INF 5490 RF MEMS

LN07: RF MEMS phase shifters
Resonators, I

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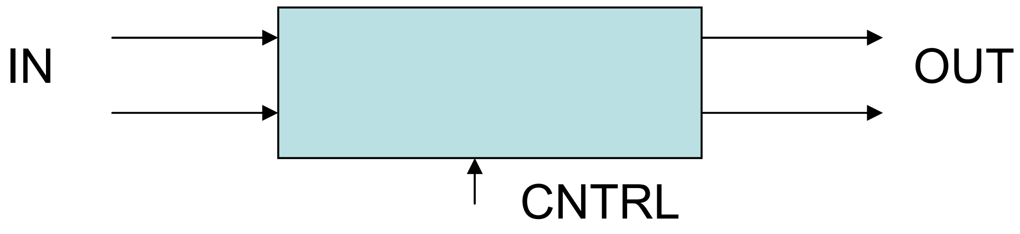
Today's lecture

- Phase shifters
  - Function
  - Applications
  - Technology
  - Analog phase shifters
  - Digital phase shifters

- Mechanical resonators
  - Basic principles
  - **Operating principles** for basic resonator structures

Function

- 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

Important (desired) properties

- Continuous tunability
- Low loss
- Impedance matching of signal
- High power signal capacity
- Low power control bias
- Fast response
- Low cost

Applications

- ”Phased array” antenna may have thousands of elements with a phase shifter for every element
  - Antenna beam can be **steered** in space without physically moving the antenna
  - Antenna beam can be **shaped**
- Use of MEMS phase shifters is a hot topic
  - Can be integrated with antenna elements on ceramic or quarts substrates
  - → Low-cost-antennas

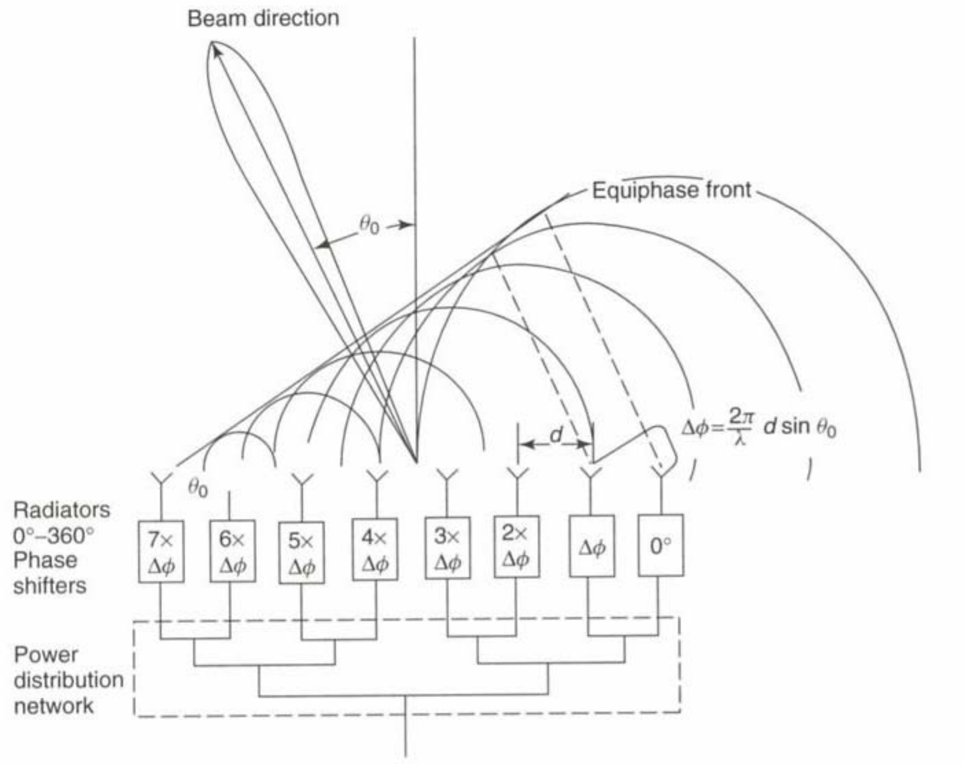


Figure 6.1 Principle of a phased array antenna using phase shifters. Varadan *et al.* 1995

Classifications

- Phase shifters are classified as
  - Analog
    - Continuous phase shift
    - Change of signal propagation speed
  - Digital
    - Phase shift in discrete steps
    - Select different signal paths

Technology

- Different electronically controllable phase shifters exist
    - Ferrite phase shifters
    - Semiconductor (solid state) phase shifters

    - → MEMS phase shifters

Ferrite phase shifters

- Phase shift set by a change of external magnetic field
  - Magnetic field interacts with electron-spin and influences **magnetic permeability = μ**
  - Propagation speed of electromagnetic waves is changed

$$v_p \approx \frac{1}{\sqrt{\mu}}$$

  - → gives variable phase shift

- + Good properties, high power capability
- - High cost, complex, not practical for high integration systems

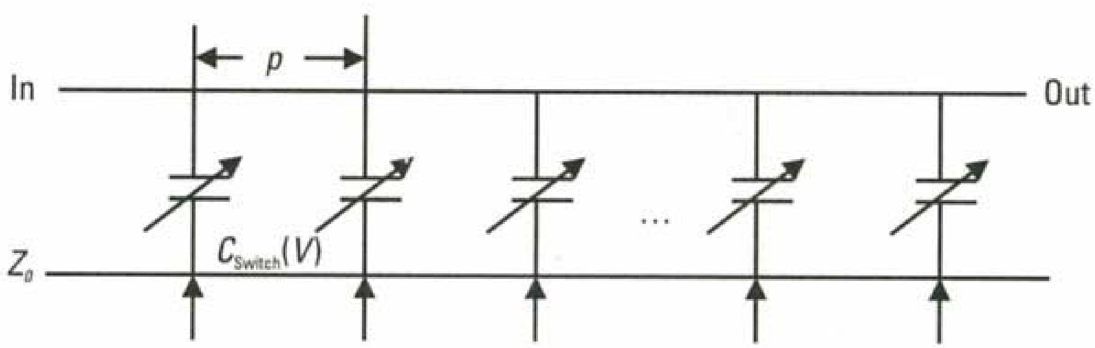
Semiconductor phase shifters

- Switching in/out different line segments by using IC switches
  - PIN-diode, GaAs FET

- + Cheap, small, monolithic integration with amplifiers is possible
- - Can not give continuous phase variation
- - Significant RF loss, high insertion loss
- - Poor power capability

MEMS phase shifters

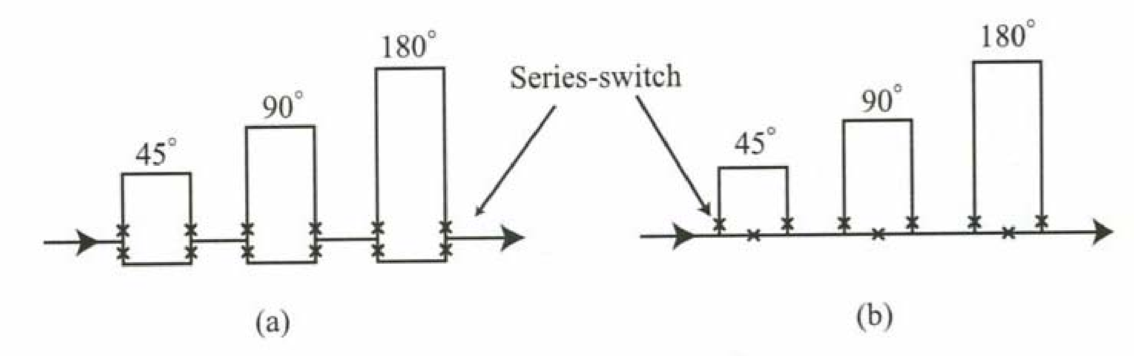
- **A. Use of distributed, capacitive shunt-switches (analog)**
  - Change the effective **capacitive load** of transmission line
  - Continuous phase change



[De Los Santos]

MEMS phase shifters, cont.

