INF5490 RF MEMS

L17: Summary, repetition

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Overview

- Motivation
- Micromachining
- Modeling
- Specific features for RF systems
- Q-factor
- RF MEMS components
  - Switches
  - Phase shifters
  - Resonators
  - Micromechanical filters
  - Capacitors
  - Inductors
- Integration and packaging
- RF MEMS in wireless systems
- Conclusion and future prospects

Choice of focus → RF MEMS

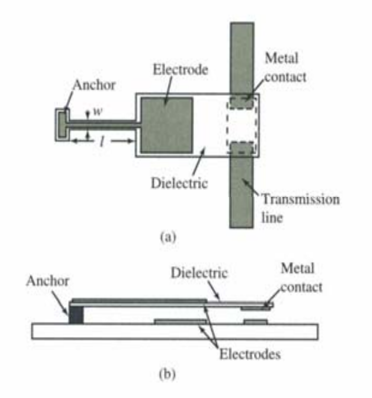
- MEMS is a *broad* field of research
  - Need of focus in NANO group → RF MEMS!

- ***”RF MEMS refers to the design and fabrication of dedicated MEMS for RF (integrated) circuits”***
  - 1a) Components **operate** micromechanical
    and/or
  - 1b) Components **fabricated** using micromachining

  - 2) Components are used in **RF systems**

Typical RF MEMS components

- Switches
- Variable capacitors
- Inductors
- Resonators
- Micromechanical filters
- Phase shifters



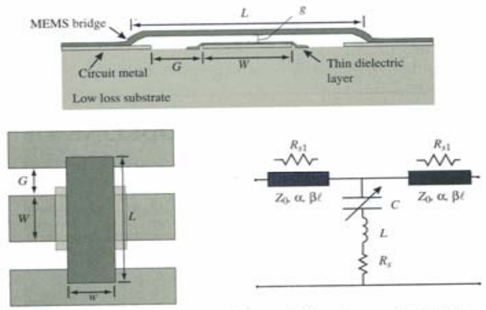
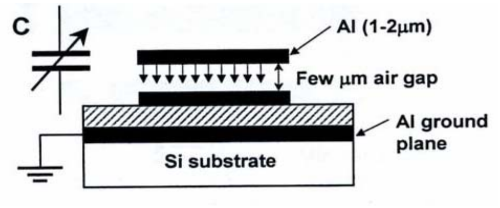
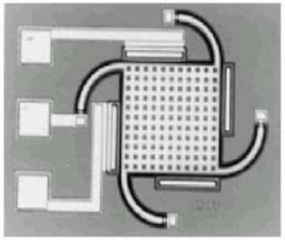
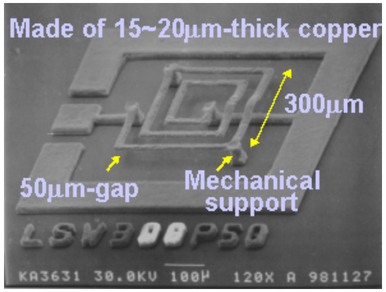


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).







Typical RF MEMS components

- Switches
- Variable capacitors
- Inductors
- Resonators
- Micromechanical filters
- Phase shifters

- **Focus on real vibrating structures →**
  - May be used to implement
    - oscillators
    - filters
    - ”mixer with filter”

Benefits of RF MEMS

- Higher **performance**
  - Increased selectivity: sharp filters
  - Increased Q-factor: stable ”tank” frequency
  - Reduced loss
  - Higher isolation, reduced cross talk
  - Reduced signal distortion
  - Larger bandwidth
- Lower **power consumption**
- **Reduced cost**
  - Batch processing
- Circuit and system **miniaturization**
  - System integration (μelectronics + MEMS)
    - Packaging: Multi-chip module
    - Monolithic integration: SoC (System-on-Chip)

Micromachining

- Micromachining, definition:
  - *Accurately, to **define** and **implement** any microscopic mechanical structure **out of** or **on** a material*

- **Silicon micromachining is mature**
  - Si processes also used by IC industry
    - ”grown out of” IC-processing
  - New specific MEMS processes also developed
    - A lot of variants, - **few standards!**

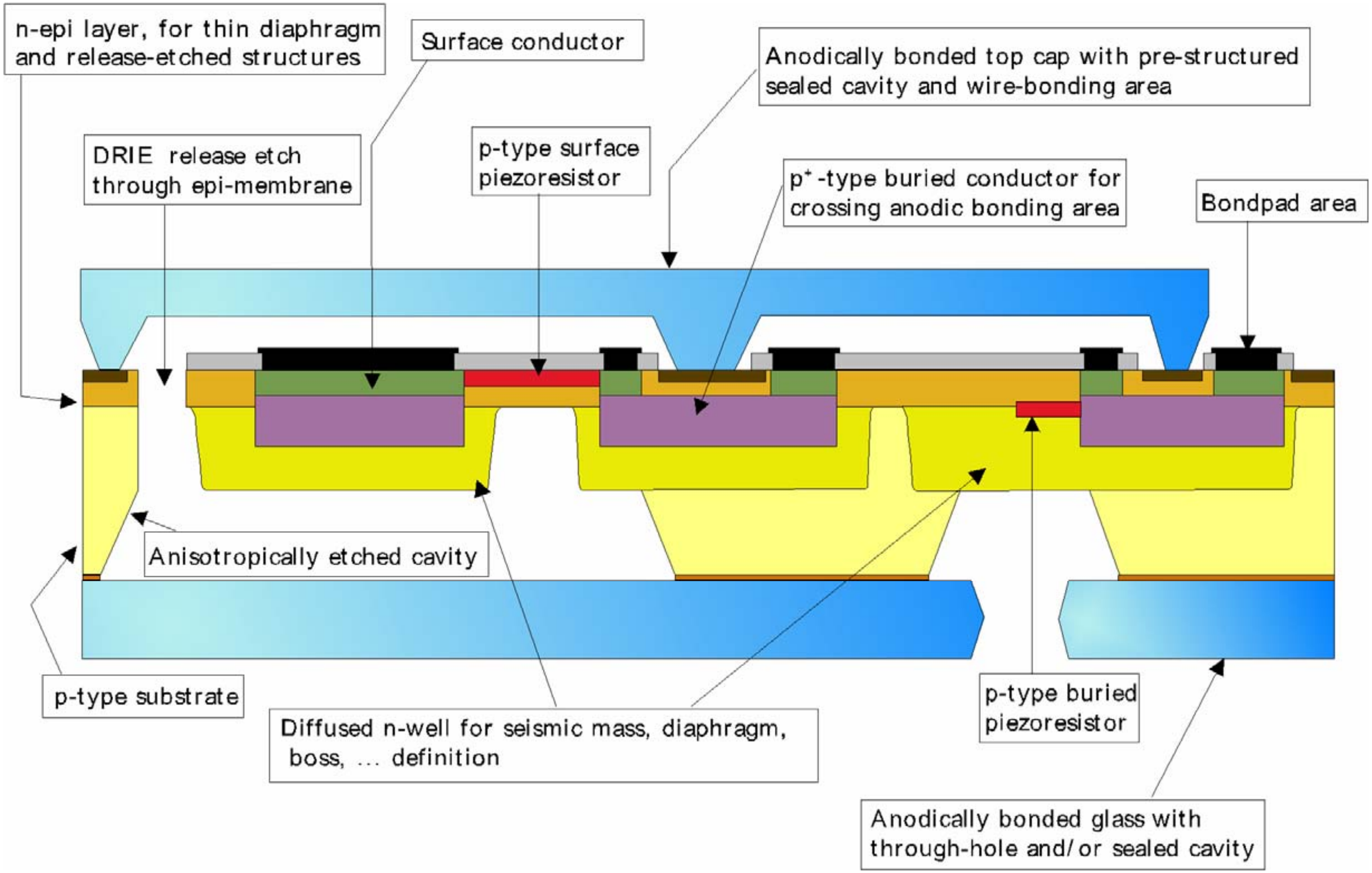
Important process steps

- Define patterns
  - ***Photolithography***
- Modify semiconductor material properties
  - ***Diffusion***
- Remove material
  - ***Ething***
- Adding material – build structures
  - ***Deposition***

Bulk micromachining

- Selective etching and diffusion into well defined areas **of a substrate**
  - Etching of the substrate → membranes
  - Etching from back side (wet etching: liquid is used)
  - Possibly combined with dry etching on the front side
- More mature than surface micromachining
- Typical examples
  - Pressure sensor, accelerometer
- ”Wafer-bonding” may be necessary
  - Interconnect whole wafers

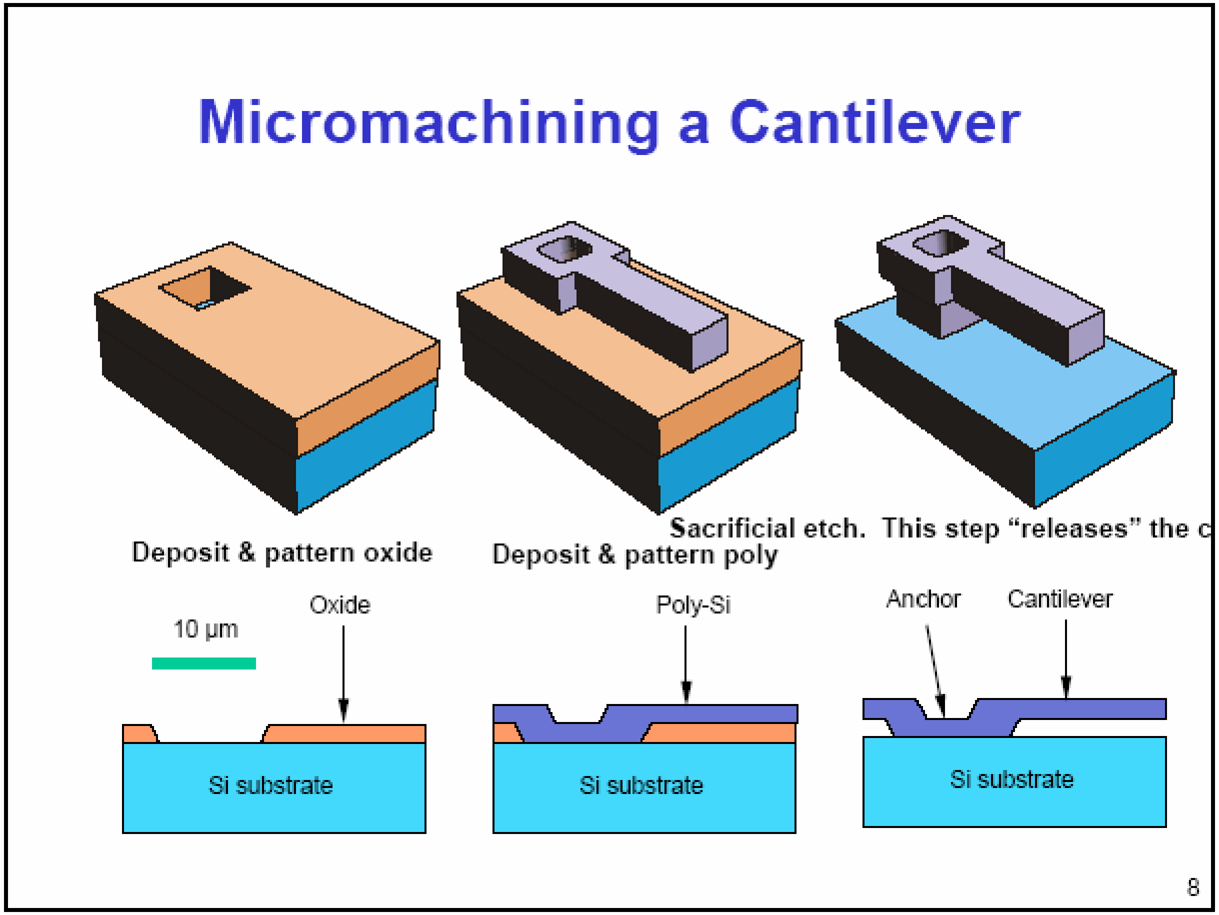
Cross section overview



Surface micromachining

- **”Surface”** micromachining
  - Deposit layers
    - **Structural layer**
    - **Sacrificial layer** = ”distance-keeping” layer

  - Selective etching of structural layers
  - Removing sacrificial layers



Micromachining a Cantilever

Deposit & pattern oxide

Deposit & pattern poly

Sacrificial etch. This step “releases” the c

Additive process steps

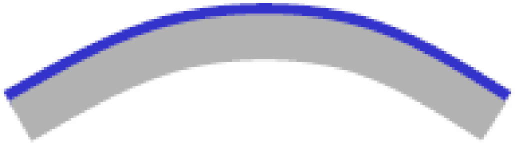
- Techniques
  - a. Epitaxial growth
  - b. Oxidation
  - c. Vaporization
  - d. CVD, Chemical Vapor Deposition
  - e. Sputtering
  - f. Moulding

- When depositing, stress may be built into the structures

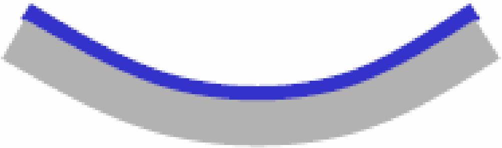
Residual Stress in Thin Films

- Residual film stress
  - Microstructure
  - Thermal mismatch

- Compressive vs. tensile stress



Under compressive stress, film wants to expand. Constrained to substrate, bends it in convex way.



Under tensile stress, film wants to shrink Constrained to substrate, bends it in concave way.

Srinivasan

Removing material: Etching

- Wet-etching or dry-etching
- **Wet-etching**
  - Deep etching of Si is essential in micromachining
  - Using liquids
  - Depends of:
    - Concentration of liquid, time, temperature
  - Low cost batch processing
  - Both **isotropic** or **anisotropic**

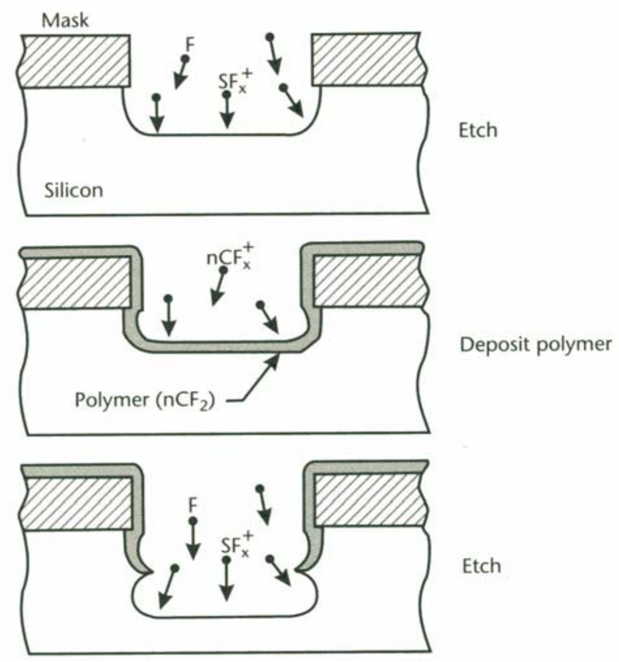
Wet-etching

- **Isotropic** = uniform etching in all directions
  - HF or blends are usual
  - 0.1 – 100 µm/min etch speed

- **Anisotropic** = etching faster along some directions
  - Etch speed depends of **crystal orientation**
  - NaOH, KOH used
  - Silicon nitride used as mask for **KOH**

RIE - DRIE

- **DRIE** – Deep Reactive Ion Etching (1995-)
  - – Vertical etching
  - – Can etch deep holes (> 500 µm) with almost perfect vertical sidewalls
  - – Bosch-process
    - Figure →
    - High ”aspect-ratio”
    - Etching and deposition every second step
      - – etch: SF6, mostly at the bottom!
      - – deposit: C4F8, polymer



Transducers for (RF) MEMS

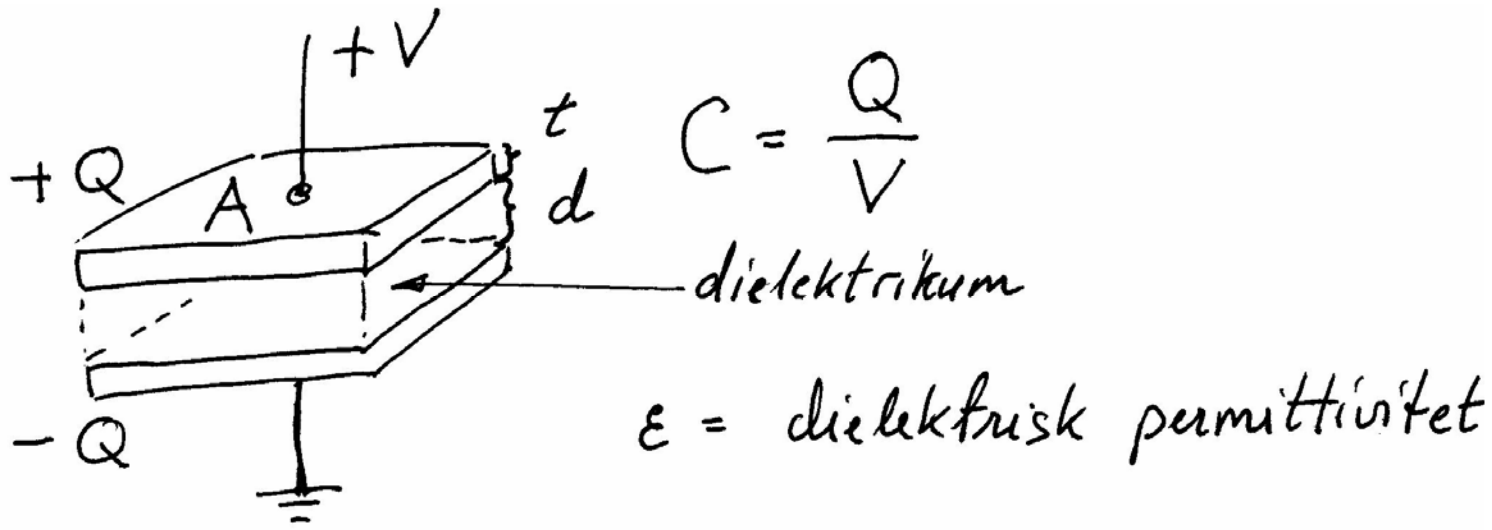
- **Electromechanical transducers**
  - Transforming
    electrical energy ←→ mechanical energy

- Transducer principles
  - Electrostatic
  - Electromagnetic
  - Electro thermal
  - Piezoelectric

Methods for modeling RF MEMS

- **1. Simple mathematical models**
  - Ex. parallel plate capacitor
- **2. Converting to electrical equivalents**
- **3. Analysis using Finite Element Methods**

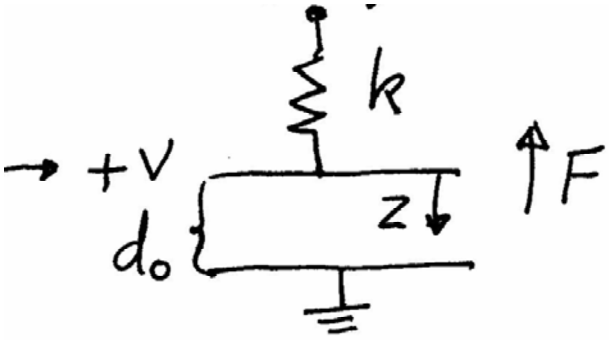
Parallel plate capacitor



Attractive force between plates

$$F = -\frac{\partial U}{\partial d} = -\frac{\partial}{\partial d}\left(\frac{\varepsilon A}{2d}V^2\right) = \frac{\varepsilon A V^2}{2d^2}$$

Force balance



k = spring constant

$$F_{spring} = k \cdot x$$

deflection from start position

d0 = gap at 0V and zero spring strain
d = d0 – z
z=d0 – d

Force on upper plate at V and d:

$$F_{net} = -\frac{\varepsilon A V^2}{2 d^2} + k\,(d_o - d)$$

= 0 at equilibrium

Two equilibrium positions

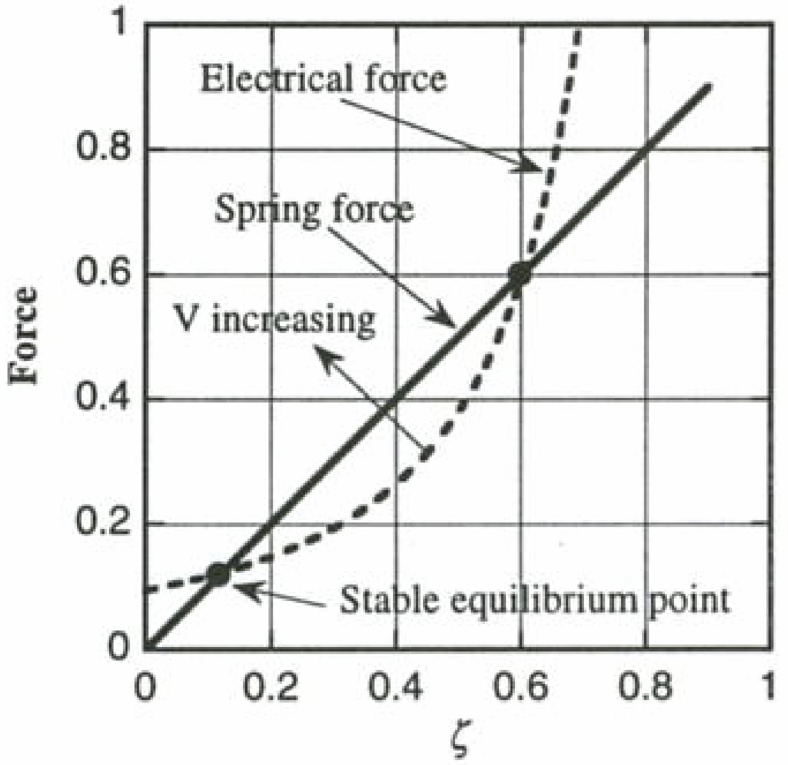


Figure 6.7. Electrical and spring forces for the voltage-controlled parallel-plate electrostatic actuator, plotted for $V/V_{PI} = 0.8$.

$\varsigma = 1 - d/d0$

Senturia

Pull-in

$$F_{net} = 0$$

$$\frac{\varepsilon A V_{PI}^2}{2 d_{PI}^2} = k\left(d_0 - d_{PI}\right)$$

$$\uparrow$$

$$= \frac{\varepsilon A V_{PI}^2}{d_{PI}^3}$$

Pull-in when:

$$d_{PI} = \frac{2}{3} d_0$$

$$\boxed{V_{PI} = \sqrt{\frac{8 k d_0^3}{27 \varepsilon A}}}$$

2. Converting to electrical equivalents

- Mechanical behavior can be modeled using **electrical circuit elements**
  - Mechanical structure → simplifications → equivalent electrical circuit
    - ex. spring/mass → R, C, L
  - Possible to “interconnect” electrical and mechanical energy domains
    - Simplified modeling and co-simulation of electronic and mechanical parts of the system
  - Proper **analysis-tools** can be used
    - Ex. SPICE

e → V - convention

- **Senturia** and **Tilmans** use the

  e→V –convention
- Ex. electrical and mechanical circuits
  - e → V (voltage) equivalent to F (force)
  - f → I (current) equivalent to v (velocity)
  - q→ Q (charge) equivalent to x (position)
  - e * f = ”power” injected into the element

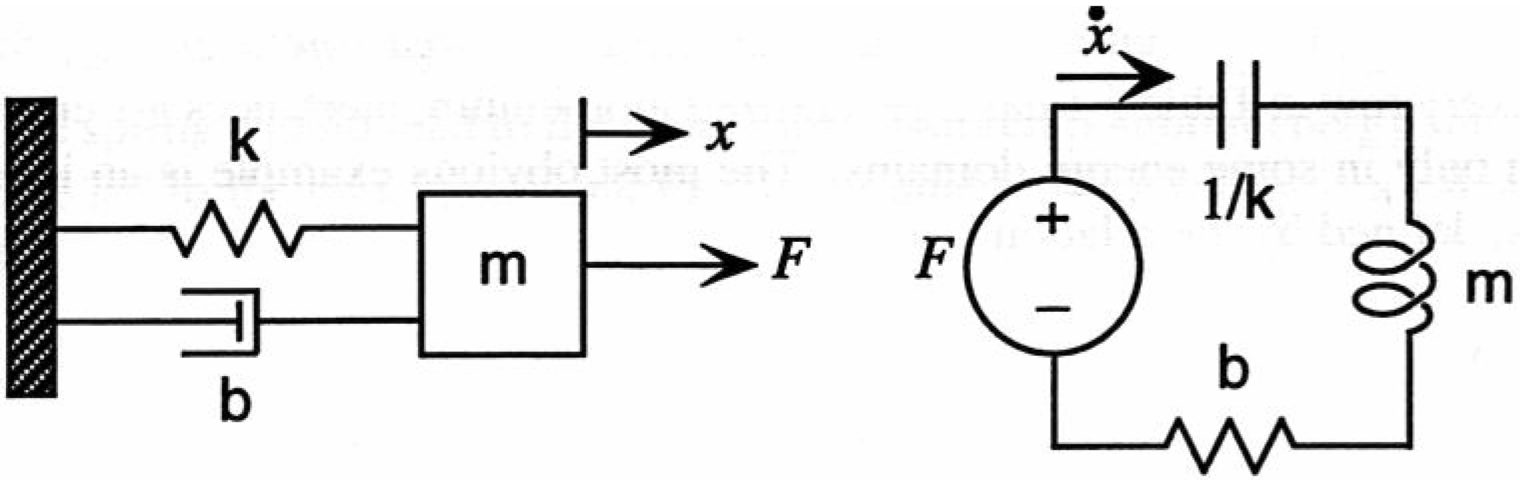
H. Tilmans, Equivalent circuit representation of electromagnetical transducers:
I. Lumped-parameter systems, J. Micromech. Microeng., Vol. 6, pp 157-176, 1996

Interconnecting elements

- e → V follows two basic principles
  - Elements that share a common flow , and hence a common variation of displacement, are connected in **series**
  - Elements that share a common effort are connected in **parallel**

Ex. of interconnection:

”Direct transformation”

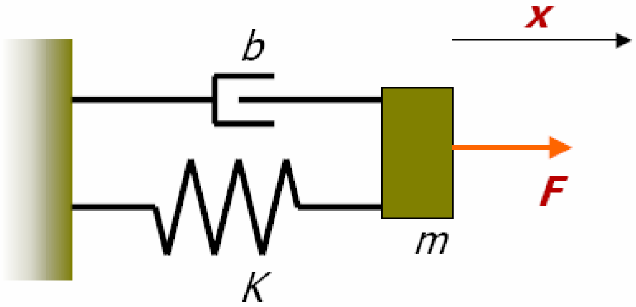


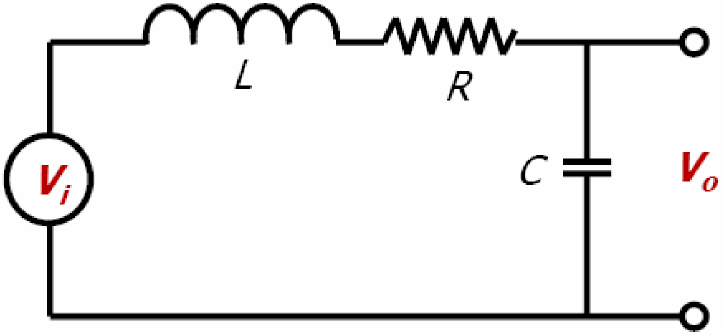
Spring-mass-dashpot system

Equivalent circuit

Figure 5.9. Translating mechanical to electrical representations.

