RF MEMS (1):
Introduction to RF Systems
Micromechanical Resonator Oscillators and
Micromechanical Filters for Wireless Applications

Reference:

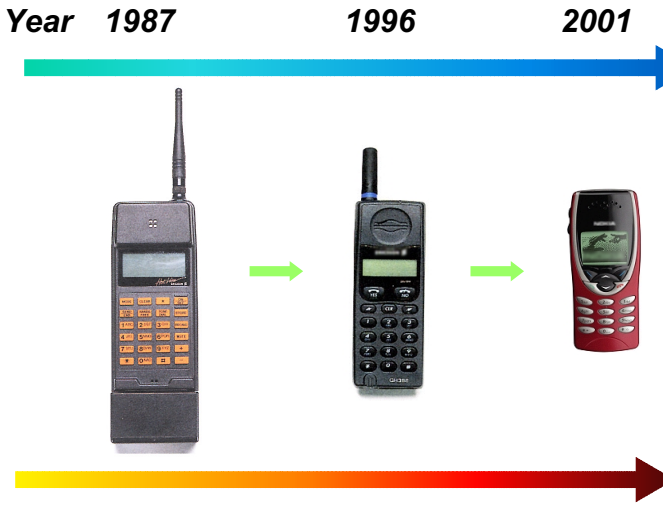
- **C.T.C. Nguyen, MTT-S 1999 (http://www.eecs.umich.edu/~ctnguyen/mtt99.pdf)**
- **C.T.C. Nguyen, et al., IEEE Trans. MTT, 1999**

Acknowledgment:

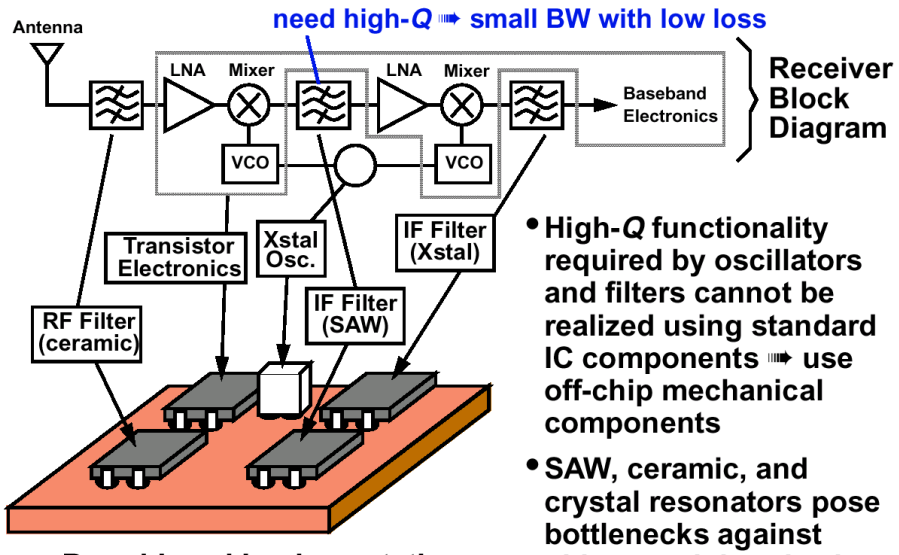
- **Dr. Dooyoung Hah**

Introduction and Background

Technology Trends of Wireless Telecommunication Systems



Miniaturization of Transceivers



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

http://www.eecs.umich.edu/~ctnguyen/mtt99.pdf

MEMS-Enabled Miniature Wireless Transceiver

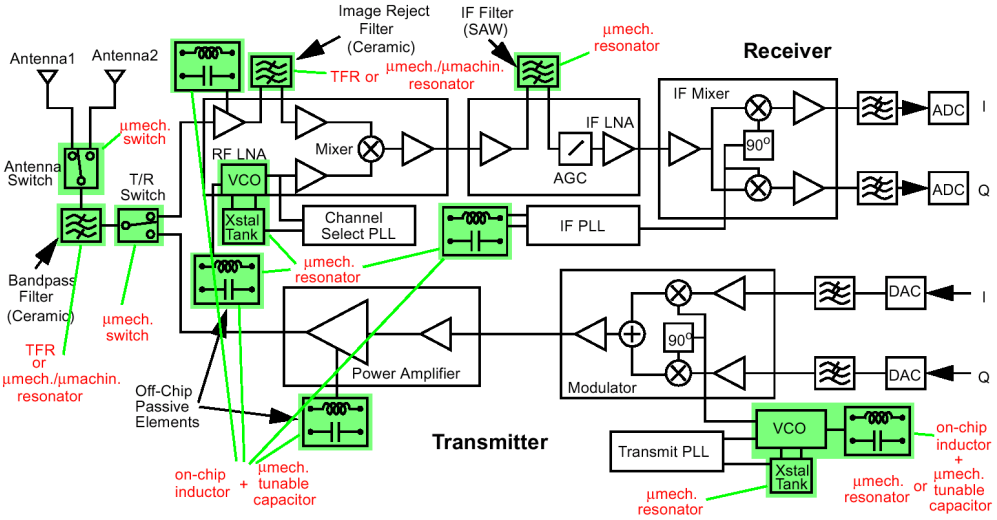
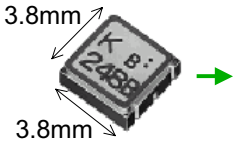


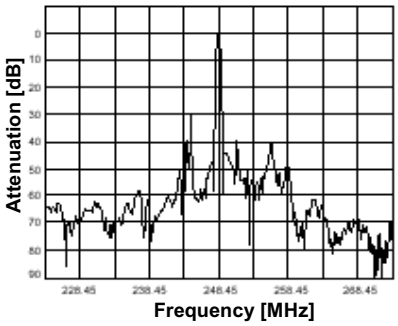
Fig. 1: System-level schematic detailing the front-end design for a typical wireless transceiver. The off-chip, high-*Q*, passive components targeted for replacement via micromechanical versions (suggestions in lighter ink) are indicated in the figure.

