INF5490 RF MEMS

LN15: 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

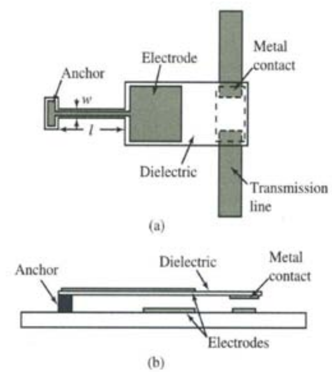
Choice of focus → RF MEMS

- 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



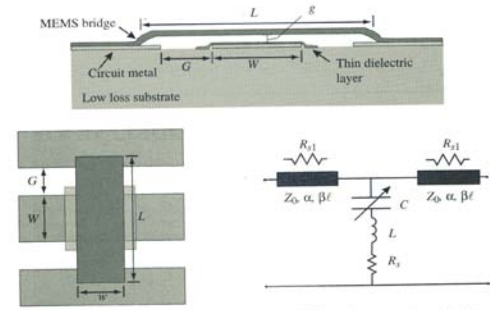
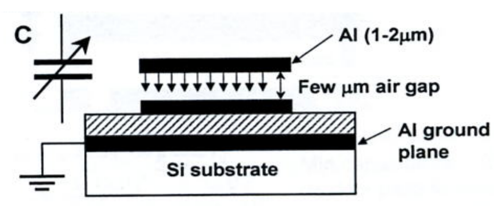
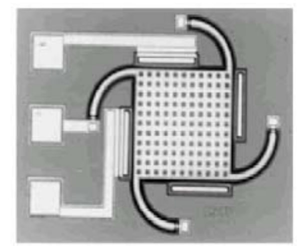
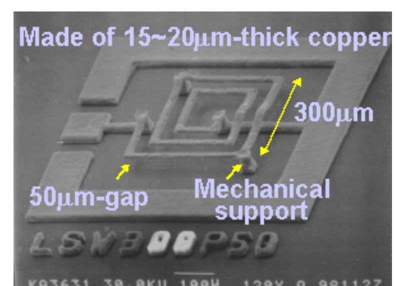


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).