Mechanical / Electrical Systems





Input : external force F

Output : displacement x

$$m\ddot{x}(t) + b\dot{x}(t) + Kx(t) = F$$

m mass, b damping, K stiffness

Transfer function :

$$H(s) = \frac{x}{F} = \frac{\frac{1}{m}}{s^2 + \frac{b}{m}s + \frac{K}{m}}$$

Input : voltage V_i

Output : voltage V_o

$$L\ddot{q}(t) + R\dot{q}(t) + \frac{1}{C}q(t) = V_i$$

L induct., R resist., C capacit.

Transfer function :

$$H(s) = \frac{V_o}{V_i} = \frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

Resonators

- Analogy between mechanical and electrical system:
  - Mass *m* - inductivity *L*
  - Spring *K* - capacitance *C*
  - Damping *b* - resistance *R* (depending where *R* is placed in circuit)

- Solution to 2nd order differential equation:

$$H(s) = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$

$$\omega_0 = 2\pi f_0 \quad \text{natural frequency}$$

$$\omega_0 = \sqrt{\frac{K}{m}} \ \text{mechanical system,} \quad \omega_0 = \sqrt{\frac{1}{LC}} \ \text{electrical system}$$

$$Q \quad \text{quality factor}$$

Frequency and wavelength

- In vacuum: $\lambda * f = c$
  - Increasing frequency → decreasing wavelength

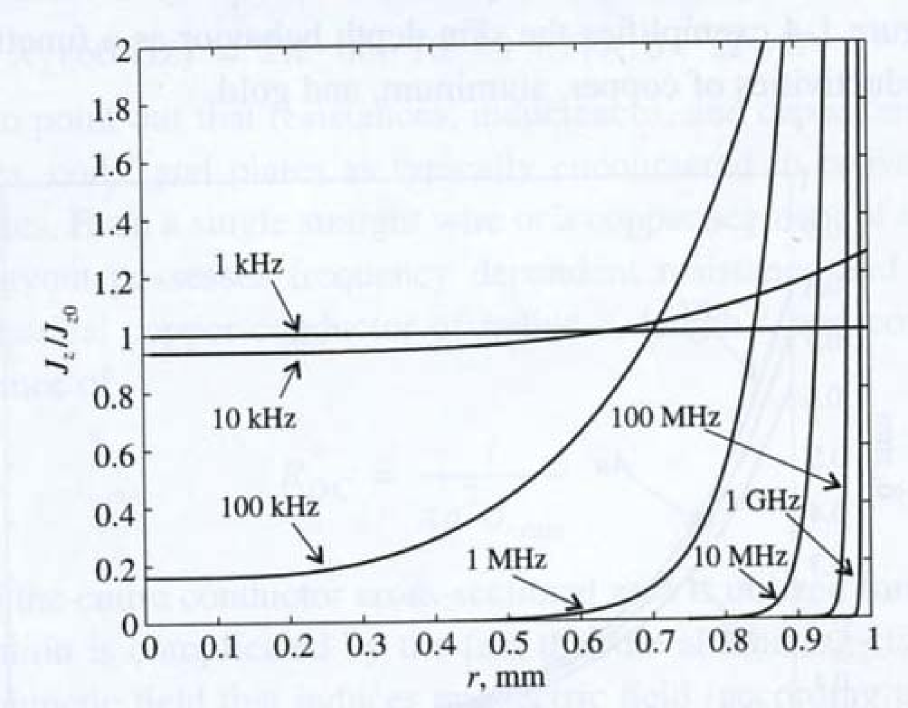
- At high frequencies (RF) is the wavelength comparable to the circuit dimensions

Skin depth

- Resistance R increases towards centre of conductor
  - Current close to **surface** at increasing frequency
  - Formula: ”skin-depth” →
    - Current density reduced by a factor 1/e

$$\delta = (\pi f \mu \sigma_{\text{cond}})^{-1/2}$$

- What does this mean for practical designs?



Transmission line

- A conductor has to be modeled as a transmission line

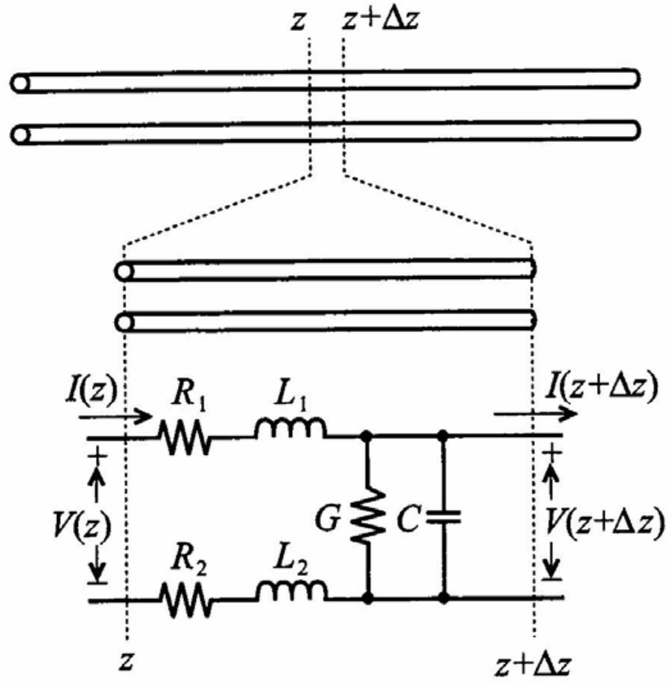


Figure 2-3 Partitioning an electric line into small elements Δz over which Kirchhoff's laws of constant voltage and current can be applied.

Solution: 2 waves

- The solution is waves in a **positive** and **negative** direction

$$V(z) = V^+ e^{-kz} + V^- e^{+kz} \tag{2.34}$$

$$I(z) = I^+ e^{-kz} + I^- e^{+kz} \tag{2.35}$$

$$I(z) = \frac{k}{(R + j\omega L)}(V^+ e^{-kz} - V^- e^{+kz}) \qquad (2.36) \qquad \text{(Jmfr.2.27)}$$

Characteristic line-impedance: $Z_0 = \frac{V^+}{I^+} = -\frac{V^-}{I^-}$

$$\boxed{Z_0 = \frac{(R + j\omega L)}{k} = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}} \tag{2.37}$$

Impedance for lossless transmission line

$$Z_0 = \sqrt{L/C}$$

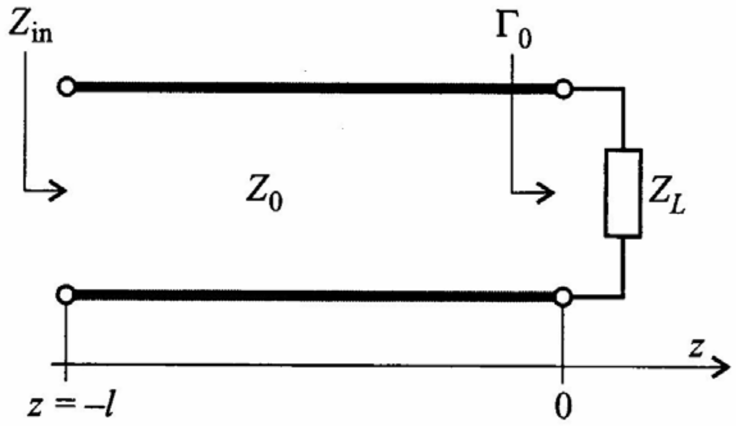


Figure 2-23 Terminated transmission line at location $z = 0$.

How to avoid reflections and have good signal propagation?

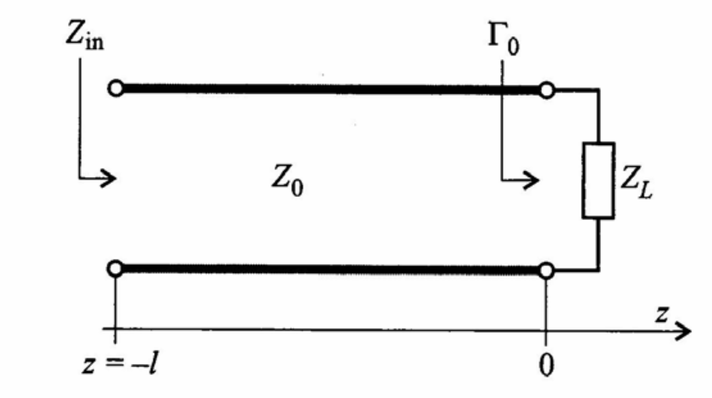
Reflection coefficient

$$\Gamma_0 = \frac{V^-}{V^+}$$

← definition of reflection coefficient for z = 0

$$V(z) = V^+(e^{-kz} + \Gamma_0 \cdot e^{+kz})$$

$$I(z) = \frac{V^+}{Z_0}(e^{-kz} - \Gamma_0 \cdot e^{+kz})$$



Impedance for z = 0:

$$Z(0) = \frac{V(0)}{I(0)} = Z_0 \frac{1+\Gamma_0}{1-\Gamma_0} = Z_L$$

= load impedance

$$\boxed{\Gamma_0 = \frac{Z_L - Z_0}{Z_L + Z_0}}$$

Various terminations

$$\Gamma_0 = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Open line

→ reflection with equal polarity

$$Z_L = \infty \Rightarrow \Gamma_0 = 1$$

Short circuit

→ Reflection with inverse polarity

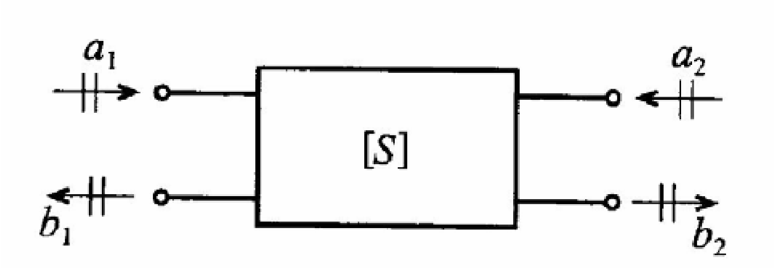
$$Z_L = 0 \Rightarrow \Gamma_0 = -1$$

No reflection when:

$$Z_0 = Z_L \Rightarrow \Gamma_0 = 0$$

→ **”MATCHING”**

Interpretation of S-parameters



$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0} \equiv \frac{\text{reflected power wave at port 1}}{\text{incident power wave at port 1}} \tag{4.42a}$$

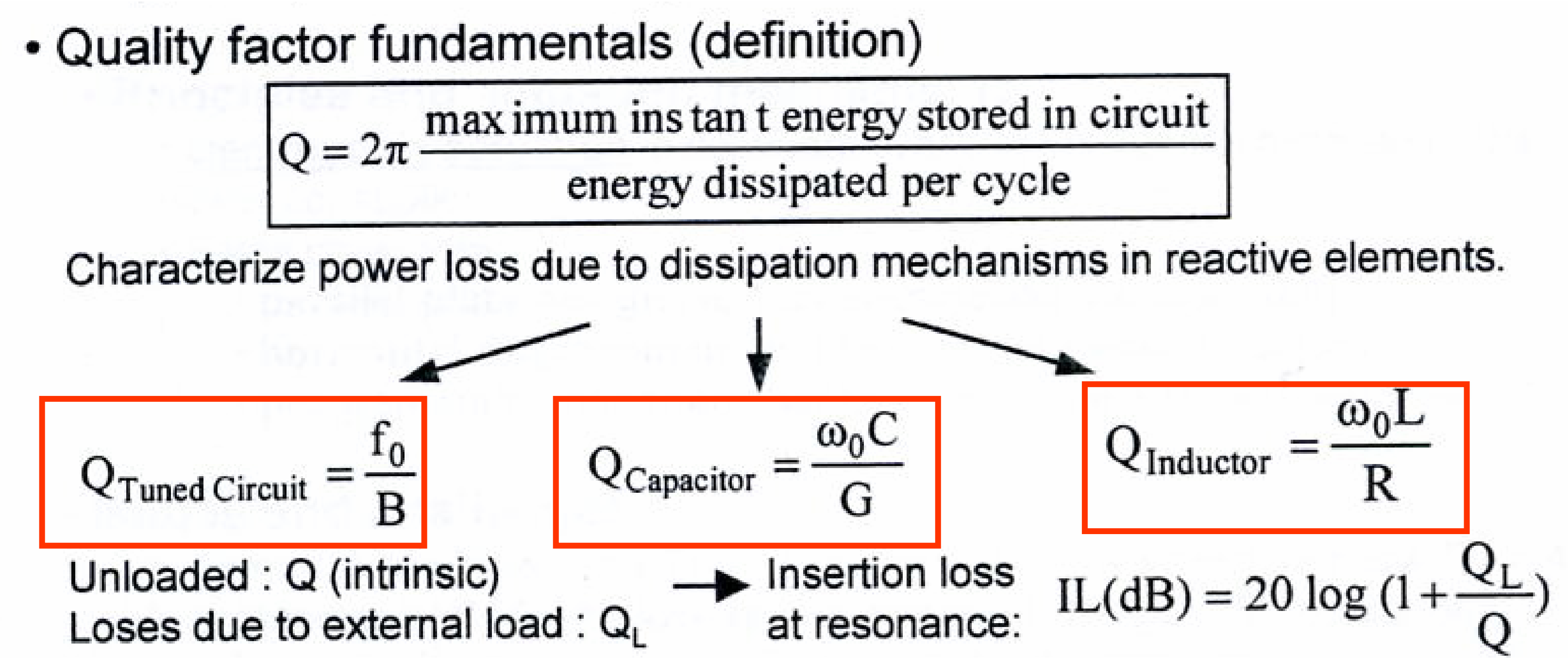
$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0} \equiv \frac{\text{transmitted power wave at port 2}}{\text{incident power wave at port 1}} \tag{4.42b}$$

$$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0} \equiv \frac{\text{reflected power wave at port 2}}{\text{incident power wave at port 2}} \tag{4.42c}$$

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0} \equiv \frac{\text{transmitted power wave at port 1}}{\text{incident power wave at port 2}} \tag{4.42d}$$

Q-value

- Q-factor characterizes loss due to power dissipation in elements
- Q should be as high as possible to reduce Insertion loss



- Quality factor fundamentals (definition)

$$\boxed{Q = 2\pi \frac{\text{maximum instant energy stored in circuit}}{\text{energy dissipated per cycle}}}$$

Characterize power loss due to dissipation mechanisms in reactive elements.

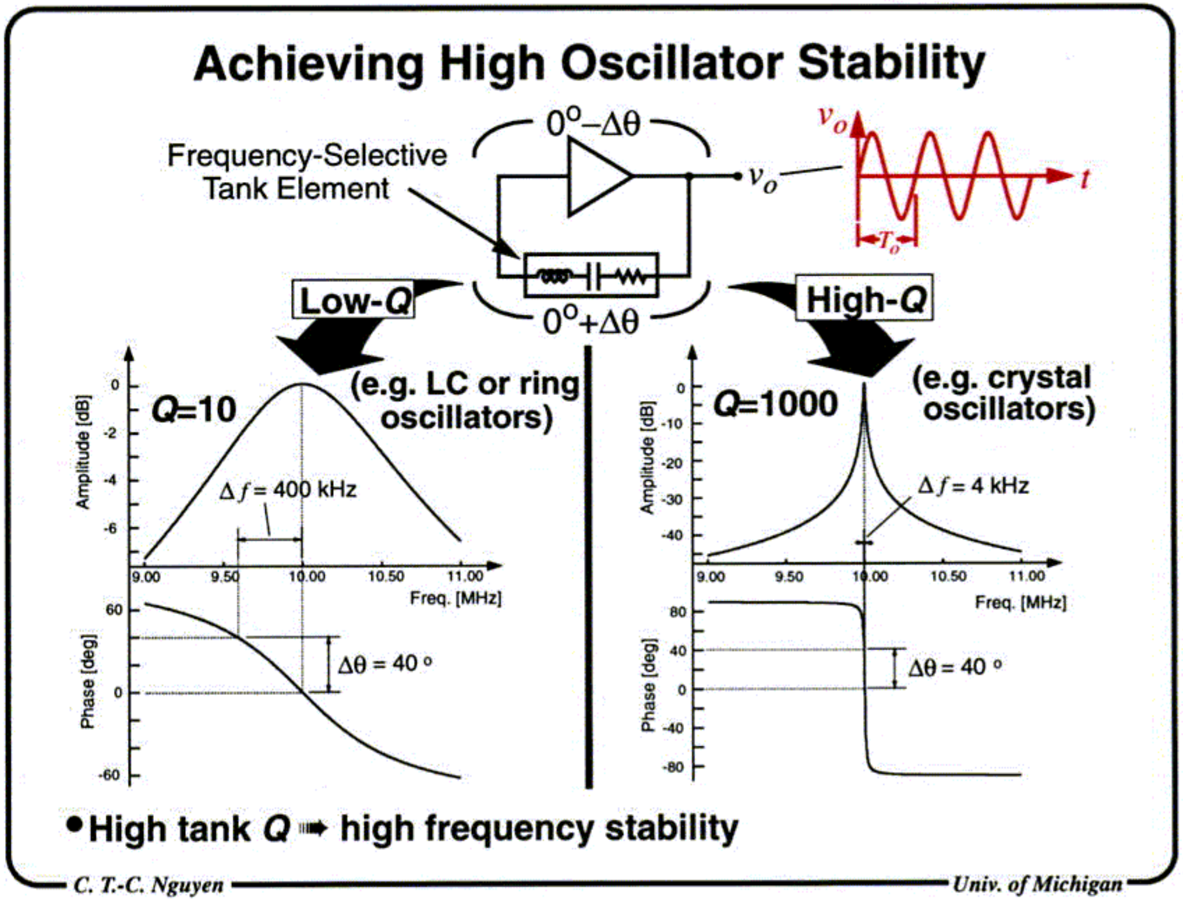
$$\boxed{Q_{\text{Tuned Circuit}} = \frac{f_0}{B}} \qquad \boxed{Q_{\text{Capacitor}} = \frac{\omega_0 C}{G}} \qquad \boxed{Q_{\text{Inductor}} = \frac{\omega_0 L}{R}}$$

Unloaded : Q (intrinsic)
Loses due to external load : Q_L

→ Insertion loss at resonance: $IL(dB) = 20 \log (1 + \frac{Q_L}{Q})$

Relation between Q-factor and oscillator stability

- **Q-factor is critical for RF circuit performance!**

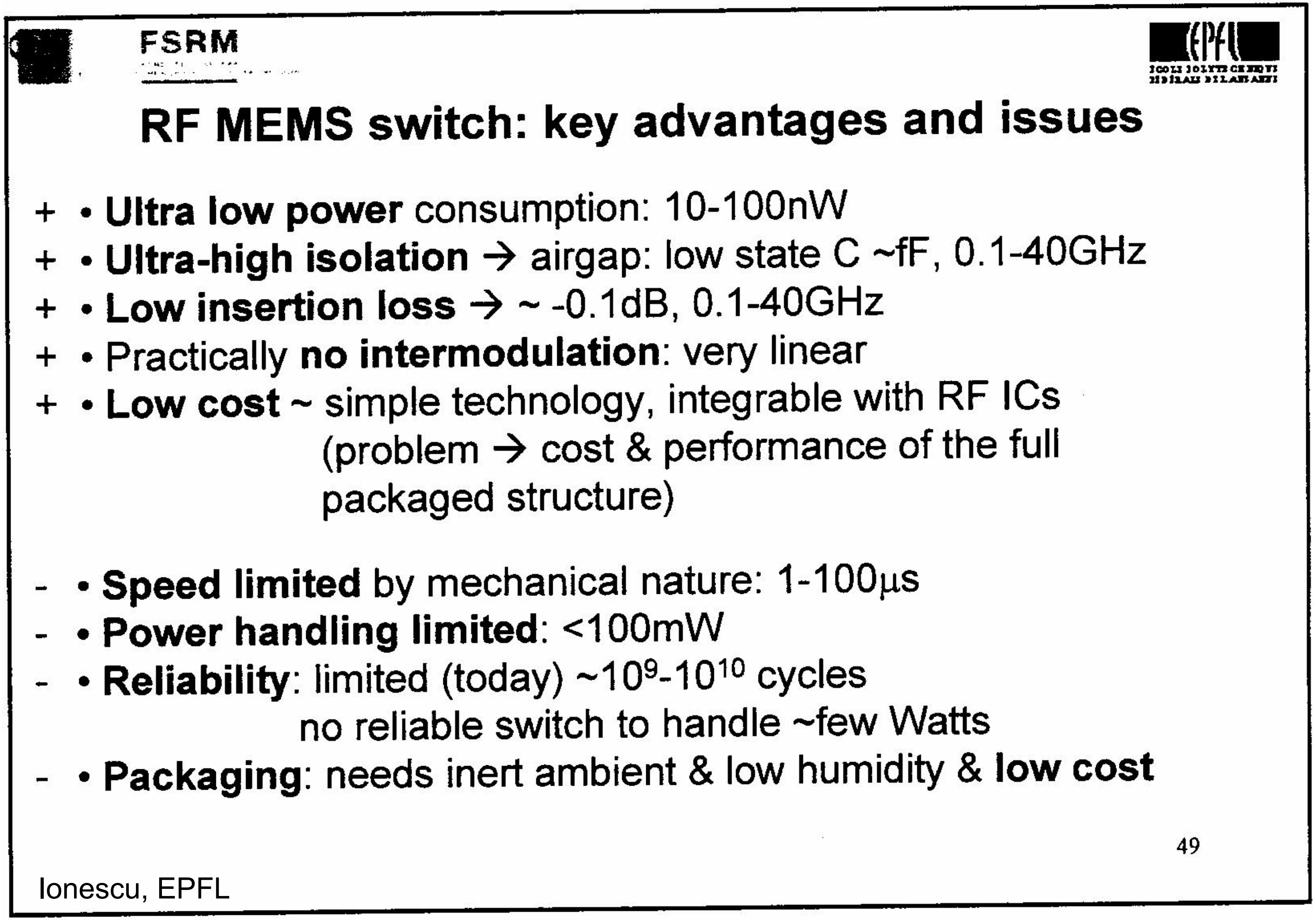


Achieving High Oscillator Stability

- **High tank *Q* ➠ high frequency stability**

C. T.-C. Nguyen — *Univ. of Michigan*

Benefits and typical characteristics of RF MEMS switches



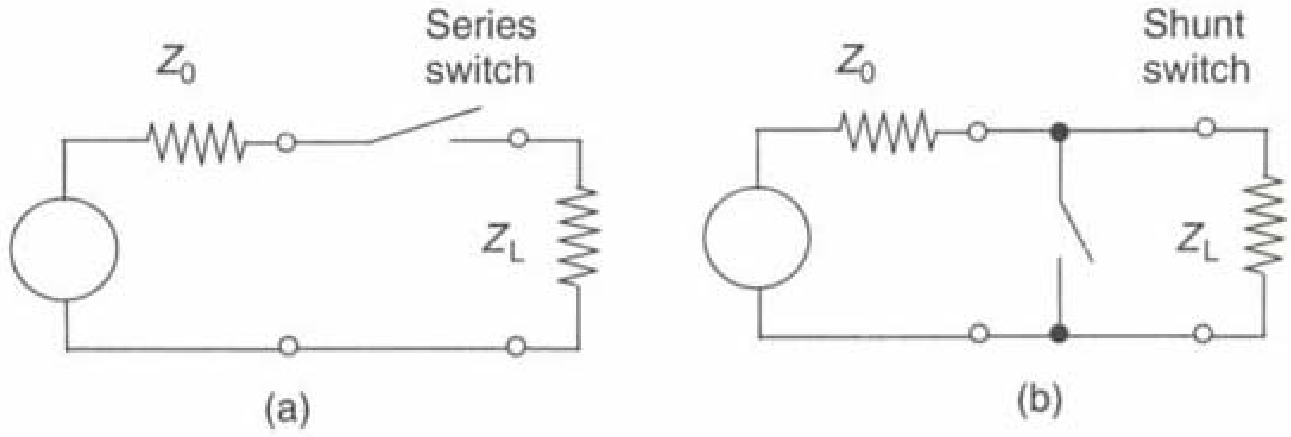
RF MEMS switch: key advantages and issues

+ • **Ultra low power** consumption: 10-100nW
+ • **Ultra-high isolation** → airgap: low state C ~fF, 0.1-40GHz
+ • **Low insertion loss** → ~ -0.1dB, 0.1-40GHz
+ • Practically **no intermodulation**: very linear
+ • **Low cost** ~ simple technology, integrable with RF ICs
(problem → cost & performance of the full
packaged structure)

- • **Speed limited** by mechanical nature: 1-100μs
- • **Power handling limited**: <100mW
- • **Reliability**: limited (today) ~10^9-10^{10} cycles
no reliable switch to handle ~few Watts
- • **Packaging**: needs inert ambient & low humidity & **low cost**

