Vibrating MEMS resonators

- Vibrating resonators can be **scaled** down to micrometer lengths

- Reduced dimensions give mass reduction and increased spring constant → **increased resonance frequency**

- Vibrating MEMS resonators can give **high Q-factor**
  - Reasons for Q degradation for MEMS resonators
    - Energy loss to substrate via anchors (structure dependent)
    - Air/gas damping (environment dependent)
    - Intrinsic friction (material dependent)
    - 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

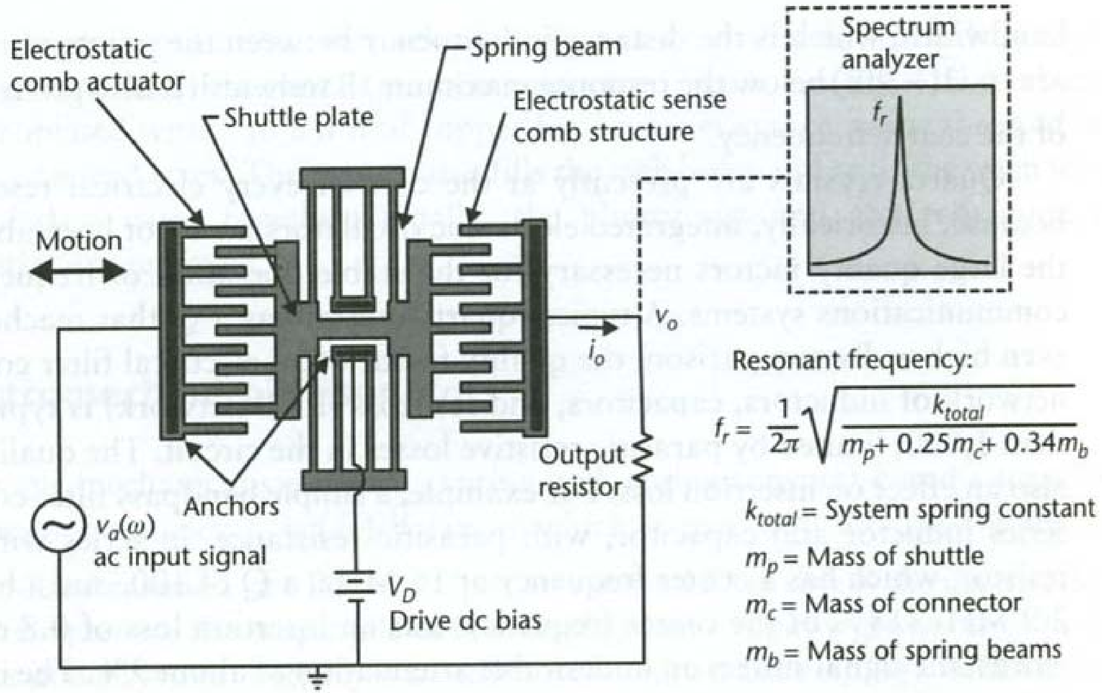
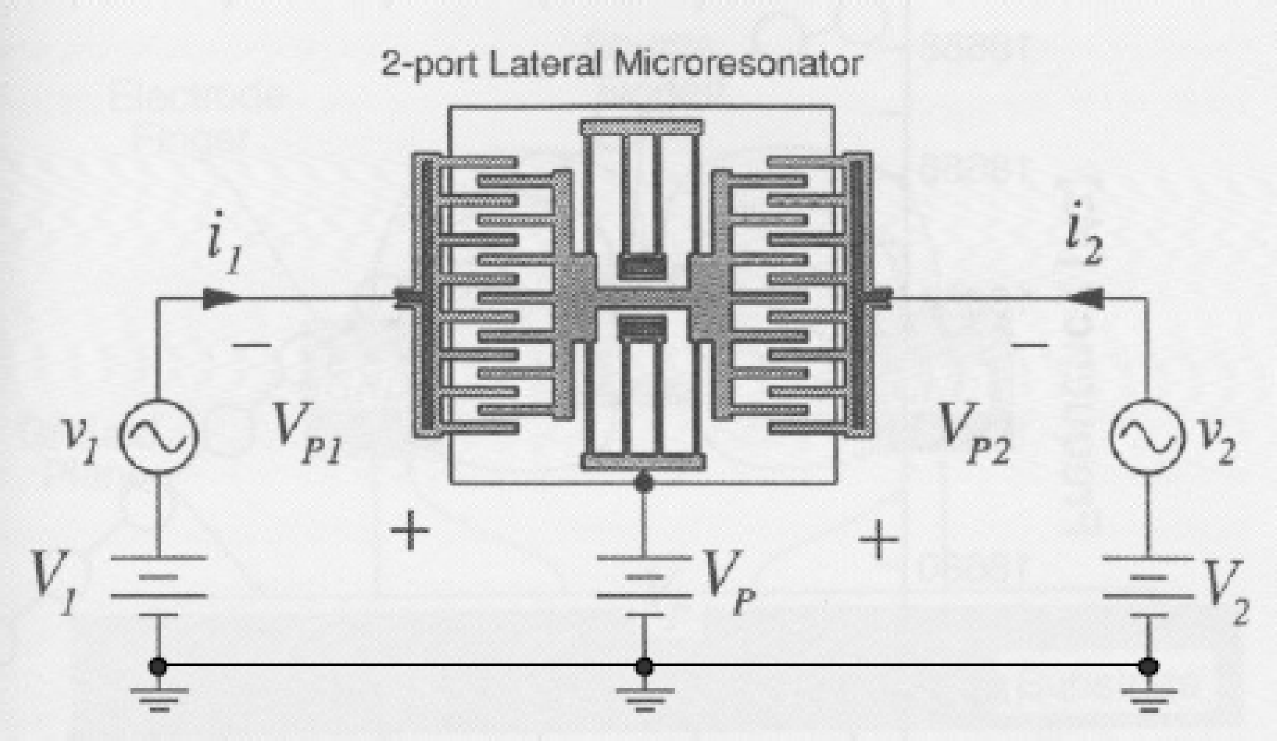


Figure 7.9 Illustration of a micromachined folded-beam comb-drive resonator. The left comb drive actuates the device at a variable frequency ω. The right capacitive-sense-comb structure measures the corresponding displacement by turning the varying capacitance into a current, which generates a voltage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

Comb-resonator, summary

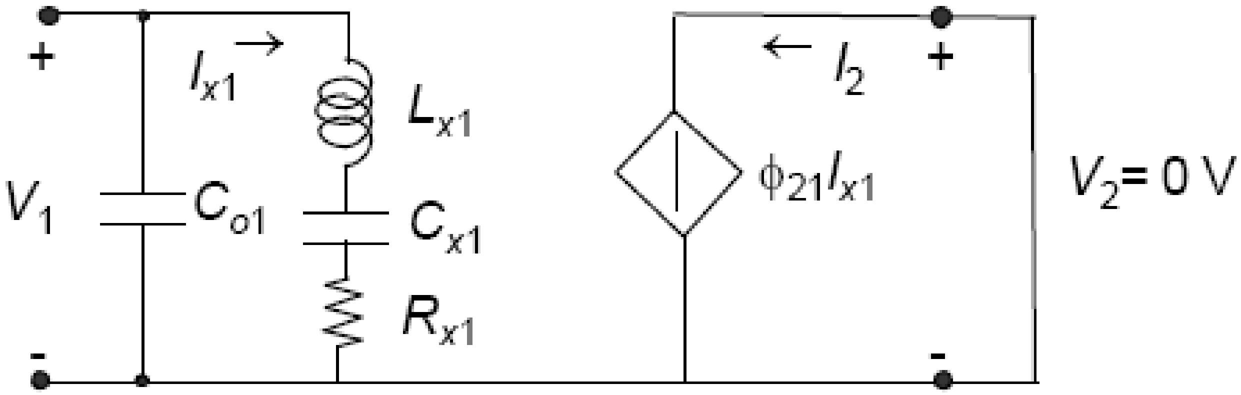
- Summary of modeling:
- Force: Fe = **½ dC/dx V ^2** (force is always attractive)
  - Input signal Va * cos (ωt)
  - Fe ~ Va^2 * ½ [1 + cos (2ωt)]
  - Driving force is 2x input frequency + DC: NOT DESIRABLE
- Add DC bias, Vd
  - Fe ~ Vd ^2 + 2 Vd * Va * cos ω t + negligible term (2ωt)
  - Linear AC 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)

The Lateral Resonator as a "Two-Port"



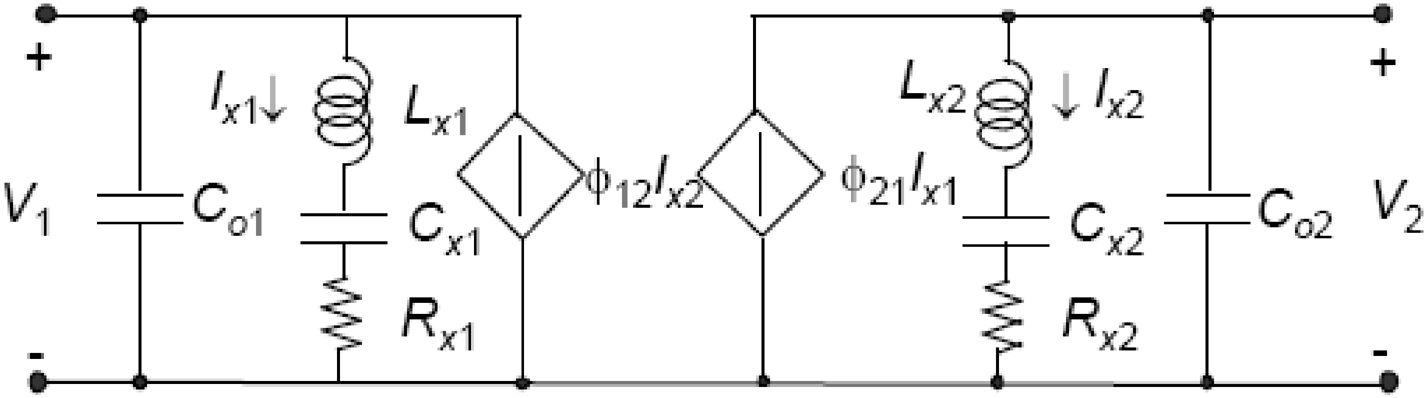
C. T.-C. Nguyen, Ph.D. Thesis, EECS Dept., UC Berkeley, 1994

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



K.