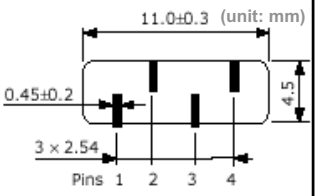
Ref: C. T.-C. Nguyen, "Micromechanical components for miniaturized low-power communications," Proceedings, 1999 IEEE MTT-S International Microwave Symposium RF MEMS Workshop June 18, 1999, pp. 48-77.

Bottlenecks in Current Microwave/MM-Wave Systems – Band Selection Filters

- **High-Q (Q ~ 1000's) filters are needed in heterodyne communication receivers for frequency selection in RF and IF bands**
- **Current solution: Off-chip surface-acoustic wave (SAW) filter**
  - **Bulky**







IF filter
f_0: 240MHz
Δf: 260kHz
Q: ~1000

RF filter
f_0: 868MHz
Δf: 600kHz
Q: ~1500

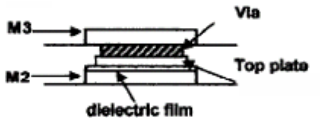
Bottlenecks in Current Microwave/MM-Wave Telecommunication Systems – Passive Elements

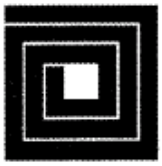
- Lack of high-Q (~ 1000) passive elements like inductors and capacitors in matching circuit or bias-Tee, etc.

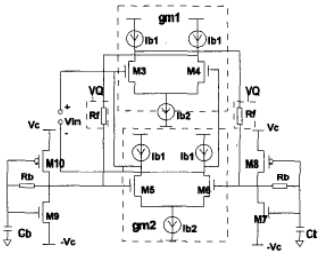
MIM Capacitor
- Low Q (< 100)

Spiral Inductor
- Low Q (~ 10)
- Low resonant frequency

Active Inductor
- Large Noise
- High Power consumption

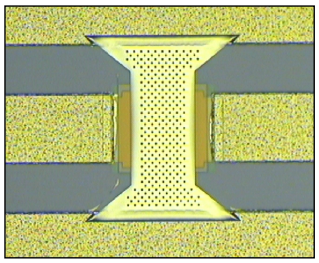




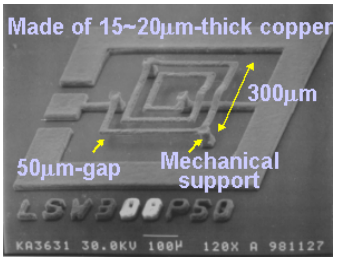


Integraable MEMS RF Components

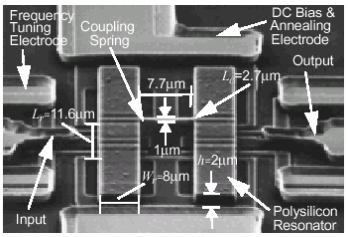
MEMS RF Switch



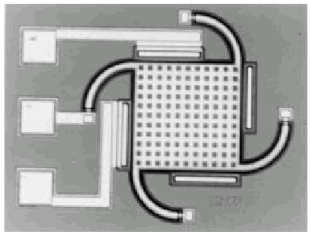
MEMS Inductor



MEMS Filter



MEMS Tunable Capacitor



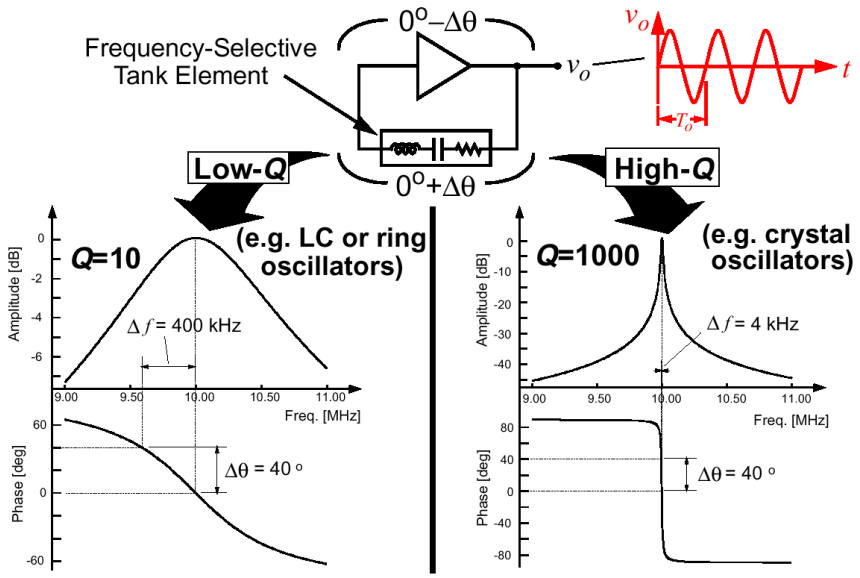
Advantages and Challenges of RF MEMS

- Advantages:
  - High-Q, Low Loss
    - Filter, Inductor, Capacitor, Switch
  - Tunability, Reconfigurability
    - Inductor, Capacitor, Switch
  - Low Power Consumption
    - Electrostatic Actuation

- Challenges
  - Actuation Speed
    - T/R Switch
  - Resonant Frequency
    - RF Filter
  - Reliability
  - Packaging