Ionescu, EPFL

Two basic switch configurations



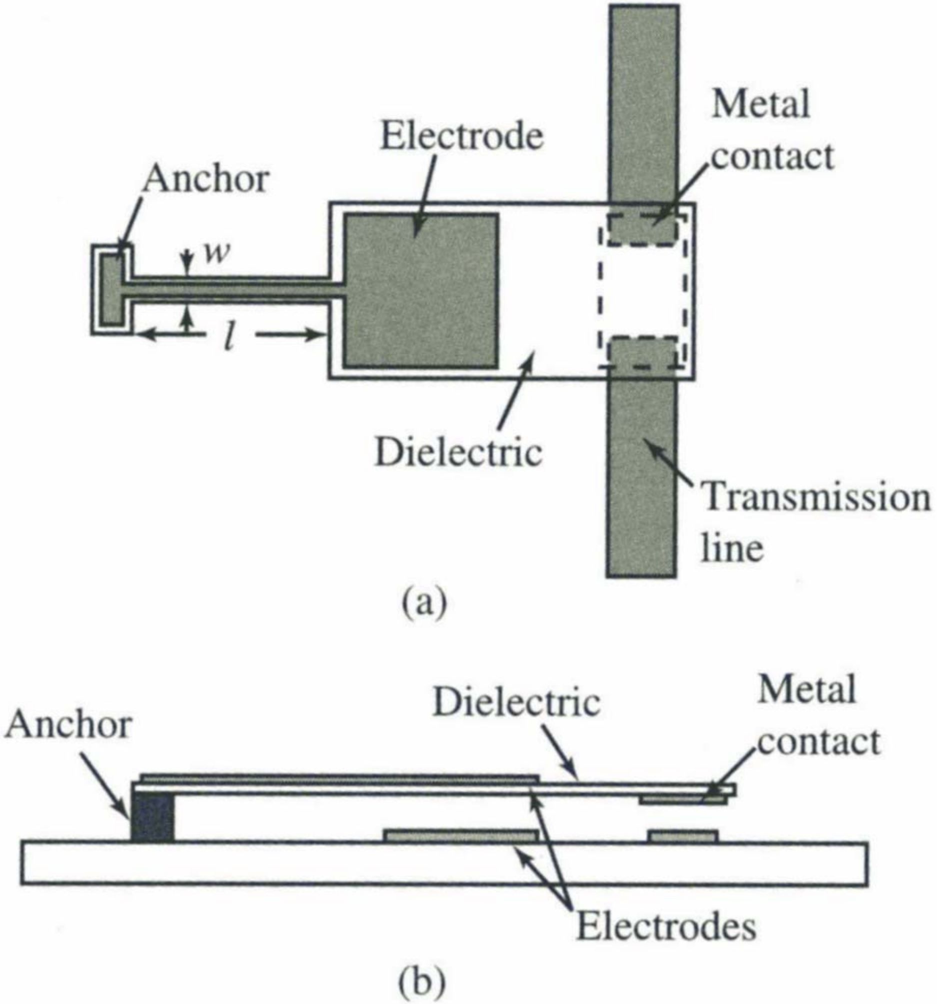
Varadan fig. 3.2

Basic switch structures

- **Series switch**
  - Contact switch, ohmic (relay) *
    - Cantilever beam
  - Capacitive switch (“contact less”)
    - RF-signals short-circuited via C ($Z=1/j\omega C$)
      - Impedance depends on value of C
- **Shunt switch**
  - Shunt capacitive switch *
    - clamped-clamped beam (c-c beam)
  - Shunt contact switch

* most used

Series switch



Rebeiz fig.2.12

Typical shunt switch

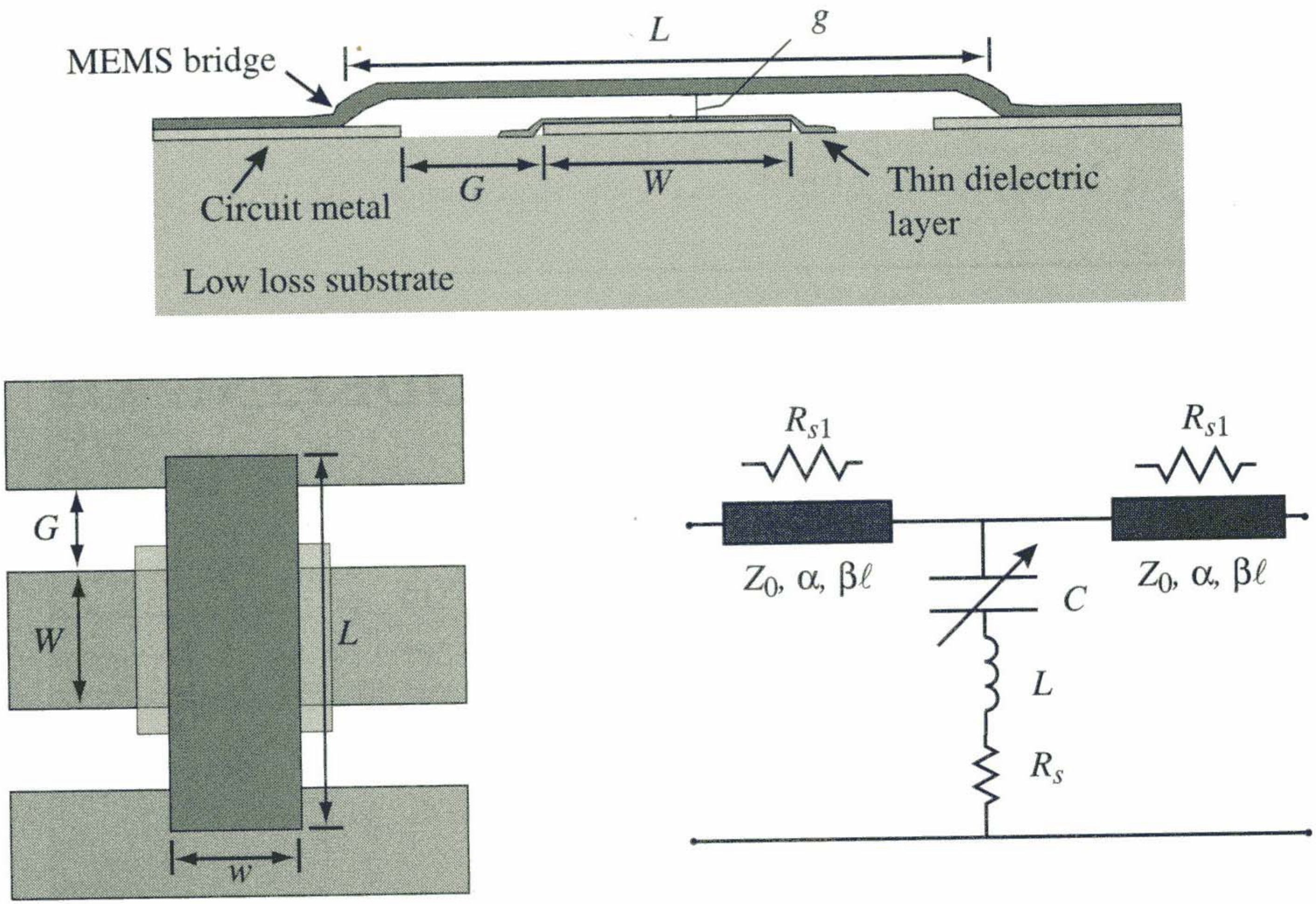


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

Rebeiz

Electromechanical operation

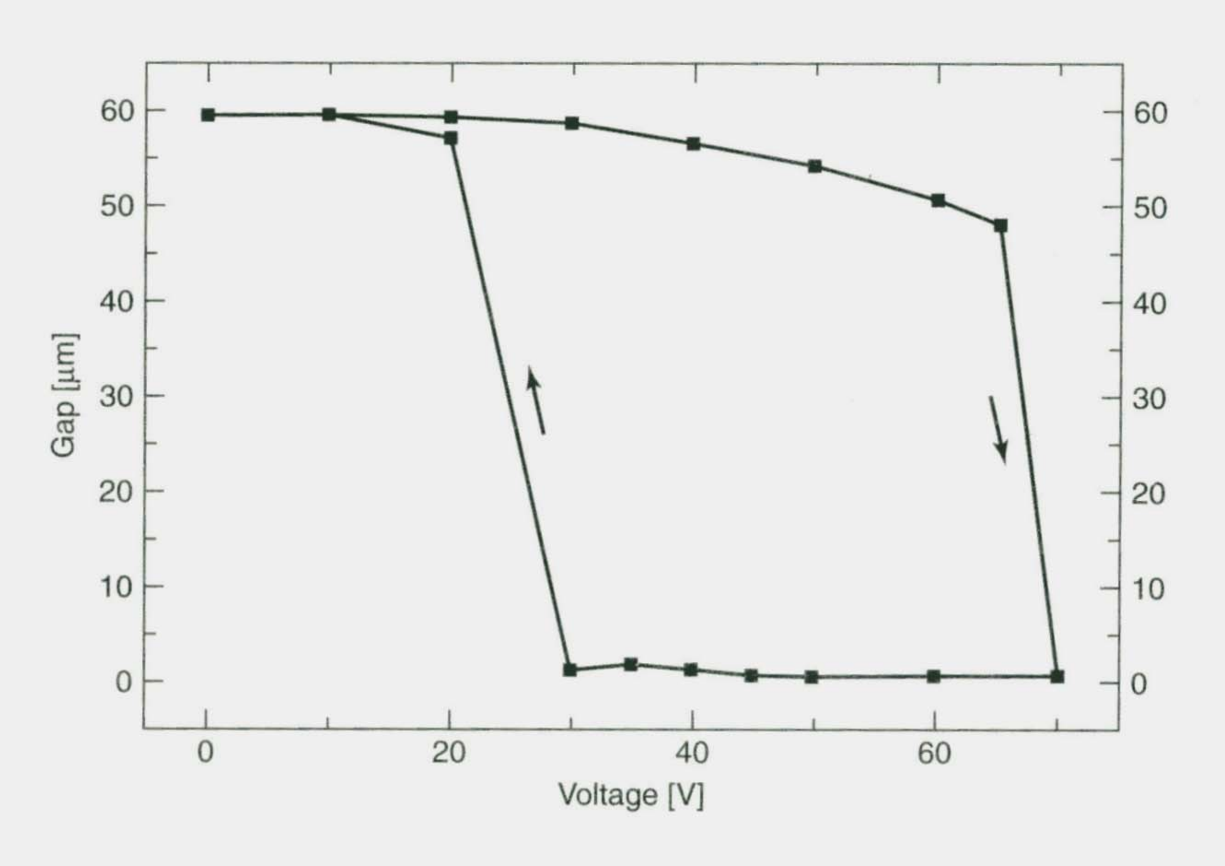
- The operation is based on the **pull-in** effect
  - Characteristics at pull-in
    - Membrane/beam pulls in at 1/3 of gap
    - Pull-in voltage:

$$\boxed{V_{PI} = \sqrt{\frac{8K}{27\varepsilon_0 W w} g_0^3}}$$

    - Definition of parameters:
      - K spring constant
      - g0 initial gap
      - A=W*w = area

Hysteresis

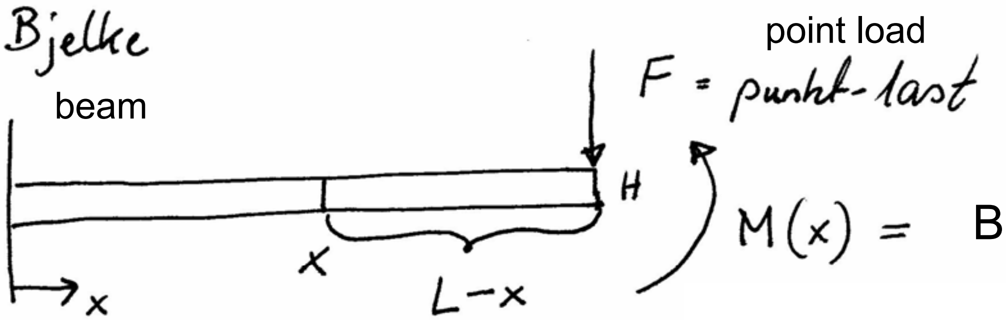
- A capacitive switch shows hysteresis when being switched on/off



Varadan fig. 3.18

Deflection of beam

- Suppose the following approximations:
  - Actuation electrode is not deflected
  - Electrostatic force concentrated at the end of the flexible beam with length L



Bending moment in x

w(x) = vertical displacement

W = width

Euler beam equation

$$\frac{d^2 w}{dx^2} = -\frac{M}{E \cdot I}$$

I = (area) moment of inertia

$$I = \frac{1}{12} W \cdot H^3$$

$$w(x) = \frac{FL}{2EI} x^2 \left(1 - \frac{x}{3L}\right)$$

Max. deflection at x = L

$$w(L) = \frac{L^3}{3EI} \cdot F$$

Beam stiffness represents a spring with spring constant k_cantilever

Compare with

$$F = k_{cantilever} \cdot \underbrace{\Delta W}_{w_{max}}$$

$$k_{cantilever} = \frac{F}{w(L)} = \frac{3EI}{L^3} = \frac{1}{4} E \cdot W \left(\frac{H}{L}\right)^3$$

Switch speed and damping

- Switch speed depends of **damping**
  - Air, gas must be pushed/pulled
  - **”squeezed-film damping”**
  - Method of modeling from fluid dynamics

- How to reduce damping?
  - Operate in vacuum
    - Hermetic sealed packages
  - Make holes in membrane
    - Perforated membrane

Switch speed

- Damping influences Q-factor
- Switch-speed depends of Q-factor

  - High Q-factor means small damping
    - → increased switch speed
  - Low Q-factor means large damping
    - System is **damping-limited** when Q ≤ 0.5 [Castaner and Senturia]

Gap vs. Time for various Q-factors

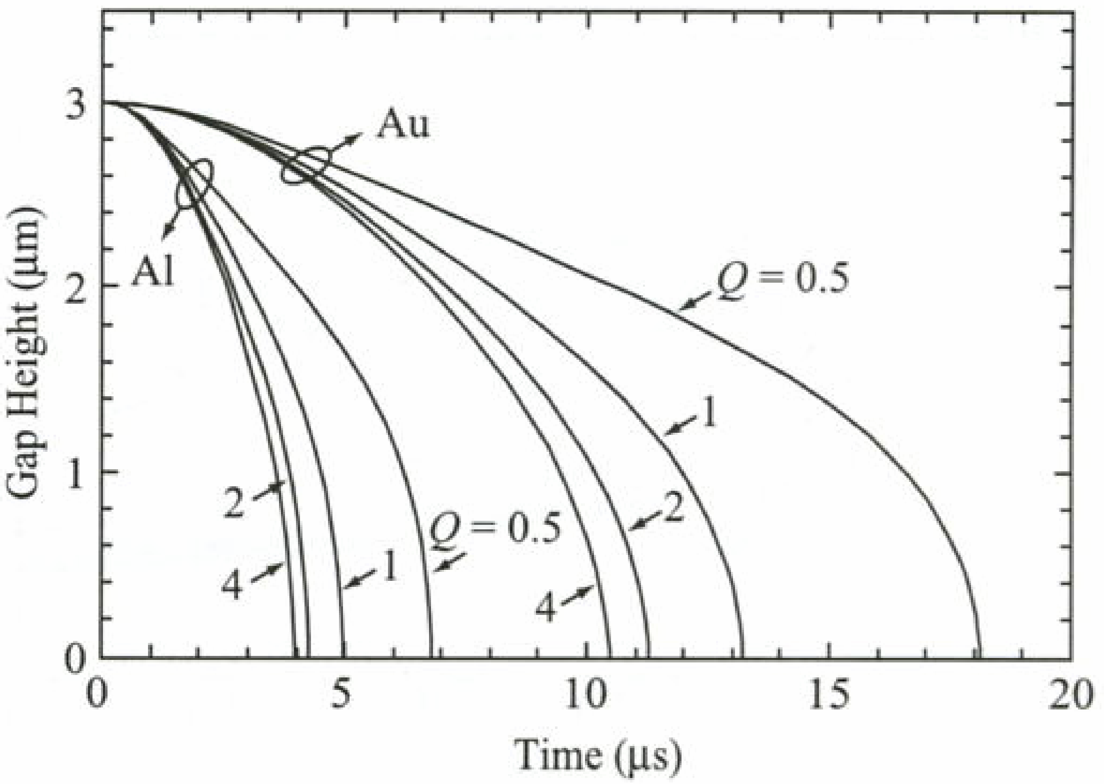


Figure 3.3. Pull-down simulations for the Au and Al beams of Table 3.1 for an applied voltage of 42 V ($V_s = 1.4V_p$).

Acceleration limited switch

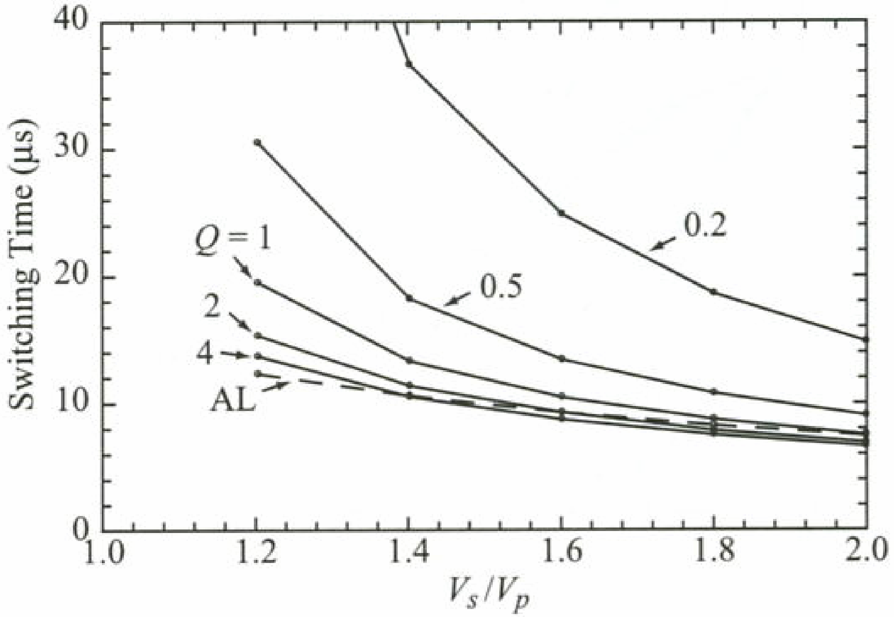


Figure 3.5. Simulated switching times for the Au beam given in Table 3.1. "AL" means acceleration-limited and is given by Eq. (3.23).

Note: The system becomes more acceleration limited when damping decreases (eg. Q-factor increases). High Vs/Vp is good.

Switch speed for increased Vs

- Switch-speed strongly depends on actuation voltage, Vs
  - Vs is usually larger than Vpi
  - Vs = const * Vpi (pull-in) = ("actuation voltage")
  - Larger voltage gives larger electrostatic force
    - → increased switch speed

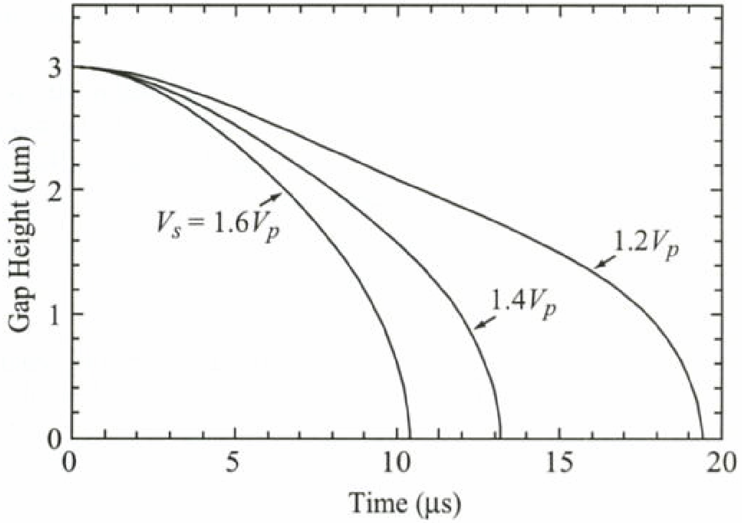
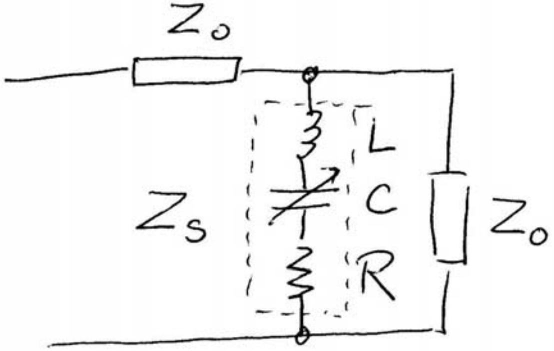


Figure 3.4. Pull-down simulations for the Au beam of Table 3.1 versus the applied voltage, and $Q = 1$.

RF modeling: Shunt configuration



$$Z_s = R + j\omega L + \frac{1}{j\omega C}$$

$$S_{11} = S_{22} = \Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{Z_s // Z_o - Z_o}{Z_s // Z_o + Z_o} = \frac{-Z_o}{2Z_s + Z_o}$$

$$S_{12} = S_{21} = 1 + \Gamma = 1 + \frac{-Z_o}{2Z_s + Z_o} = \frac{2Z_s}{2Z_s + Z_o}$$

Shunt switch

Return loss (up-state)

$$Z_s \approx \frac{1}{j\omega C}$$

$$S_{11} = \frac{-Z_0}{2Z_s + Z_0} = \frac{-Z_0}{2 \cdot \frac{1}{j\omega C} + Z_0} = \frac{-j\omega C Z_0}{2 + j\omega C Z_0}$$

$$|S_{11}|^2 = S_{11} \cdot S_{11}^* = \frac{(\omega C Z_0)^2}{4 + (\omega C Z_0)^2}$$

Return loss (down-state)

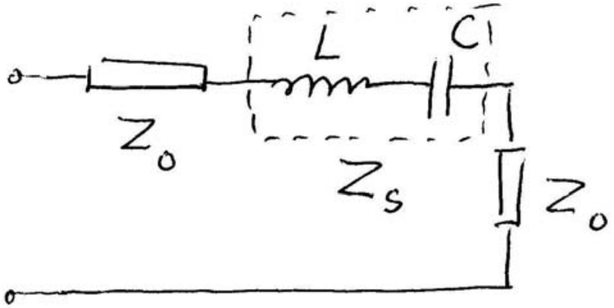
$$Z_s = R + j\omega L + \frac{1}{j\omega C}$$

$$S_{11} = \frac{-Z_0}{2Z_s + Z_0} = \frac{-Z_0}{2\left(R + j\omega L + \frac{1}{j\omega C}\right) + Z_0} = \frac{-j\omega C Z_0}{(2 - 2\omega^2 LC) + j\omega(2R + CZ_0)}$$

$$|S_{11}|^2 = S_{11} \cdot S_{11}^* = \frac{(\omega C Z_0)^2}{(2 - 2\omega^2 LC)^2 + (2\omega R + \omega C Z_0)^2}$$

Series contact cantilever switch

OFF (up-state)



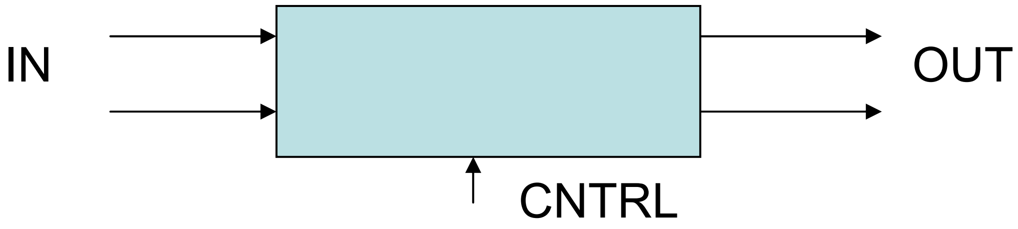
$$Z_s = j\omega L + \frac{1}{j\omega C}$$

$$S_{11} = S_{22} = \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{(Z_s + Z_0) - Z_0}{(Z_s + Z_0) + Z_0} = \frac{Z_s}{2Z_0 + Z_s}$$

$$S_{12} = S_{21} = 1 - \Gamma = 1 - \frac{Z_s}{2Z_0 + Z_s} = \frac{2Z_0}{2Z_0 + Z_s}$$

Phase shifter

- A phase shifter is a 2-port



- Output signal is delayed relative to the input signal
- The effective ”path-length” of the transmission line can be changed
  - Signal propagates a longer distance → ”delayed” → phase change
  - Phase difference can be controlled by a DC bias

Analog phase shifters

- Phase velocity for a transmission line

$$v_p = \frac{1}{\sqrt{L_t \cdot C_t}}$$

  - Variables are inductance and capacitance per unit length
- Idea: C-value can be controlled by a bias voltage
  - For example by **shunt capacitive loaded line**

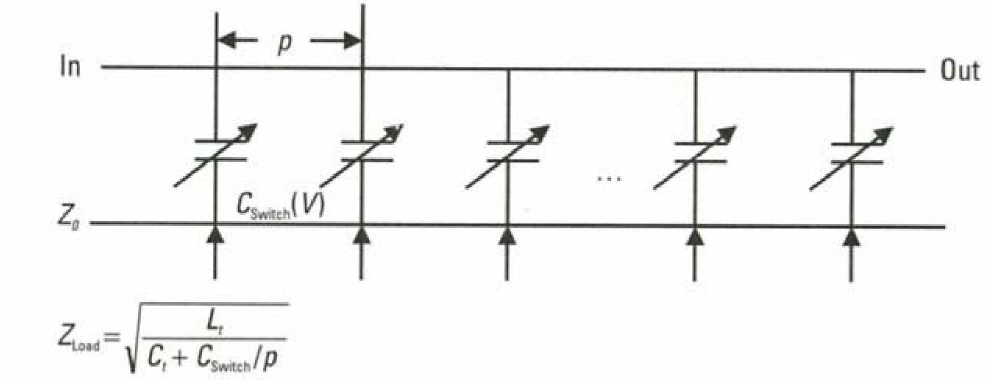
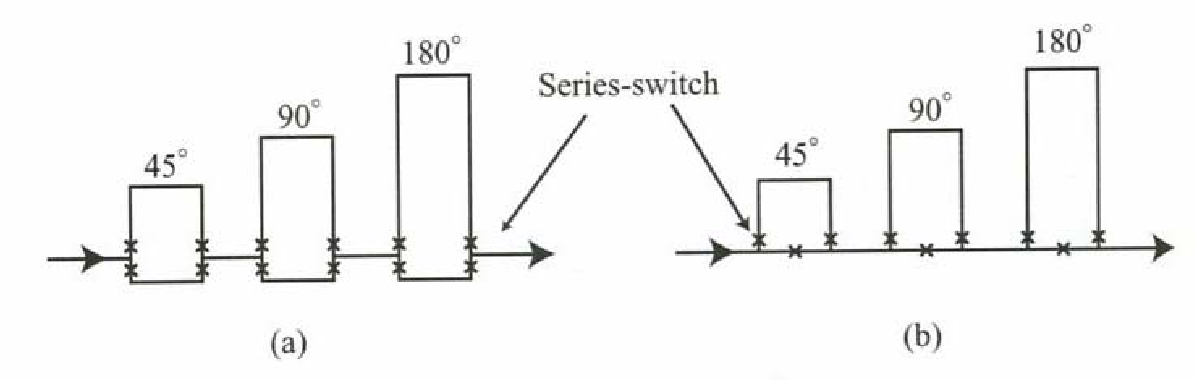


Figure 5.1 Schematic of analog phase shifter.

