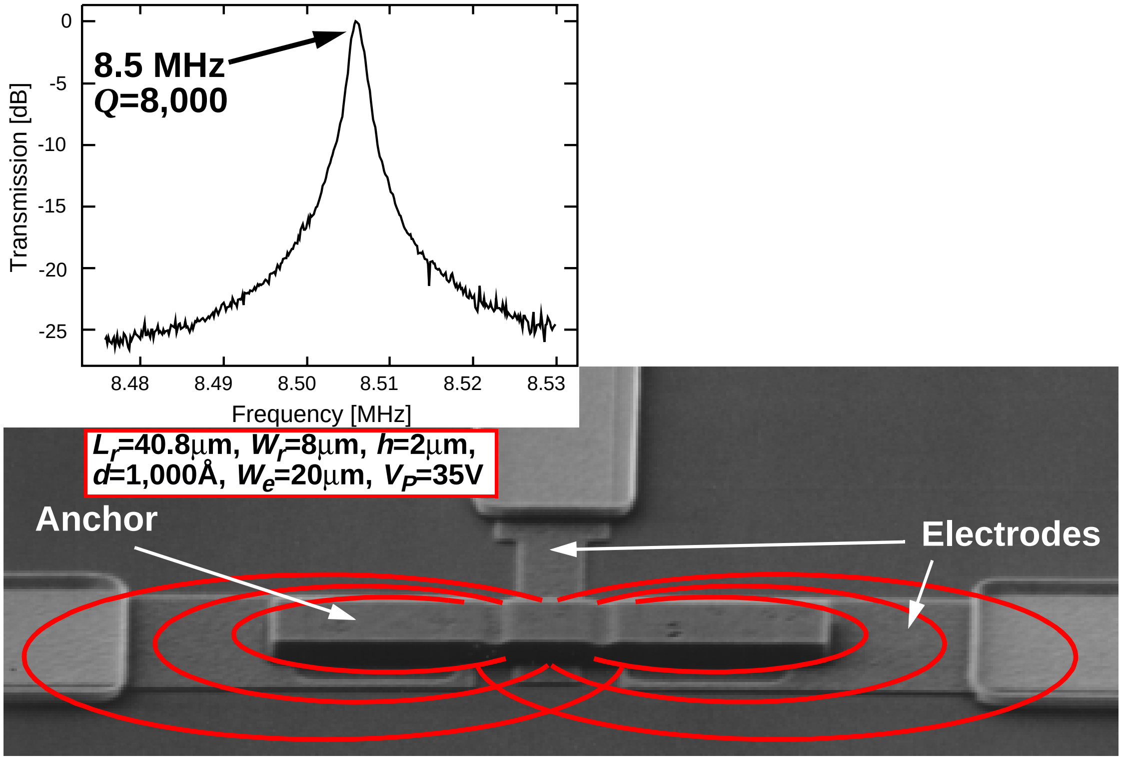
- The useful frequency range will, however, depend on other factors:
  - thermal stability ➠ soln: design, compensation, control
  - noise limitations ➠ soln: transducer design
  - power handling ➠ soln: geometric and transducer design
  - fabrication tolerances (absolute and matching)
  - quality factor ➠ soln: material and design research