Micromechanical Resonator Oscillators

High-Q Resonators

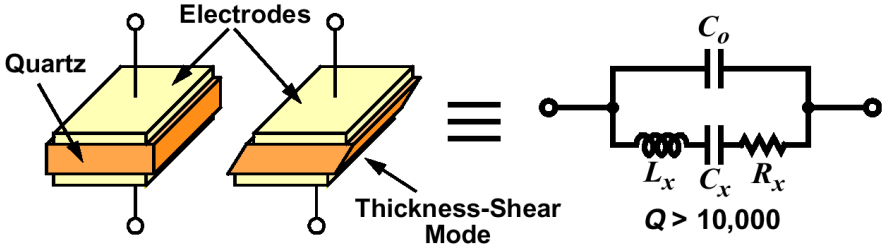


- High tank Q ➠ high frequency stability

http://www.eecs.umich.edu/~ctnguyen/mtt99.pdf

Attaining High Q

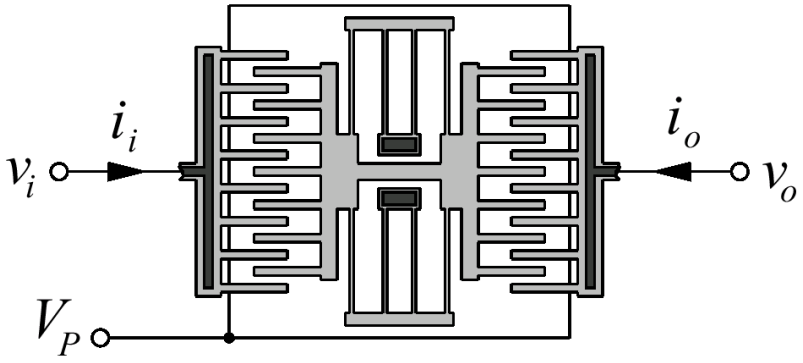
- ***Problem***: *LC* tanks cannot achieve *Q*'s in the thousands
  - — on-chip spiral inductors ➠ *Q*'s no higher than ~10
  - — off-chip inductors ➠ *Q*'s in the range of 100's
- ***Observation***: vibrating mechanical resonances ➠ $Q > 1{,}000$
- ***Example***: quartz crystal resonators
  - — extremely high *Q*'s ~ 10,000 or higher ($Q \sim 10^6$ possible)
  - — mechanically vibrates at a distinct frequency in a thickness-shear mode



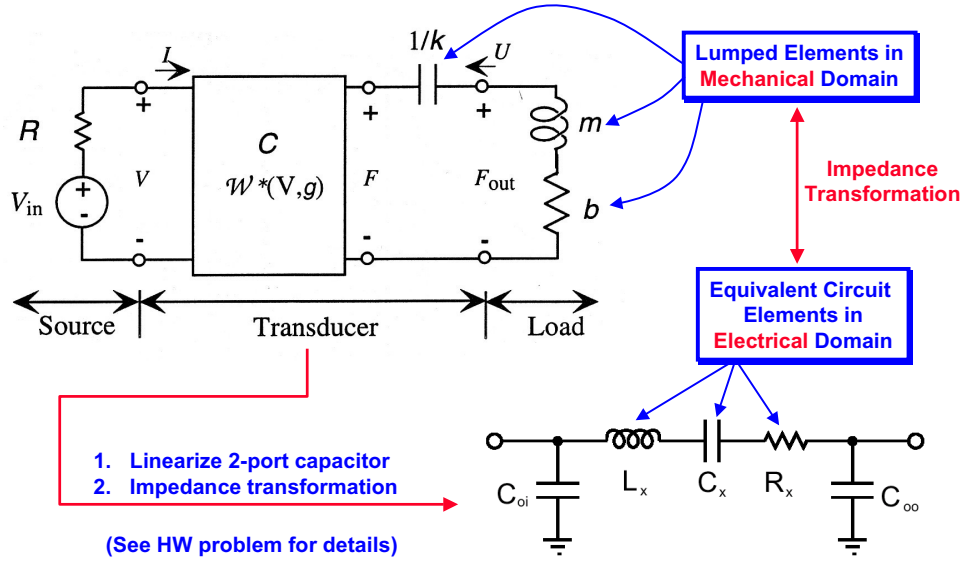
- ***Solution***: use vibrating *micro*mechanical resonators

Two-Port Micromechanical Resonator Using Comb-Drive Actuator

2-port Lateral Microresonator



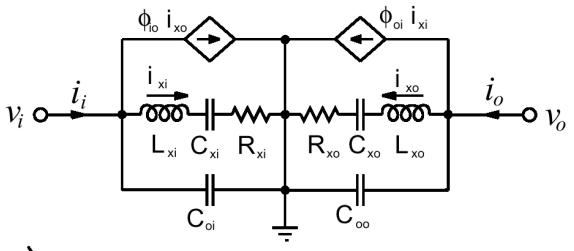
Lumped Element Model (Senturia's Book)

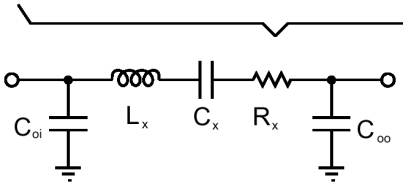


1. Linearize 2-port capacitor
2. Impedance transformation

(See HW problem for details)

Equivalent Circuit of 2-Port Resonator
(in Electrical Domain)





C_x = 0.5 fF
L_x = 200 kH
R_x = 500 kΩ
C_{oi}, C_{oo} = 15 fF

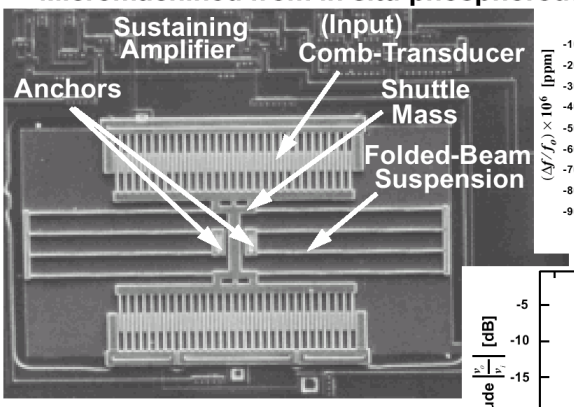
$$R_{xn} = k\left[\omega_o Q V_P^2 (\partial C/\partial x)_n^2\right]^{-1} \qquad C_{xn} = k^{-1} V_P^2 (\partial C/\partial x)_n^2$$

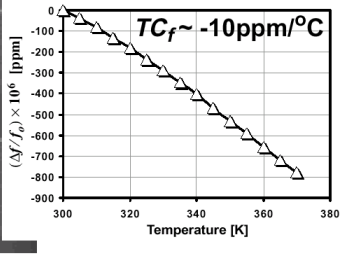
$$L_{xn} = k\left[\omega_o^2 Q V_P^2 (\partial C/\partial x)_n^2\right]^{-1} \qquad \phi_{mn} = \frac{(\partial C/\partial x)_m}{(\partial C/\partial x)_n}$$

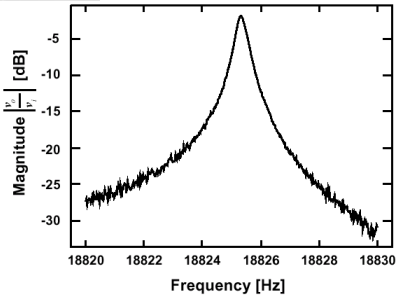
C. T.-C. Nguyen and R. T. Howe, "CMOS micromechanical resonator oscillator," *Technical Digest*, IEEE IEDM, Washington, D. C., December 5-8, 1993, pp. 199-202.