- **B. Based on MEMS switches (digital)**
  - Phase shift set by switching between different paths
  - Discrete phase change



  - MEMS **switches** have high performance!
    - Better properties than semiconductor switches

- **→ High-performance phase shifters are possible!**

Propagation in a transmission line

Voltage wave in positive z-direction $V(z) = V^{+}e^{-kz}$

(R,L,G,C per length) $k = \sqrt{(R + j\omega L)(G + j\omega C)}$

Lossless line $R = G = 0 \Rightarrow k = j\omega\sqrt{LC} = j\beta$

$$V(z) = V^{+}e^{-j\beta z}$$

$$V(z,t) = V_0 \cos(\omega t - \beta z)$$

The wave repeats in space when $\beta \cdot z = 2\pi \Rightarrow z = \lambda = \frac{2\pi}{\beta}$

Propagation velocity = phase velocity, Vp $v_p \cdot T = \lambda \Rightarrow v_p = \frac{2\pi}{T} \cdot \frac{1}{\beta} = 2\pi f \frac{1}{\omega\sqrt{LC}} = \frac{1}{\sqrt{LC}}$

Characteristic impedance $Z_0 = \sqrt{\frac{L}{C}}$

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
  - Tre result is a **shunt capacitive loaded transmission line**

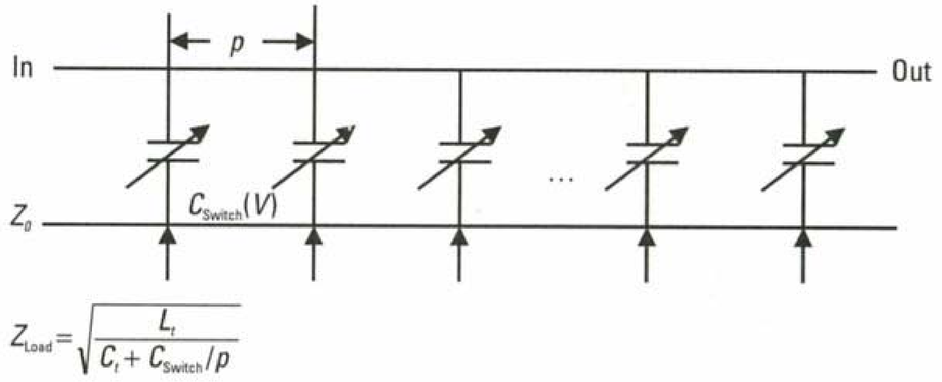


Figure 5.1 Schematic of analog phase shifter.

[De Los Santos]

C_t = line capacitance

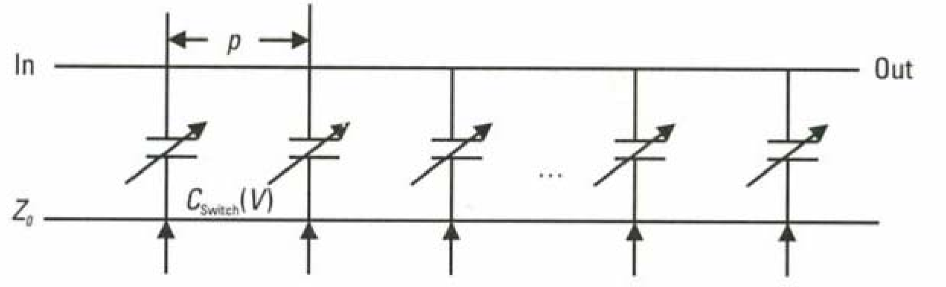
Shunt capacitive loaded line

- Transmission line (TL) periodic loaded with variable capacitors
- Working principle
  - C_t increases → v_p decreases $$v_p = \frac{1}{\sqrt{L_t \cdot C_t}}$$
  - It will take a longer time for the signal to propagate a given distance

- All C_switch capacitors change at the same time with a continuous phase shift by tuning the bias voltage
- A challenge for analog phase shifters:
  - Sensitive to noise on bias voltage line

Distributed MEMS phase shifters

- Capacitive shunt switches loading the line
  - Beam over centre electrode in a co-planar wave guide, CPW
  - Beam pulled down by a electrostatic force controlled by DC voltage relative to the bottom electrode (< pull-down voltage!)
  - Gap determines the distributed MEMS-capacitance
    - ”loaded” TL-impedance changes
  - Can be modeled by simple analytical expressions
  - Good for broad bandwidth signals



- Periodic loading by shunt capacitors gives a “Bragg-frequency” limiting the maximum frequency of operation (“grating” effect)

Formulas for lossless and loaded lines

Lossless line

ε = dielectric constant
μ = magnetic permeability

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}}$$

$$v_p = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{1}{\sqrt{\varepsilon_0\varepsilon_r\mu}} \approx \frac{1}{\sqrt{\varepsilon_r}} \cdot \frac{1}{\sqrt{\varepsilon_0\mu_0}} = \frac{c}{\sqrt{\varepsilon_r}}$$

Time delay per section

$$\tau = \frac{p}{v_p} = \frac{p\sqrt{\varepsilon_r}}{c}$$

Loaded line

$$Z_{0\_loaded} = \sqrt{\frac{L}{C + C_{switch}/p}}$$

$$v_{p\_loaded} = \frac{1}{\sqrt{L \cdot (C + C_{switch}/p)}}$$

$$\tau_{loaded} = \frac{p}{v_{p\_loaded}} = \sqrt{pL \cdot (pC + C_{switch})}$$

$$Z_0 = \sqrt{\frac{L}{C}} \Rightarrow L = Z_0^{\,2} \cdot C$$

$$v_p = \frac{1}{\sqrt{LC}} = \frac{1}{Z_0 C}$$

$$C = \frac{1}{v_p Z_0} = \frac{\sqrt{\varepsilon_r}}{cZ_0}$$

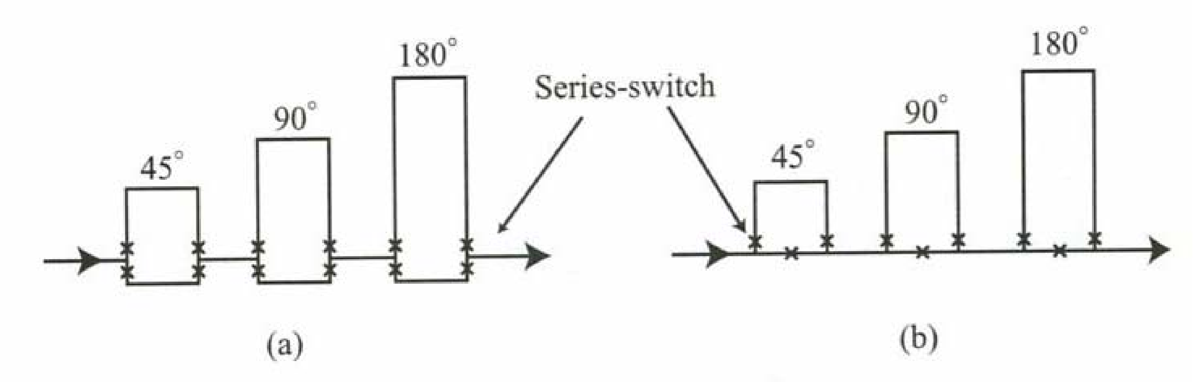
$$L = Z_0^{\,2} C = \frac{Z_0\sqrt{\varepsilon_r}}{c}$$

Time delay per section

Challenges for MEMS shunt-switch phase shifters

- Low switch speed (µs) → slow adaptation to given delay
- High actuation voltage, Vs = 20 – 100 V
  - Vs reduced by **reducing the gap**
    - Complex fabrication (yield)
    - Parasitic up-state capacitance contributes significantly
    - More sensitive to pull-in
  - Vs reduced by using materials with **lower Youngs modulus**
    - Use polymers (E = 5 GPa, metals have 50 – 100 GPa)
    - Polymers can give 1/3 actuation voltage compared with metals
    - How to use micro stereo lithography to fabricate such structures is described in Varadan (not syllabus)
- **→ Good enough properties for phased array antennas**