De Los Santos

C_t = line capacitance

Digital phase shifters with series-switches



(a)

(b)

- Working principle
  - Different line paths connected in/out
  - Interconnections through switches
- Switches for ”180°, 90°, 45°, 22.5°, 11.25° -sections in a cascade arrangement
- Several bits used
  - Controlling line sections individually
  - F.ex. 3 bits: 45/90/180° give phase shift 0, 45, 90, 135, … , 315°
  - 3 bit and 4 bit phase shifters have been demonstrated

Reflection type phase shifter, N-bit

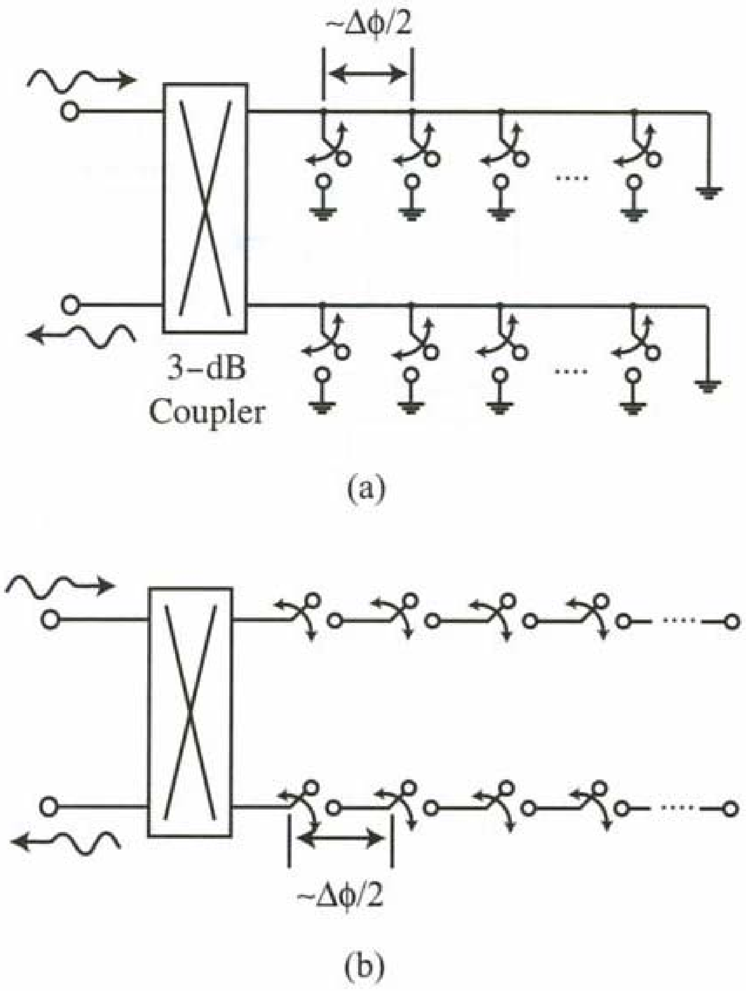


Figure 9.1. A reflect-line *N*-bit phase shifter using (a) shunt and (b) series switches.

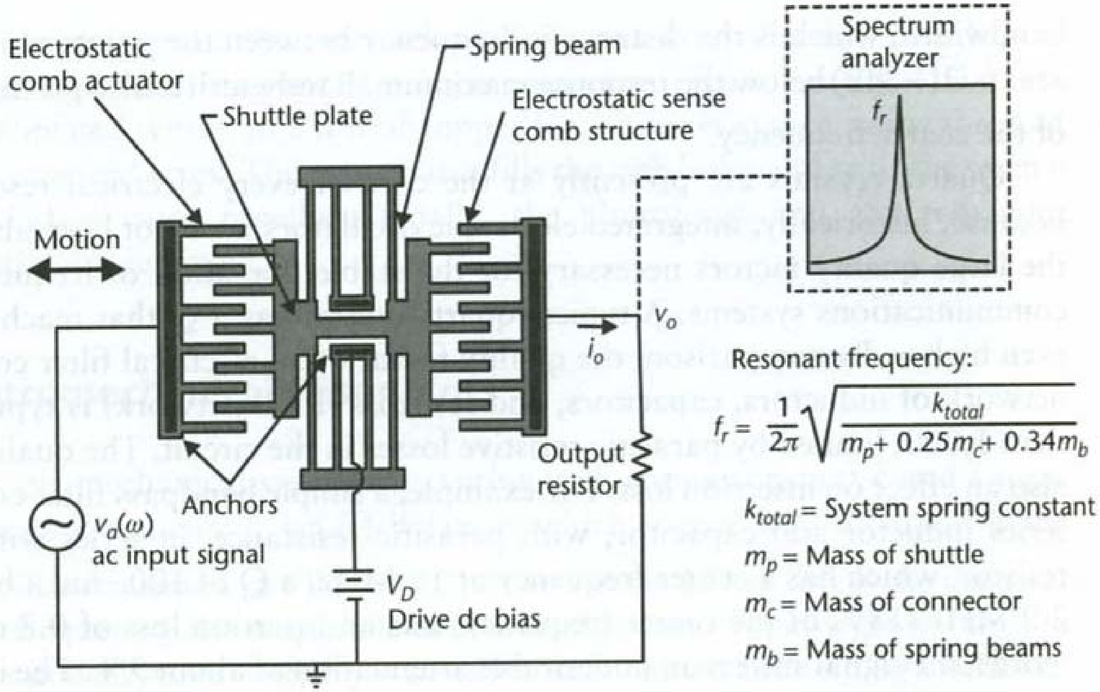
Vibrating MEMS resonators

- Vibrating resonators can be **scaled** down to micrometer lengths
  - Analogy with IC-technology
- Reduced dimensions give mass reduction and increased spring constant → **increased resonance frequency**

- Vibrating MEMS resonators can give **high Q-factor**
  - Reduced insertion loss (BP-filters)
  - Reasons for Q degradation for MEMS resonators
    - Energy loss to substrate via anchors
    - Air/gas damping
    - Intrinsic friction
    - Small dimensions (low stored energy compared to energy loss)

Comb-resonator

- Fixed comb + movable, suspended comb
- Using folded springs, compact layout
- Total capacitance between combs can be varied
- Applied voltage (+ or -) generates electrostatic force between left anchor comb and ”shuttle”-comb. Plate pulled left laterally controlled by drive voltage



Resonant frequency:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k_{total}}{m_p + 0.25m_c + 0.34m_b}}$$

k_{total} = System spring constant

m_p = Mass of shuttle

m_c = Mass of connector

m_b = Mass of spring beams

Figure 7.9 Illustration of a micromachined folded-beam comb-drive resonator. The left comb drive actuates the device at a variable frequency ω. The right capacitive-sense-comb structure measures the corresponding displacement by turning the varying capacitance into a current, which generates a voltage across the output resistor. There is a peak in displacement, current, and output voltage at the resonant frequency.

Comb-resonator, summary

- Summary of modeling:
- Force: Fe = **½ dC/dx V ^2** (force is always attractive)
  - Input signal Va * cos (ωt)
  - Fe ~ Va^2 * ½ [1 + cos (2ωt)]
  - Driving force is 2x input frequency + DC: NOT DESIRABLE
- Add DC bias, Vd
  - Fe ~ Vd ^2 + 2 Vd * Va * cos ω t + negligible term (2ωt)
  - Linear AC force-component **~ Vd * Va**, has same frequency as Va: ω. Is emphasized!
- C increases when finger-overlap increases
  - ε * A/d (A = comb thickness * overlap-length)
- dC/dx = constant for a given design (linear change, C is proportional to length variation)

Feedback → oscillator

- Structure can have **2 output ports**
  - Feedback is isolated from any variation of output load
  - Ex. 16.5 kHz oscillator, Q = 50.000 in vacuum

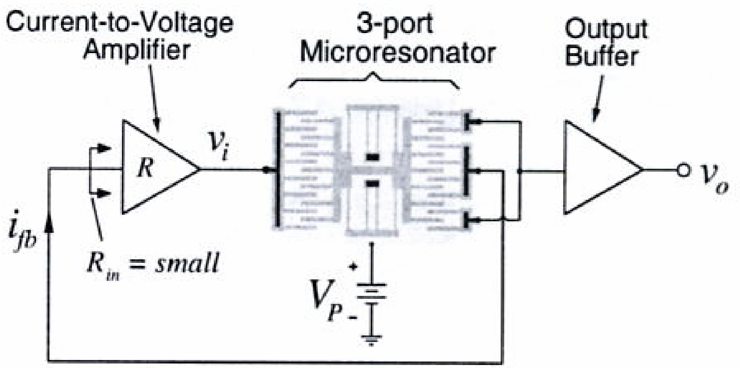


Fig. 8: System level schematic for the μresonator oscillator.

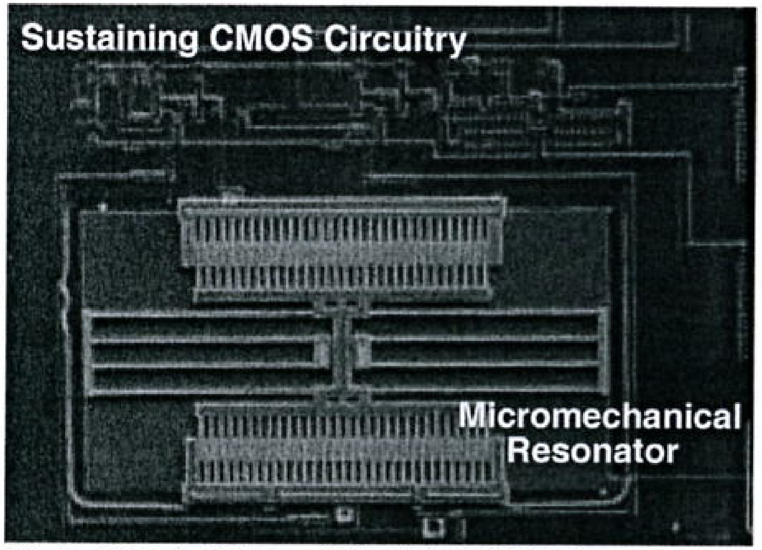
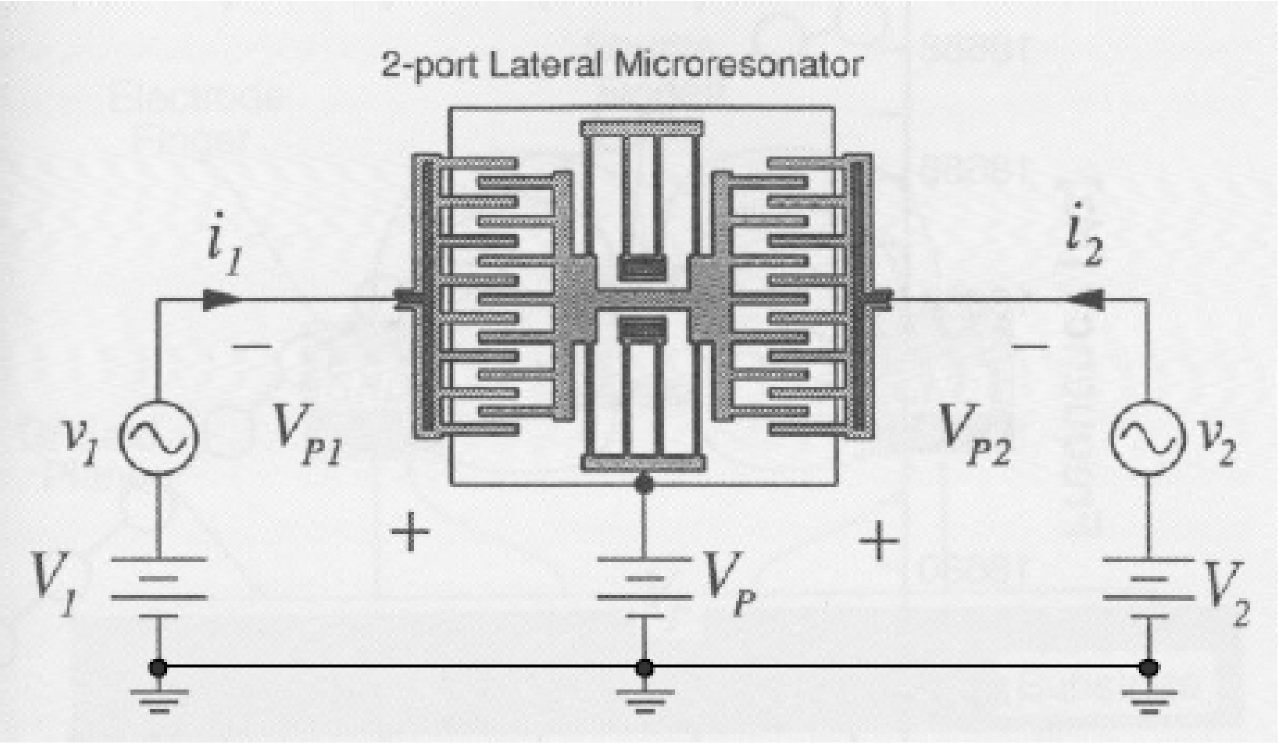


Fig. 9: SEM of a fully monolithic high-Q CMOS micromechanical resonator oscillator.

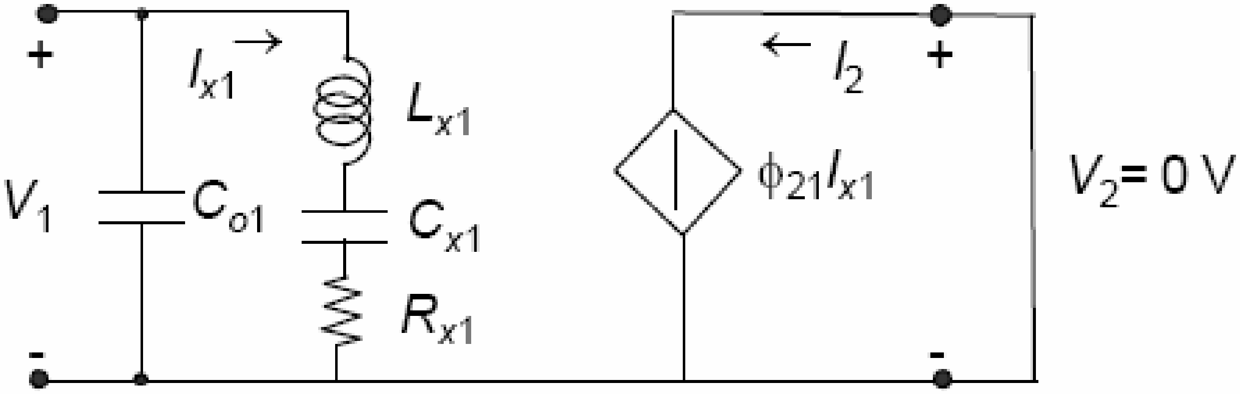
Nguyen, 1995

The Lateral Resonator as a "Two-Port"



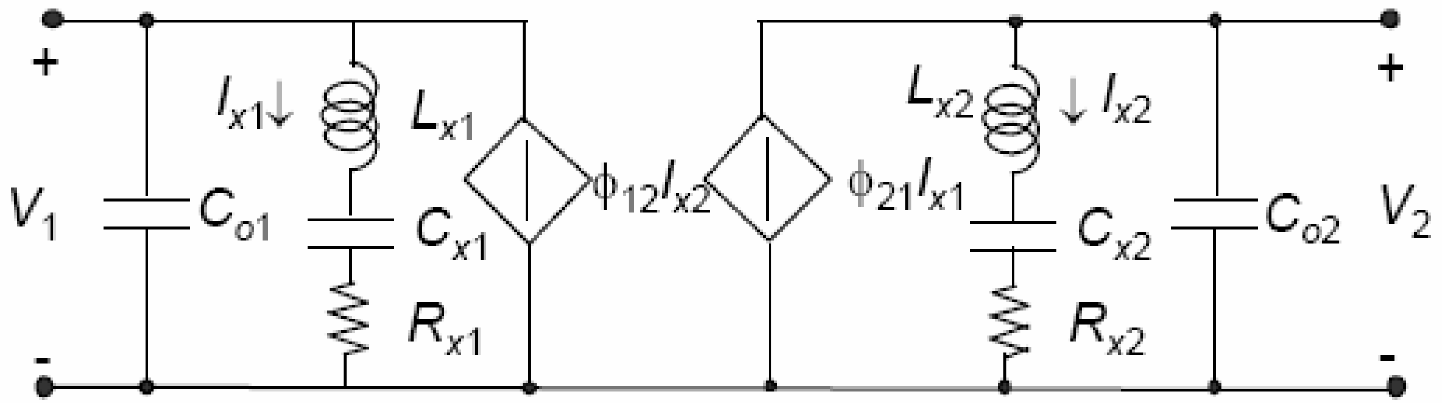
C. T.-C. Nguyen, Ph.D. Thesis,
EECS Dept., UC Berkeley, 1994

J. Two-Port Equivalent Circuit ($v_2 = 0$)



K.

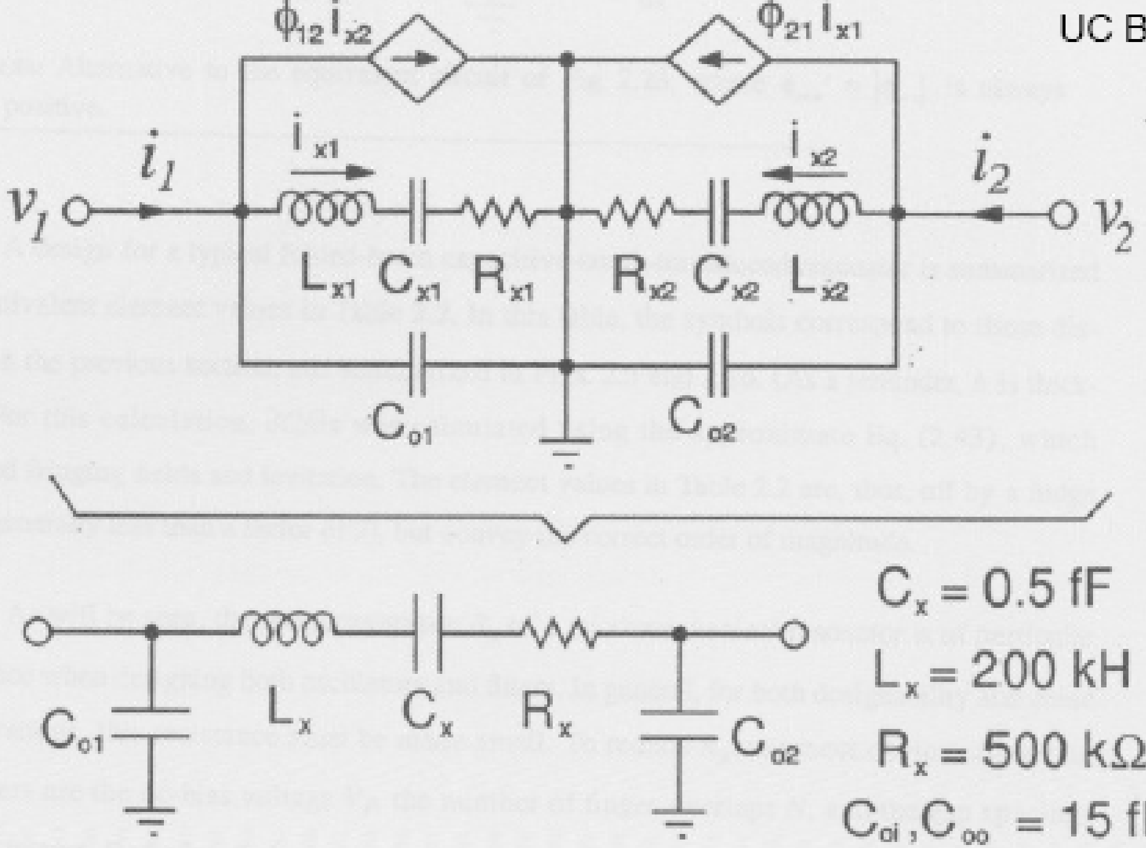
Complete Two-Port Model



Symmetry implies that modeling can be done from port 2, with port 1 shorted → superimpose the two models

Equivalent Circuit for Symmetrical Resonator ($\phi_{21} = \phi_{12} = 1$)

C. T.-C. Nguyen, Ph.D.,
UC Berkeley, 1994



$C_x = 0.5$ fF

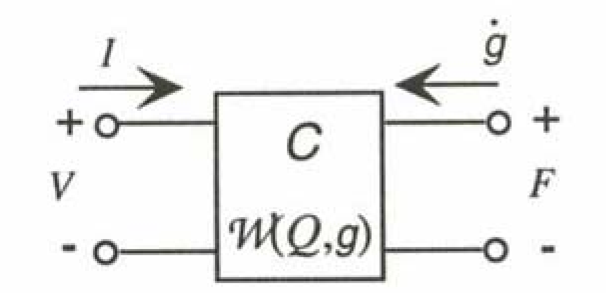
$L_x = 200$ kH

$R_x = 500$ kΩ

$C_{oi}, C_{oo} = 15$ fF

Conversion between energy domains

- Both vertical and lateral resonator structures may be described by a **generalized non-linear capacitance, C**, interconnecting energy-domains



Electrical domain

Mechanical domain

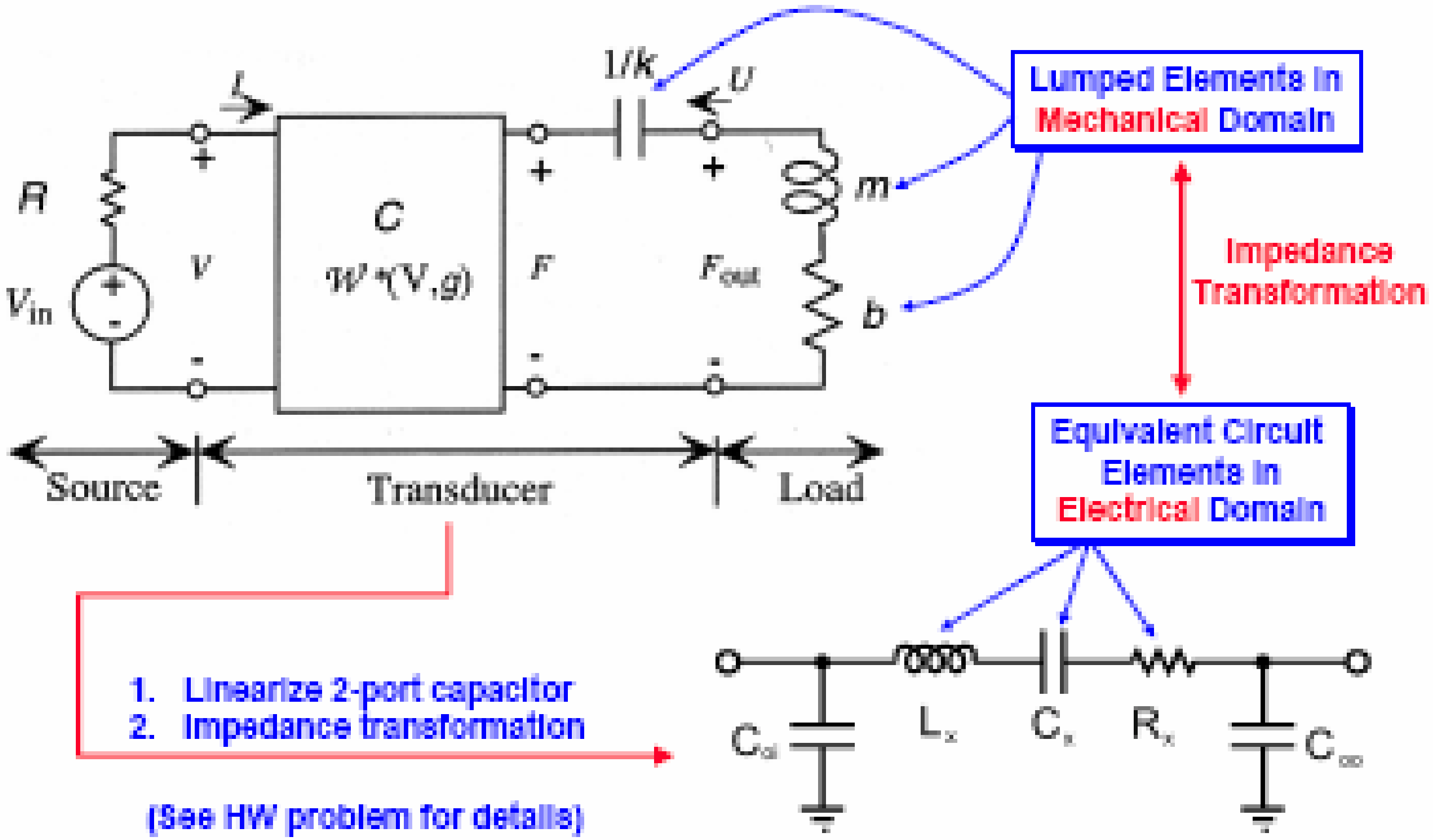
Transducer

Interconnecting where there is **no energy loss**

Interconnecting different energy domains

- 1. Each energy domain is transformed to its electrical equivalent
- 2. Domains are interconnected by a generalized non-linear capacitance, C
- 3. Transformer and gyrator may be used for **interconnecting** if a **linear relationship** exists between the power-variables!
  - Problem: Transducer C is generally **NOT** a linear 2-port
- 4. Must **linearize** the 2-port transducer to be able to substitute it with a **transformer**
- 5. The transformer can ”be removed” by recalculating the component **values** to **new** ones
  - → **Electromechanical coupling coefficient used! =** turn ratio
  - → Results in a common circuit diagram