Comb-Transduced Folded-Beam Microresonator

- Micromachined from *in situ* phosphorous-doped polysilicon



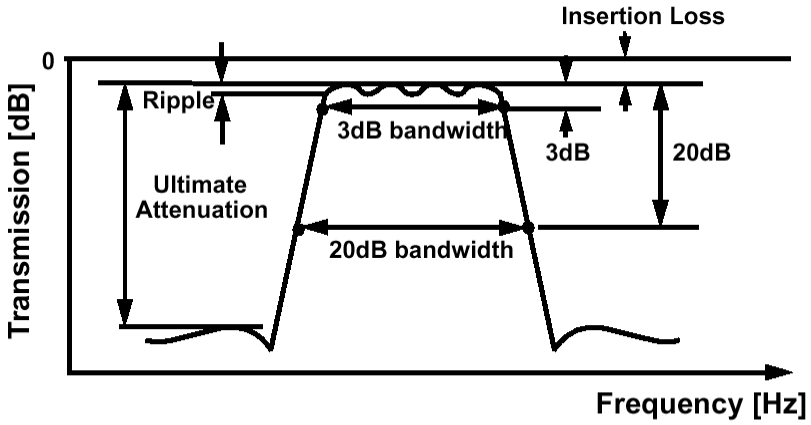




- <u>At right</u>: Q = 50,000 measured at 20 mTorr pressure
- (Q = 27 at atmospheric pressure)
- <u>Problems</u>: large mass ➠ limited to low frequencies; low coupling

Micromechanical Filters

Quality Factor and Shape Factor



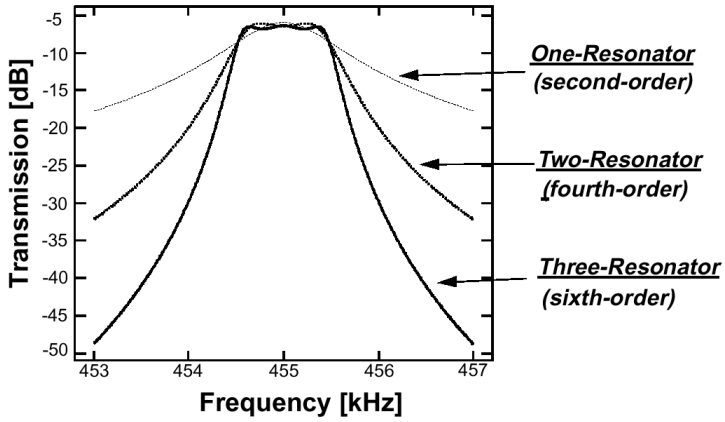
- 20 dB-down Shape Factor = $\frac{\text{20 dB-down Bandwidth}}{\text{3 dB-down Bandwidth}}$
- Small shape factor is preferred ➠ better selectivity

$$Q = \frac{f_0}{\Delta f}$$

f_0: resonant frequency
Δf: bandwidth

High-Order Resonators

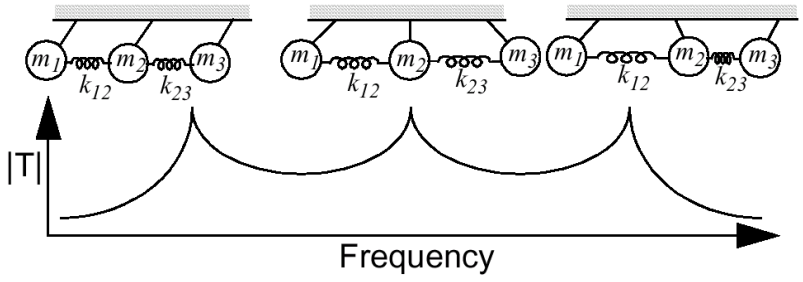
- Use more resonators to attain higher order
- Filter Order = 2 x (# of resonators)



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

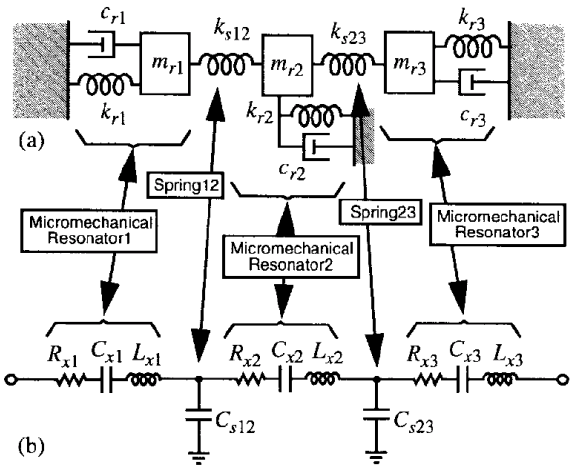
Coupled Resonator System

Mode shapes of 3-resonator micromechanical filters and their corresponding frequencies :



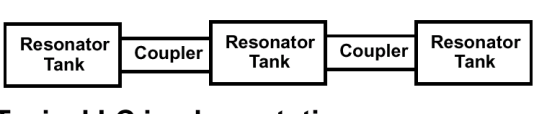
Coupling removes the degeneracy of resonant frequencies of free-running oscillators

High-Order Micromechanical Filters: Lumped Mechanical Model and Its Equivalent LCR Circuit