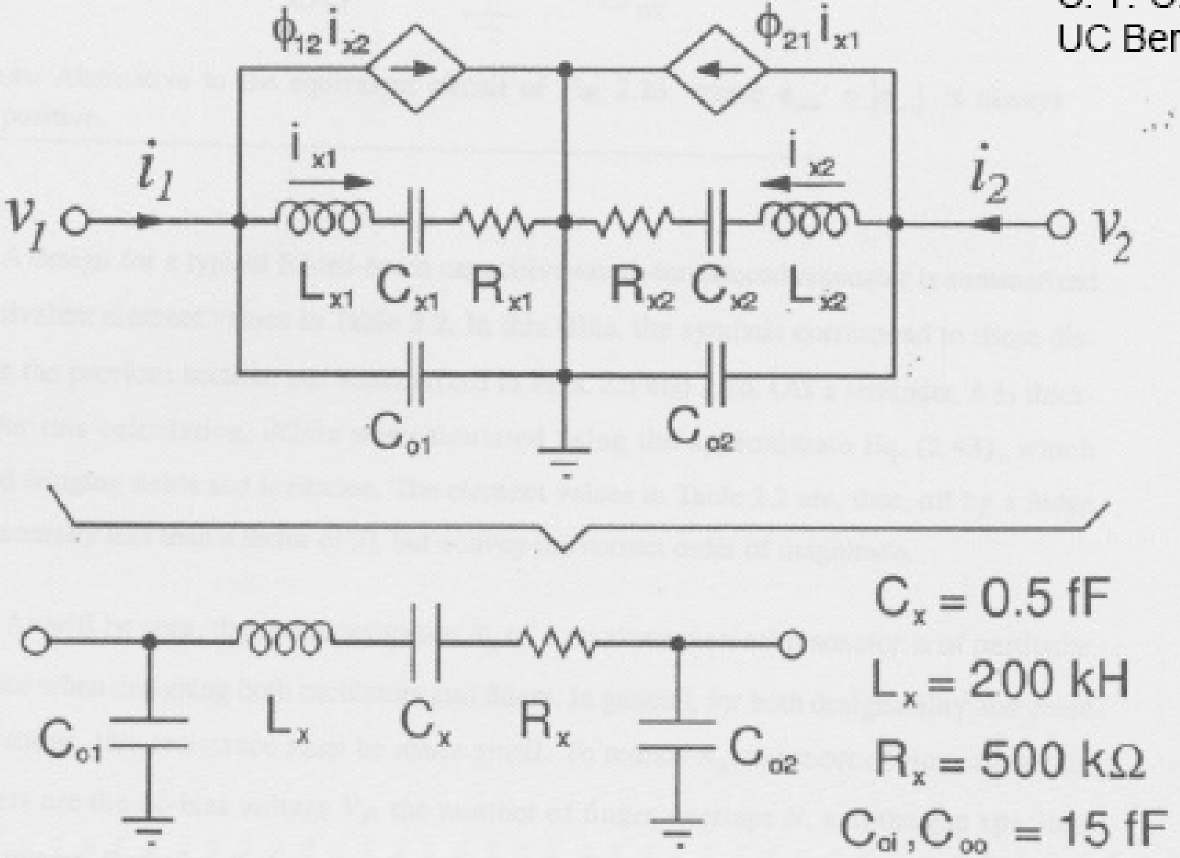
Complete Two-Port Model



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

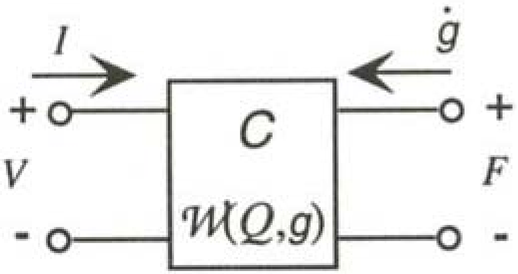
$L_x = 200$ kH

$R_x = 500$ 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



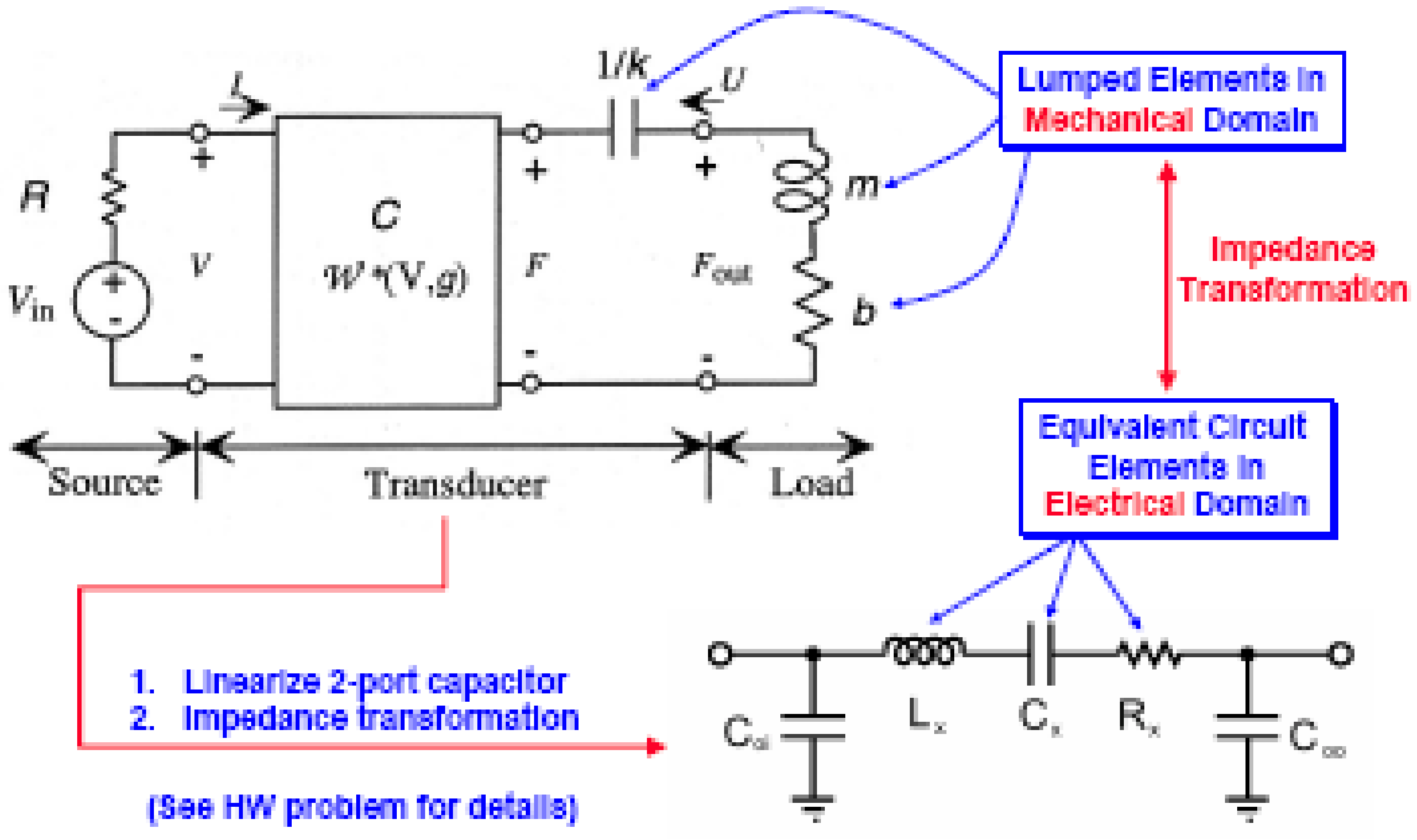
Electrical domain

Mechanical domain

Transducer

Interconnecting where there is **no energy loss**

Lumped Element Model (Senturia's Book)



Lumped Elements in Mechanical Domain

Impedance Transformation

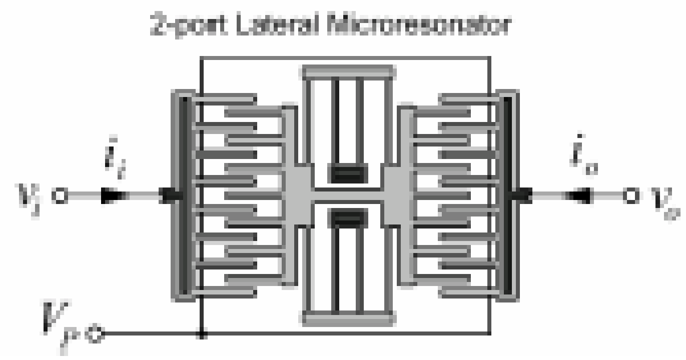
Equivalent Circuit Elements in Electrical Domain

1. Linearize 2-port capacitor
2. Impedance transformation

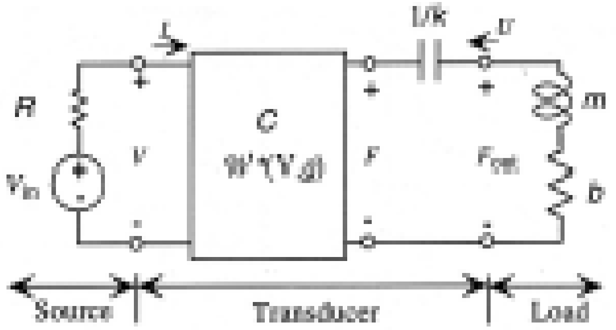
(See HW problem for details)

Linearized Transducers

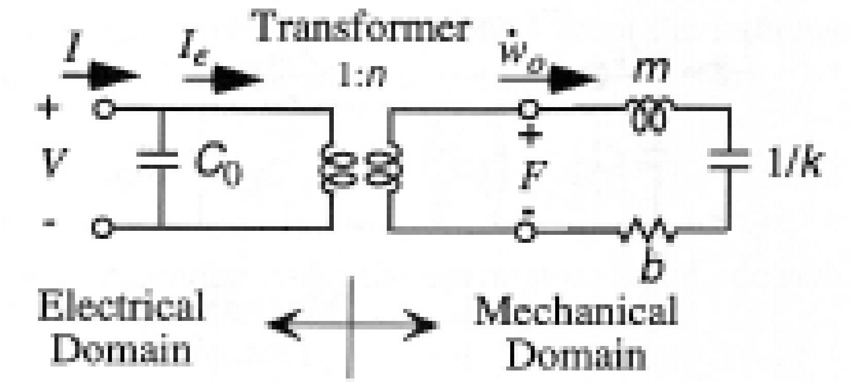
Physical Circuit



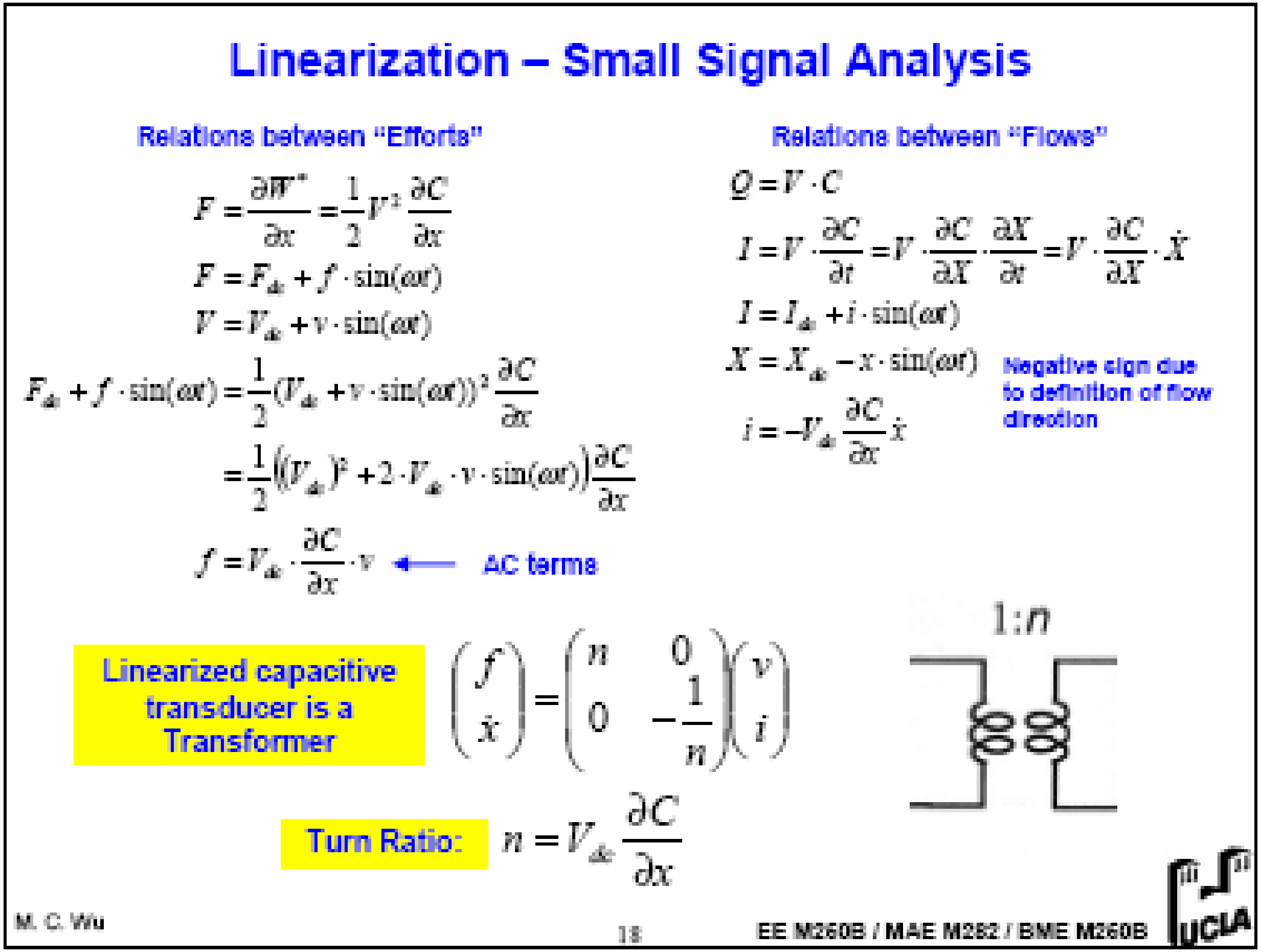
Equivalent Circuit (Nonlinear)