Digital phase shifters with series-switches



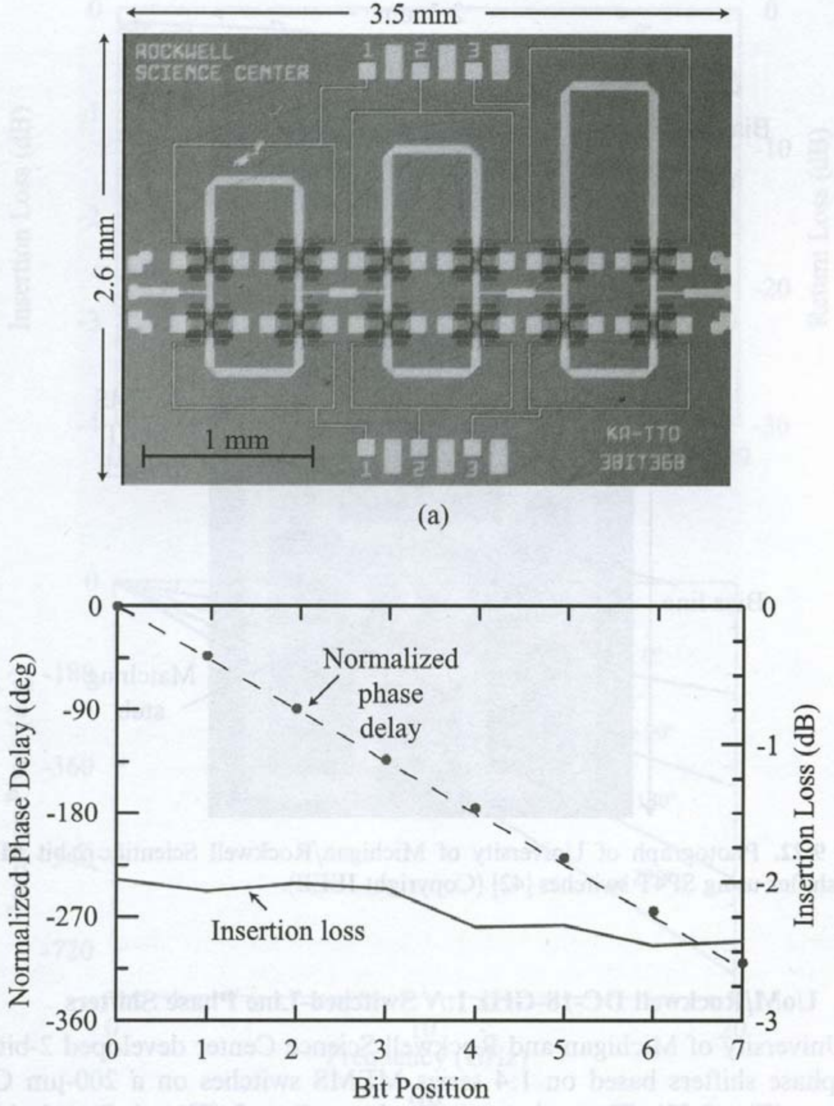
- Working principle
  - Different line paths switched in/out
  - Interconnections through switches
- Switches for ”180°, 90°, 45°, 22.5°, 11.25° -sections in a cascade arrangement
- Several bits used
  - Controlling line sections individually
  - F.ex. 3 bits: 45/90/180° give phase shift 0, 45, 90, 135,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

Digital MEMS phase shifters

- **Based on MEMS switches**
- MEMS **switches** have **high performance!**

  - Negligible actuation power
  - Negligible standby power consumption
  - Low insertion loss
  - High isolation
  - Limited speed, 1 – 30 μs
    - Not always critical

Rockwell’s 35 GHz MEMS phase shifter



(a)

(b)

Figure 9.21. Rockwell Scientific 35-GHz MEMS phase shifter: (a) Layout and (b) measured performance [41] (Copyright IEEE).

Main types of digital phase shifters (De Los Santos)

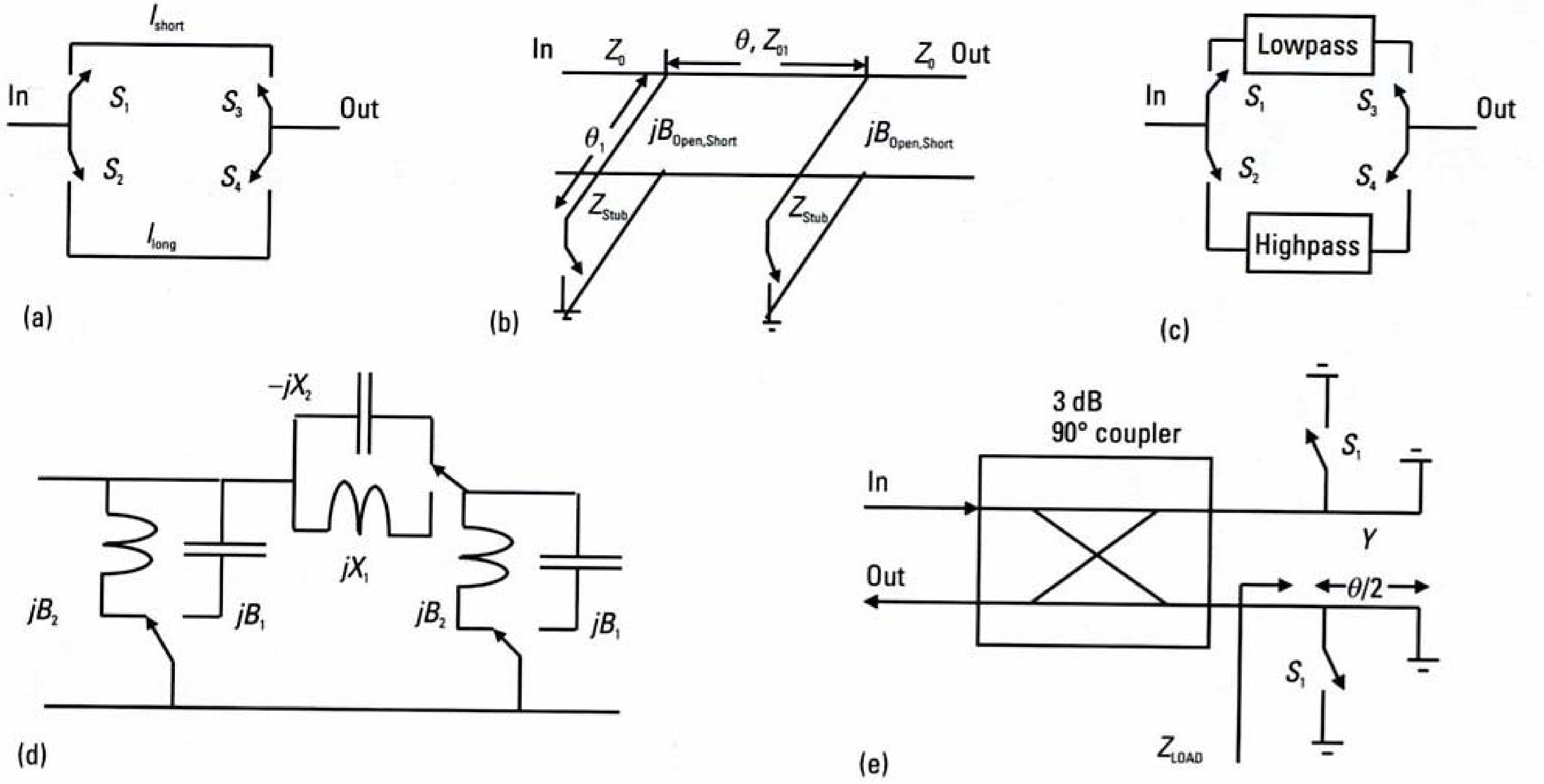
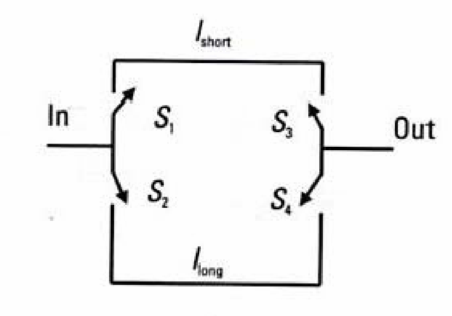


Figure 5.2 Schematic of 1-bit digital phase shifters: (a) switched line, (b) loaded line, (c) switched lowpass-/highpass-filter concept, (d) switched lowpass-/highpass-filter LC implementation, and (e) reflection. Y is the characteristic admittance of the short-terminated line of length $\theta/2$.

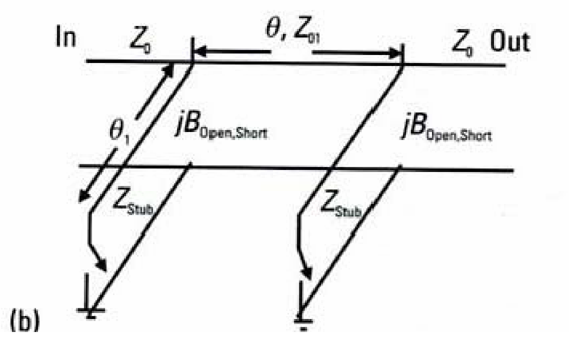
Digital phase shifters, contd.