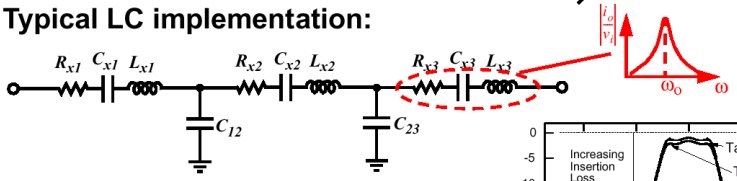
Analogies
C - k
L - m

Importance of High Q: Low Loss Filters

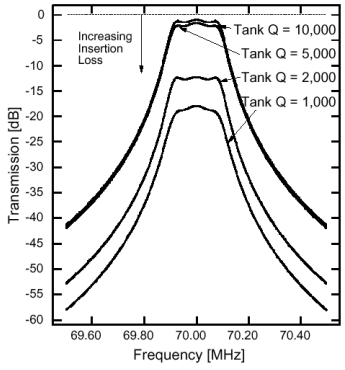


General BPF Implementation

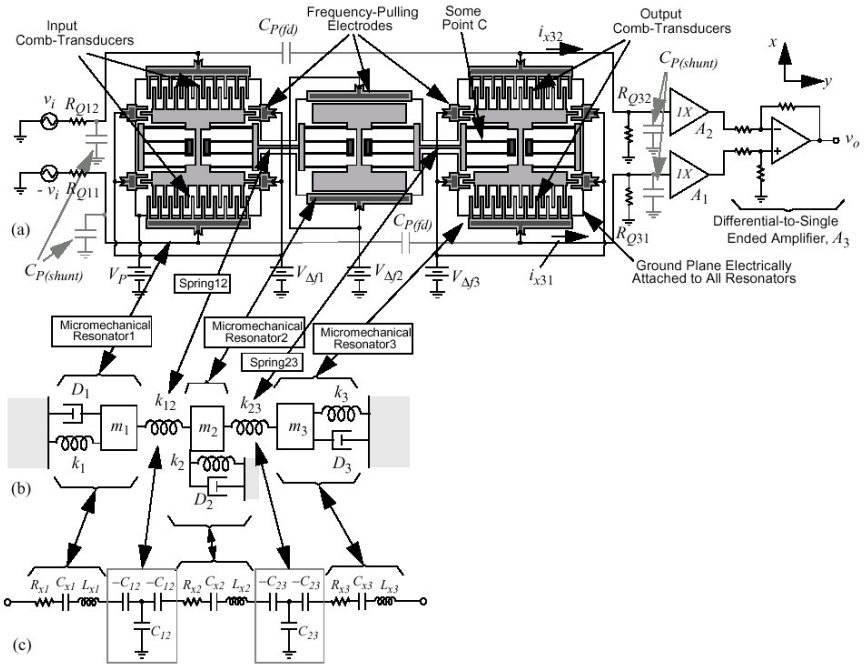
Typical LC implementation:



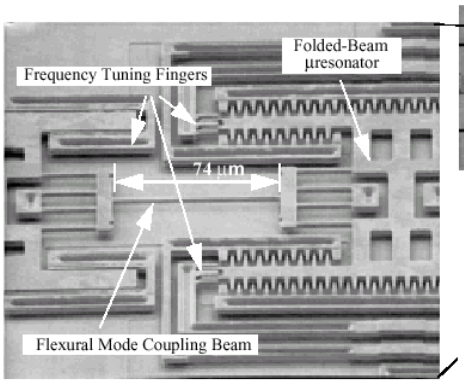
- In resonator-based filters: high tank Q ⇔ low insertion loss
- At right: a 0.3% bandwidth filter @ 70 MHz (simulated)
  — heavy insertion loss for resonator Q < 5,000

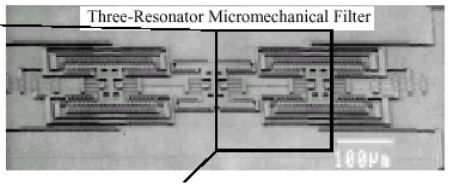


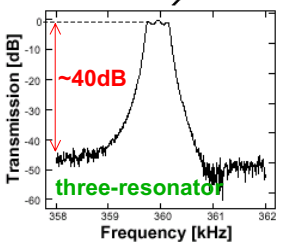
Three-Coupled-Resonator Filter



Three-Resonator Spring-Coupled Filter







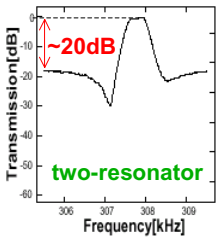
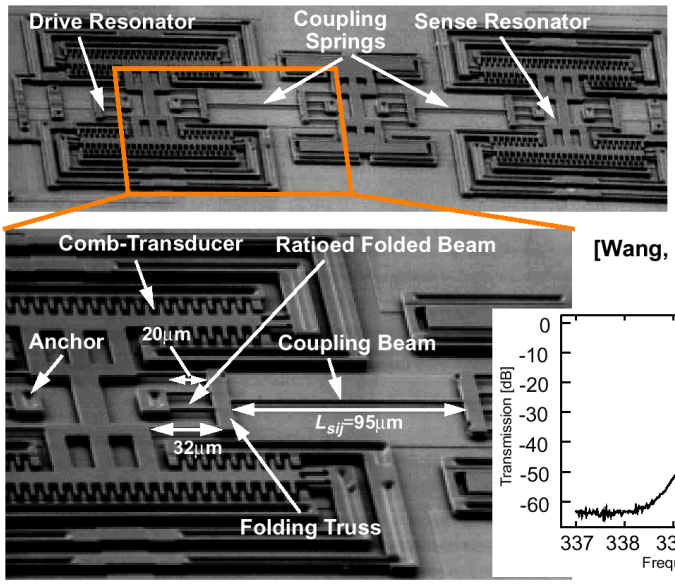
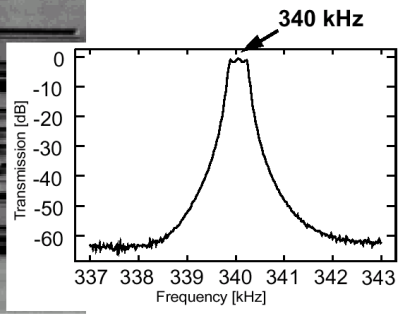


Fig. 5: SEM of a three-resonator micromechanical filter along with (a) its spectrum; and (b) the spectrum for a two-resonator filter for comparison.