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

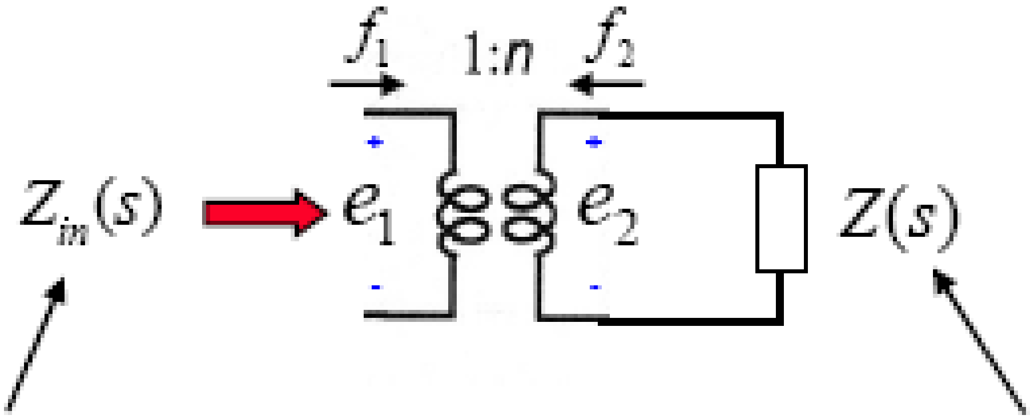
M. C. Wu

18

EE M260B / MAE M282 / BME M260B

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

Impedance Transformation



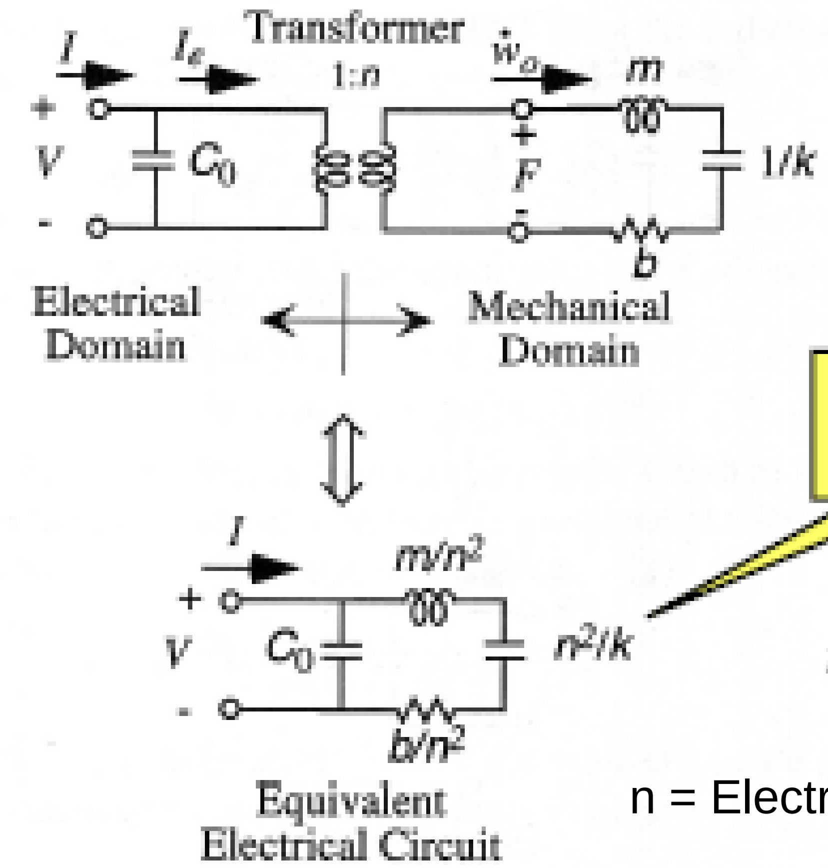
Equivalent Impedance in Electrical Domain

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

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

n = Electromagnetic coupling coefficient

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

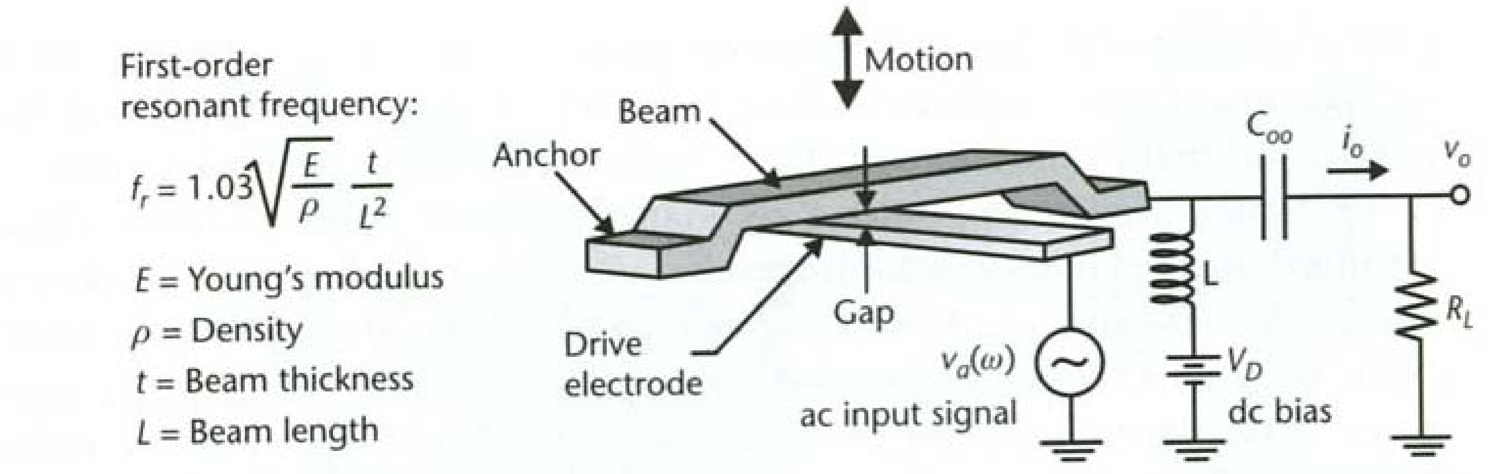


Figure 7.10 Illustration of a beam resonator and a typical circuit to measure the signal. The beam is clamped on both ends by anchors to the substrate. The capacitance between the resonant beam and the drive electrode varies with the deflection.

Clamped-clamped beam

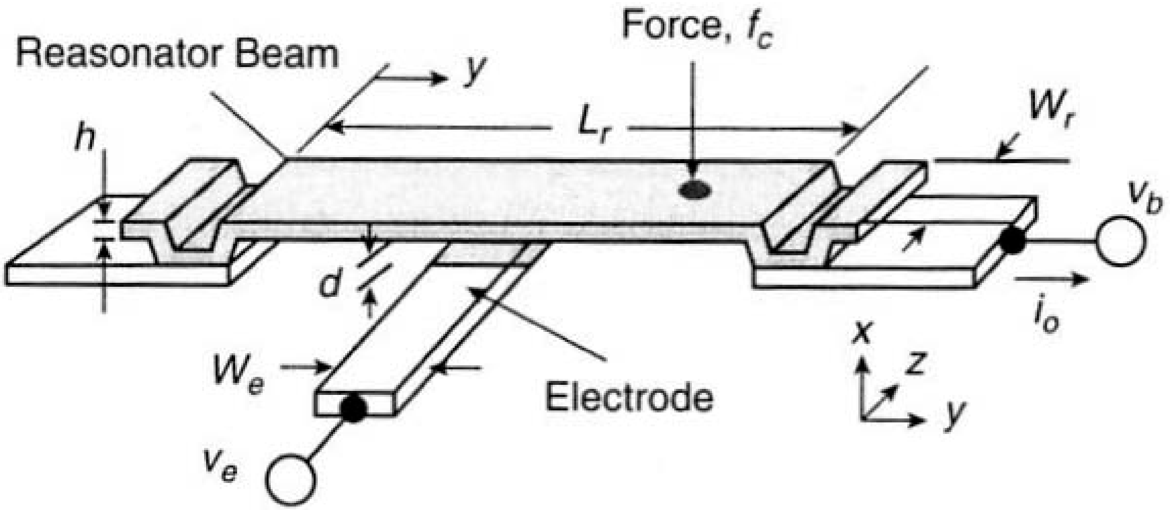


Figure 12.4. Perspective-view schematic of a clamped–clamped beam μmechanical resonator in a general bias and excitation configuration.

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

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

The term can usually be neglected

Topology

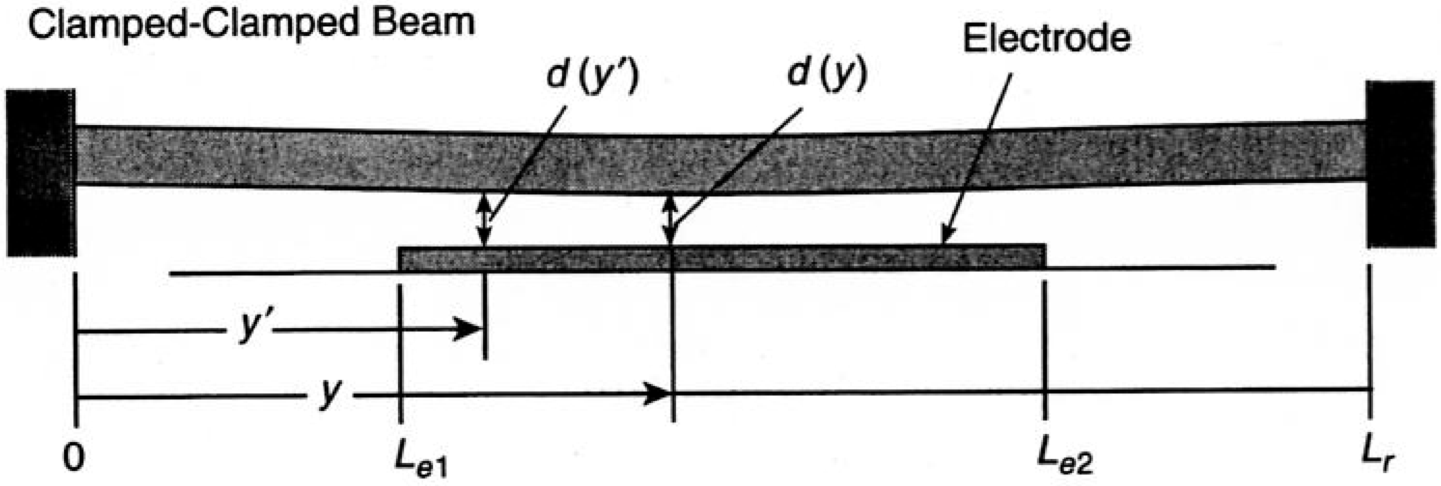


Figure 12.9. Resonator cross-sectional schematic for frequency-pulling and impedance analysis.