- **Switched line**
  - Single-pole double throw (SPDT)
  - Differential phase shift given by

$$\Delta\varphi = \beta\left(l_{long} - l_{short}\right)$$

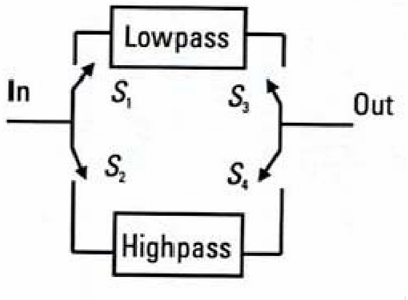


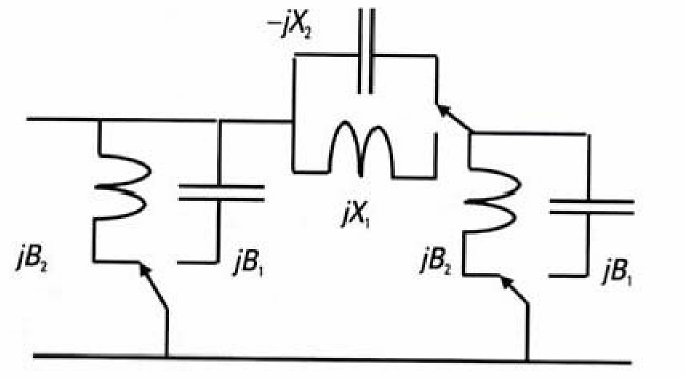
- **Loaded line**
  - Switchable stubs introduced
    - Give contribution to phase shift
  - Each stub is terminated by a switch to ground
    - Phase shift depending on the existing/non-existing ground connection



Digital phase shifters, contd.

- **Switched LP/HP –filter**
  - Use dual lumped LC-circuits
  - Choose between two circuits with different phase delays
    - LP = phase delay
    - HP = phase advance
    - Input/output impedance can be chosen to Z0
  - Phase shift between the two settings can be calculated
  - Compact implementation possible



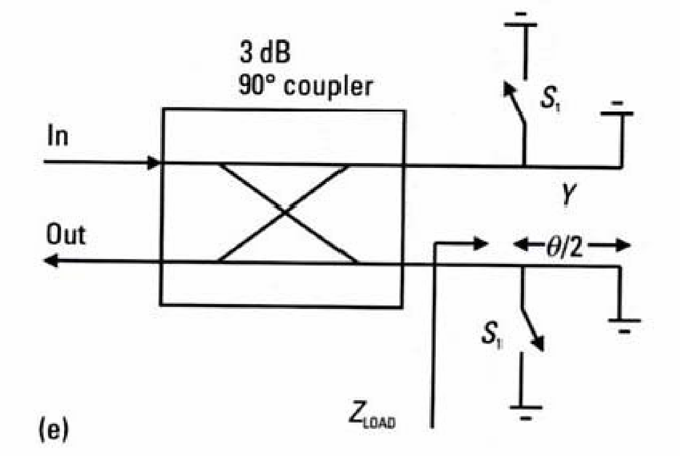


Reflection type phase shifters

- Two-port terminated by short-circuited transmission lines with electrical length

$$\Delta\varphi / 2$$

  - If MEMS switches are connected to ground: *The termination will **reflect** the signal with a smaller delay than if the switches were open*
  - Two equal terminations → the lines are balanced
- A special Lange coupler is used
  - The signals are reflected and added in phase at the output port ("short circuit termination")



Reflection type phase shifter, N-bit

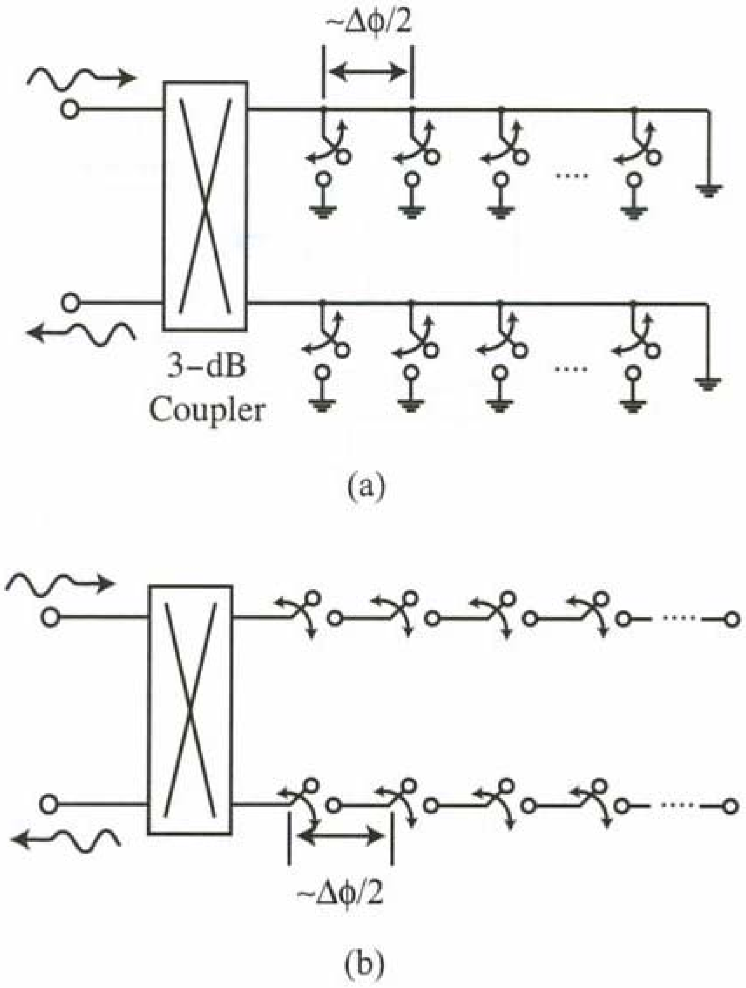
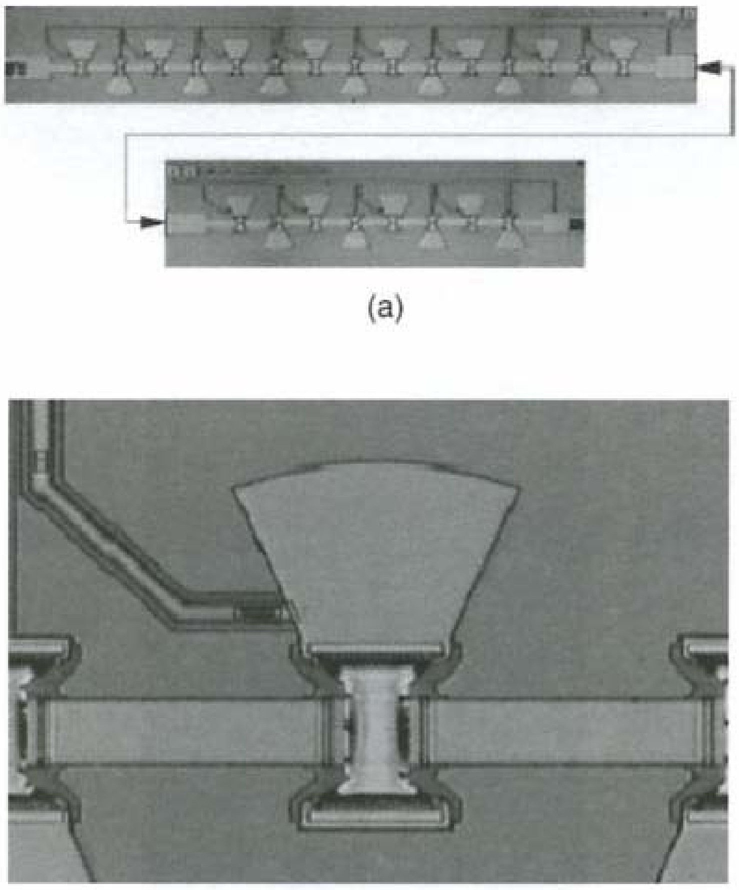


Figure 9.1. A reflect-line N-bit phase shifter using (a) shunt and (b) series switches.

Reflection type phase shifters, contd.