High-Order Microresonator Filter



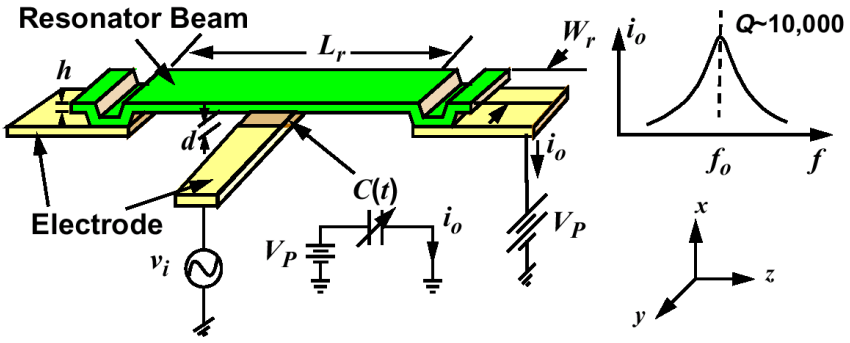
3-Resonator MF
(6th Order, 1/5-Velocity Coupled)
***f*$_o$=340kHz**
***BW*=403Hz**
***%BW*=0.09%**
***Stop.R.*=64 dB**
***I.L.*<0.6 dB**
[Wang, Nguyen 1997]



High Frequency Resonators

Vertically Driven Micromechanical Resonator

- To date, most used design to achieve VHF frequencies



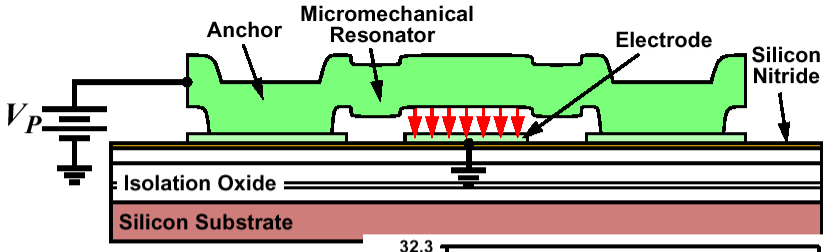
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}} = 1.03\sqrt{\frac{E}{\rho}}\frac{h}{L_r^2}$$

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

E = Youngs Modulus
ρ=density

- Smaller mass ➠ higher frequency range and lower series R_x

Electronic Tuning of Center Frequency



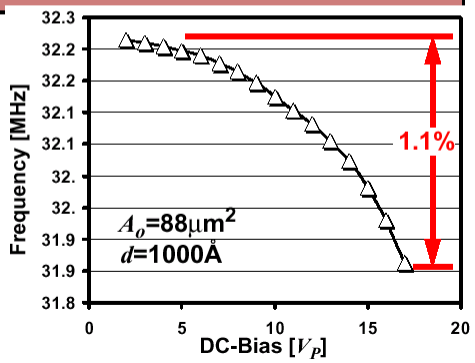
- Quadrature force ➠ voltage-controllable electrical stiffness:

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

Electrode Overlap Area

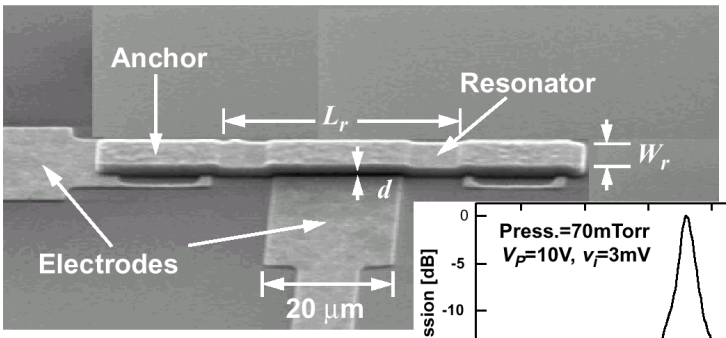
Finger Gap

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



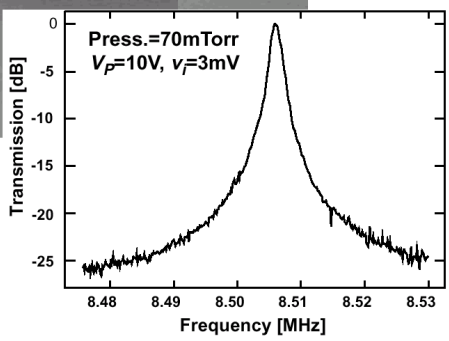
Experimental Vertically Driven Resonator