Lumped Element Model (Senturia's Book)



Lumped Elements in Mechanical Domain

Impedance Transformation

Equivalent Circuit Elements in Electrical Domain

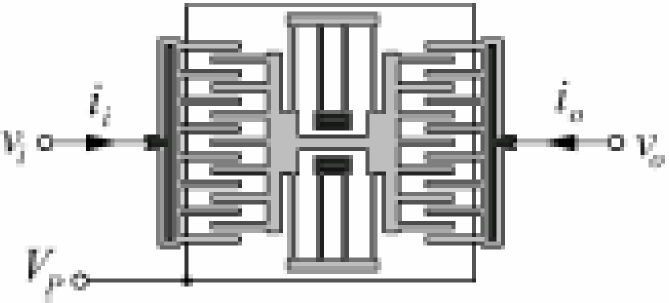
1. Linearize 2-port capacitor
2. Impedance transformation

(See HW problem for details)

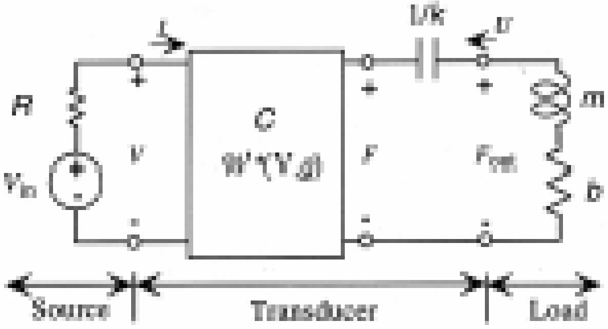
Linearized Transducers

Physical Circuit

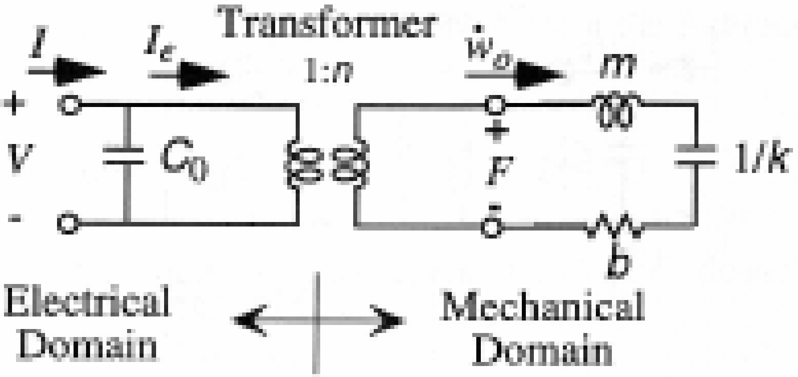
2-port Lateral Microresonator



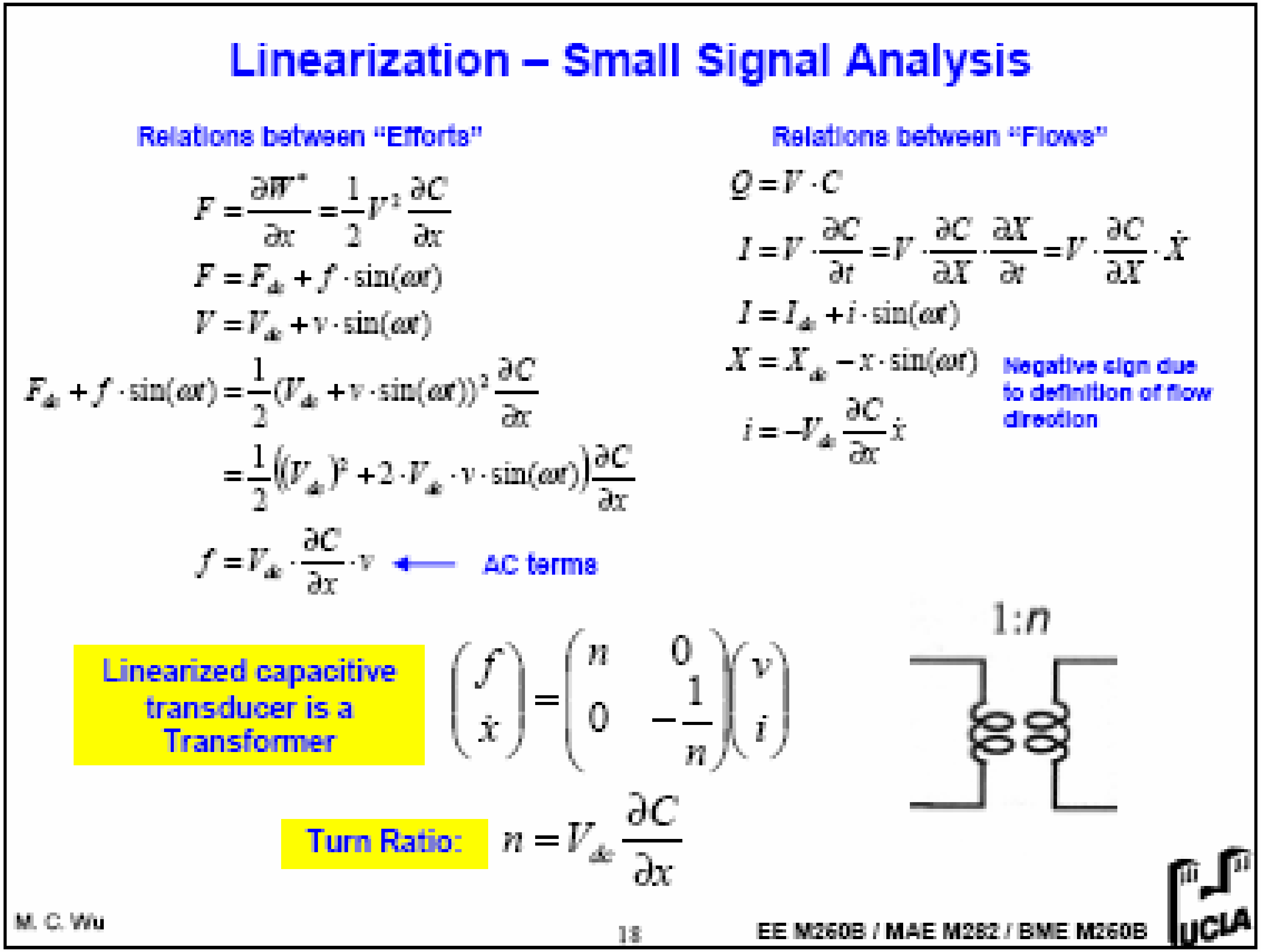
Equivalent Circuit (Nonlinear)



Linearized Equivalent Circuit



Similarly for relationship between FLOWS:



Linearization – Small Signal Analysis

Relations between "Efforts"

$$F = \frac{\partial W^*}{\partial x} = \frac{1}{2}V^2\frac{\partial C}{\partial x}$$

$$F = F_{dc} + f\cdot\sin(\omega t)$$

$$V = V_{dc} + v\cdot\sin(\omega t)$$

$$F_{dc} + f\cdot\sin(\omega t) = \frac{1}{2}(V_{dc} + v\cdot\sin(\omega t))^2\frac{\partial C}{\partial x}$$

$$= \frac{1}{2}\left((V_{dc})^2 + 2\cdot V_{dc}\cdot v\cdot\sin(\omega t)\right)\frac{\partial C}{\partial x}$$

$$f = V_{dc}\cdot\frac{\partial C}{\partial x}\cdot v \longleftarrow$$ AC terms

Relations between "Flows"

$$Q = V\cdot C$$

$$I = V\cdot\frac{\partial C}{\partial t} = V\cdot\frac{\partial C}{\partial X}\cdot\frac{\partial X}{\partial t} = V\cdot\frac{\partial C}{\partial X}\cdot\dot{X}$$

$$I = I_{dc} + i\cdot\sin(\omega t)$$

$$X = X_{dc} - x\cdot\sin(\omega t)$$

Negative sign due to definition of flow direction

$$i = -V_{dc}\frac{\partial C}{\partial x}\dot{x}$$

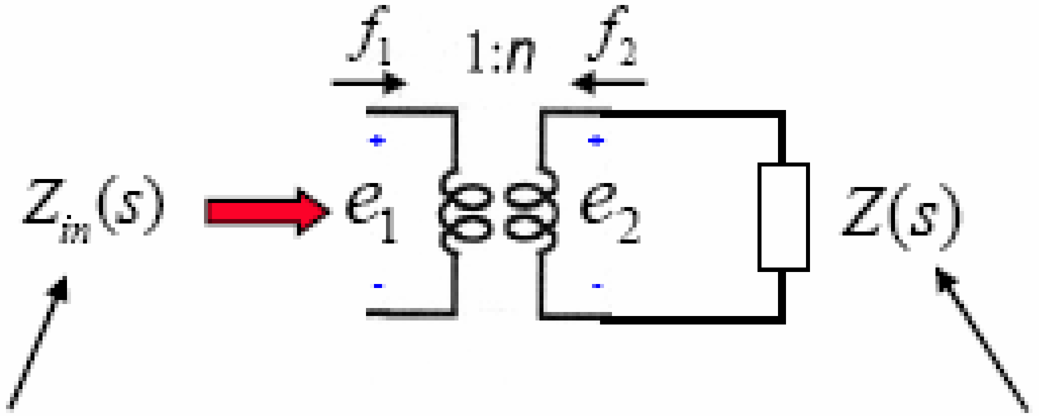
Linearized capacitive transducer is a Transformer

$$\begin{pmatrix} f \\ \dot{x} \end{pmatrix} = \begin{pmatrix} n & 0 \\ 0 & -\frac{1}{n} \end{pmatrix}\begin{pmatrix} v \\ i \end{pmatrix}$$

Turn Ratio: $n = V_{dc}\frac{\partial C}{\partial x}$

flow (electrical domain) = - const. * flow (mechanical domain)

Impedance Transformation



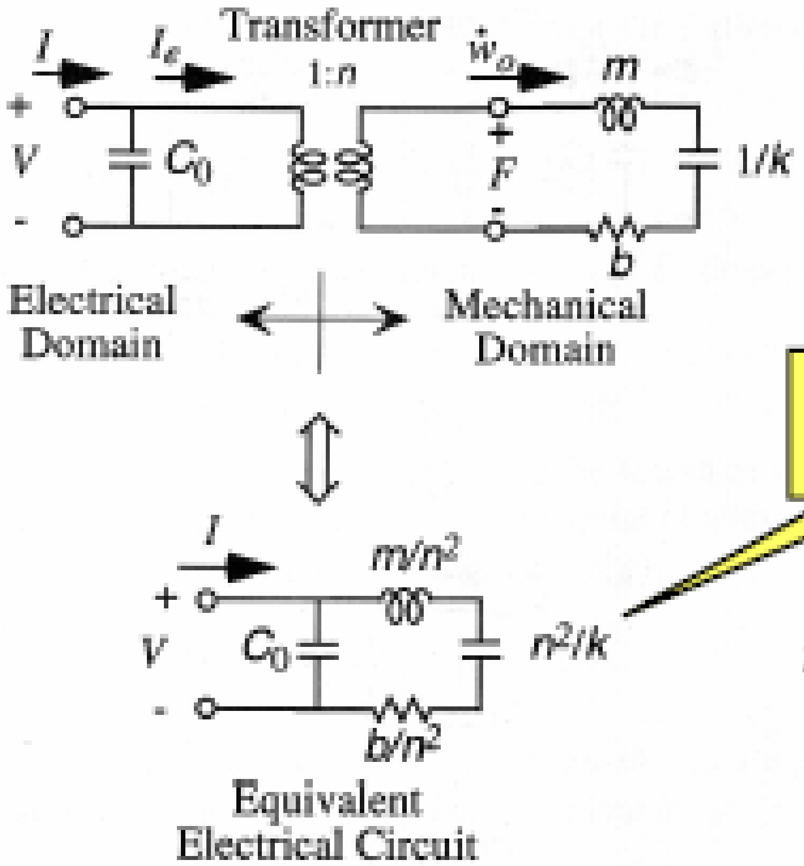
Equivalent Impedance In Electrical Domain

Impedance In Mechanical Domain

$$\begin{pmatrix} f \\ \dot{x} \end{pmatrix} = \begin{pmatrix} n & 0 \\ 0 & -\frac{1}{n} \end{pmatrix} \begin{pmatrix} v \\ i \end{pmatrix}$$

$$Z_{in}(s) = \frac{1}{n^2} Z(s)$$

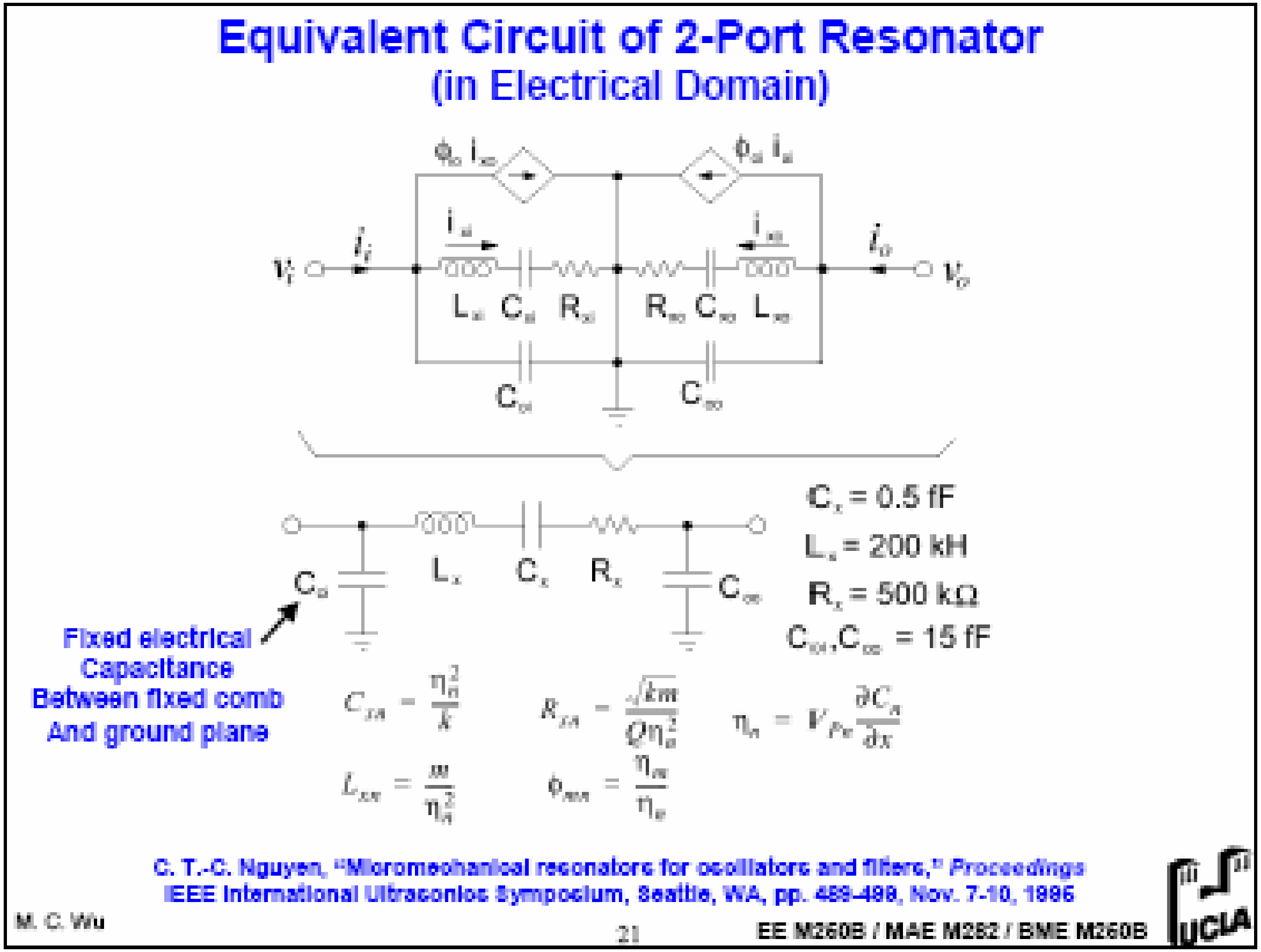
Small Signal Equivalent Circuit of Microresonators



Unit of n^2/k is Farad

$$n = V_{dc}\frac{\partial C}{\partial x}$$

Both methods result in the same equivalent circuit:



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

Fixed electrical Capacitance Between fixed comb And ground plane

$$C_{xn} = \frac{\eta_n^2}{k} \qquad R_{xn} = \frac{\sqrt{km}}{Q\eta_n^2} \qquad \eta_n = V_{Pn}\frac{\partial C_n}{\partial x}$$

$$L_{xn} = \frac{m}{\eta_n^2} \qquad \phi_{mn} = \frac{\eta_m}{\eta_n}$$

C. T.-C. Nguyen, "Micromechanical resonators for oscillators and filters," *Proceedings IEEE International Ultrasonics Symposium, Seattle, WA, pp. 489-498, Nov. 7-10, 1995*

Beam resonator

- How to obtain a higher resonance frequency than that which is possible with the comb-structure?
  - Mass should be reduced more -> **beam resonator**
- Beam resonator benefits
  - Smaller dimensions
  - Higher resonance frequency
  - Simple
  - Many frequency references on a single chip
  - Frequency variation versus temperature is more linear over a broader temperature range
  - Integration with electronics possible → lower cost

Beam-resonator, contd.

- Electrode under beam, electrostatic actuation
- Plate attracted for both positive and negative wave. Actuated with double frequency
  - → Need a polarization voltage, Vd, between beam and actuation electrode
  - As for ”lateral shuttle”: When Vd is combined with ac-signal, then beam oscillates with same frequency as ac signal
  - At resonance the amplitude is maximum

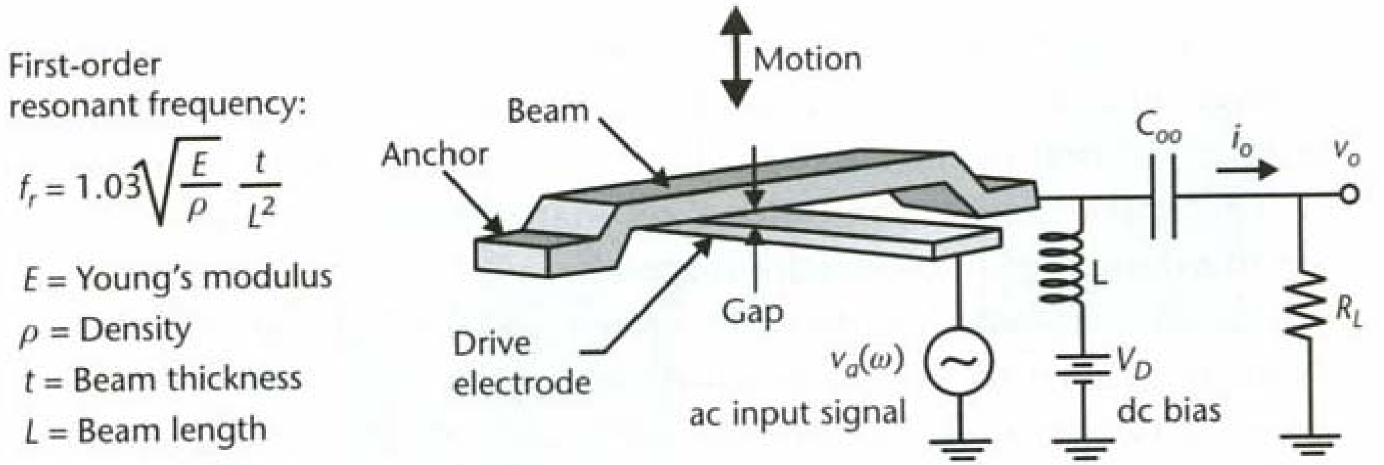


Figure 7.10 Illustration of a beam resonator and a typical circuit to measure the signal. The beam is clamped on both ends by anchors to the substrate. The capacitance between the resonant beam and the drive electrode varies with the deflection.

Clamped-clamped beam

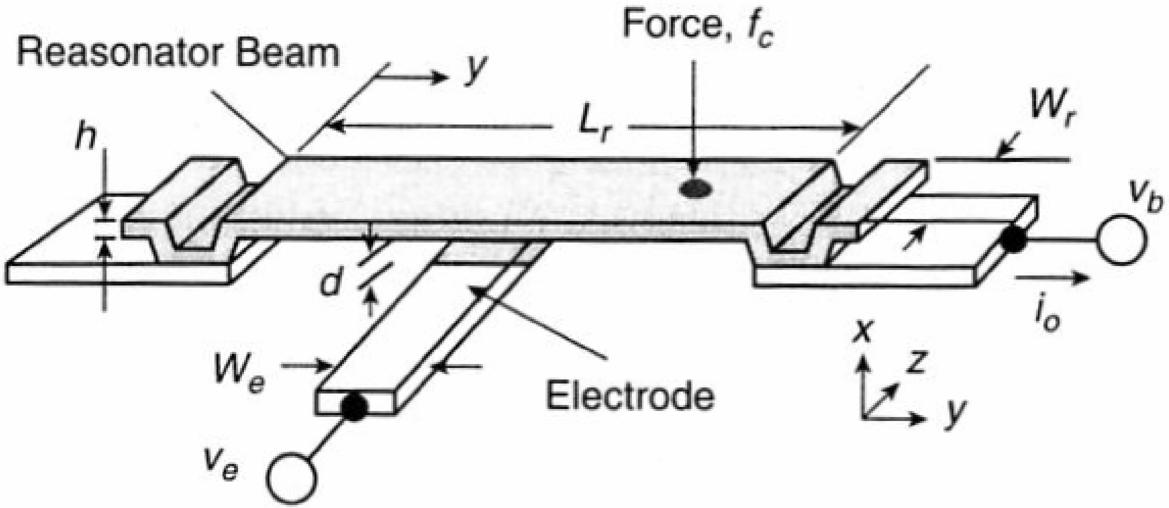


Figure 12.4. Perspective-view schematic of a clamped–clamped beam μmechanical resonator in a general bias and excitation configuration.

Then

$$F_d = \left(\frac{1}{2}V_P^{\ 2} - V_P V_i \cos\omega_i t + \frac{1}{2}\frac{V_i^2}{2} + \frac{1}{2}\frac{V_i^2}{2}\cos 2\omega_i t\right)\frac{\partial C}{\partial x}$$

E.

$$F_d = \underbrace{\frac{\partial C}{\partial x}\left(\frac{V_P^{\ 2}}{2} + \frac{V_i^2}{4}\right)} - \underbrace{V_P \frac{\partial C}{\partial x} V_i \cos\omega_i t} + \frac{\partial C}{\partial x}\frac{V_i^2}{4}\cos 2\omega_i t$$

Off-resonance DC force
Static bending of beam

Force driven by the input frequency,
amplified by V_P

$$\frac{\partial C}{\partial x}\frac{V_i^2}{4}\cos 2\omega_i t$$

This term can drive the beam into vibrations at

$$2\omega_i = \omega_0, \ \ and \ \ \omega_i = \frac{\omega_0}{2}$$

The term can usually be neglected

Topology

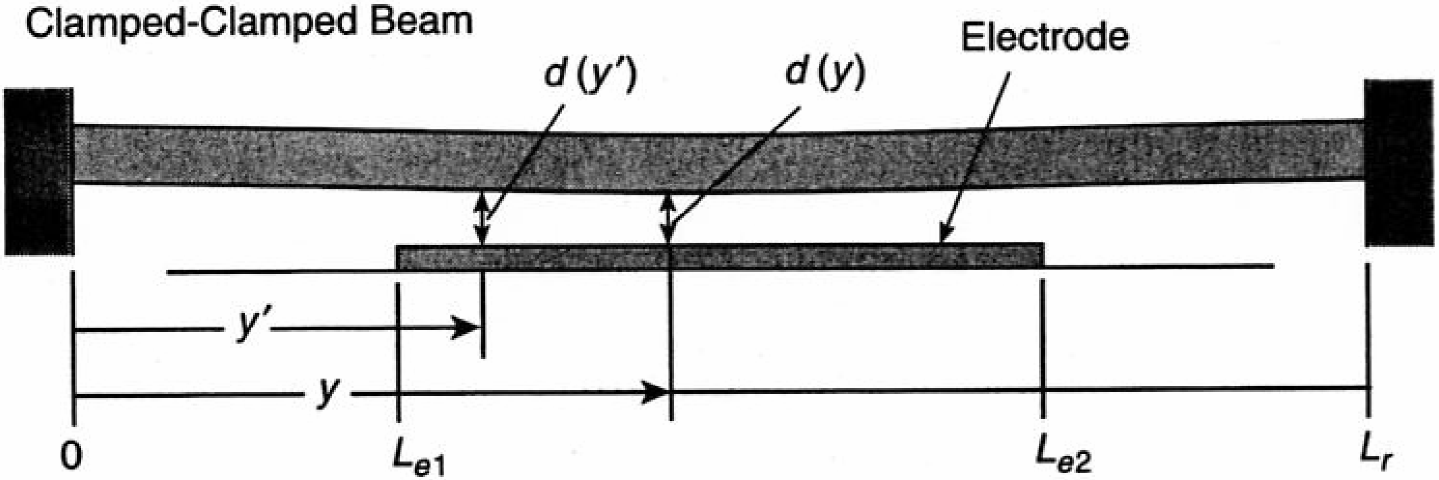


Figure 12.9. Resonator cross-sectional schematic for frequency-pulling and impedance analysis.