- Properties
  - Electric distance between switches is half the lowest bit resolution
  - Reflection type phase shifters have small dimensions
    - Give double phase delay per unit length compared to switched line topology

2 bit distributed phase shifter



(a)

(b)

Figure 6.8 Photograph of (a) the two-bit 180° phase shifter on top and 90° on the bottom; (b) single MEMS section. Reproduced from J.S. Hayden, A. Malczewski, J. Kleber, C.L. Goldsmith and G.M. Rebeiz, 2001, '2 and 4-Bit DC-18 GHz microstrip MEMS distributed phase shifters', in *Proceedings of IEEE MTT-S International Microwave Symposium*, IEEE, Washington, DC: 219–222, by permission of IEEE, © 2001 IEEE

Choose upper and/or lower section

Each section implemented by shunt capacitive line

Today's lecture

- Phase shifters
  - Functionality
  - Applications
  - Technology
  - Analog phase shifters
  - Digital phase shifters

- Mechanical resonators
  - Basic principles
  - **Operating principles** for basic resonator structures

Mechanical resonators

- Basic **principles**
- Various types of resonators
- Typical properties

- **Working principle** for
  - Comb-resonator
  - Clamped-Clamped (c-c) beam resonator
  - ”free-free (f-f) beam” resonator

Basic principles

- Simple oscillating mechanical system: **mass/spring with damping**
  - Amplitude increases when f → fr
    - Large oscillations close to the natural resonance frequency (non-damped resonance frequency)
  - Limited by damping
  - Electrical equivalents, 2 types: series or parallel combination of C, L and R (small)
  - Resonance when reactances cancel each other
  - Can calculate resonance frequency from the s-polynomial for the oscillating circuit

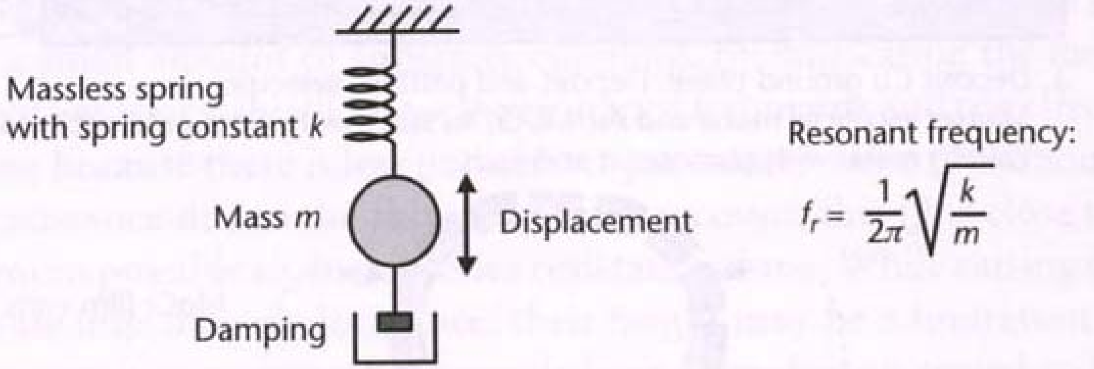


Figure 7.7 Illustration of a mechanical oscillator consisting of a spring, a mass, and a damping element that represents mechanical losses. When driven at its natural (resonant) frequency, the amplitude of the oscillation is greatest; at lower and higher frequencies, the amplitude is smaller.

Q-factor for oscillating circuits

- Q-factor limited by resistive loss
- High Q gives large displacement at resonance frequency
  - Higher peak, smaller bandwidth

$$Q = \frac{\text{maximum energy stored during cycle}}{\text{energy lost per cycle}} = \frac{\text{resonant frequency}}{\text{bandwidth at } 1/\sqrt{2} \text{ of maximum}}$$

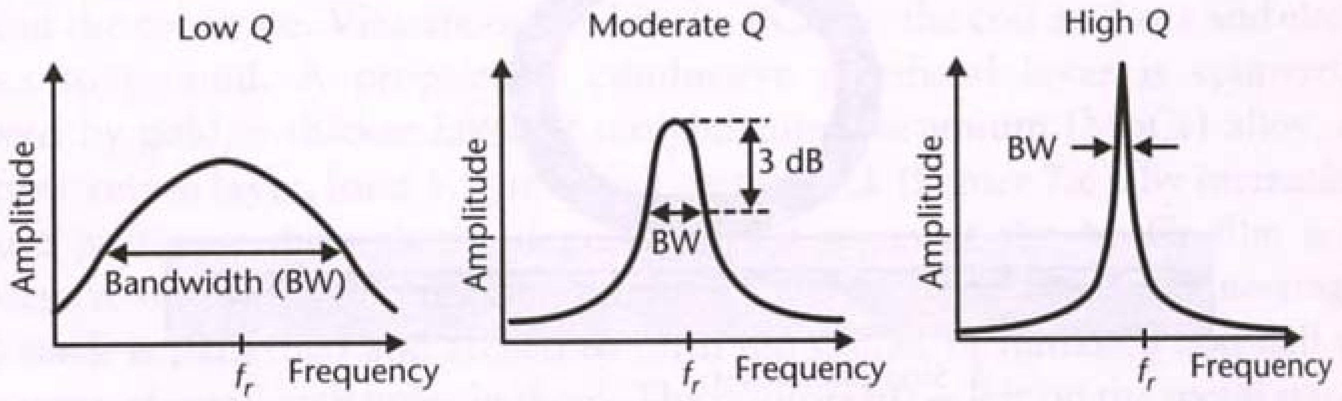
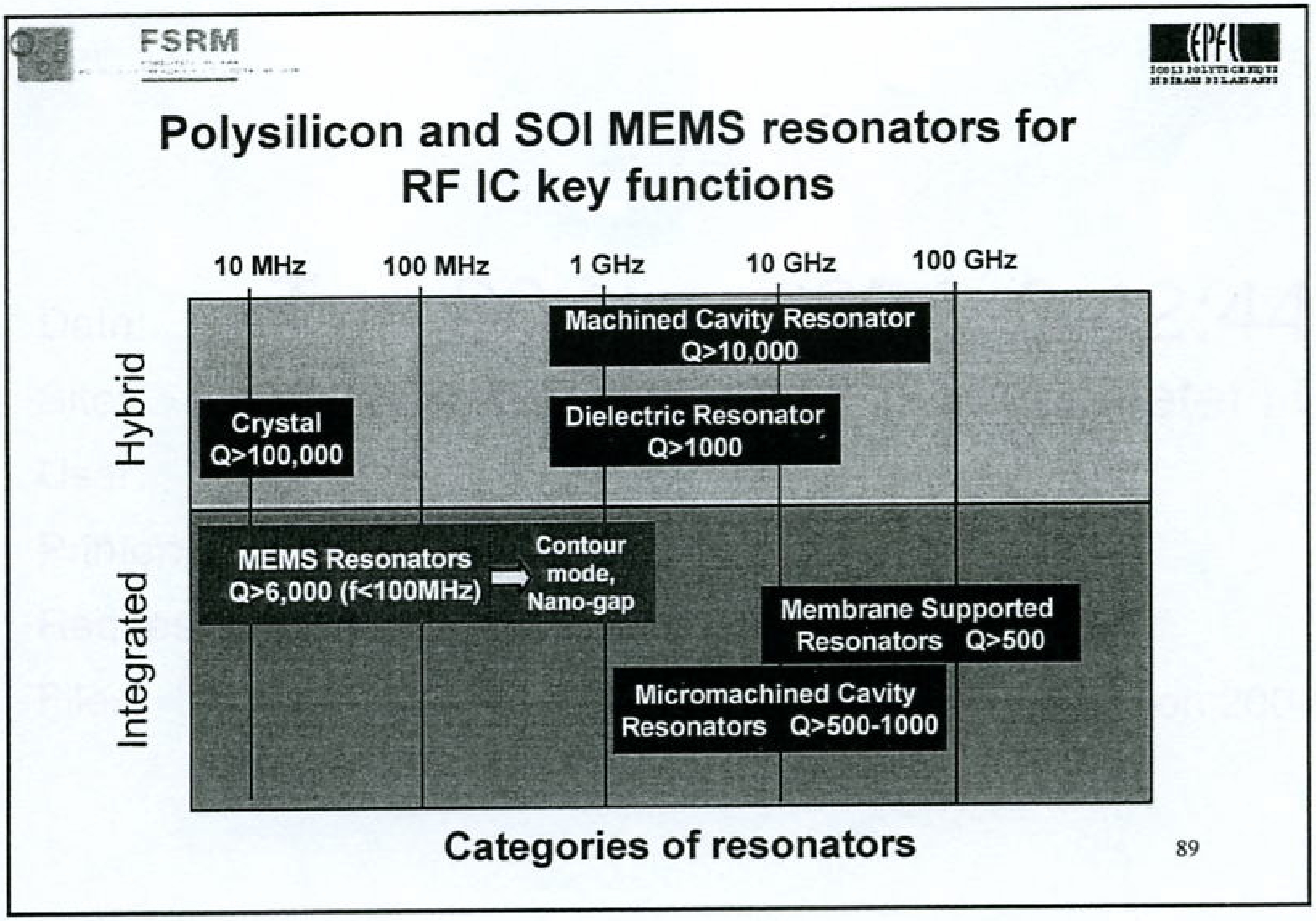


Figure 7.8 Illustration of the effect of the quality factor, Q, on the relationship between amplitude of oscillation and frequency.