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

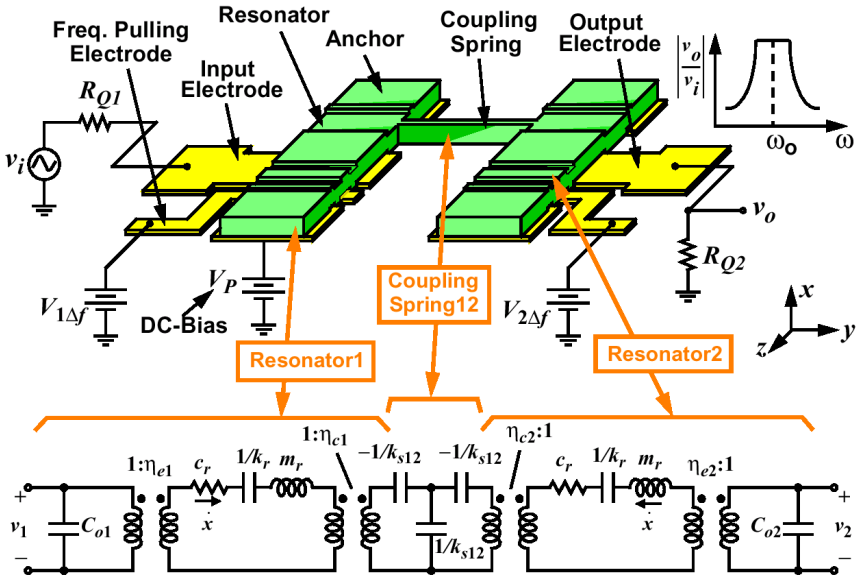


L_r=40.8 μm, W_r=8 μm,
h=2 μm, d=0.1μm

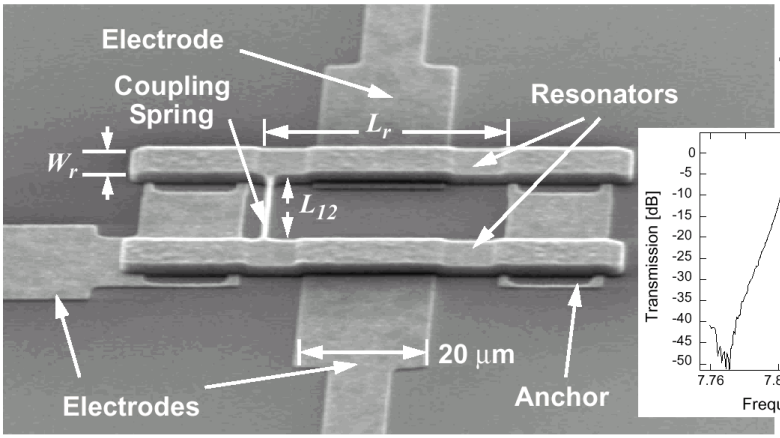
- Extracted Q = 8,000 (vacuum)
- Freq. influenced by dc-bias and anchor effects



Coupled Vertically Driven Resonators



Two Coupled Vertically Driven Resonator



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

Performance

f_o=7.81MHz, *BW*=15kHz

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

Scaling of Resonant Frequency and Q

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}} = 1.03\sqrt{\frac{E}{\rho}}\frac{h}{L_r^2}$$

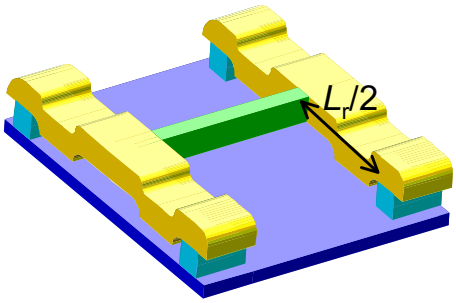
$$Q = \frac{f_0}{\Delta f} = \frac{k_r k_{12}}{k_{s12}}$$

k_r: spring constant of resonator
m_r: resonator mass
E: Young's modulus
ρ: density

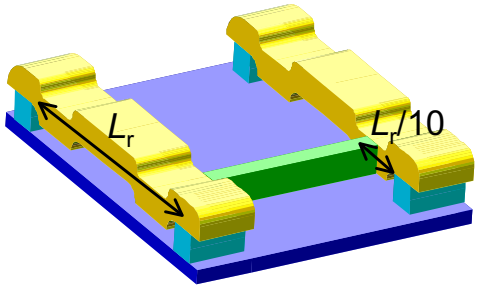
k_{s12}: coupling beam spring constant
k_{12}: normalized coupling coefficient for a given filter type (Chebyshev,…)

Position of Coupling Spring

- Coupling spring and resonators are of similar size
  - Low Q
- Dynamic spring constant k_r of a clamped-clamped beam is larger at locations closer to the anchor points
  - Low velocity point
  - Q can be increased

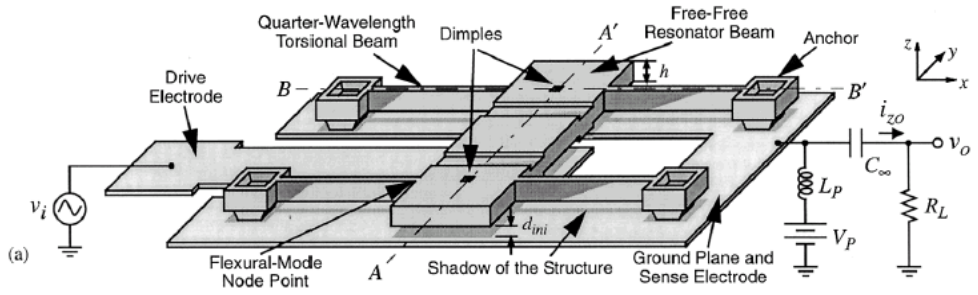


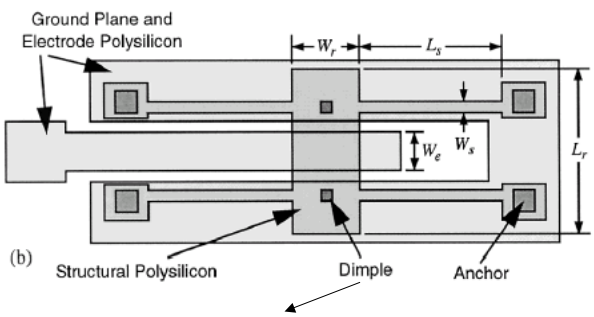
Q=24



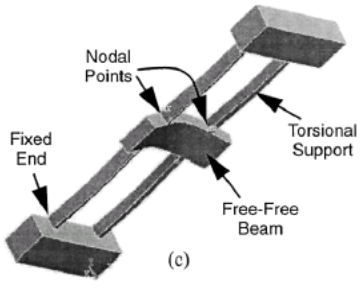
Q=341

VHF Free-Free Beam High-Q Micromechanical Resonator



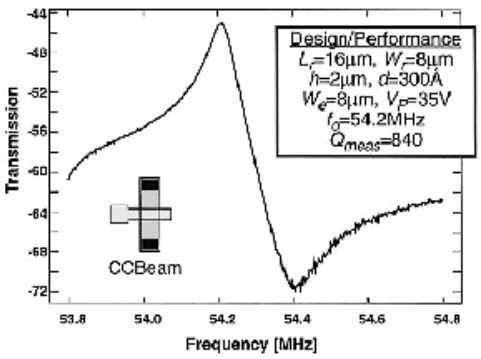


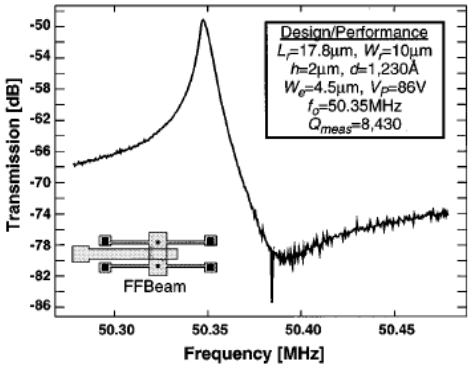
(determined the gap)