Simplification **(De Los Santos):**

Assume that the beam is flat over the electrode

Potential energy $$U_1 = \frac{1}{2} C V_P^2$$

Work being done to move the beam a distance g AGAINST the force due to the electrical beam stiffness k_e
(The spring stiffness is now considered to be CONSTANT in each pont y´)

$$U_2 = \int_0^g k_e \cdot x \cdot dx = \frac{1}{2} k_e \cdot g^2$$

The energies can be set equal $$\frac{1}{2} k_e \cdot g^2 = \frac{1}{2} C \cdot V_P^2$$

Simplified expression for the electrical beam stiffness $$k_e = \frac{C \cdot V_P^2}{g^2}$$

Simplified expression for frequency

$$f = \frac{1}{2\pi}\sqrt{\frac{k_m - k_e}{m_r}} = \frac{1}{2\pi}\sqrt{\frac{k_m}{m_r}\left(1 - \frac{k_e}{k_m}\right)}$$

$$= \frac{1}{2\pi}\sqrt{\frac{k_m}{m_r}} \cdot \sqrt{1 - \frac{k_e}{k_m}} = f_{nom} \cdot \sqrt{1 - \frac{C \cdot V_P{}^2}{k_m \cdot g^2}}$$

Substitute for C: $C = \varepsilon_0 \cdot \frac{A}{g}$

$$f = f_{nom} \cdot \sqrt{1 - \frac{\varepsilon_0 \cdot A \cdot V_P{}^2}{k_m \cdot g^3}}$$

Beam-softening

- Resonance frequency decreases by

$$\sqrt{1 - C_0 \cdot V_P{}^2 / (k_m \cdot g^2)}$$

  - **→ resonance frequency may be tuned electrically!**

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}} = 1.03\kappa\sqrt{\frac{E}{\rho}\frac{h}{L_r^2}}\,[1 - g(V_P)]^{1/2}, \qquad (12.2)$$

”free-free-beam”

- f-f-beam is suspended with 4 support-beams in width-direction
  - **Torsion-springs**
  - Suspension points at **nodes** for beam ”flexural mode”
- Support-dimension is a **quarter-wavelength** of f-f-beam resonance frequency
  - The impedance seen at the nodes is infinite preventing energy propagating along the beam to the anchor
  - Beam is free to vibrate as it was not anchored
  - Beneficial for reducing energy loss via anchors to substrate

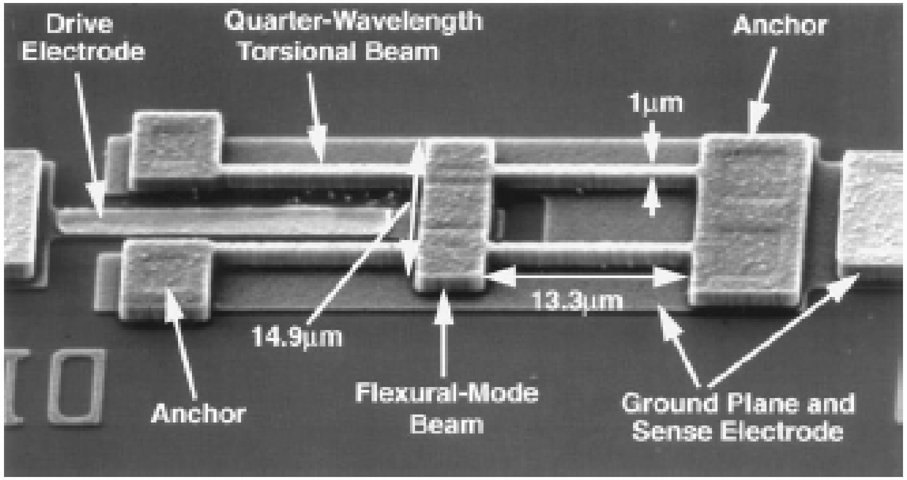
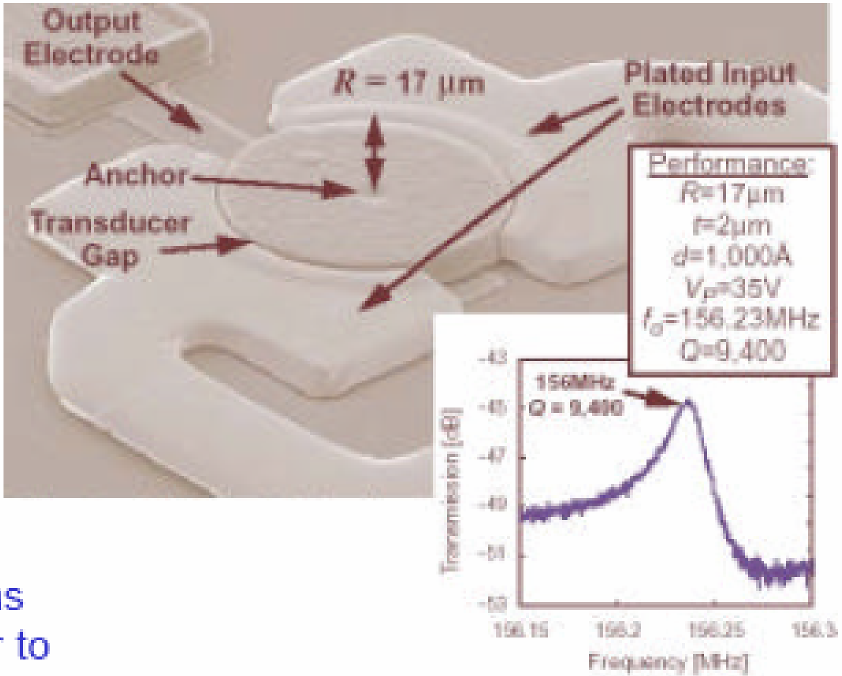


Fig. 29. SEM of free–free beam virtually levitated micromechanical resonator with relevant dimensions for $f_o = 71$ MHz.

Nguyen, 1999

Increasing the Resonant Frequency

option 2. spring rate → ∞



Clark Nguyen, Michigan

Motivation: keep mass as large as possible in order to improve precision of fab, power handling

IEEE IEDM 2000.

Disk resonators

- Advantages of using disks compared to beams
  - Reduced air damping
    - Vacuum not needed to measure Q-factor
  - Higher stiffness
    - Higher frequency for given dimensions
  - Larger volume
    - Higher Q because more energy is stored
    - Less problems with thermal noise
- Periphery of the disk may have different motional patterns
  - Radial, wine-glass

Micromechanical filter: 3 * resonators

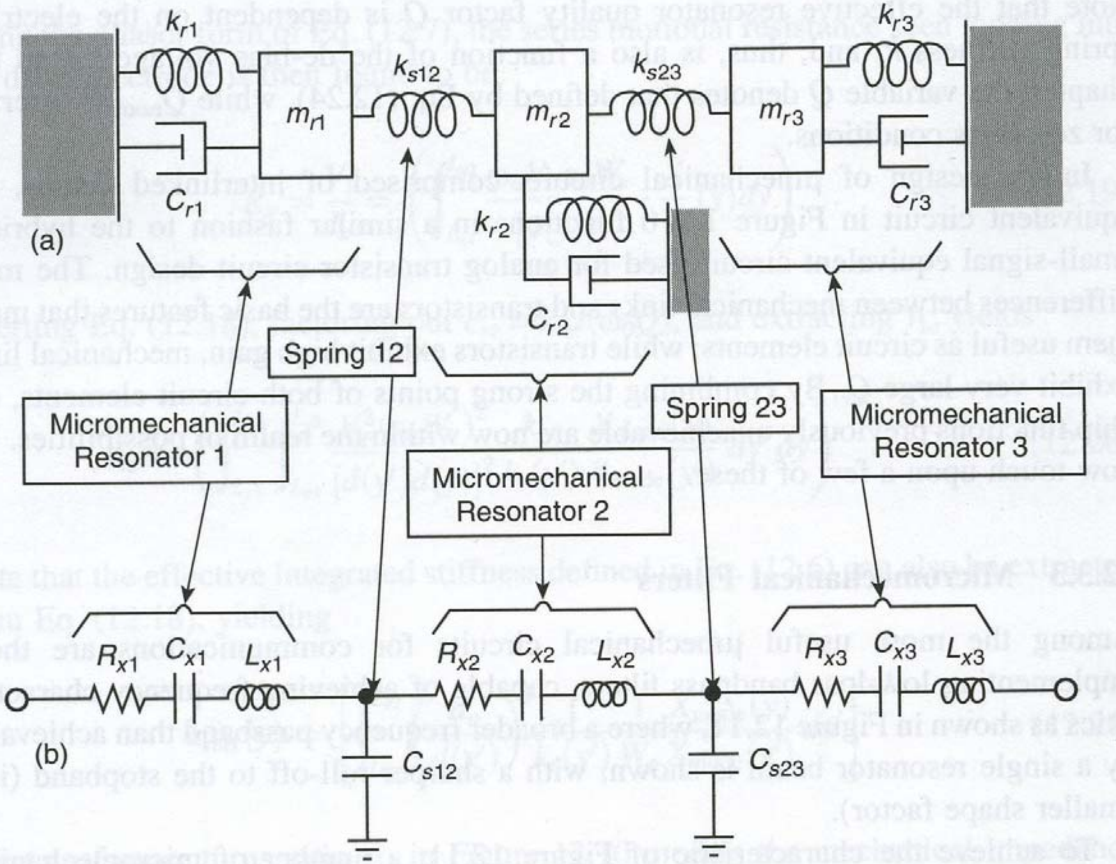
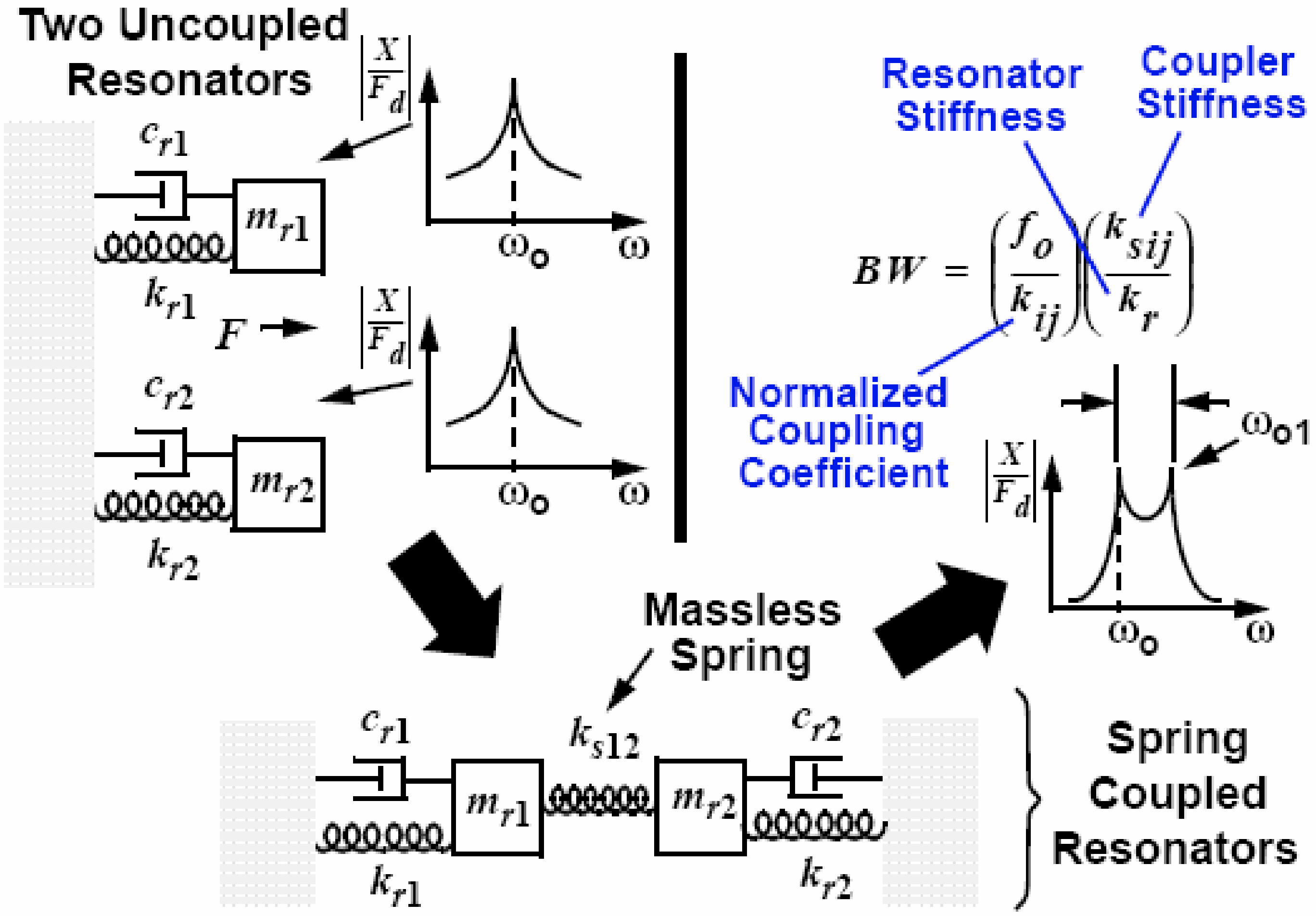


Figure 12.12. (a) Equivalent lumped-parameter mechanical circuit for a mechanical filter. (b) Corresponding equivalent *LCR* network.

Ideal Spring Coupled Filter



Two Uncoupled Resonators

Resonator Stiffness

Coupler Stiffness

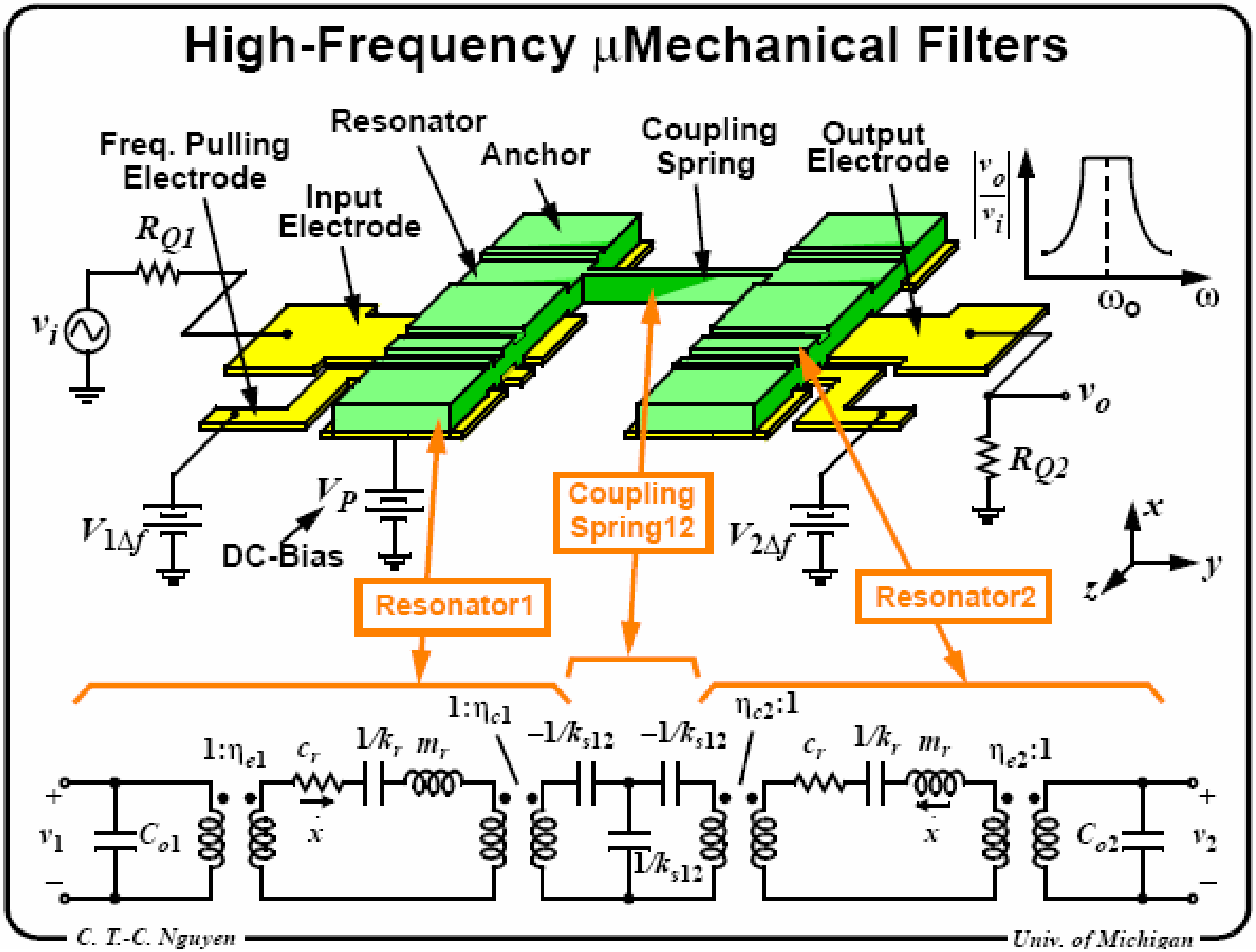
$$BW = \left(\frac{f_o}{k_{ij}}\right)\left(\frac{k_{sij}}{k_r}\right)$$

Normalized Coupling Coefficient

Massless Spring

Spring Coupled Resonators

2-resonator HF-VHF micromechanical filter



Design

- At centre frequency f0 and bandwidth B, spring constants must fulfill

$$B = \left(\frac{f_0}{k_{ij}}\right) \cdot \left(\frac{k_{sij}}{k_r}\right)$$

  - k_{ij} = normalized coupling coefficient taken from filter cook books
  - **Ratio** $\left(\frac{k_{sij}}{k_r}\right)$ important, NOT absolute values
- **Theoretical** design procedure *
- (* can not be implemented)
  - Determine f_0 and k_r Choose k_{sij} for required B
  - I real life this procedure is **modified**

Design procedures c-c beam filter

- A. Design resonators first
  - This will give constraints for selecting the stiffness of the coupling beam
  - → bandwidth B can not be chosen freely!

or

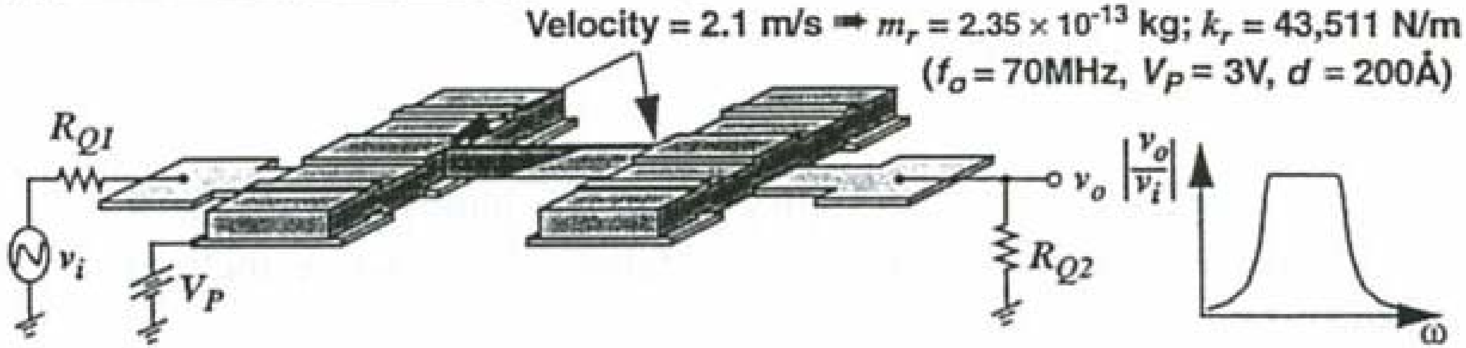
- B. Design coupling beam spring constant
  - Determine the spring constant the resonator must have for a given B
  - → this determines the coupling point!

Design procedure B

- **B1.** Use **coupling points** on the resonator to determine filter bandwidth
  - B determined by the ratio $\dfrac{k_{s12}}{k_{rc}}$
    - k_{rc} is the value of k at the **coupling point!**
    - k_{rc} position dependent, especially of the **speed** at the position
    - k_{rc} **can be selected by choosing a proper coupling point of resonator beam!**
- The dynamic spring constant k_{rc} for a c-c beam is largest nearby the anchors
  - k_{rc} **is larger for smaller speed of coupling point at resonance**

Position of coupling beam

(a) Max. Velocity Coupling: yields large % bandwidth


Velocity = 2.1 m/s ➡ $m_r = 2.35 \times 10^{-13}$ kg; k_r = 43,511 N/m
(f_o = 70MHz, V_P = 3V, d = 200Å)

(b) Low Velocity Coupling: allows much smaller % bandwidth

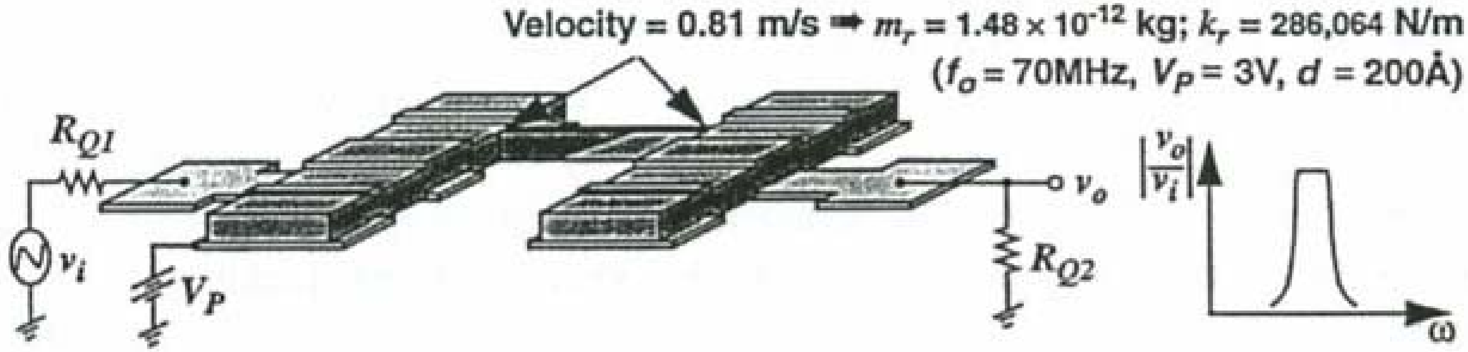

Velocity = 0.81 m/s ➡ $m_r = 1.48 \times 10^{-12}$ kg; k_r = 286,064 N/m
(f_o = 70MHz, V_P = 3V, d = 200Å)

Figure 12.15. Filter schematics showing (a) maximum velocity coupling to yield a large percent bandwidth and (b) low-velocity coupling to yield a smaller percent bandwidth.

Mixer -filter

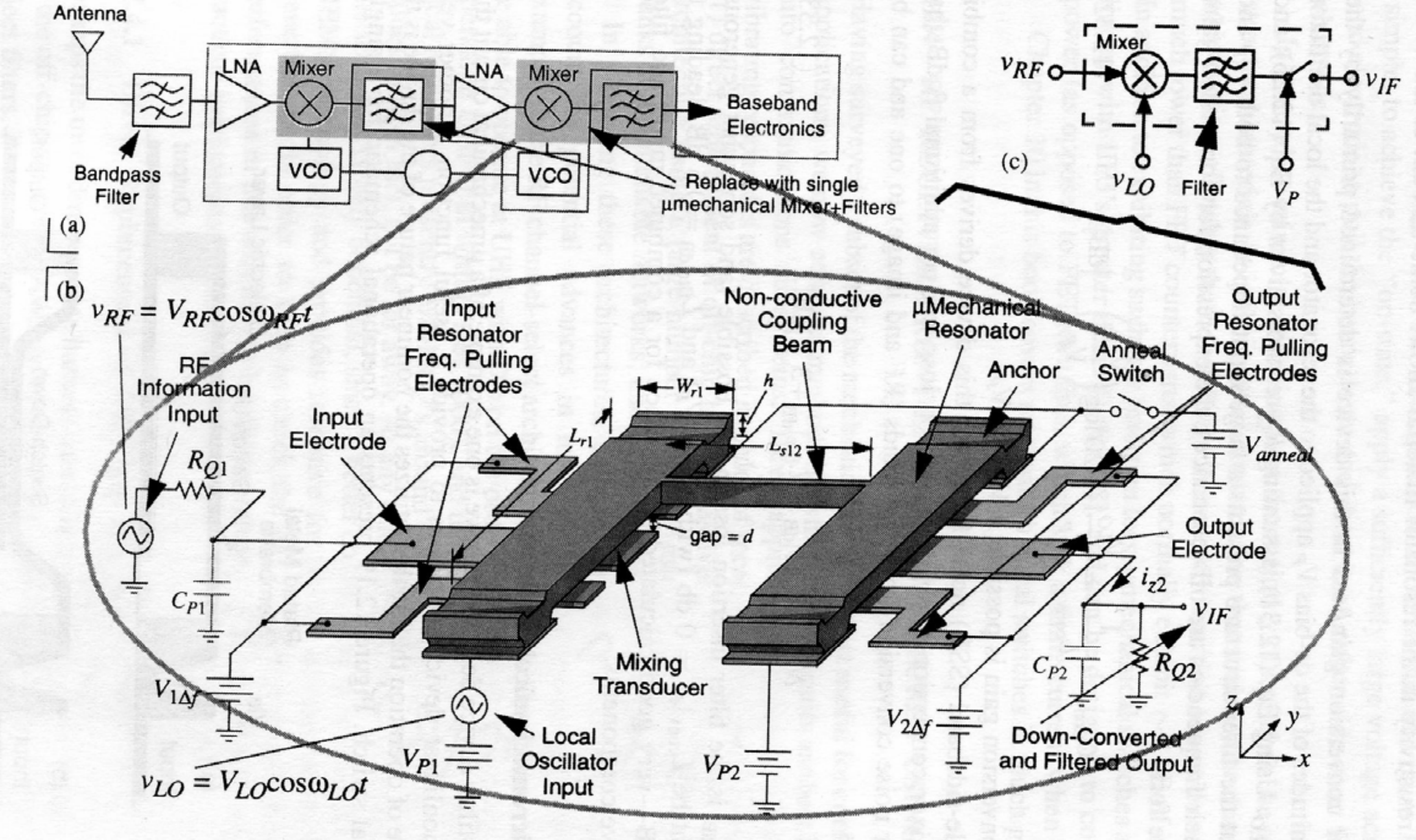


Figure 12.18. (a) Simplified block diagram of a wireless receiver, indicating (with shading) the components replaceable by mixer-filter devices. (b) Schematic diagram of the described µmechanical mixer–filter, depicting the bias and excitation scheme needed for downconversion. (c) Equivalent block diagram of the mixer–filter scheme.