Simplification **(De Los Santos):**

Assume that the beam is <u>flat</u> 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!**

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

”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

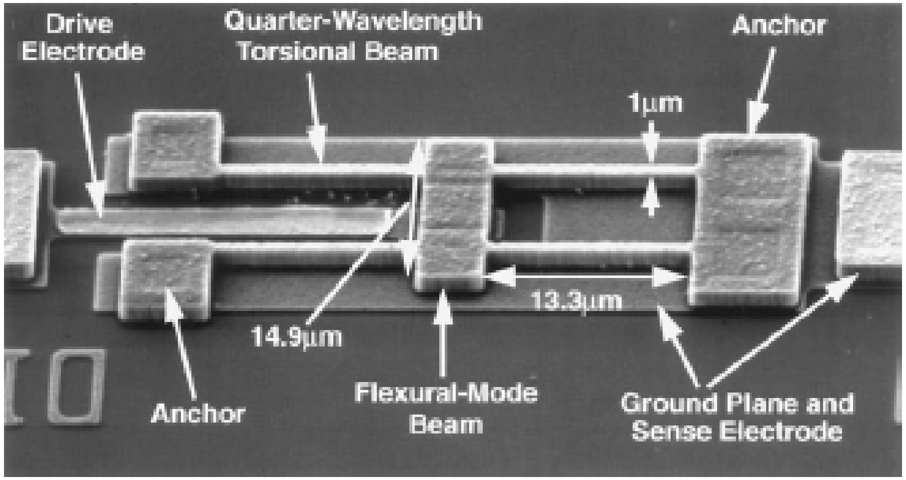
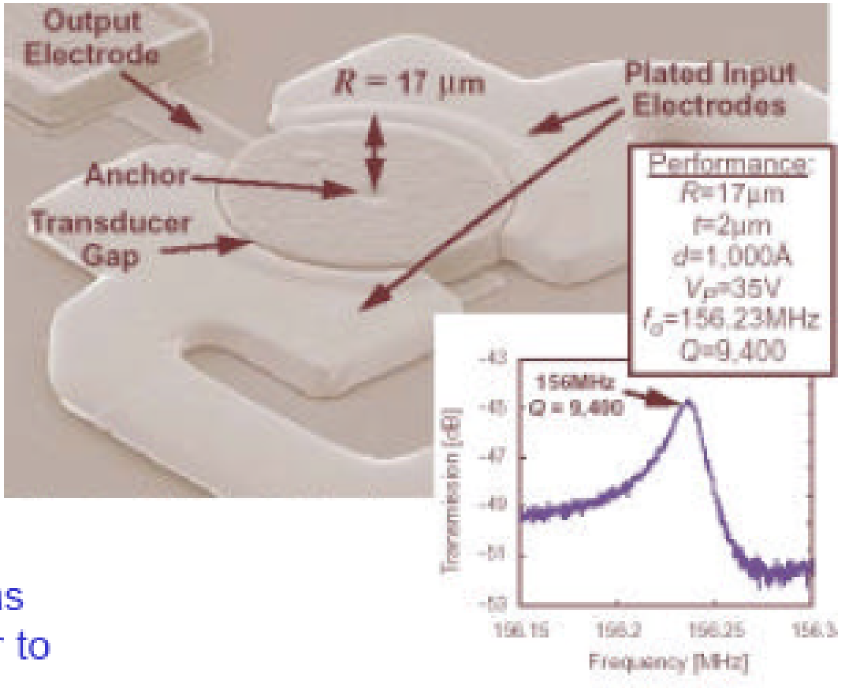


Fig. 29. SEM of free–free beam virtually levitated micromechanical resonator with relevant dimensions for $f_o = 71$ MHz.

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 (“breathing”), wine-glass (“standing waves”)

Micromechanical filter: 3 * resonators

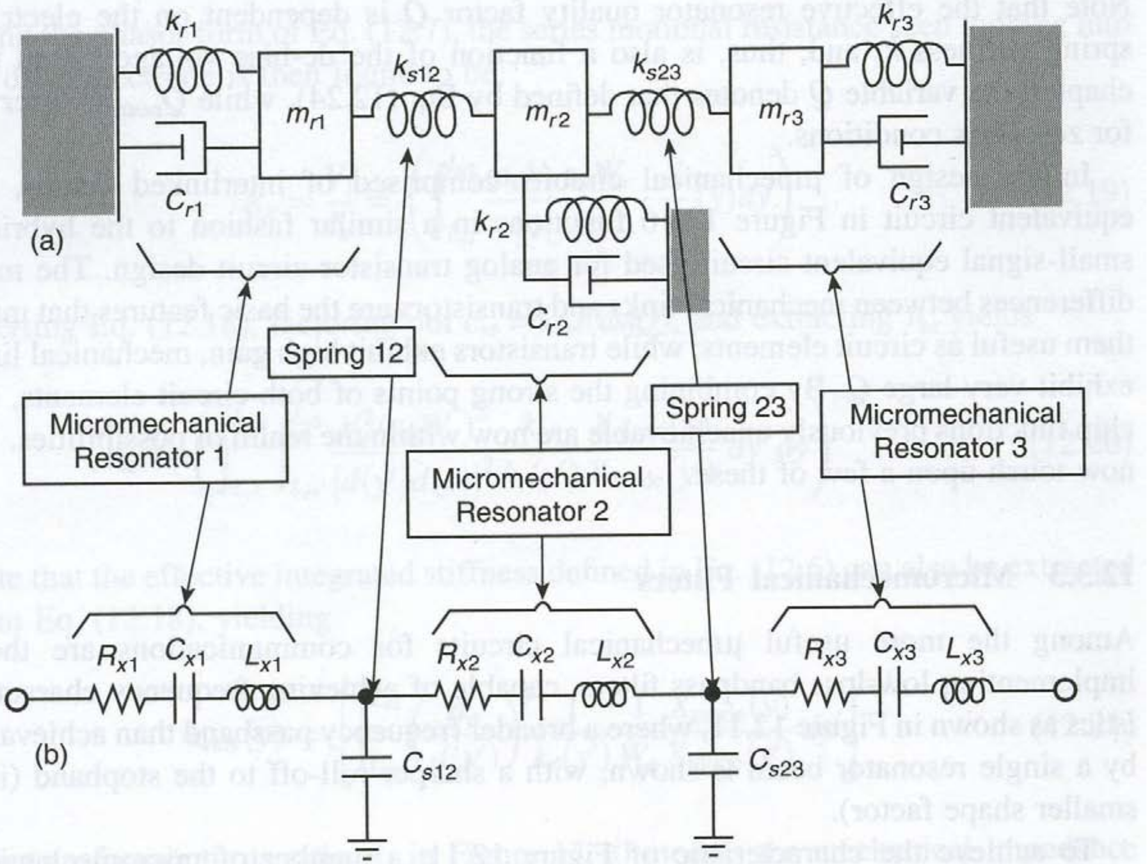
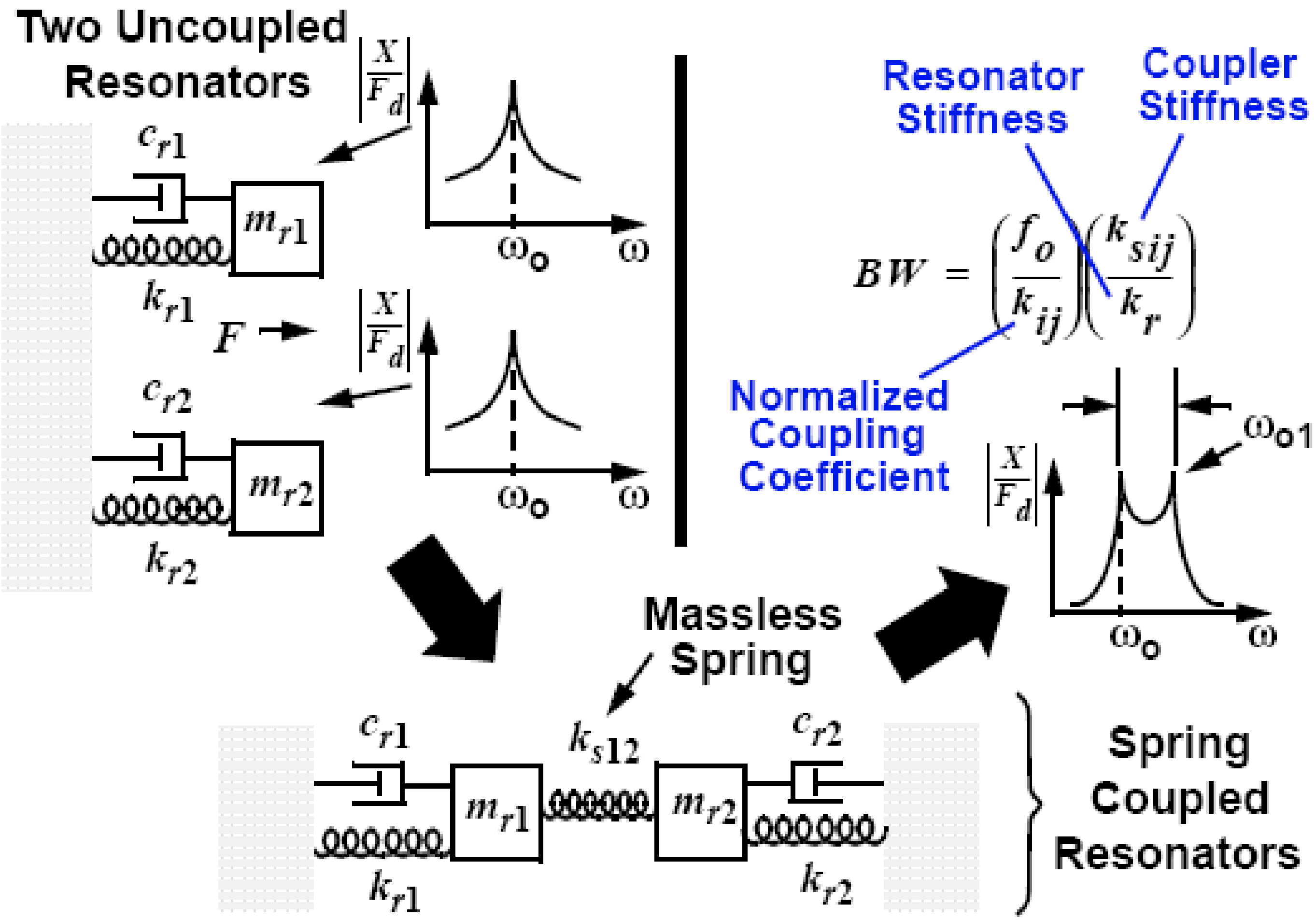


Figure 12.12. (a) Equivalent lumped-parameter mechanical circuit for a mechanical filter. (b) Corresponding equivalent *LCR* network.

Ideal Spring Coupled Filter



Two Uncoupled Resonators

Resonator Stiffness

Coupler Stiffness

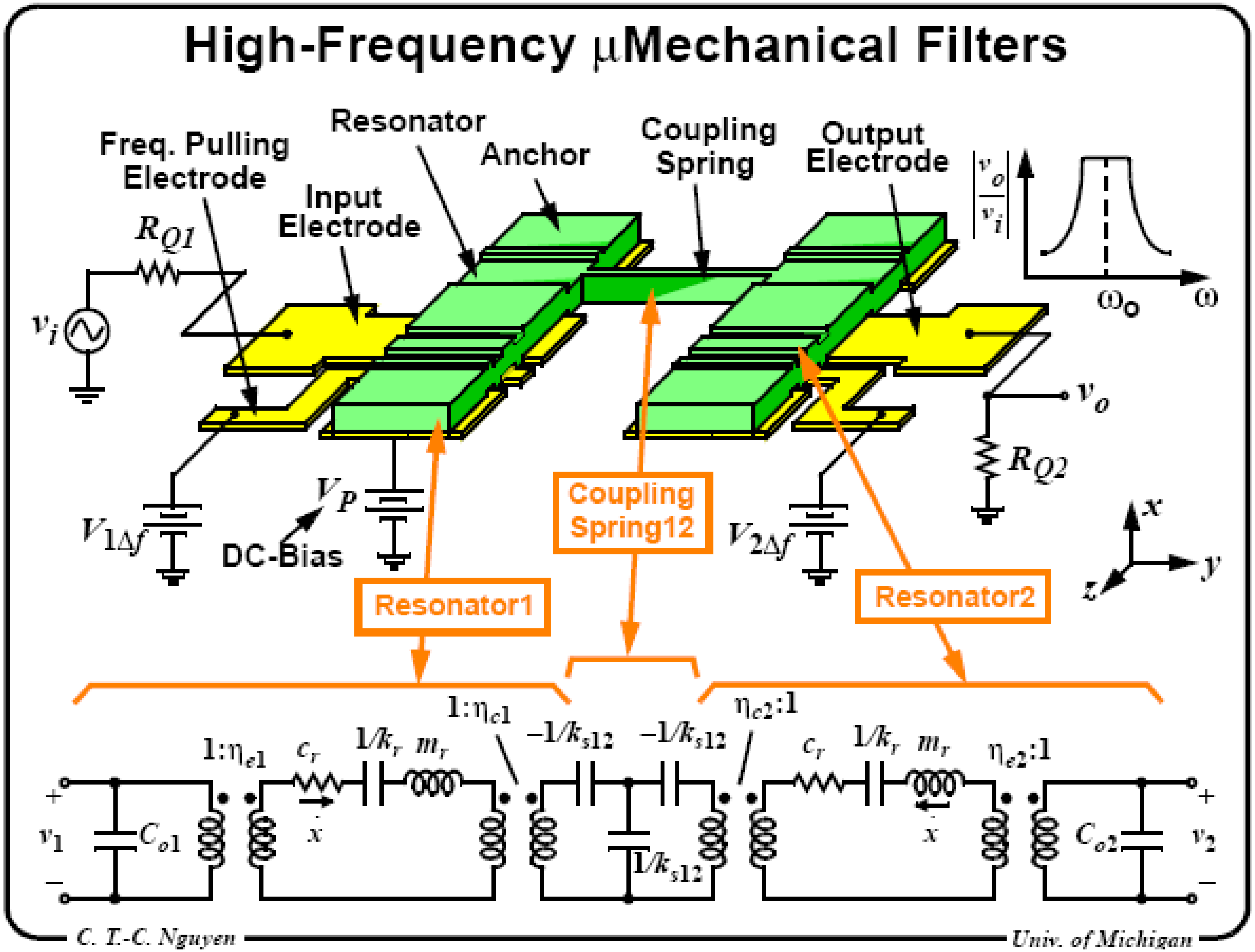
$$BW = \left(\frac{f_o}{k_{ij}}\right)\left(\frac{k_{sij}}{k_r}\right)$$