Anchor Dissipation in Clamped-Clamped Beams



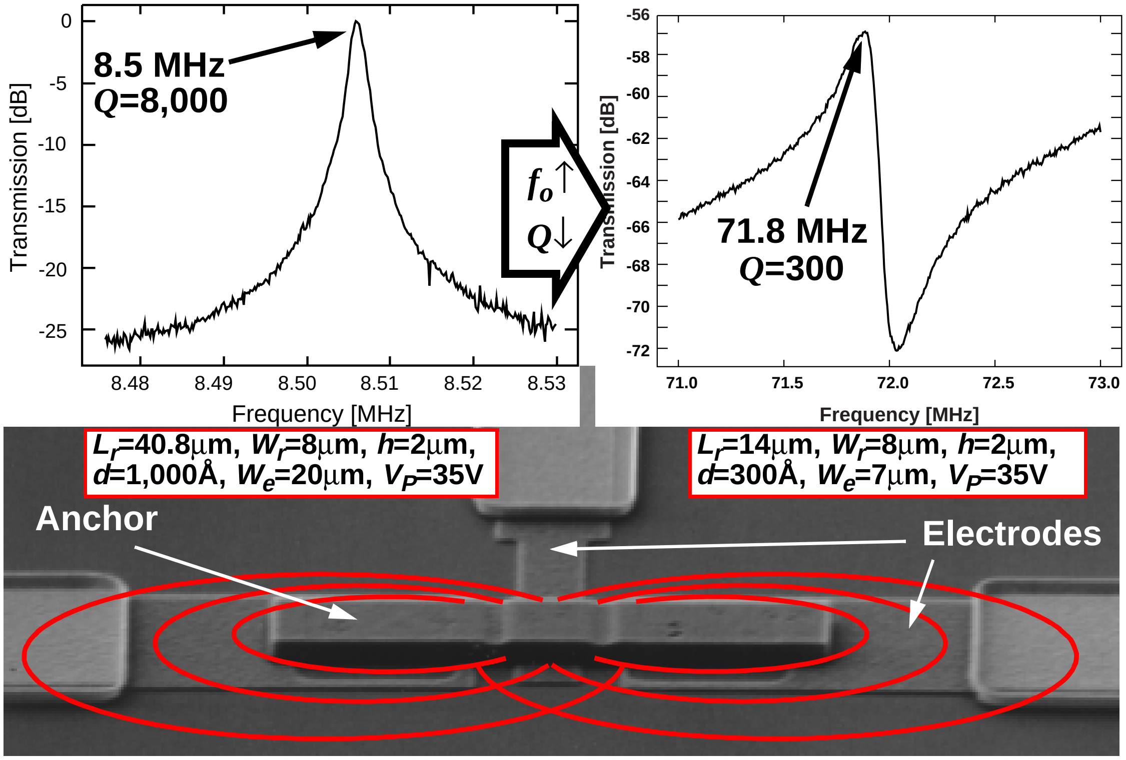
L_r=40.8μm, W_r=8μm, h=2μm, d=1,000Å, W_e=20μm, V_P=35V

Anchor Dissipation in Clamped-Clamped Beams



L_r=40.8μm, W_r=8μm, h=2μm, d=1,000Å, W_e=20μm, V_P=35V

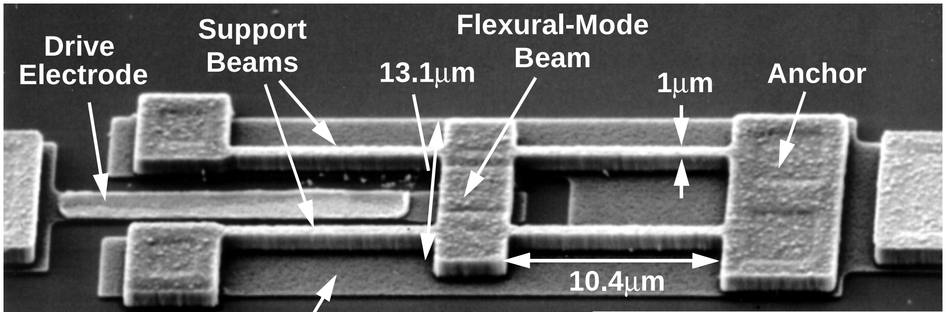
Anchor Dissipation in Clamped-Clamped Beams