Today´s resonators

- **Quarts crystals** used a lot
  - Q → 10,000
- RCL-resonators
  - Q < 1,000
  - Resistive, parasitic loss

Different resonator types



FSRM

Polysilicon and SOI MEMS resonators for RF IC key functions

Categories of resonators

89

Ionescu, EPFL

→ We focus on real vibrating resonators!

Typical properties

- 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**

MEMS resonators

- MEMS resonators can be used for basic circuit functions
  - Frequency reference: oscillator
    - Can be realized without external discrete passive components!
    - Relevant frequencies for MEMS resonators
      - 0.8 – 2.5 GHz for front-end wireless systems
      - 500 kHz → for IF frequency
  - Filtering
  - Mixing and filtering (”mixlers”, Nguyen)

Vibrating MEMS resonators

- Classification (De Los Santos)
  - **One-port:** same electrode used for excitation and detection of beam vibration
  - **Two-port:** separate electrodes for excitation and detection of the vibrating beam structure

Lateral and vertical movement

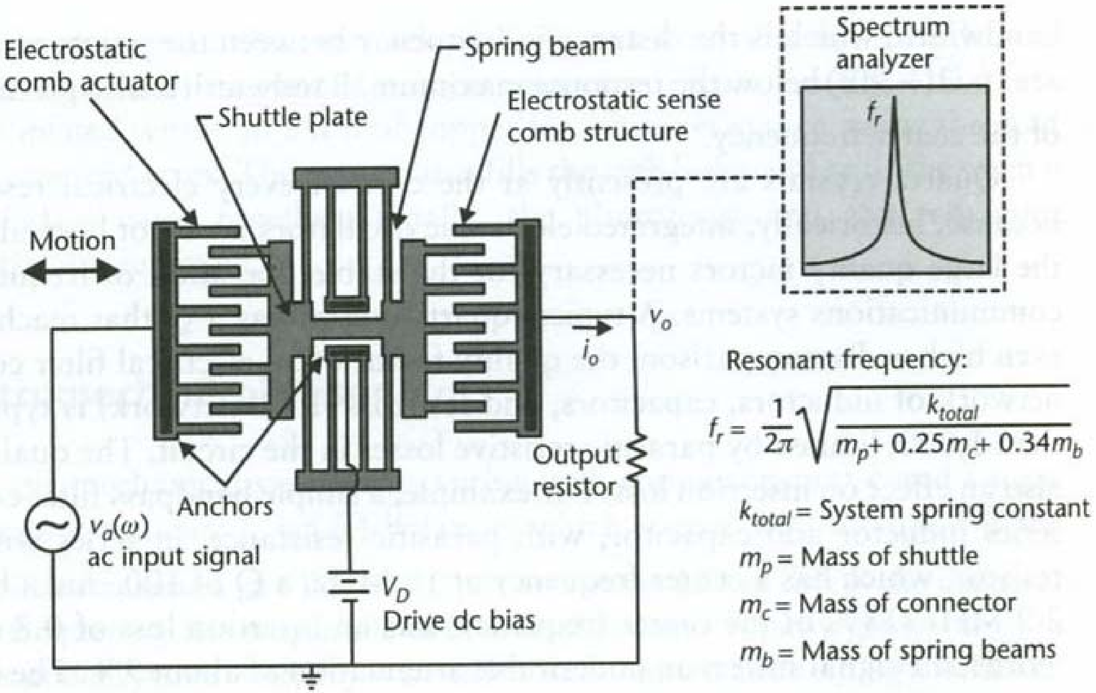
- Lateral movement
  - Parallel to substrate
  - Ex.: Folded beam **comb-structure**
- Vertical movement
  - Perpendicular to substrate
  - Ex.: clamped-clamped beam (**c-c beam**)
  - **”free-free beam”** (f-f beam)

Working principles for basic resonator structures

- Resonator using **folded beam comb-structure**
  - Developed at UoC, Berkeley
  - One of the earliest resonator designs fabricated
- Comb-structures are in general used in many types of MEMS systems
  - For example used for **accelerometer, gyro,** variable **capacitance**

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

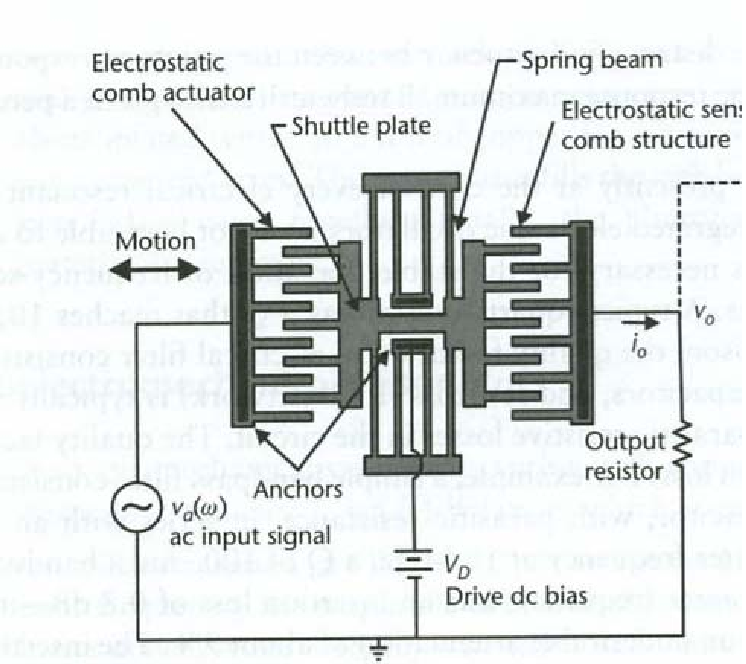
m_c = Mass of connector

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.

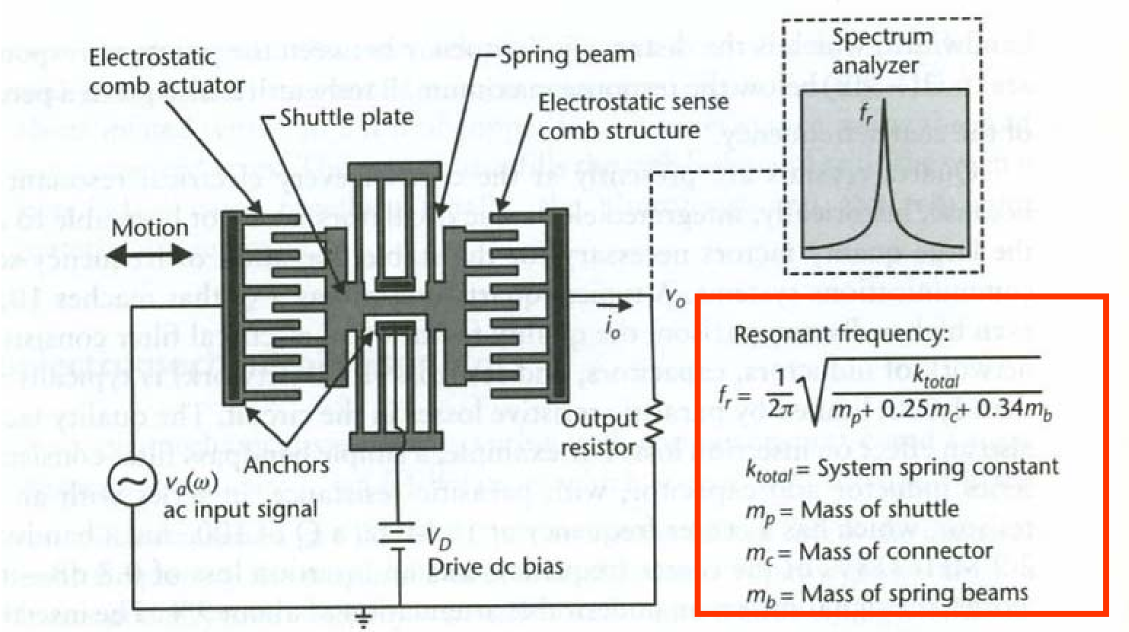
Comb-resonator, spring constant

- Spring constant for simple c-c beam deflected to the side
  - k_beam = 4* ¼ * E * t * (w/L) ^3
    - E = Youngs modulus, t = thickness, w = width, L = length
    - eg. 4 folded= 4 *¼ (¼ for each cantilever)
- In figure k_total = 2 * k_beam



Comb-resonator, mass

- m-contributions to resonance frequency
  - Spring moves less than shuttle mass
  - Beam mass is partly added to shuttle mass



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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)

Comb-resonator, output current

- A time varying capacitance at the output comb is established
  - Calculating of output current when Vd is constant and C is varying
    - I0 = d/dt (Q) = d/dt (C*V) = Vd * dC/dt = Vd * dC/dx * dx/dt
    - I0 = Vd * dC/dx * ω * x_max
    - I0 plotted versus frequency, shows a BP -characteristic

  - **Detailed modeling in next lecture!**

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

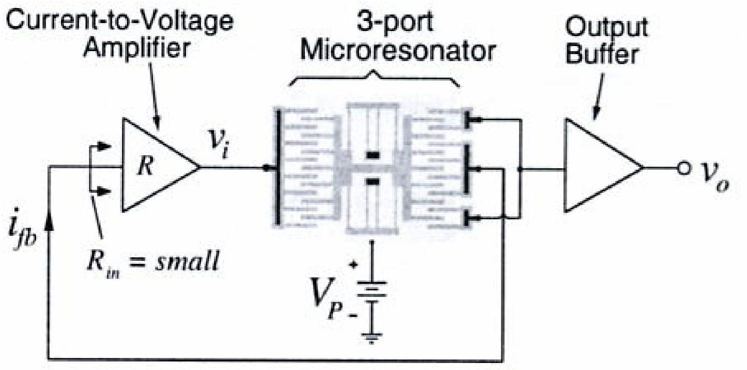


Fig. 8: System level schematic for the μresonator oscillator.