Normalized Coupling Coefficient

Massless Spring

Spring Coupled Resonators

2-resonator HF-VHF micromechanical filter



Design

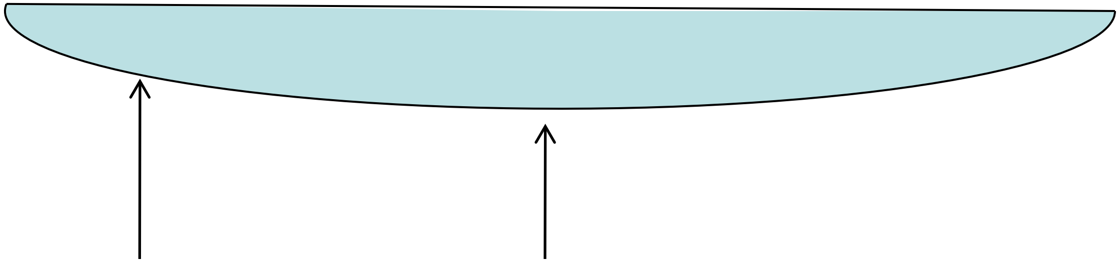
- At centre frequency f0 and bandwidth B, spring constants must fulfill

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

  - 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 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 the 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**



Smaller speed

Max. speed

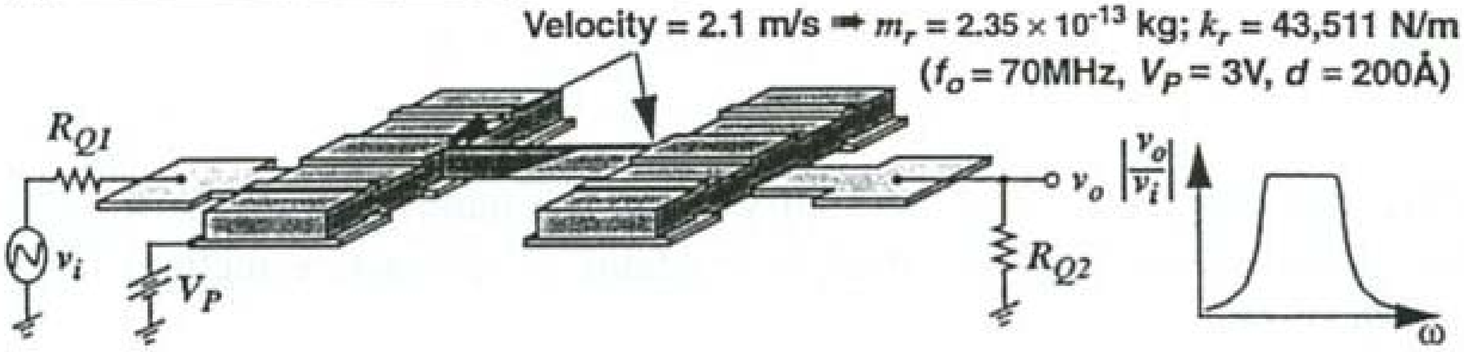
$$\omega_0 = const = \sqrt{\frac{k_{eff}}{m_{eff}}}$$

$$m_{eff} = \frac{KE}{\frac{1}{2}v^2}$$

Smaller speed → eff. mass higher
→ eff. spring stiffness higher

Position of coupling beam

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



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

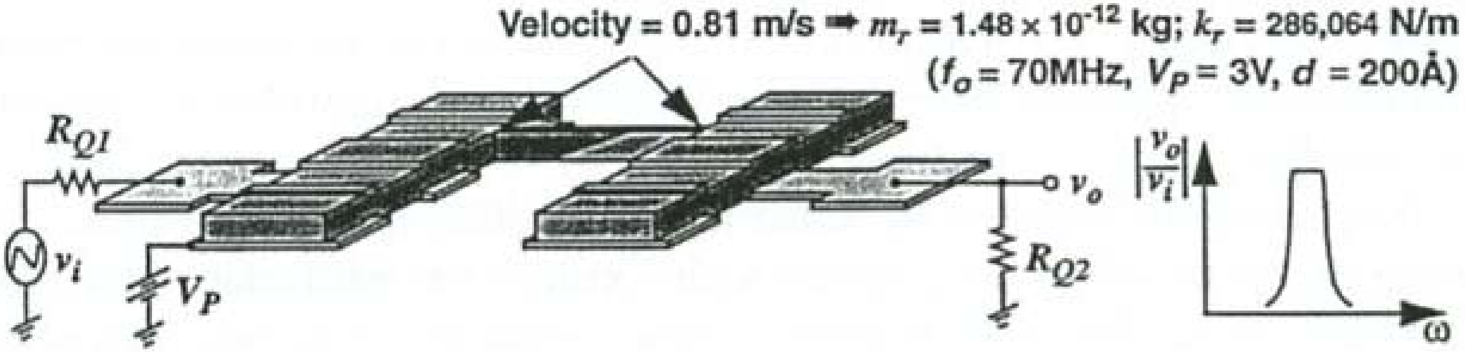


Figure 12.15. Filter schematics showing (a) maximum velocity coupling to yield a large percent bandwidth and (b) low-velocity coupling to yield a smaller percent bandwidth.

Mixer -filter

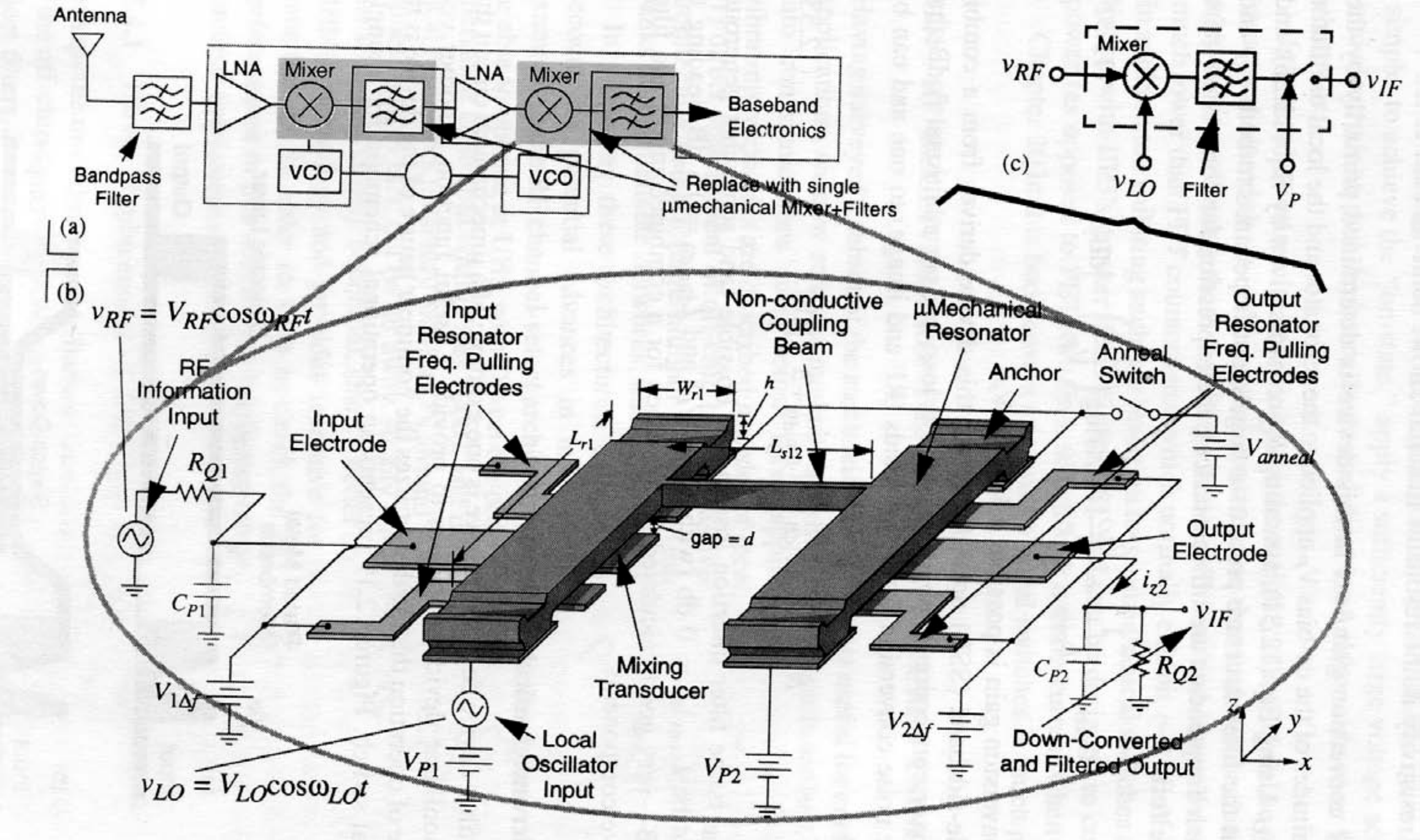


Figure 12.18. (a) Simplified block diagram of a wireless receiver, indicating (with shading) the components replaceable by mixer-filter devices. (b) Schematic diagram of the described μmechanical mixer–filter, depicting the bias and excitation scheme needed for downconversion. (c) Equivalent block diagram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

Passive components in RF circuits

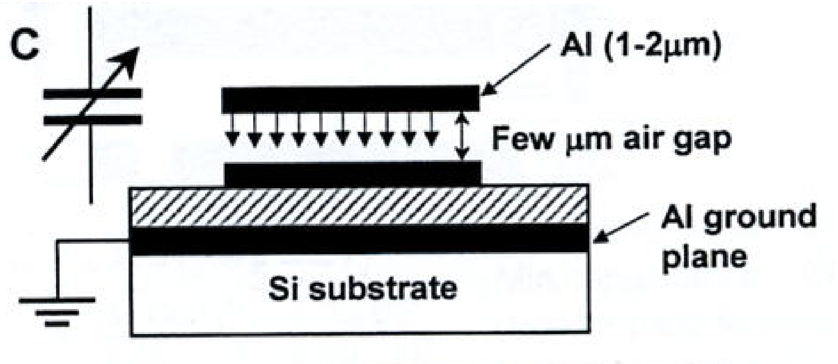
- **→ MEMS capacitors and inductors**
  - Relevant as **replacements** for traditional ”off-chip” passive components
  - Tuneability and programability are desired!
- **MEMS capacitors**
  - Simple, tunable capacitances
    - **= varactor** (”variable reactor”)
  - Programable capacitance banks with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