---

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

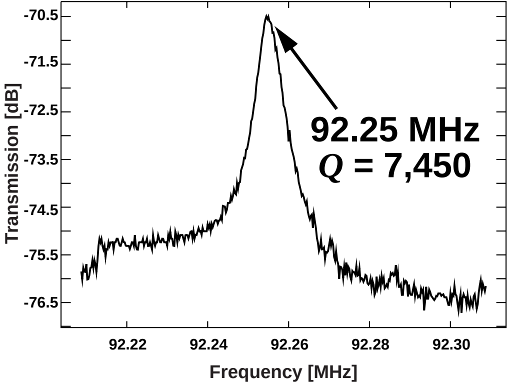
h=2μm, d=1000Å

V_P=28V, W_e=2.8μm

f_o~92.25MHz

Q~7,450 @ 10mTorr

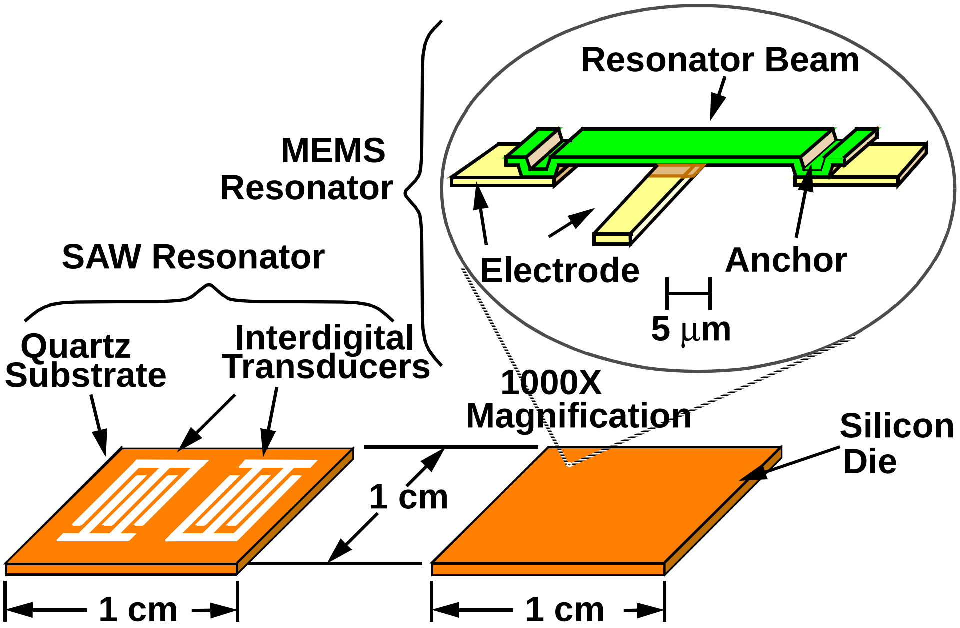
[Wang, Yu, Nguyen 1998]



Outline

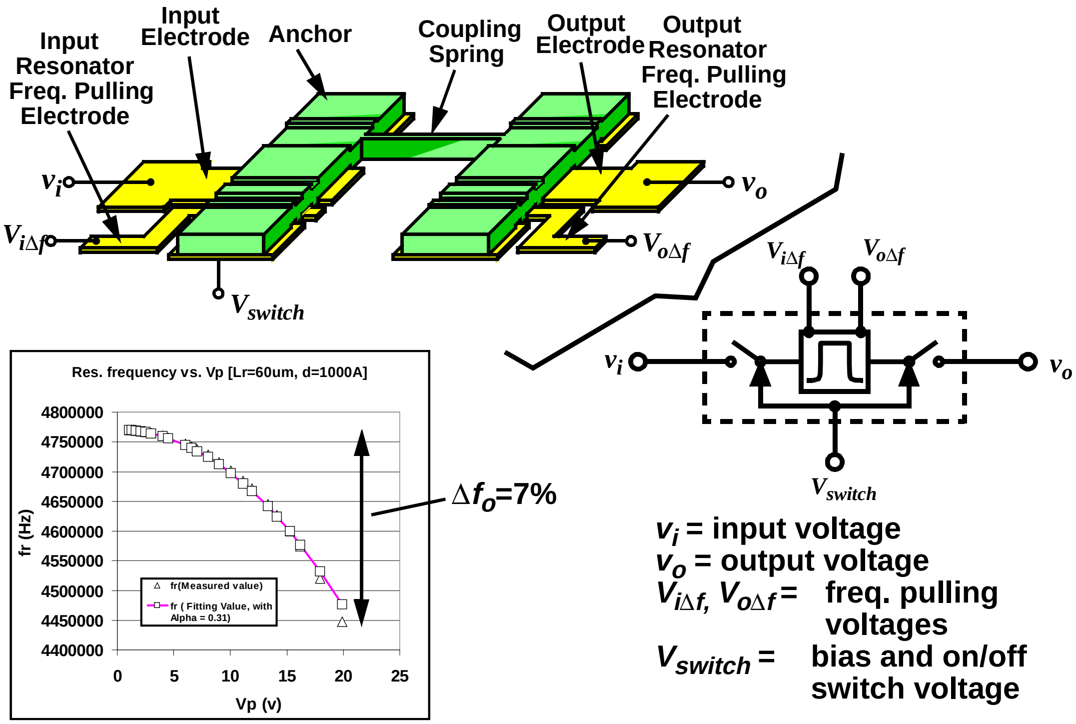
- Background: Target Application
  - — need for high-*Q*
- Medium *Q* Passives: VCO
  - — micromechanical capacitors
  - — micromachined inductors
- High *Q* Passives: IF and RF Filters
  - — micromechanical resonators
  - — micromechanical filters
  - — frequency extension
- ☞ Conclusions