J. MEMS, Vol. 9, No. 3, 2000, C. T. –C. Nguyen, et al.

Comparison of Frequency Characteristics





Clamped-clamped beam
- L_r=16 μm, d=0.03 μm
- V_p=35 V, f_0=54.2 MHz
- Q=840

Free-free beam
- L_r=17.8 μm, d=0.12 μm
- V_p=86 V, f_0=50.35 MHz
- Q=8,430

New Development in GHz Micromechanical Resonators

Scaling of Lateral Micromechanical Resonators

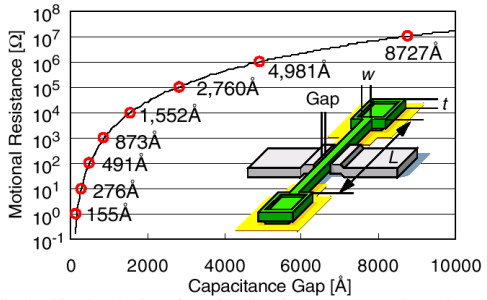


Fig. 1: Simulated plot of motional resistance versus electrode-to-resonator gap for a 40µm-long, 2µm-wide, 3µm-thick, lateral clamped-clamped beam µmechanical resonator.

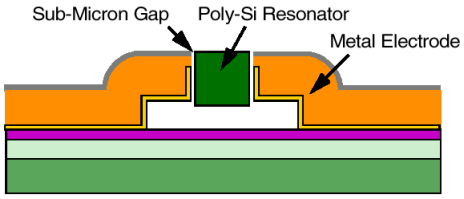
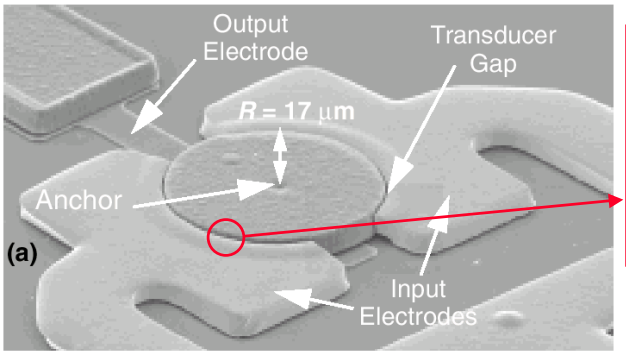


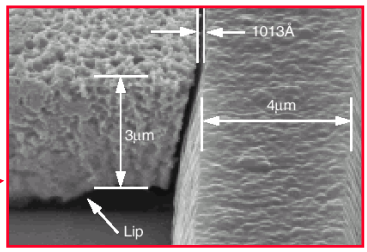
Fig. 2: Cross-section of the described sub-µm electrode-to-resonator gap process for lateral µstructures with metal electrodes.

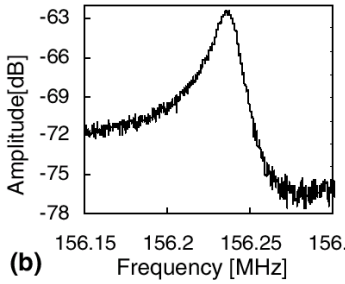
- **Advantages of lateral resonator**
  - **Wider variety of resonant modes**
  - **Balanced resonators (push-pull)**
  - **More design flexibility**
- **As frequency scales up**
  - **Resonator size shrinks**
  - **Capacitive transducer gaps must also shrink (to sub-100 nm for VHF)**
  - **High aspect ratio structures**
- **Combine Poly-Si (high-Q structural materials) with metal electrode (high conductivity)**
  - **Self-aligned process**

Hsu, Clark, Nguyen, "A sub-micron capacitive gap process for multiple-metal-electrode lateral micromechanical resonators," MEMS 2001, p. 349

Radial Contour-Mode Disk µ-mechanical Resonator







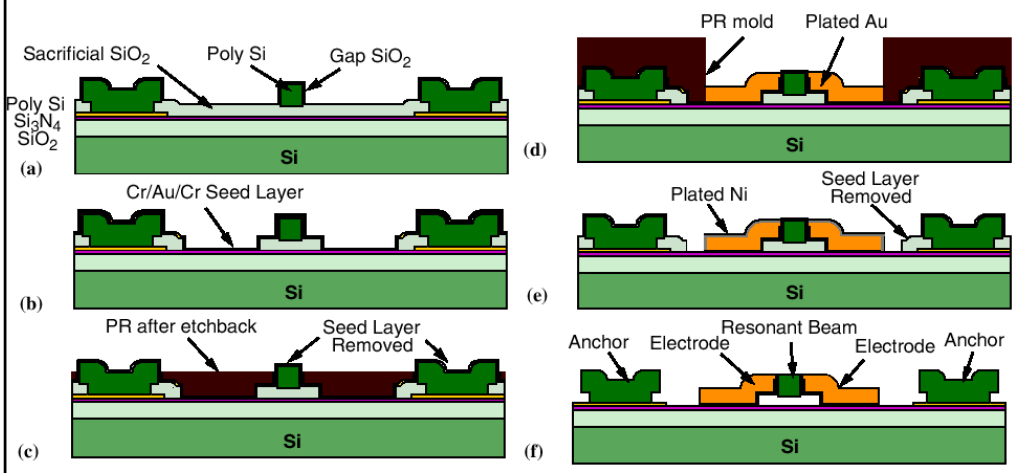
Data:
R=17µm, h=2µm
d=1,000Å, V_P=35V
f_o=156.23MHz, Q=9,400

Fig. 5: SEM and measured frequency characteristic for a 156.23 MHz contour-mode disk µmechanical resonator fabricated via the process of Fig. 3.

- **Radial contour mode allows high resonant frequency without requiring sub-micron structures**
- **Place anchor at disk center – nodal point of contour mode**
  Reduce mechanic loss and increase Q

Hsu, Clark, Nguyen, "A sub-micron capacitive gap process for multiple-metal-electrode lateral micromechanical resonators," MEMS 2001, p. 349

Process Flow for Lateral Resonator with Sub-Micron Gap



Hsu, Clark, Nguyen, "A sub-micron capacitive gap process for multiple-metal-electrode lateral micromechanical resonators," MEMS 2001, p. 349