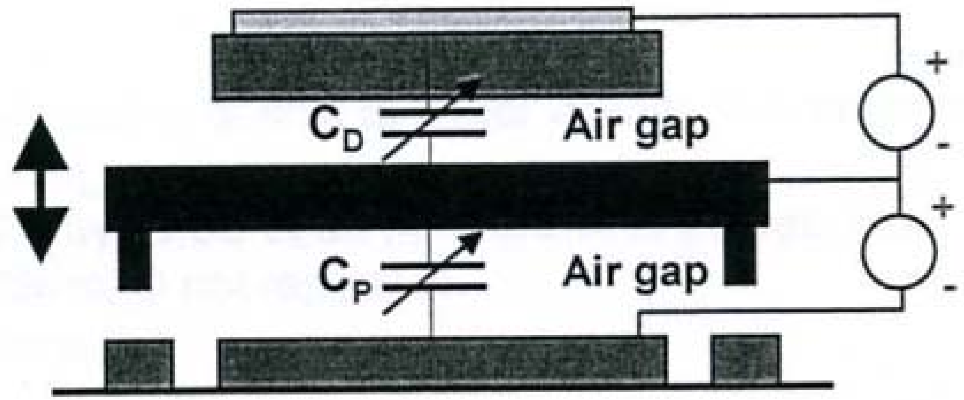
Two-plate tunable MEMS capacitance

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



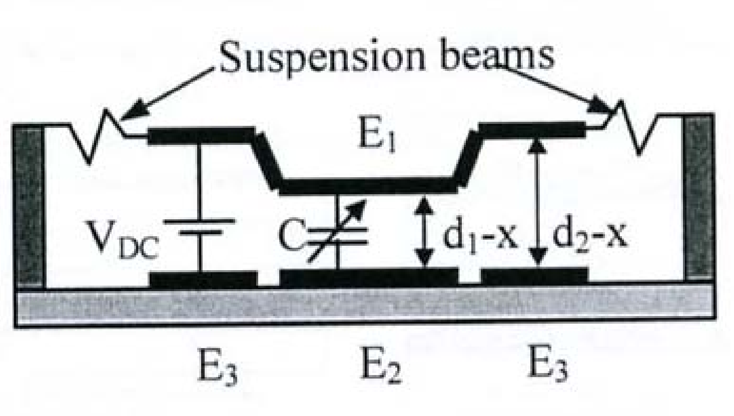
3-plate tunable MEMS capacitance

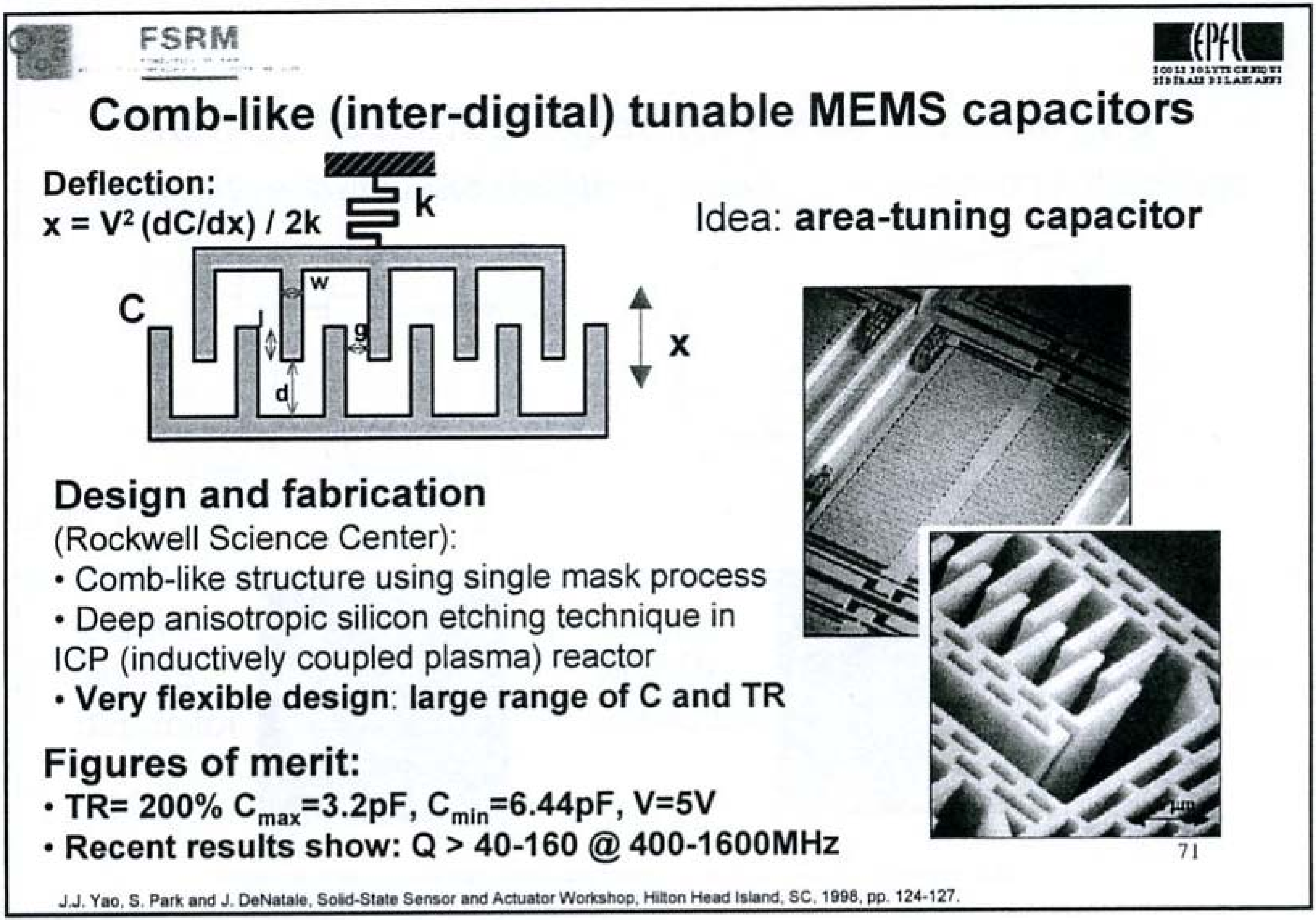
- TR can be increased by introducing a 3rd plate
  - A. Dec & K. Suyama: ”Micromachined Electro-Mechanically Tunable Capacitors and Their Applications to RF IC´s” 1998. **Columbia University**



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!**





FSRM

Comb-like (inter-digital) tunable MEMS capacitors

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

Idea: **area-tuning capacitor**

Design and fabrication

(Rockwell Science Center):

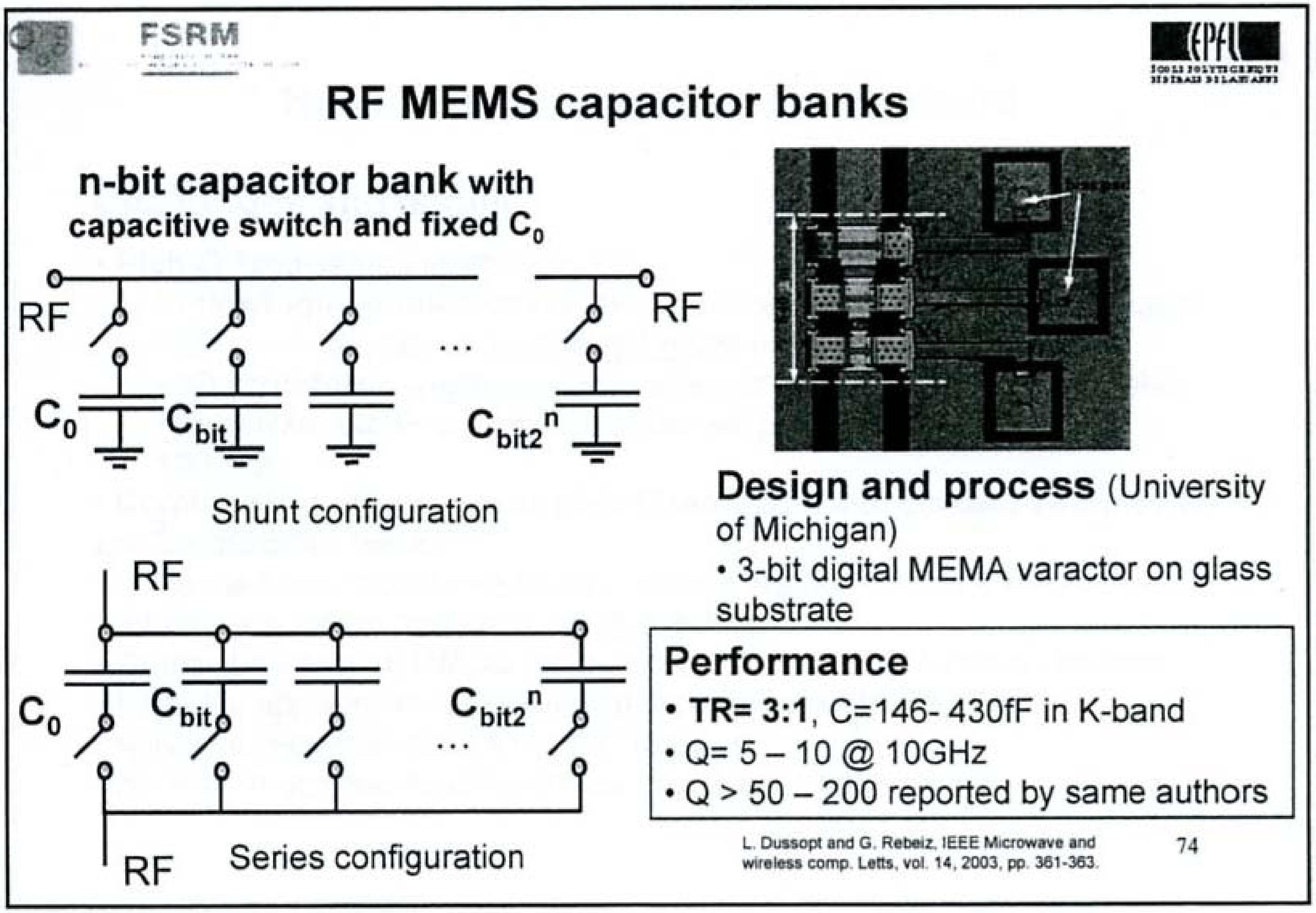
- Comb-like structure using single mask process
- Deep anisotropic silicon etching technique in ICP (inductively coupled plasma) reactor
- **Very flexible design**: **large range of C and TR**

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



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.

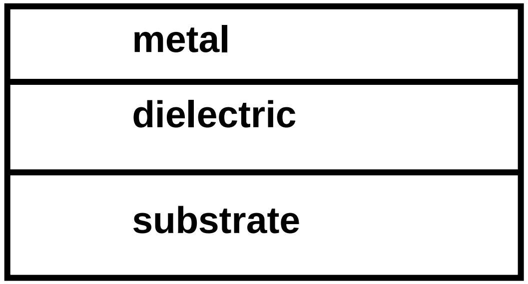
RF MEMS inductors

- 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

- Spiral or meander
  - 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 inductance achieved by increasing the number of turns
  - Self resonance frequency decreases due to the increase in capacitance → limits the region of use

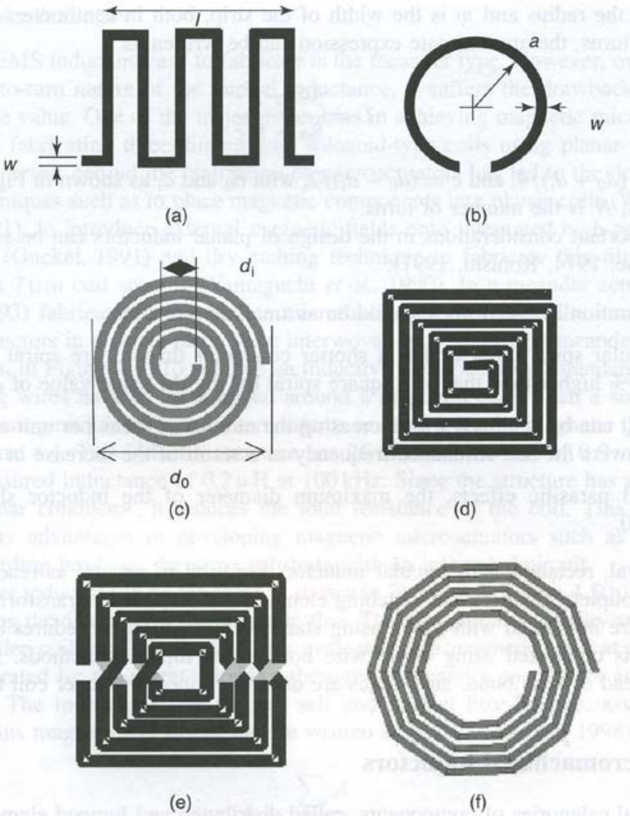


Figure 4.3 Schematic diagram of common planar inductors: (a) meander; (b) loop; (c) circular spiral; (d) square spiral; (e) symmetric spiral; (f) polygon spiral