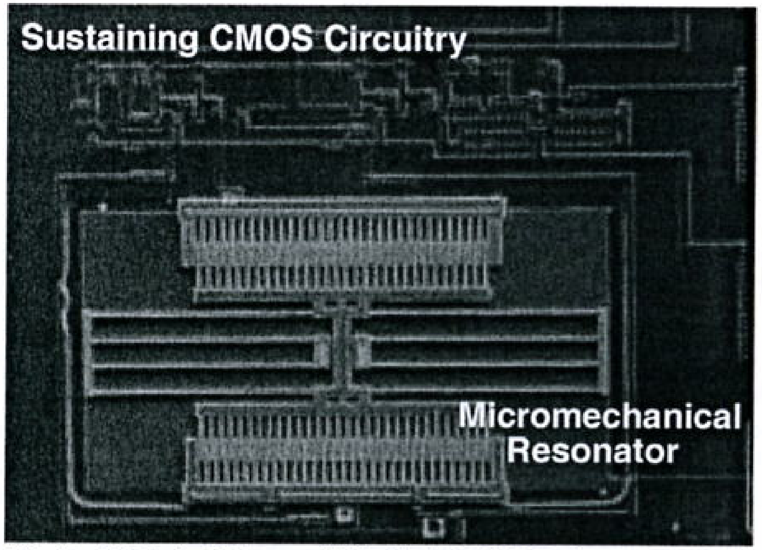


Fig. 9: SEM of a fully monolithic high-Q CMOS micromechanical resonator oscillator.

Nguyen, 1995

Micro resonator oscillator

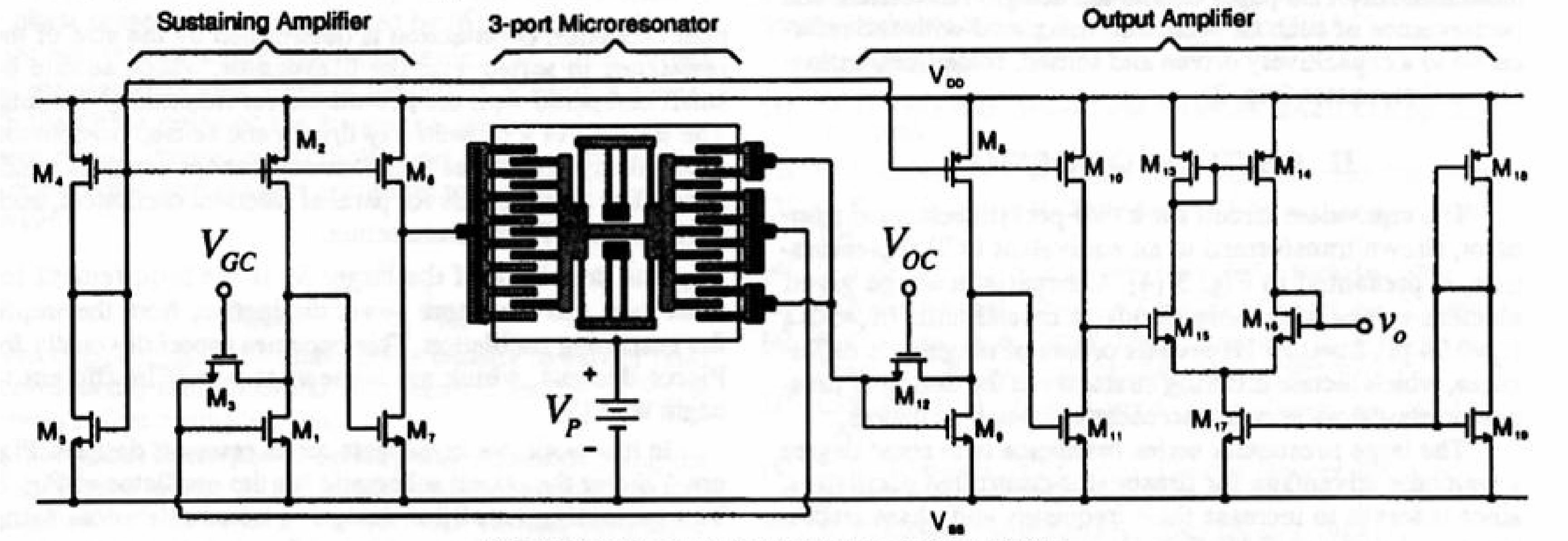


Fig. 4: Circuit schematic for the μresonator oscillator.

Nguyen, 1993

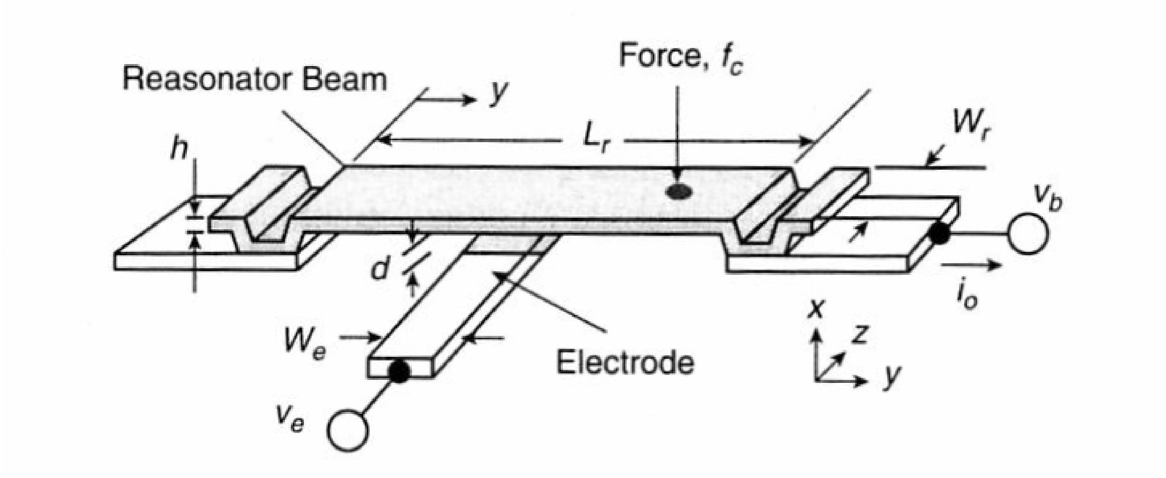
Design parameters for comb-structure

- To achieve high resonance frequency
  - Total **spring constant** should increase
  - Or **dynamic mass** should decrease
    - Difficult, since a given number of fingers are needed for electrostatic actuation
  - k and m depend on material choice, layout, dimensions
- **E/ρ** expresses the spring constant relative to mass
  - Frequency can increase by using a material with larger E/ρ ratio than Si
    - Aluminium and Titanium has E/ρ lower than for Si
    - Si carbide, poly diamond has E/ρ higher than for Si (poly diamond is a relevant research topic)
- Alternatively: use of other structures →

Beam-resonator

- Obtain **higher resonance frequency** than comb structure
  - Mass must be reduced more → **beam resonator**
- Studied in detail at UoMichigan
  - Commercialized by Discera, Inc., Ann Arbor, Michigan
    - Produces reference frequency oscillators substituting quarts crystals in mobile phones