Passive components in RF circuits

- → **MEMS capacitors and inductors**
  - Relevant as **replacements** for traditional ”off-chip” passive components
  - Tuneability and programability are desired
- **MEMS capacitors**
  - Simple, tunable capacitances
    - **= varactor** (”variable reactor”)
  - Programable capacitance banks with fixed C
- **MEMS inductors**
  - Simple, fixed inductors
  - Programable inductance banks with fixed L

Tunable RF MEMS capacitors

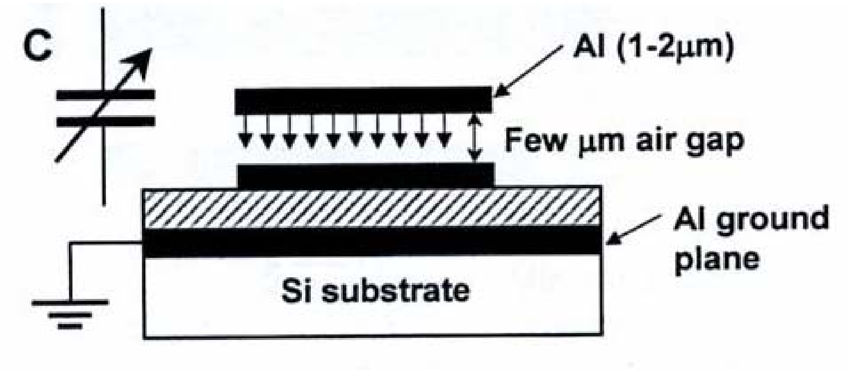
- Electrostatic actuation is a dominating mechanism for tuning
  - Low power consumption, simple
- **Vertical** electrostatic displacement
  - Tuning the gap (**non-linear** change) in parallel plate capacitor
    - 2-plate capacitance
    - 3-plate capacitance
    - Double air-gap capacitance
    - Other examples
- **Horizontal** (lateral) displacement
  - Tuning of area (**linear** change)
- **Thermal** tunable MEMS capacitance
- **Piezoelectric** actuator tunable capacitance
- Tuning by change of **dielectric** material

Challenges for RF MEMS capacitors

- ÷ Tuning ratio for MEMS varactors is small
  - 1.2 – 2.5
  - For semiconductor varactors: 4 – 6
  - → Obtain required **Tuning Ratio (TR)**
    - Definition TR: $C_{\max}/C_{\min}$
    - Should be > 2
- ÷ MEMS is sensitive to various noise effects present for low spring constant, k
  - Low k is desired for 3 – 5 V applications
  - Is a challenge due to
    - Acceleration, RF power self actuation, noise effects

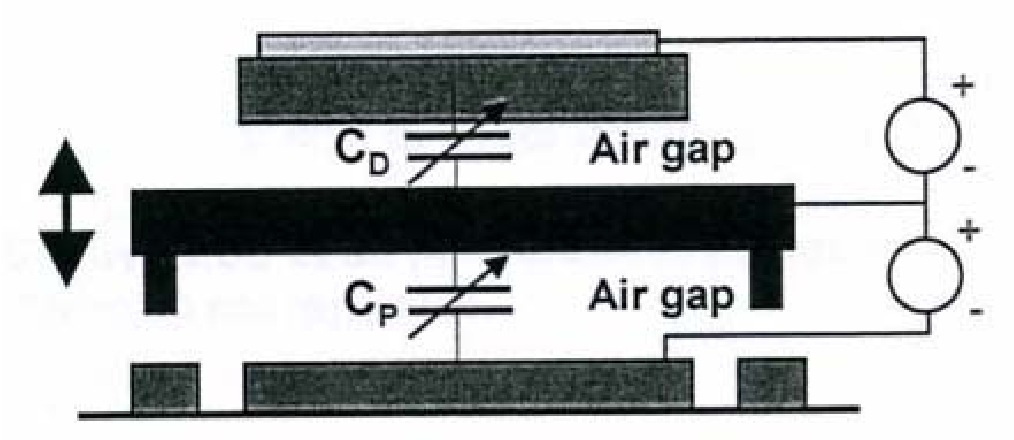
Two-plate tunable MEMS capacitance

- Young & Boser, Berkeley
- Gap-tuning
- One plate can move by electrostatic actuation
- Equilibrium between elastic and electrical forces



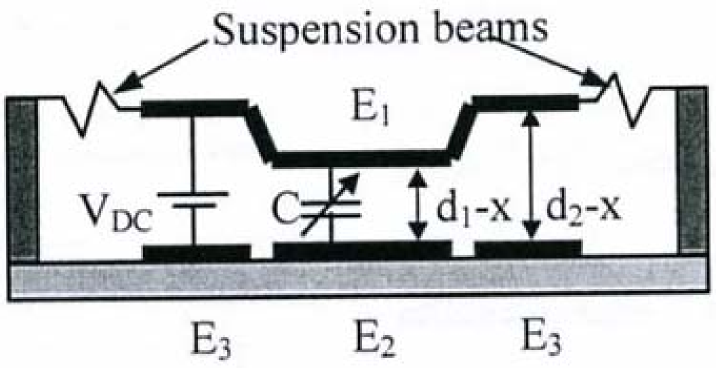
3-plate tunable MEMS capacitance

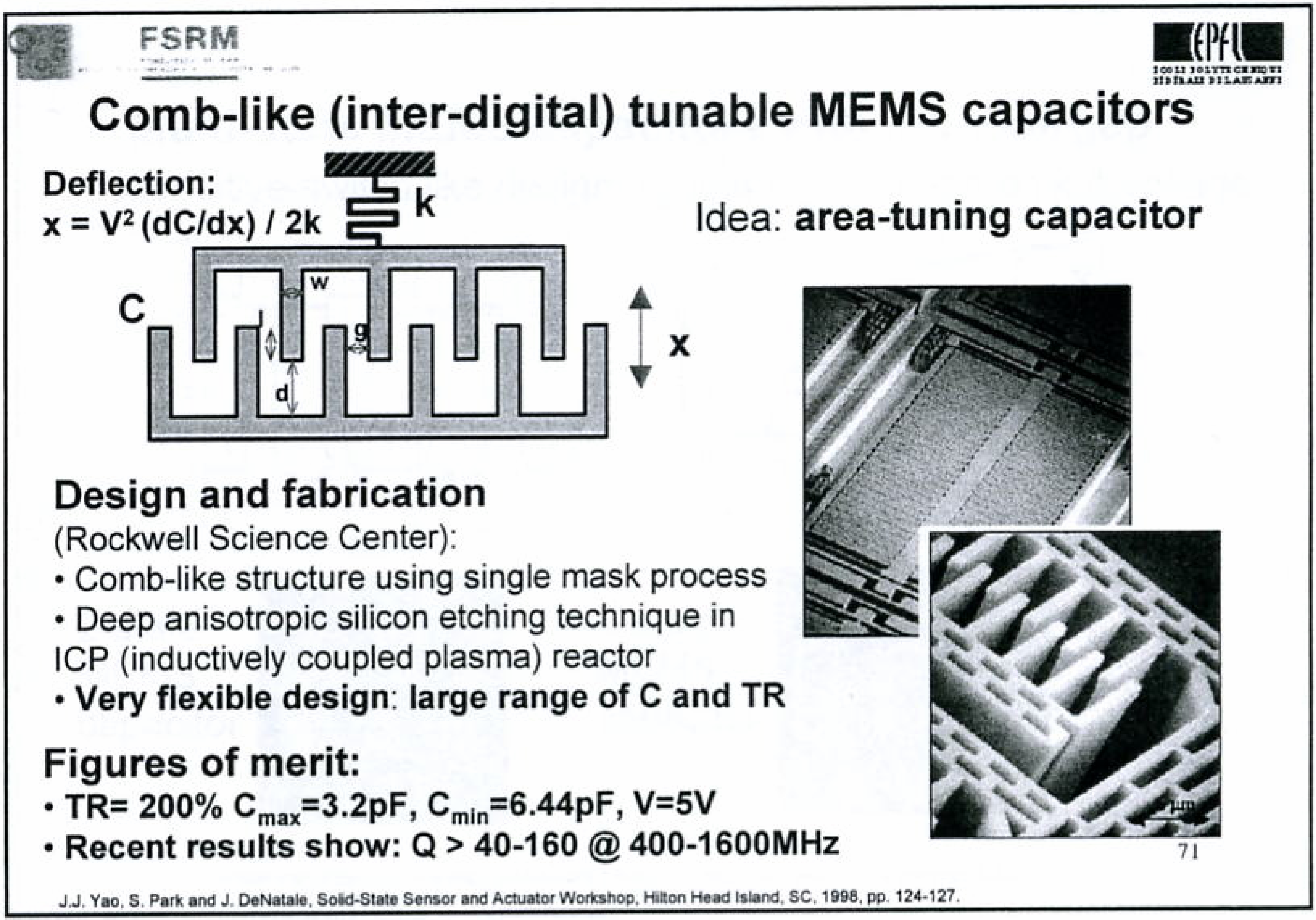
- TR can be increased by introducing a 3rd plate
  - A. Dec & K. Suyama: ”Micromachined Electro-Mechanically Tunable Capacitors and Their Applications to RF IC´s” 1998. **Columbia University**



Double air-gap capacitance

- J. Zou et al, 2000, Univ of Illinois
- Why double air-gap?
  - – Increase TR
    - Eliminate pull-in effect
  - – May deflect down to 1/3 d_2 before pull-in
  - – TR may increase significantly if 1/3 $*d_2 > d_1$
    - Eg. **centre electrode can be fully deflected without pull-in!**





Comb-like (inter-digital) tunable MEMS capacitors

Deflection:
$x = V^2 (dC/dx) / 2k$

Idea: **area-tuning capacitor**

Design and fabrication
(Rockwell Science Center):

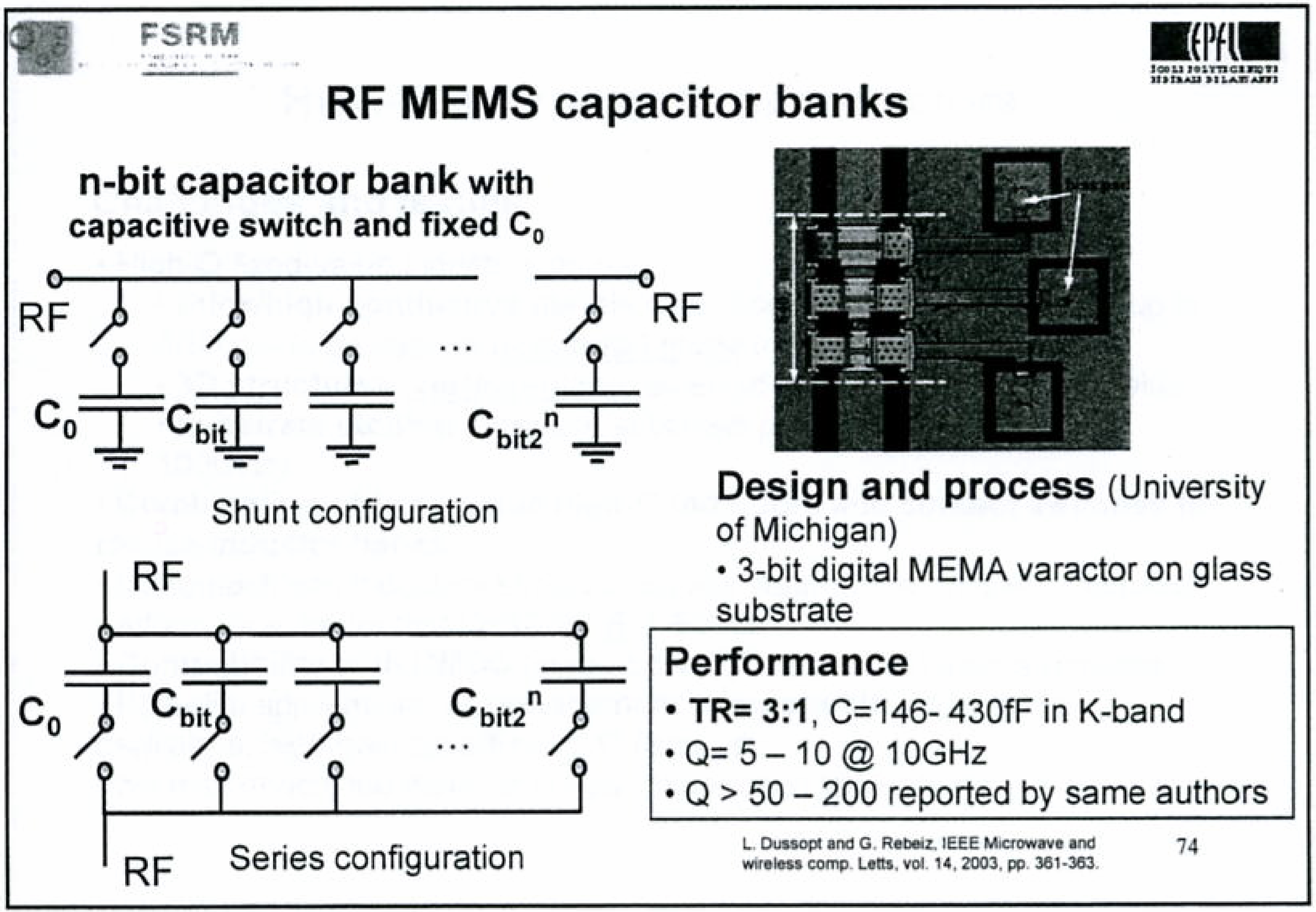
- Comb-like structure using single mask process
- Deep anisotropic silicon etching technique in ICP (inductively coupled plasma) reactor
- **Very flexible design**: **large range of C and TR**

Figures of merit:

- **TR= 200% C_{max}=3.2pF, C_{min}=6.44pF, V=5V**
- **Recent results show: Q > 40-160 @ 400-1600MHz**

J.J. Yao, S. Park and J. DeNatale, Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, 1998, pp. 124-127.

Ionescu, EPFL: J. J. Yao et al, Rockwell



FSRM

RF MEMS capacitor banks

n-bit capacitor bank with capacitive switch and fixed C_0

Shunt configuration

Series configuration

Design and process (University of Michigan)

- 3-bit digital MEMA varactor on glass substrate

Performance

- **TR= 3:1**, C=146- 430fF in K-band
- Q= 5 – 10 @ 10GHz
- Q > 50 – 200 reported by same authors

L. Dussopt and G. Rebeiz, IEEE Microwave and wireless comp. Letts, vol. 14, 2003, pp. 361-363.

Ionescu, EPFL

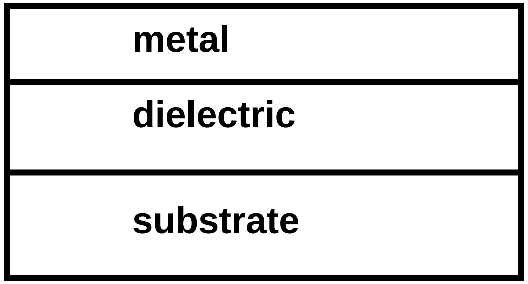
RF MEMS inductors

- Two-dimensional (planar) inductors
- Three-dimensional inductors, solenoids

- Only fixed-value inductor can be implemented
  - No practical implementation of tunable inductors exist
- Variable inductance values: implemented as **inductor bank**
  - Many inductors with fixed, high Q-value
  - In combination with MEMS contact switches

Planar inductors, in general

- Implemented in a single plane
- One **metal layer** patterned by etching
- Inductor rest on a **substrate** covered by a **dielectric**
- **Loss** in inductor due to:
  - Finite metal conductivity
  - Loss in dielectric
  - Loss in substrate



metal

dielectric

substrate

- Area limitations for RF
  - Total length of an inductor has to be significantly shorter than the wavelength
    - Gives then negligible phase shift of signal

Different planar geometries

- Distance between lines is critical
- Circular spiral has a shorter length than a quadratic spiral
  - → Lower R
  - Q is about 10% higher with same "diameter", d_0
- Higher Q achieved by increasing number of turns per area
  - Self resonance frequency decreases due to the increase in capacitance → limits the region of use

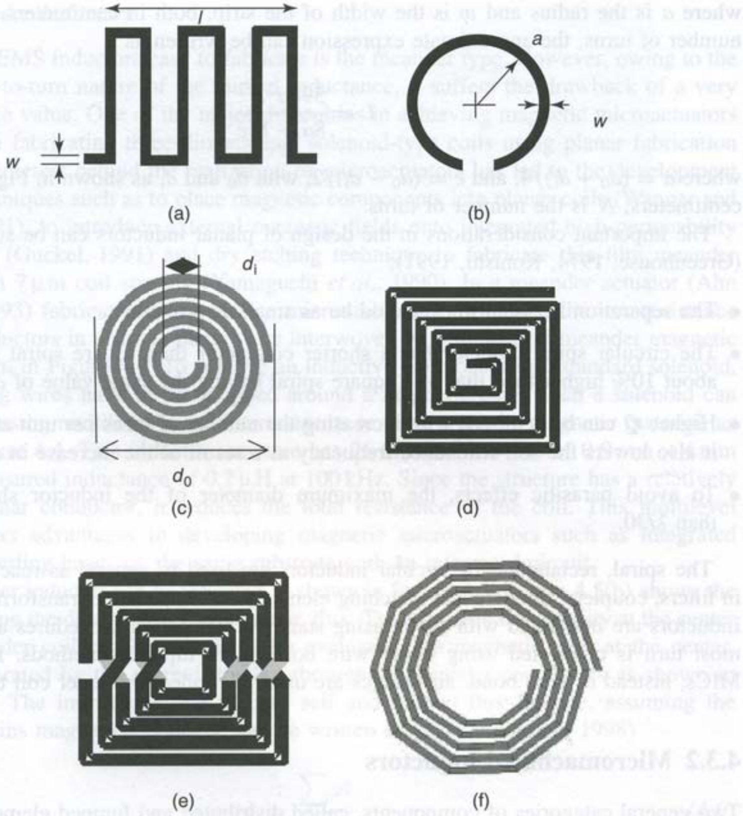


Figure 4.3 Schematic diagram of common planar inductors: (a) meander; (b) loop; (c) circular spiral; (d) square spiral; (e) symmetric spiral; (f) polygon spiral

General model for a planar inductor

Ls is low frequency inductance

Rs is series resistance

Cs is capacitance between windings

C1 is capacitance in oxide layer between inductor and substrate

Cp is capacitance to ground through substrate

Rp is **”eddy current”** loss in substrate

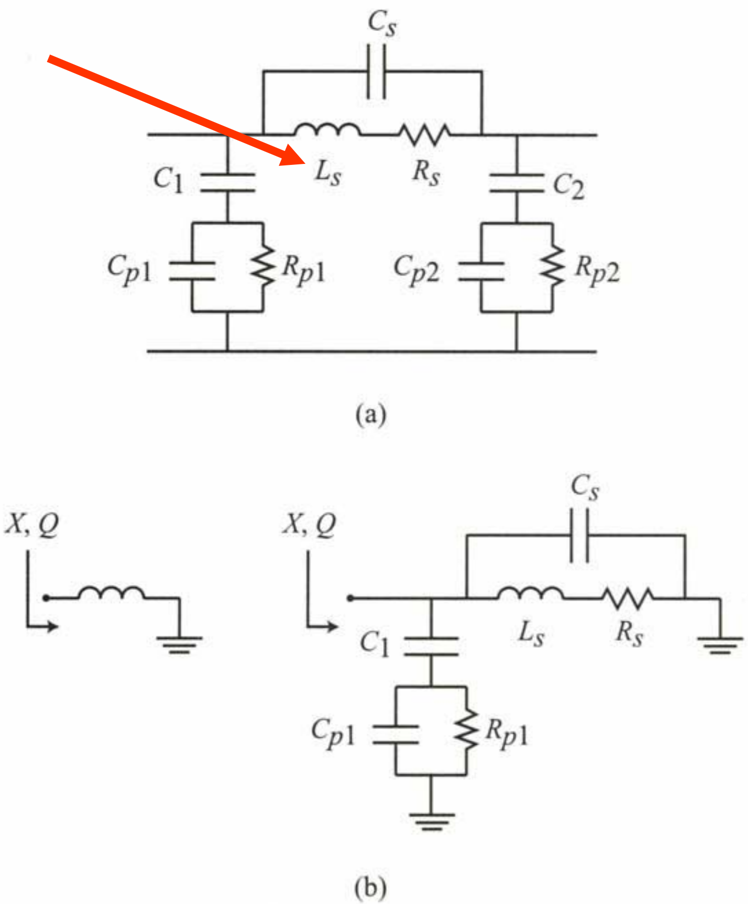


Figure 12.1. (a) The equivalent LRC model of a planar inductor. (b) A short-circuited inductor model typically used in S-parameter and Q measurements. C_{p1} and C_{p2} are often assumed identical and equal to C_p.

Various design parameters

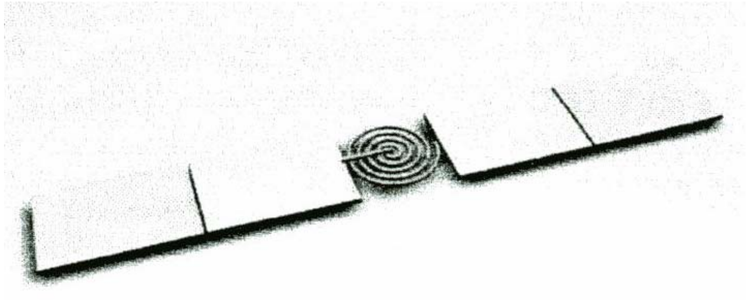
- Structure
  - 2D or 3D, form
- Line spacing
- Line width
- Number of turns
- Magnetic core
- Metal thickness
- Sheet resistance
- Thickness of dielectrics
- Substrate resistivity

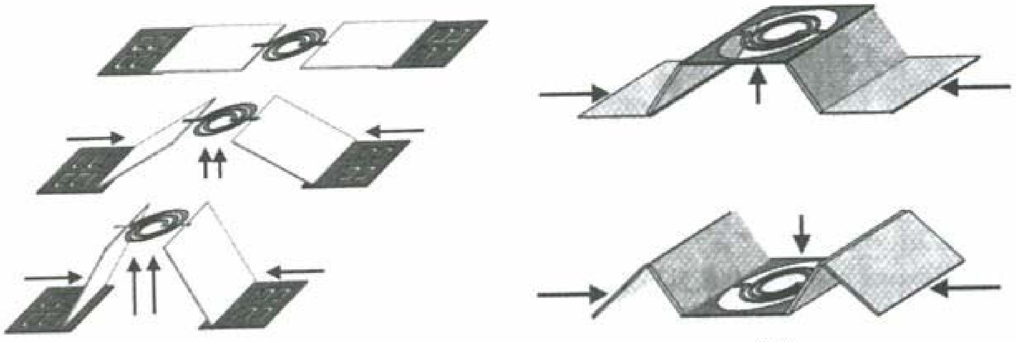
Summary: How to increase performance?