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

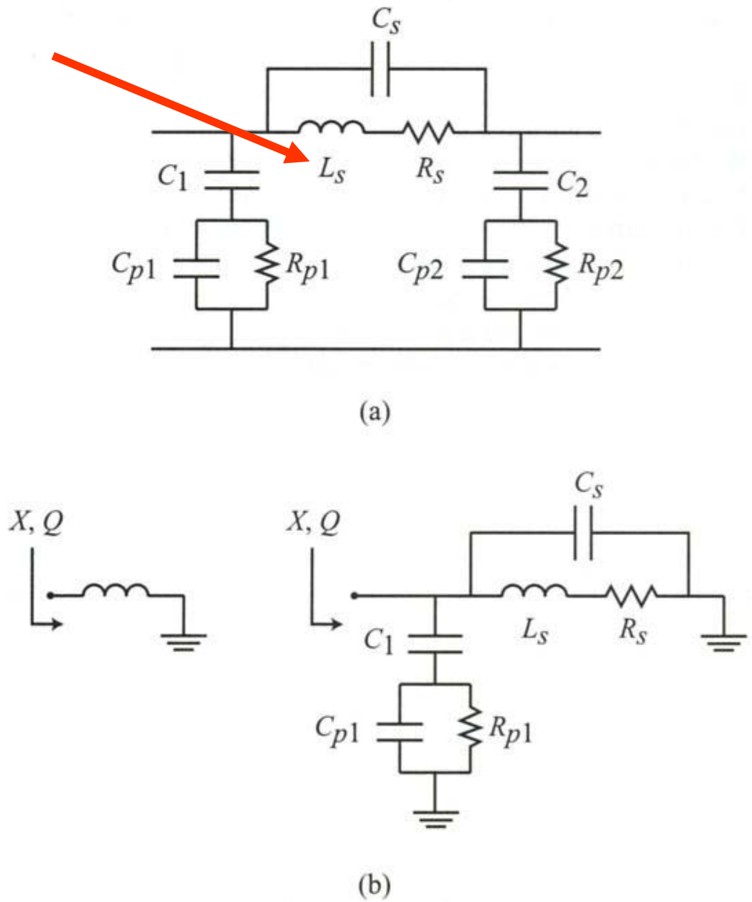


Figure 12.1. (a) The equivalent LRC model of a planar inductor. (b) A short-circuited inductor model typically used in S-parameter and Q measurements. C_{p1} and C_{p2} are often assumed identical and equal to C_p.

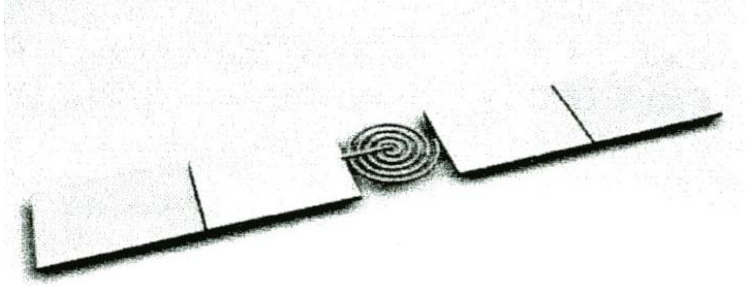
Various design parameters

- Structure
  - 2D or 3D, form
- Line spacing
- Line width
- Number of turns
- Magnetic core
- Metal thickness and type
- 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

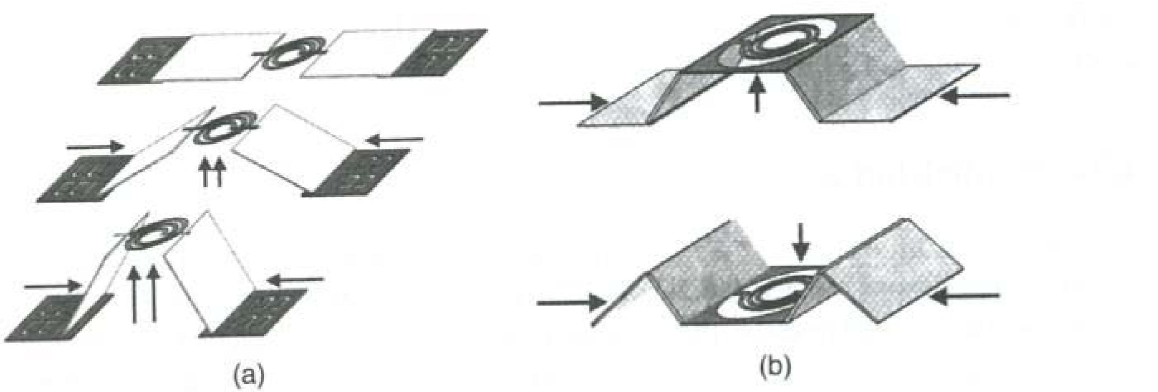


Figure 4.31 (a) Schematic diagram of the MESA micro-elevator by self-assembly structure; (b) the center platform can move upward or downward. Reproduced from L. Fan, R.T. Chen, A. Nepolsa and M.C. Wu, 1998, ‘Universal MEMS platforms for passive RF components: suspended inductors and variable capacitors’,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

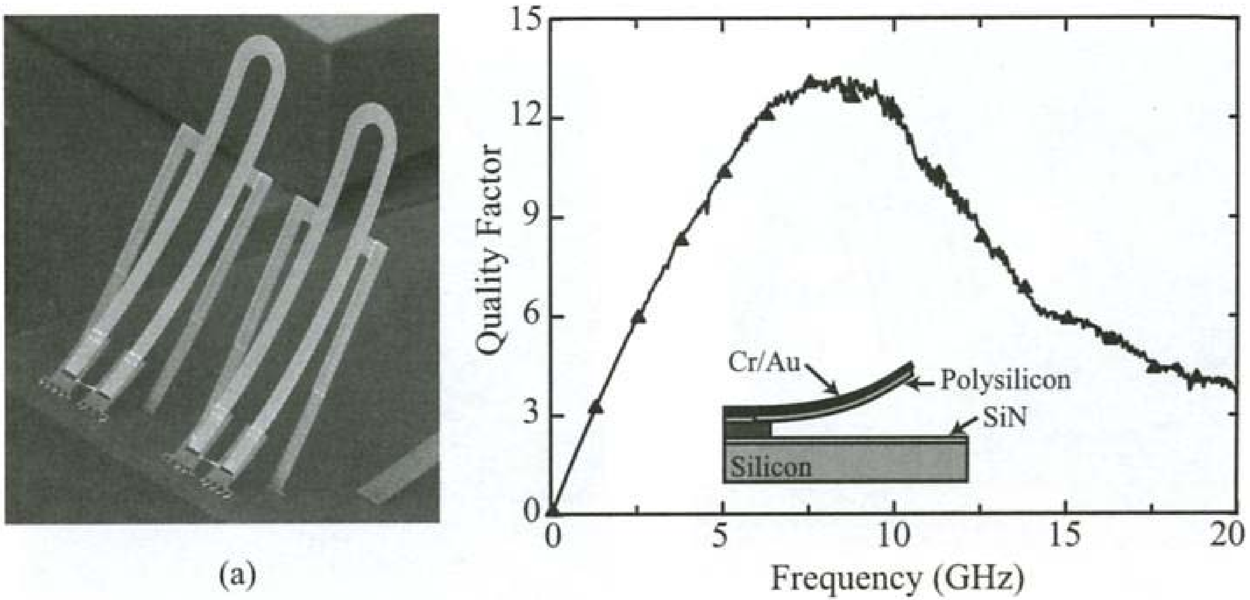
Micromachining using self-assembly

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

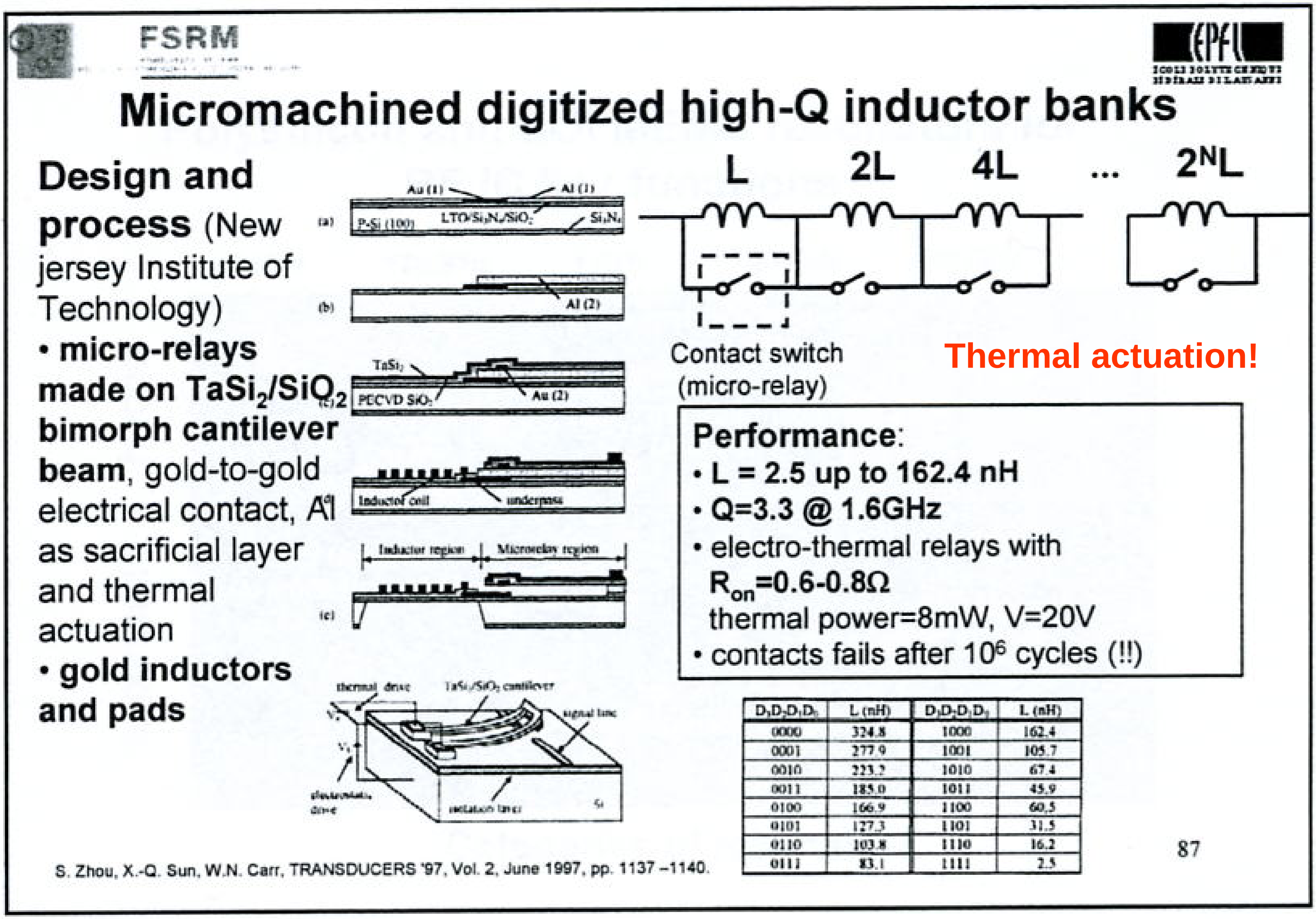


(a)