- **Clamped-clamped beam**



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

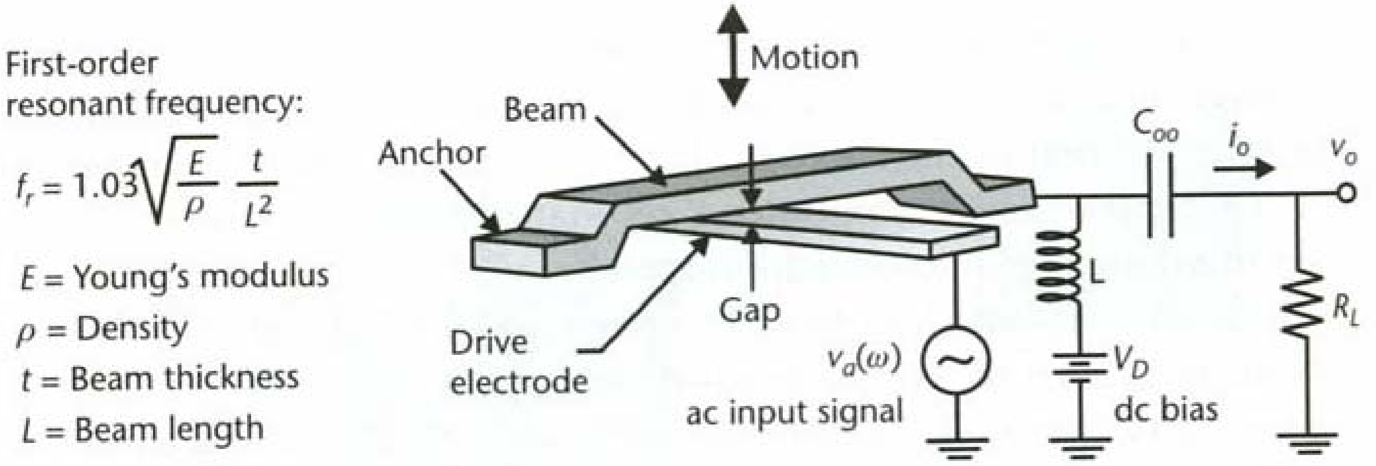
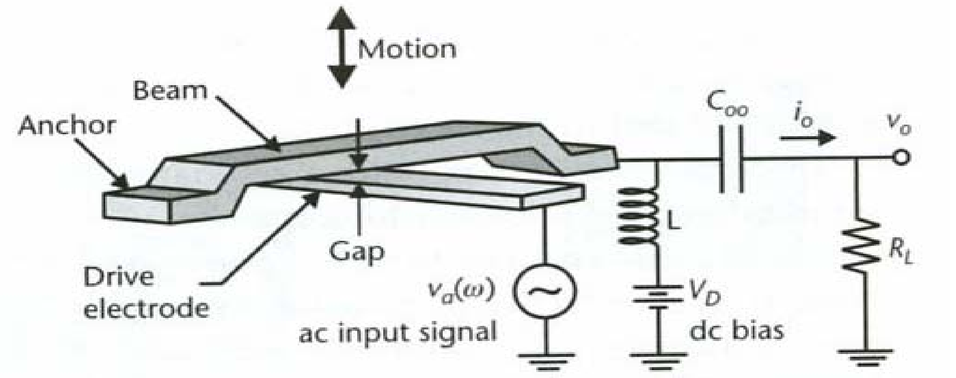


Figure 7.10 Illustration of a beam resonator and a typical circuit to measure the signal. The beam is clamped on both ends by anchors to the substrate. The capacitance between the resonant beam and the drive electrode varies with the deflection.

Beam-resonator, contd.

- Detection of output signal
  - Mechanical vibrations establish a time varying capacitance with constant voltage, Vp, on the beam
  - Q = Vp * C will then vary
  - A displacement current is generated
    - i0 ~ dC/dx * dx/dt
    - I0 versus frequency shows a BP -behaviour
      - Q ~ 10,000 in vacuum



Benefits of beam-resonators

- Simple structure
- Smaller dimensions, smaller mass → higher resonance frequency
- Can have many frequency references on one single chip
- More linear frequency variation with respect to temp over a larger interval
- Integration with electronics possible → reduced cost

c-c beam

- c-c beam can be used as a reference-oscillator or HF/VHF filter/mixer

- An example: poly beam [Nguyen et al]
  - l = 41 µm, w = 8 µm, t = 1.9 µm
  - g = 130 nm, Vd = 10 V, va = 3 mV
  - fr = 8.5 MHz
  - Deflection amplitude = 4.9 nm at beam centre
  - Q = 8,000 at 9 Pa
  - Q < 1,000 at 1 atm

Loss in c-c-beam

- Reasons for Q degradation for MEMS resonators
  - **Energy loss to substrate via anchors**
  - **Air/gas damping**
  - **Intrinsic friction**
  - **Small dimensions (low stored energy compared with energy loss)**

- To obtain higher resonance frequency: stiffness of a given resonator beam has to be increased
  - More energy pr cycle leaks to substrate via anchors
  - → Q-factor decreases

- c-c-beam is not the best structure for high frequencies!
  - Eks. Q = 8,000 at 10 MHz, Q = 300 at 70 MHz
- **→ ”free-free beam” can be used to reduce substrate loss via anchors!**

”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 if it was not anchored
  - Beneficial for reducing energy loss via anchors to substrate

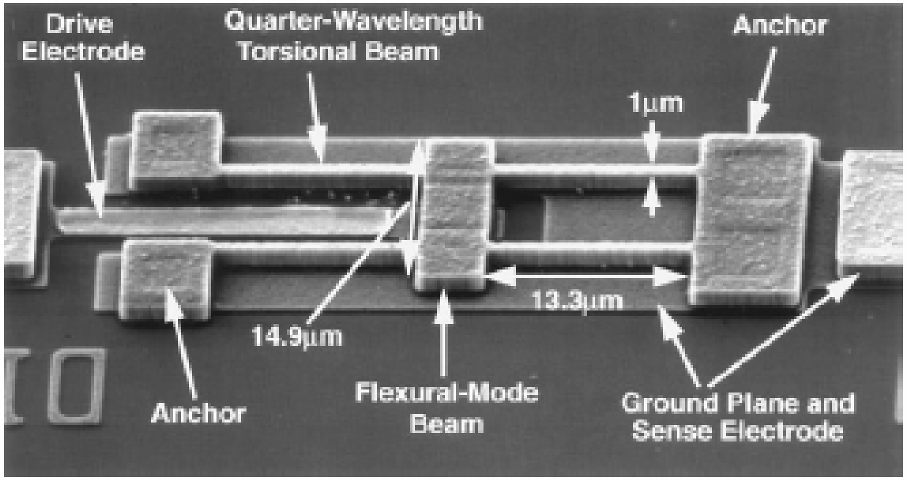
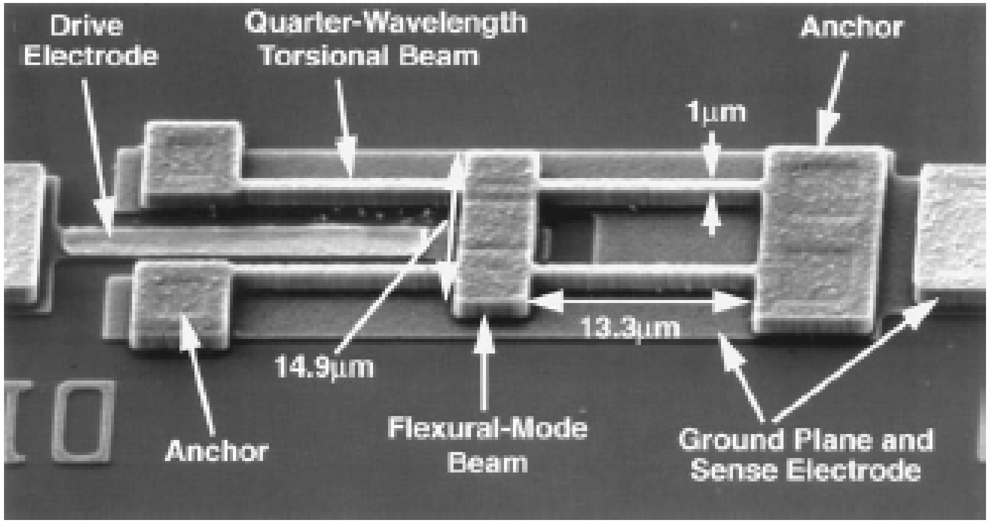


Fig. 29. SEM of free–free beam virtually levitated micromechanical resonator with relevant dimensions for $f_o = 71$ MHz.

Nguyen, 1999

free-free-beam

- Higher Q can be obtained with f-f-beams
  - Ex. Q= 20,000 at 10 – 200 MHz
  - Used as reference oscillators, HF/VHF-filters/mixers



→ Other structures, **vibrating discs**, in a future lecture