MEMS vs. SAW Comparison



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

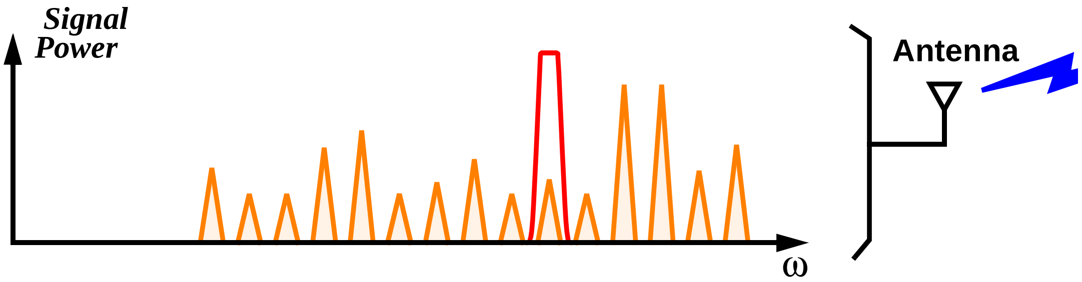
Switchable, Tunable Micromechanical Filters



v_i = input voltage
v_o = output voltage
$V_{i\Delta f}$, $V_{o\Delta f}$ = freq. pulling voltages
V_{switch} = bias and on/off switch voltage

Front-End Channel Selection

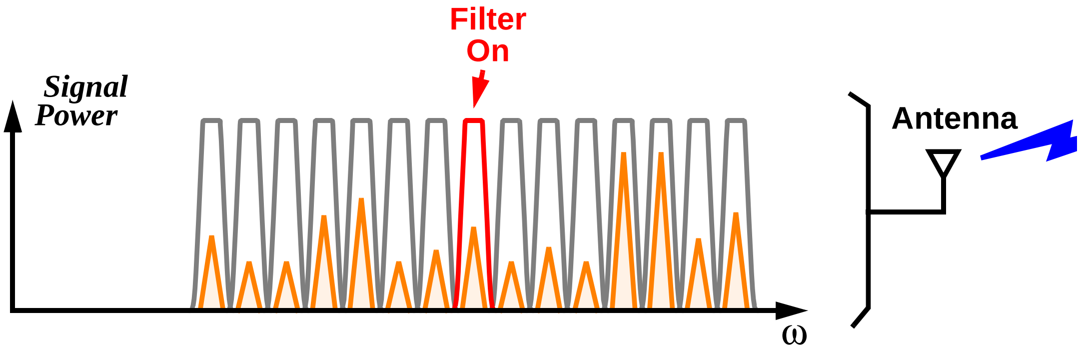
- ***Observation***: **Higher RF selectivity relaxes linearity and phase noise specifications for subsequent stages**
  — rather than select a band of channels, select individual channels right at RF
- ***Approach***: **Use a highly selective low-loss filter that is tunable from channel to channel:**