- Have **thick metal layer** with good conductivity
  - To reduce series resistance
- Use **substrate etching**
  - Reduce substrate parasitic capacitance
- Use **3-D** structures
  - For vertical plane solenoids the L-value may increase
- Use of **core material**

Out of plane inductors

- Inductor can be elevated by ”scratch actuators”
  - L. Fan et al, MEMS 1998
  - Elevated 250 µm over Si substrate
  - Resonance at 1.8 – 6.6 GHz after elevation of solenoid





(a) (b)

Figure 4.31 (a) Schematic diagram of the MESA micro-elevator by self-assembly structure; (b) the center platform can move upward or downward. Reproduced from L. Fan, R.T. Chen, A. Nepolsa and M.C. Wu, 1998, ‘Universal MEMS platforms for passive RF components: suspended inductors and variable capacitors’, in *Proceedings of 11th Annual International Workshop on MEMS ’98*, IEEE, Washington, DC: 29–33, by permission of IEEE. © 1998 IEEE

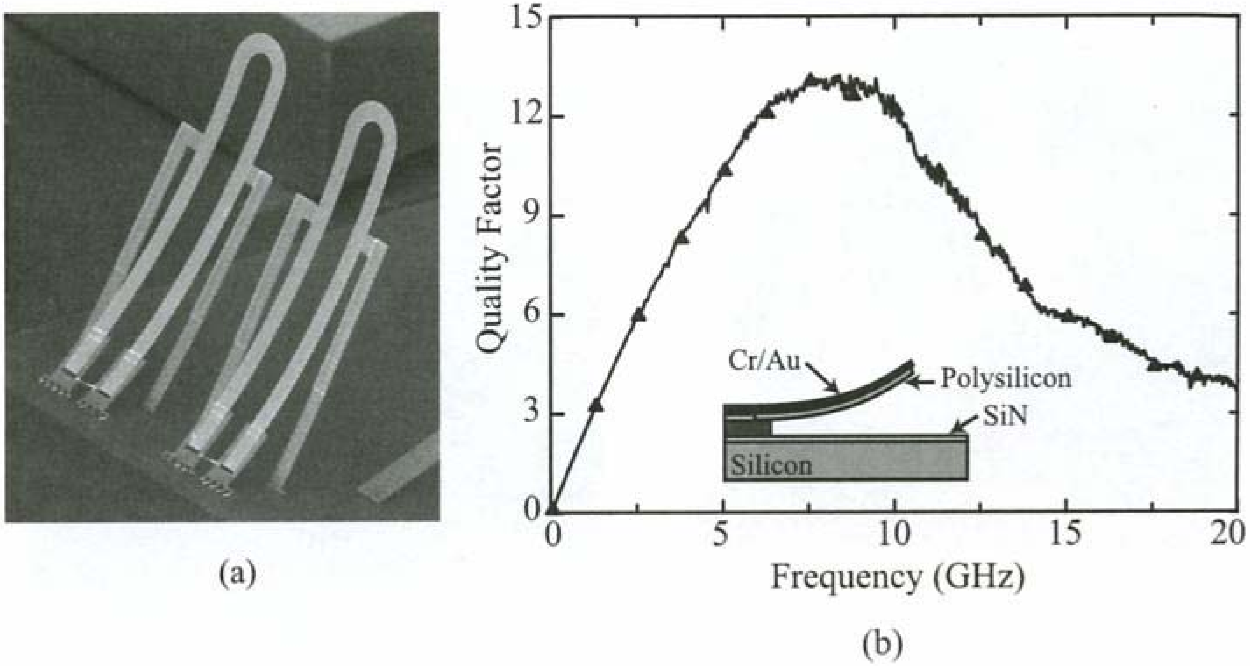
Micromachining using self-assembly

Elevate inductor above substrate to reduce parasitic capacitance

Cr-Au layer over poly-layer

Different residual **stress** in materials make the inductor **”curl”** above substrate

Anchor causes a significant parasitic capacitance

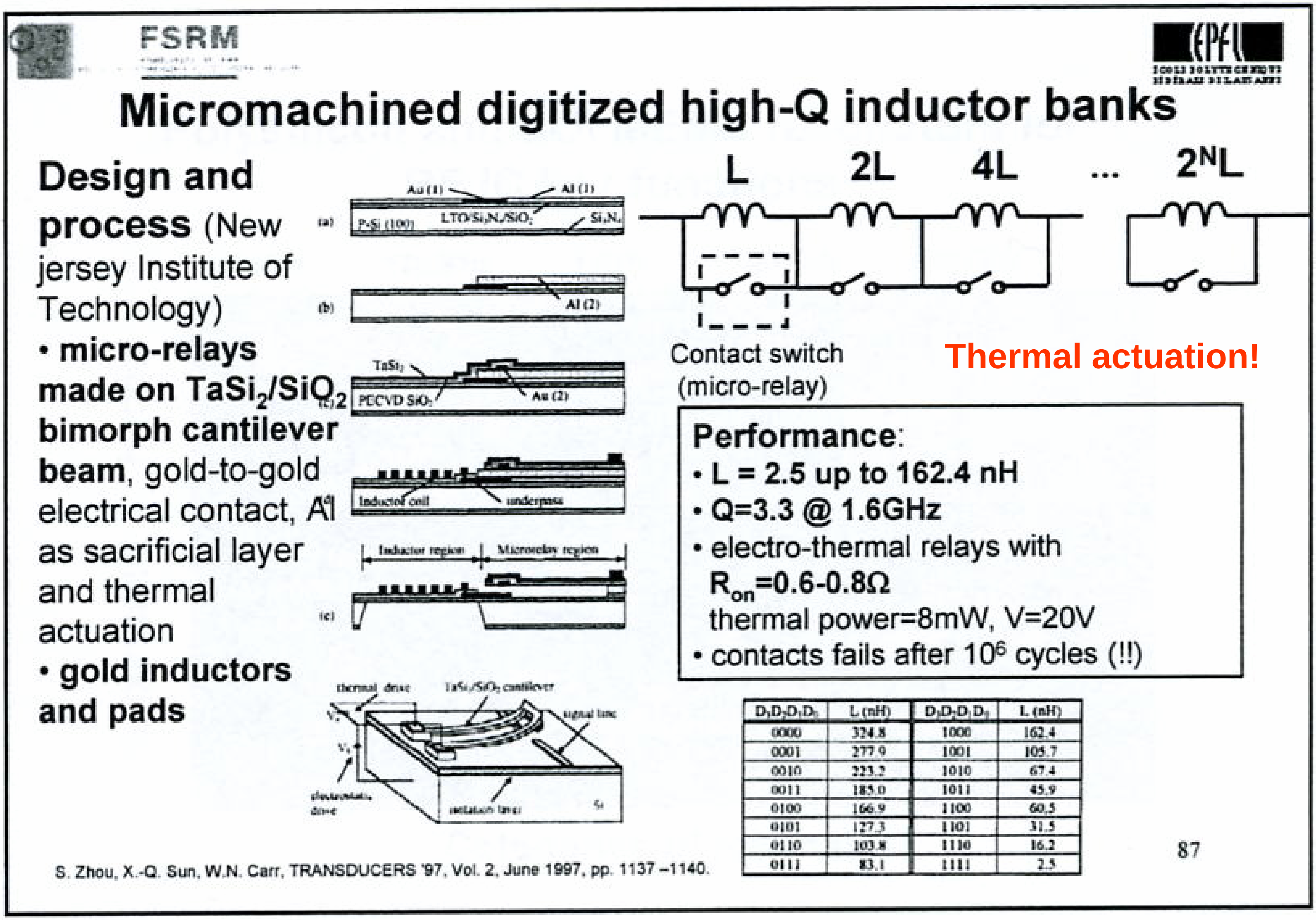


(a)

(b)

Figure 12.12. Picture (a) and measured Q (b) of a self-assembled 1.2-nH inductor [20] (Copyright IEEE).

Programmable inductor banks



Micromachined digitized high-Q inductor banks

Design and process (New jersey Institute of Technology)

- **micro-relays made on $TaSi_2/SiO_2$ bimorph cantilever beam**, gold-to-gold electrical contact, Al as sacrificial layer and thermal actuation
- **gold inductors and pads**

Contact switch (micro-relay)

Thermal actuation!

Performance:

- **L = 2.5 up to 162.4 nH**
- **Q=3.3 @ 1.6GHz**
- electro-thermal relays with **R_{on}=0.6-0.8Ω** thermal power=8mW, V=20V
- contacts fails after 10^6 cycles (!!)

$D_3D_2D_1D_0$	L (nH)	$D_3D_2D_1D_0$	L (nH)
0000	324.8	1000	162.4
0001	277.9	1001	105.7
0010	223.2	1010	67.4
0011	185.0	1011	45.9
0100	166.9	1100	60.5
0101	127.3	1101	31.5
0110	103.8	1110	16.2
0111	83.1	1111	2.5

S. Zhou, X.-Q. Sun, W.N. Carr, TRANSDUCERS '97, Vol. 2, June 1997, pp. 1137 –1140.

Purpose of packaging

- For **secure** and **reliable** interaction with environment **packaging** is needed
- Package:
  - Is a mechanical **support**
  - Has **signal connections** to the physical world
  - Provides **heat transport**
  - Gives environmental **protection**
  - Makes **contact** with environment possible
    - Pressure sensor
    - Liquid system

Different packages used

- Important issues
  - Package size, form, number of pins
  - Package material
- Different package types
  - **Ceramic packages**
  - **Metal packages**
  - **Polymer packages**
- Package can be combined with a 1. level encapsulation
  - Die level encapsulation: ”microcaps”
  - Interesting if MEMS does not need direct contact with liquids and gasses

Integration of IC and MEMS

- Separate MEMS- and IC-dies can be impractical and costly
  - Often the only possibility
    - Due to different technology requirements
  - **+** MEMS and CMOS may then be individually **optimized**
  - **-** Parasitic capacitances, impedances!
  - **→ One-chip solution desired! (monolithic integration)**

- Technologies for monolithic integration
  - **Pre-circuits (Pre-CMOS)**
  - **Mixed circuit- and micromechanics (Intermediate CMOS)**
  - **Post-circuits (Post-CMOS)**

Pre-CMOS circuits

- Fabricate micromechanics first, - then IC
- Benefits
  - May fabricate MEMS optimally
  - Only one passivation step needed after micromechanics processing
  - Upgrade each process module individually

- Drawbacks
  - Large topography variations present after MEMS (ex. of 9 µm)
  - CMOS photo resist spinning and patterning become more difficult
    - Especially for submicron circuits
    - CMOS and MEMS have different minimum geometries!
  - Must make the surface planar before CMOS processing
  - CMOS foundry processes do not allow ”dirty” MEMS wafers into the fabrication line

Mixed circuit- and micromechanics

- IC and MEMS-processes integrated into one process
  - ”MEMS in the middle”

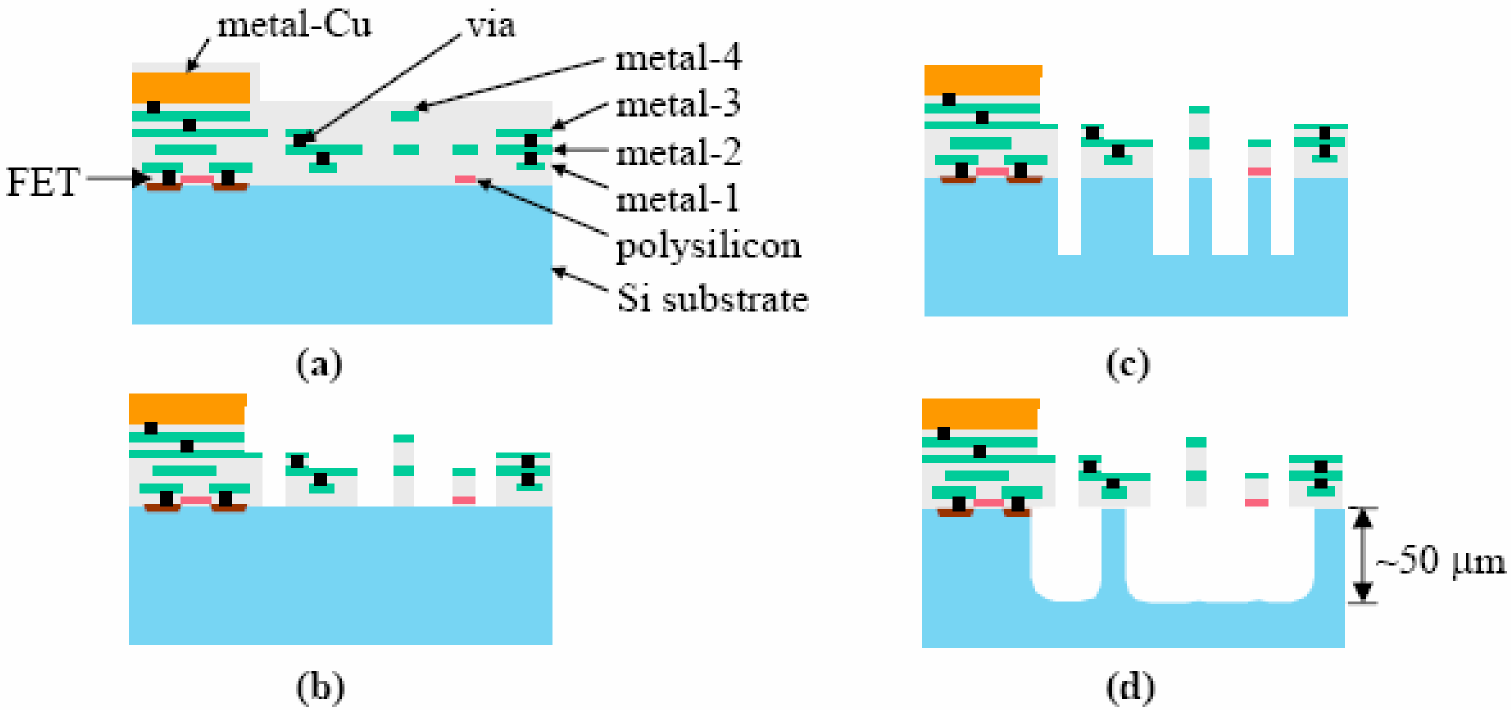
- Drawbacks
  - Limitations on MEMS structures that can be fabricated
  - Many passivation layers needed
    - When switching between circuit and micromechanics process
  - Only custom CMOS-processes can be used
  - Total redesign of the whole process if one of the combined technologies (“modules”) is changed
  - Ex. of a combination process →

Post-CMOS circuits

- CMOS circuit processing performed **before** MEMS
  - Possibly the most promising procedure
  - Planarization not needed
  - May use advanced/standard IC foundries and succeeding micromechanical processing
  - Method gradually developed

- Drawbacks
  - **Difficulties with CMOS Al-based metallization**
    - Al can not withstand the **high temperature steps** needed for several micromechanical process steps
      - Especially those needed for high Q: f.ex. polySi deposition/annealing
  - Compromises must be done for one or both processes
    - Ex. MICS process: Tungsten (“wolfram”) as CMOS metal
    - Ex. UoC Berkely: use SiGe as MEMS structure material

ASIMPS at CMU

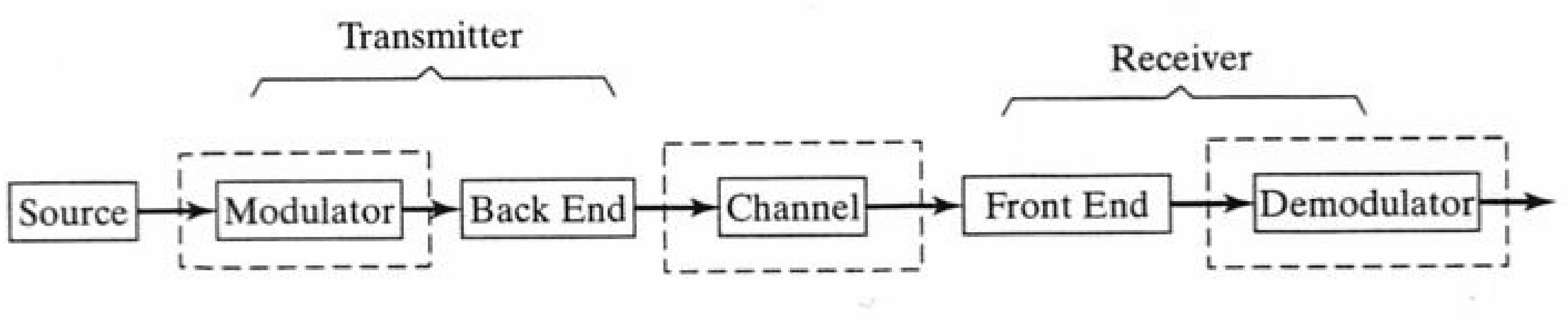


(a) (c)

(b) (d)

Figure 1. ST7RF CMOS MEMS process flow. (a) Foundry CMOS before micromachining; (b) CHF$_3$/O$_2$ reactive-ion etch of dielectric stack down to the silicon substrate; (c) Deep reactive-ion etch of Si substrate (nominal 35 μm deep); and (d) Si undercut (nominal 15 μm undercut and 50 μm deep).

General communication system



Bit streams are modulated (coded) onto a **carrier**

Radio channel introduces noise, interference, disturbances

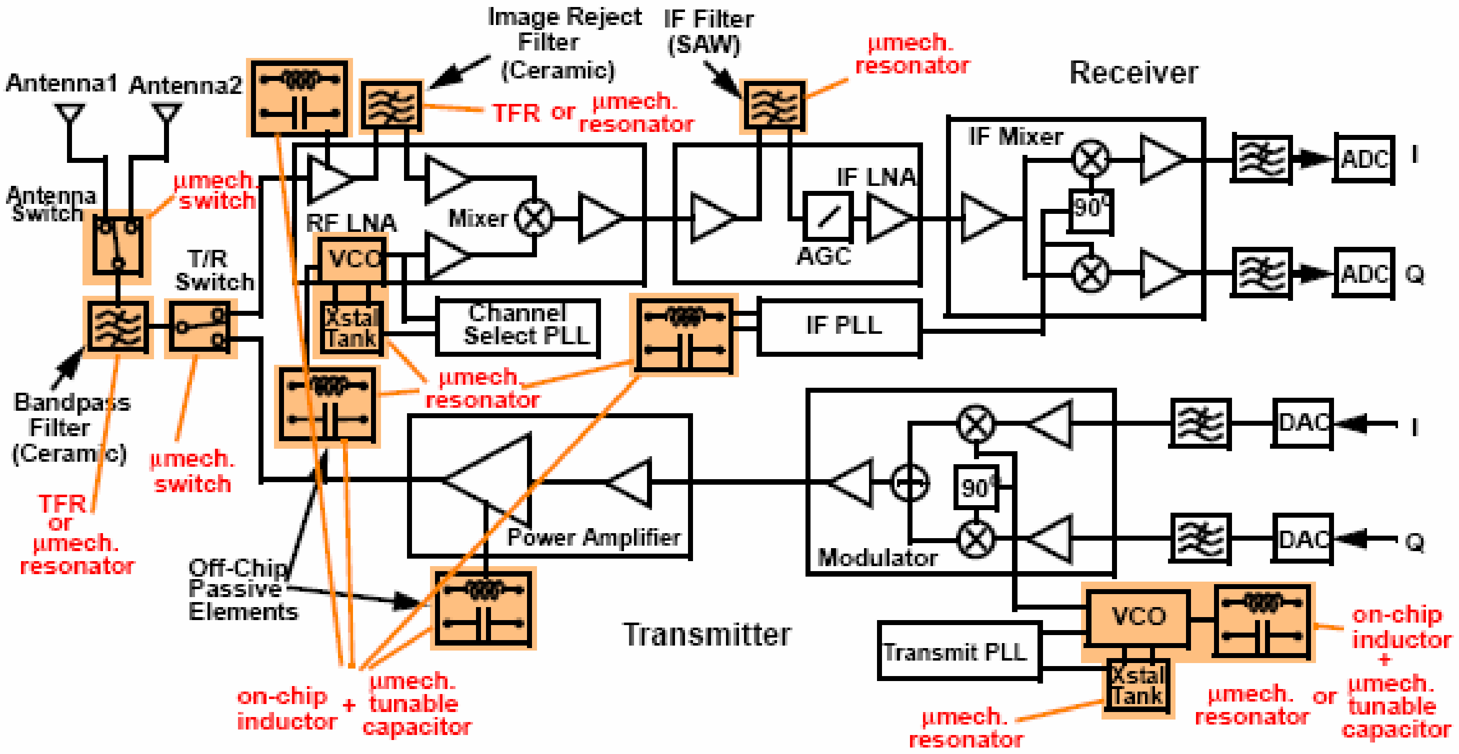
Receiver shapes the signal for demodulation

Present technology

- Technology and components used today
  - **Discrete**, **passive** components with good properties
    - R, C, L
    - Ex. crystals, inductors
  - Such components needed due to **high performance and precision requirements**
  - **Off-chip solutions** are the result
    - PCB assembly
    - Systems take a lot of space
    - Integrated solutions not possible

  - **Active** components
    - Amplifiers, switches
    - GaAs, bipolar Si, CMOS Si, PIN-diodes

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

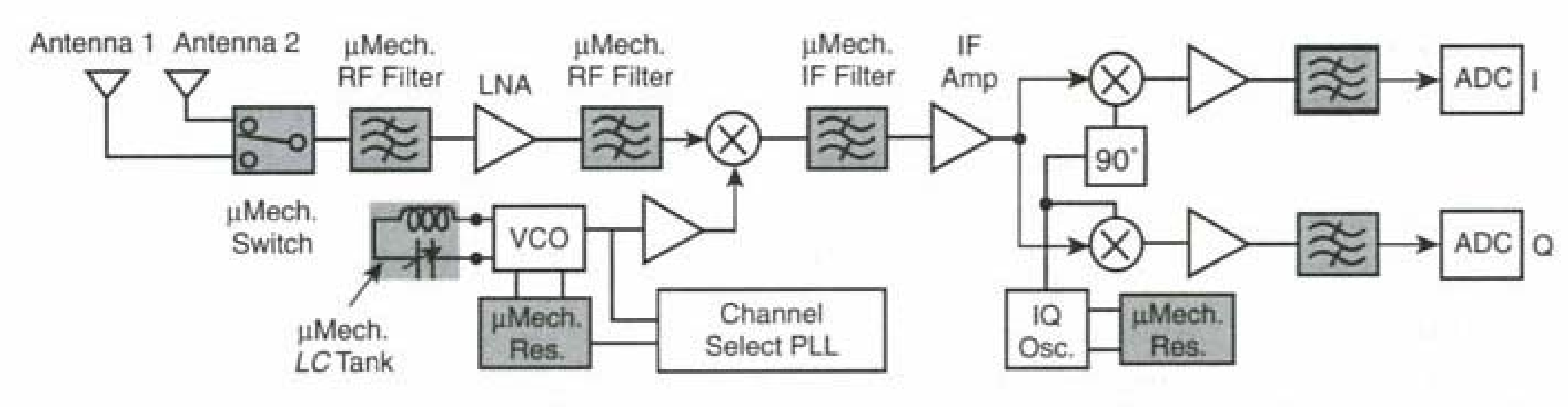
C. T.-C. Nguyen *Univ. of Michigan*

Itoh et al, fig 12.1

Benefits of MEMS substitutes

- Reduction of **dimensions**
- Possible **integration**
  - Multi-chip
  - Monolithic
- **Power reduction**
- More flexibility for **impedance matching** of MEMS filters

- **Termination impedance** matched to the following LNA (Low Noise Amplifier)
  - ”Higher” (than 50 Ω) LNA input impedance can be used → power reduction and reduced noise



B. Special RF MEMS blocks

- Figure shows 3 basic blocks that are substituted by RF MEMS
  - **B1.** Switchable RF **channel-select filter bank**
  - **B2.** Switchable micromechanical **frequency synthesizer**
  - **B3.** Micromechanical **mixer-filter** block

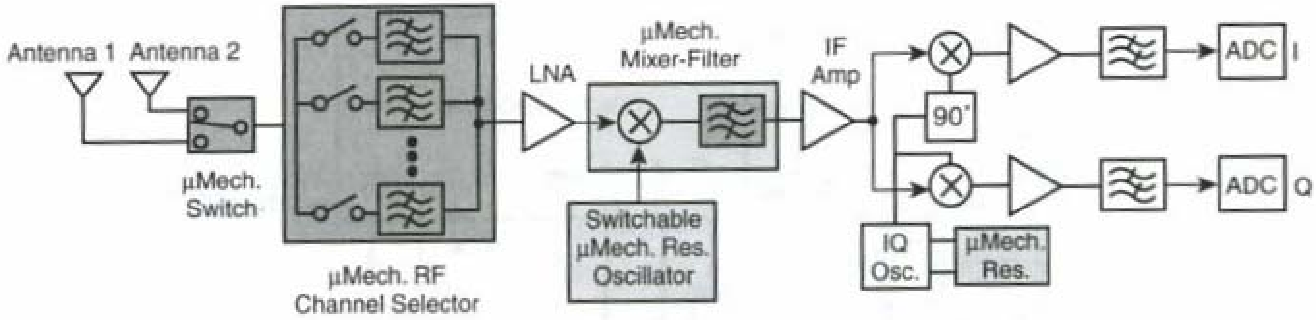
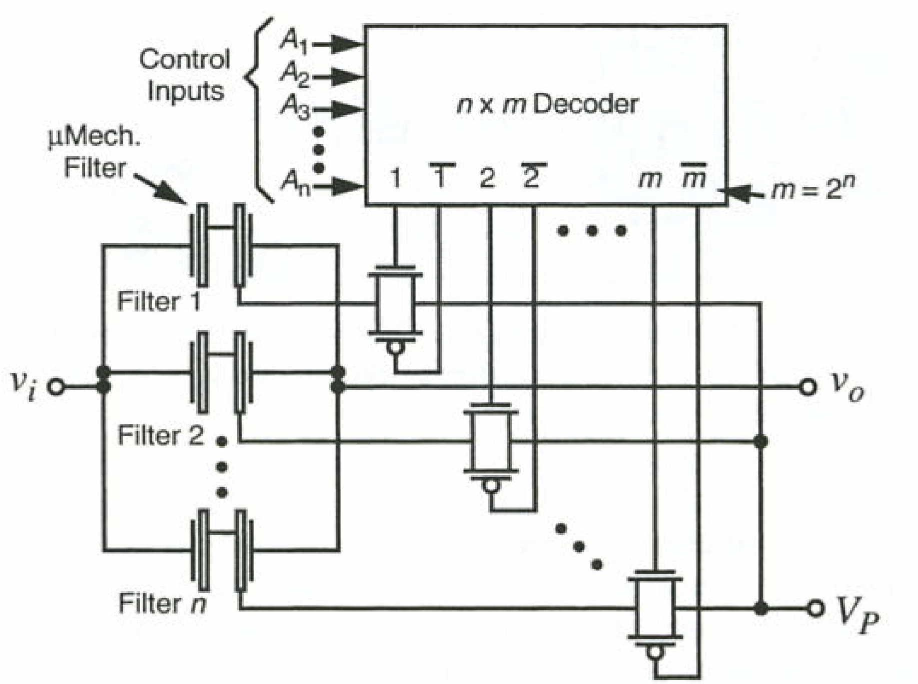


Figure 12.21. System block diagram for an RF channel-select receiver architecture utilizing large numbers of micromechanical resonators in banks to trade *Q* for power consumption. (On-chip µmechanics are shaded.)

B1. Switchable RF channel-select filter bank

- Idea
  - Use **many, simple,** non-tunable filters with high Q
  - One for each channel, - switched on command
  - A communication standard needs 100 – 1000 of filters



- Block diagram
  - Common input and output
  - Controlled by Vp from decoder
    - With no Vp the outputs are effectively ”open-circuited”

Relevant research topics

- The architectures shown are to some extent based on resonators with performance not yet achieved

- Research topics
  - **1.** Obtain required **high Q at UHF**
  - **2.** Set specific **impedance levels**
  - **3.** Good enough **linearity** and capability to sustain **power**
  - **4.** Efficient **integration methods**

Conclusion (source: Ionescu, EPFL)

- RF MEMS is a promising technology for **communication applications**
  - Miniaturisation of critical parts
  - Great potential for low cost
    - Co-integration with IC
  - Increased RF performance
  - Low power applications

Conclusion, contd.

- Central features
  - **Micro mechanical processing!**
  - Co-design of ”elektromechanical / IC” -components
  - Full circuit functionality (filtering og mixing) in **one** function block
  - High Q tunable passive components have been demonstrated
  - New functionality of RF circuits → programmability

- RF IC with only MEMS components
  - Challenging goal for the research within the field
  - ***Vision: Low effect radio with RF MEMS blocks***

Future prospects for RF MEMS

(source: Ionescu, EPFL)

- The success of RF MEMS is dependent of co-integration with more traditional IC technology
  - High performance and reconfigurable units can be achieved
  - SOI is promising for co-integration

- Passive RF MEMS components will probably be the first units to reach market

- RF MEMS switches will be used in more specific applications (niches)
  - Capacitive switches for > 10 GHz
  - Still much effort is needed to reach acceptable reliability and effective packaging

Future prospects for RF MEMS, contd.

- **Resonators are very promising!**
  - Such units can replace complete circuit functions
  - The technology is CMOS compatible and relatively scalable

- **”Improvements in reliability and packaging during the next years will determine the impact RF MEMS will have!”**