(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

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

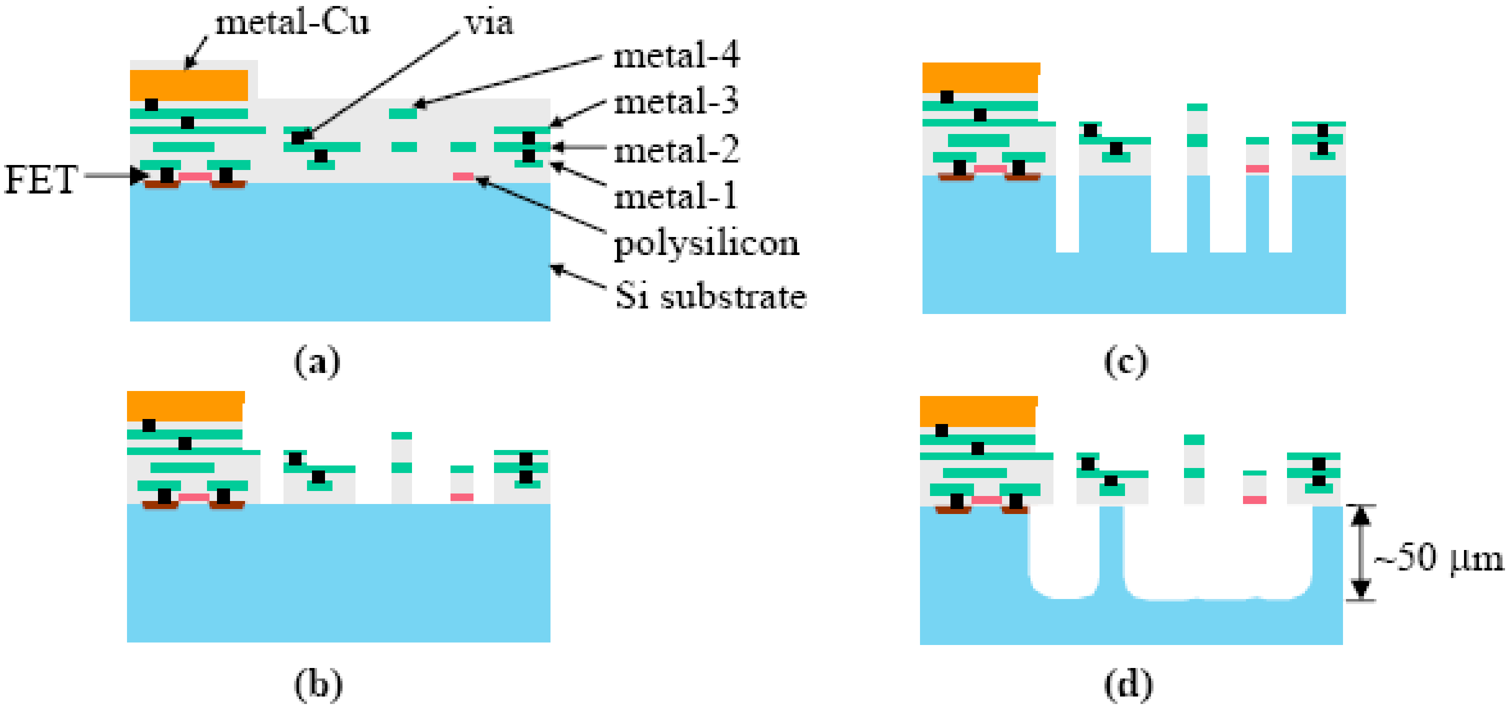
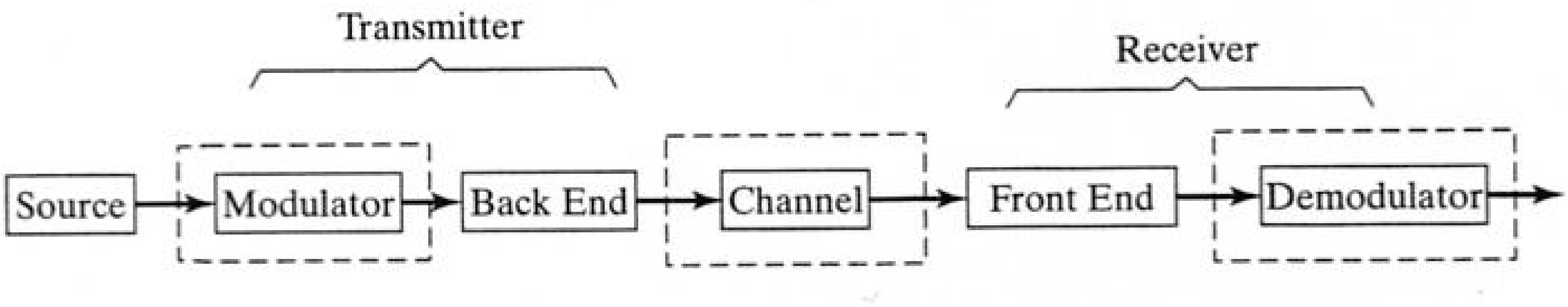


Figure 1. ST7RF CMOS MEMS process flow. (a) Foundry CMOS before micromachining; (b) CHF_3/O_2 reactive-ion etch of dielectric stack down to the silicon substrate; (c) Deep reactive-ion etch of Si substrate (nominal 35 µm deep); and (d) Si undercut (nominal 15 µm undercut and 50 µm deep).

General communication system

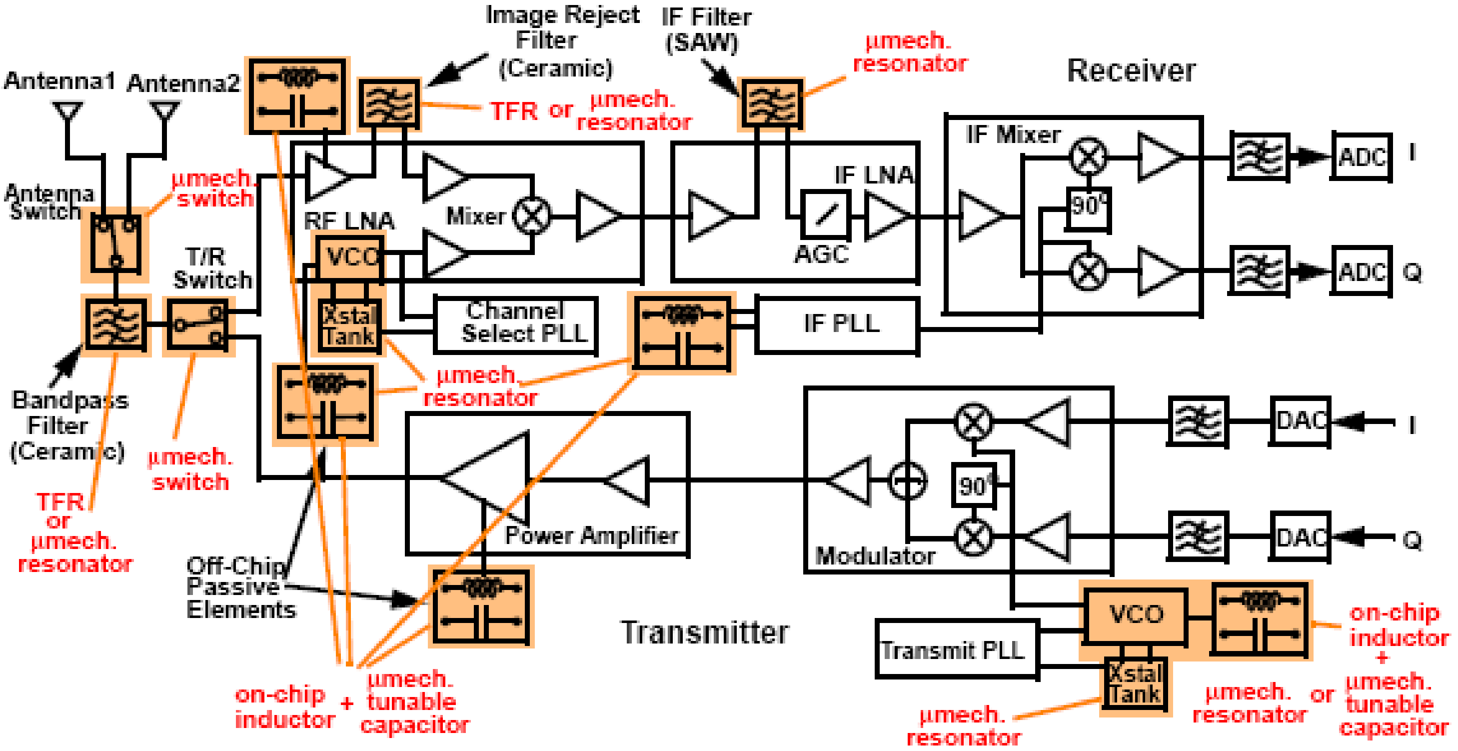


Bit streams are modulated (coded) onto a **carrier**

Radio channel introduces noise, interference, disturbances

Receiver shapes the signal for demodulation

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

Itoh et al, fig 12.1

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

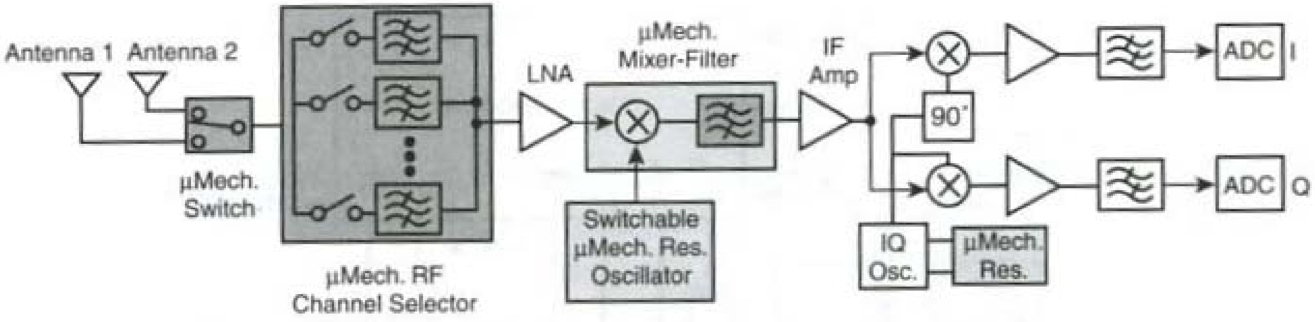
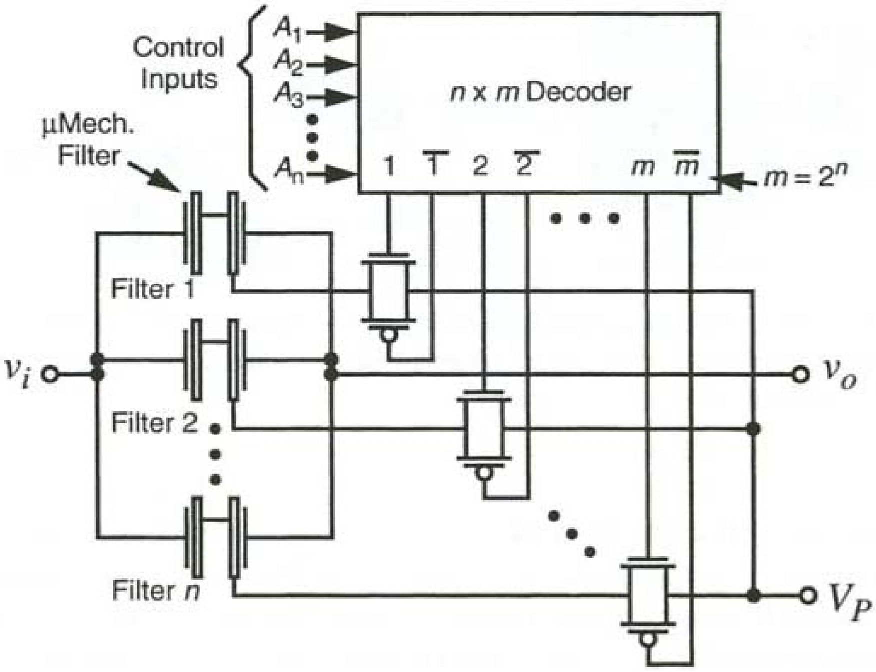


Figure 12.21. System block diagram for an RF channel-select receiver architecture utilizing large numbers of micromechanical resonators in banks to trade Q for power consumption. (On-chip μmechanics are shaded.)

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”



Conclusion (source: Ionescu, EPFL)

- Central features
  - **Micro mechanical processing!**
- RF MEMS is a promising technology for **communication applications**
  - Miniaturisation of critical parts
    - **Co-design** of ”electromechanical / IC” -components
    - **Co-integration** with more traditional IC technology
  - Increased RF performance
    - High performance components
    - High Q tunable passive components have been demonstrated
  - New functionality of RF circuits → programmability
    - Reconfigurable units can be achieved
  - Low power applications
  - Great potential for low cost

Future prospects for RF MEMS

(source: Ionescu, EPFL)

- 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
- RF IC with only MEMS components (?)
- Full circuit functionality (filtering og mixing) in **one** function block!

Future prospects for RF MEMS, contd.

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

- ***Vision: Low effect radio with RF MEMS blocks***

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