- ***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

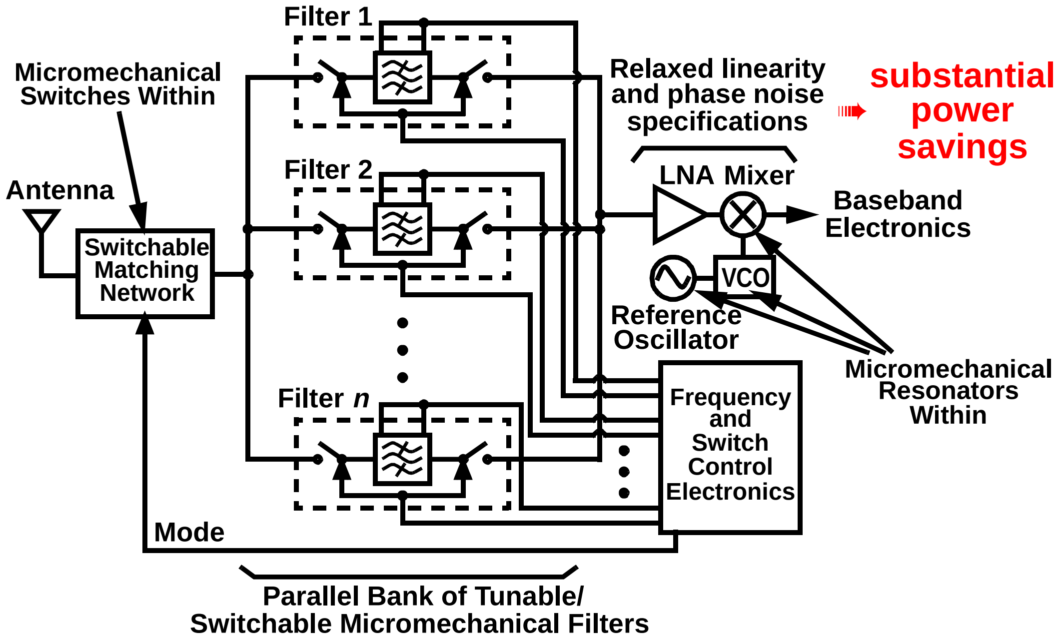


- ***Problem***: macroscopic high-*Q* filters are too big
- ***Requirement***: tiny filters ➠ micromechanical high-*Q* filters present a good solution

---

Micromechanical RF Channel-Selector

- Use a massively parallel array of tunable, switchable filters
  - — suppress adjacent channel interferers
  - — relax dynamic range requirements in subsequent stages



Filter 1

Micromechanical Switches Within

Relaxed linearity and phase noise specifications ➠ **substantial power savings**

Filter 2

LNA Mixer

Antenna

Baseband Electronics

Switchable Matching Network

VCO

Reference Oscillator

Micromechanical Resonators Within

Filter *n*

Frequency and Switch Control Electronics

Mode

Parallel Bank of Tunable/ Switchable Micromechanical Filters

Conclusions

- High-*Q* functionality required in communication transceivers presents a major bottleneck against ultimate miniaturization and power reduction
- Micromechanical *L*'s and tunable *C*'s offer improved *Q* performance over on-chip alternatives and can be applied advantageously to VCO's and tuning/matching networks
- With *Q*'s in the thousands, µmechanical resonators can serve well as miniaturized high-*Q* on-chip tanks for use in extremely sharp IF and RF filters
- With µmechanical components the number of frequency selective components no longer needs to be minimized ➠ encourages architectures that trade power for *Q*

Micromechanical Signal Processors

- ***Micromechanical advantages***:
  — orders of magnitude smaller size
  — better performance than other single-chip solutions
  — methods for batch fabrication and integration with ckts.
  — zero dc power consumption
  — potentially large reduction in power consumption
  — alternative transceiver architectures for improved performance
- Research Issues:
  — frequency extension to UHF and beyond
  — stability enhancement (w/r to temperature, aging, mass loading, etc. ...)
  — manufacturing aides: (automated) frequency tuning/ trimming, CAD tool development
  — dynamic range optimization
  — cost-effective integration with electronics
  — transceiver architecture exploration, harnessing the size and zero dc power consumption advantages

Acknowledgments

- B. Boser, D. Young (UC Berkeley): tunable *C*'s and *L*'s
- Former and present graduate students, especially Kun Wang, Frank Bannon III, and Ark-Chew Wong, who are largely responsible for the micromechanical filter work
- My government funding sources: DARPA, NASA/JPL, NSF, and an ARO MURI