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!**

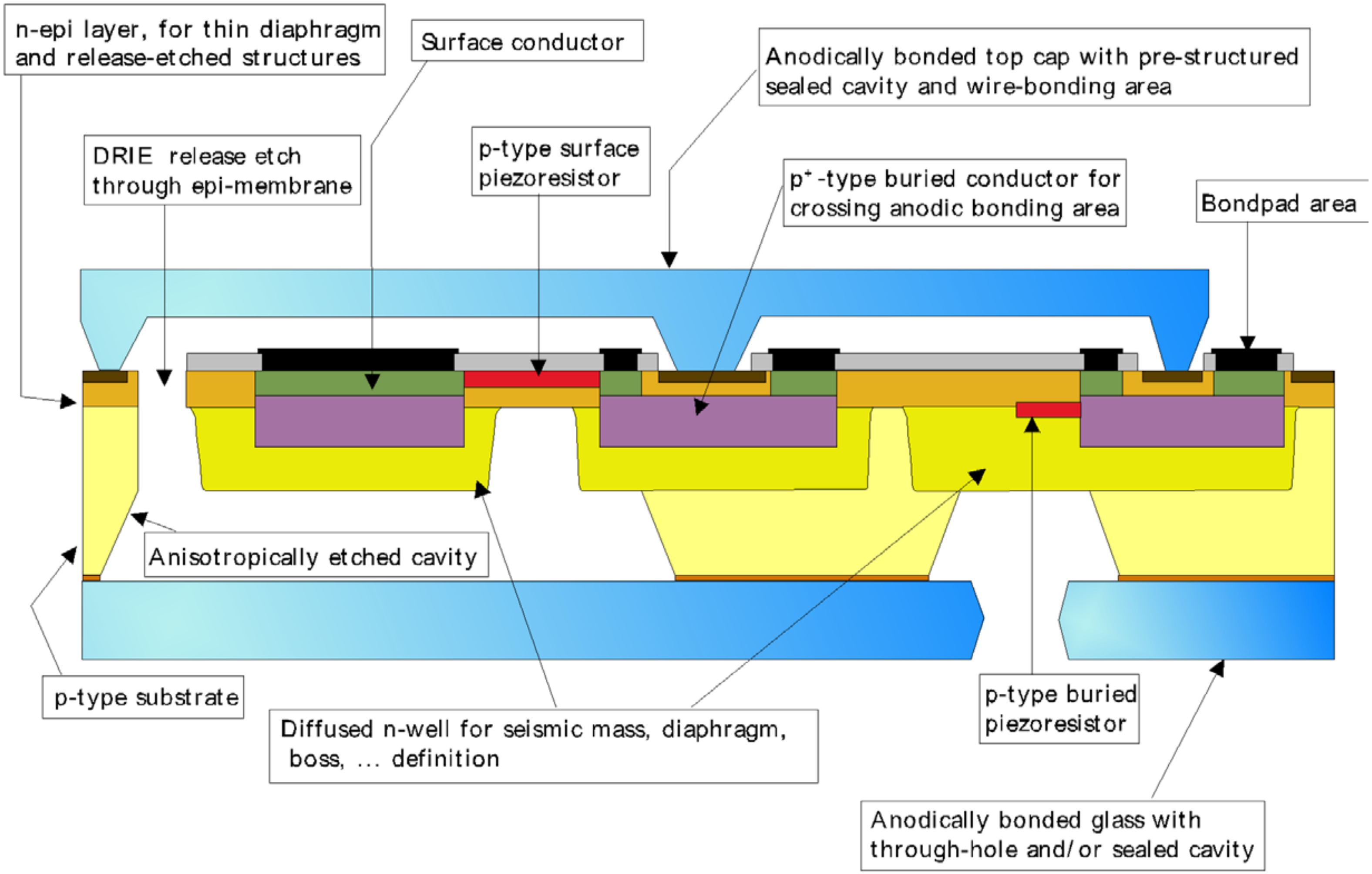
Important process steps

- 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

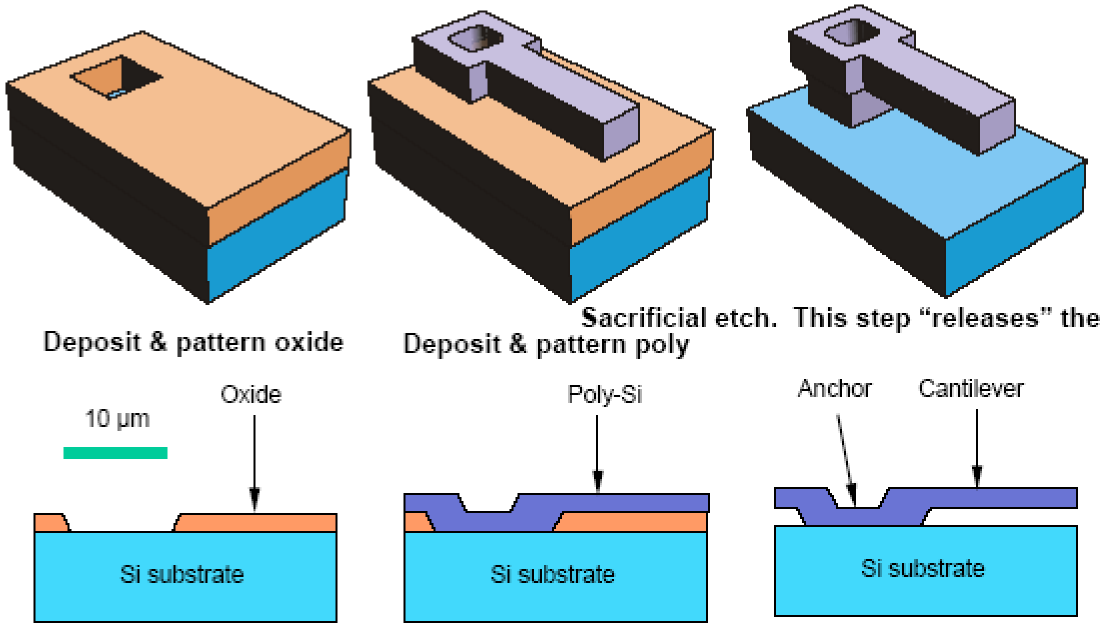
Cross section overview



Surface micromachining

- **”Surface”** micromachining
  - Deposit layers
    - **Structural layer**
    - **Sacrificial layer** = ”distance-keeping” layer
  - Selective etching of structural layers
  - Removing sacrificial layers

Micromachining a Cantilever



Srinivasan

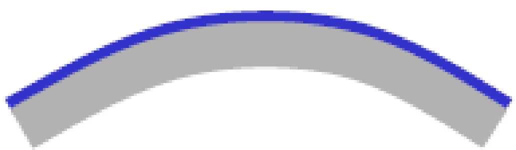
Additive process steps

- 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

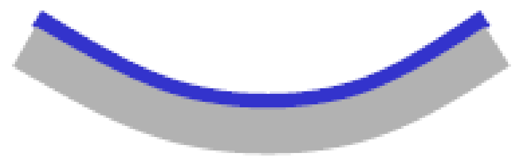
Residual Stress in Thin Films

- 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**

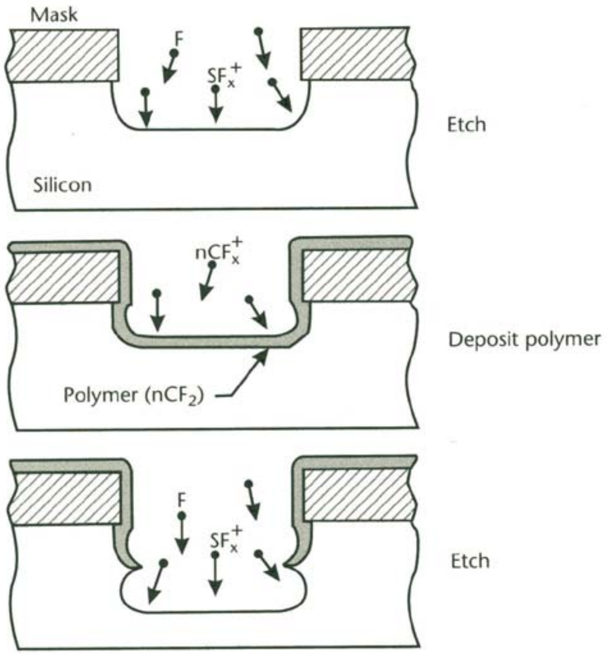
Wet-etching

- **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

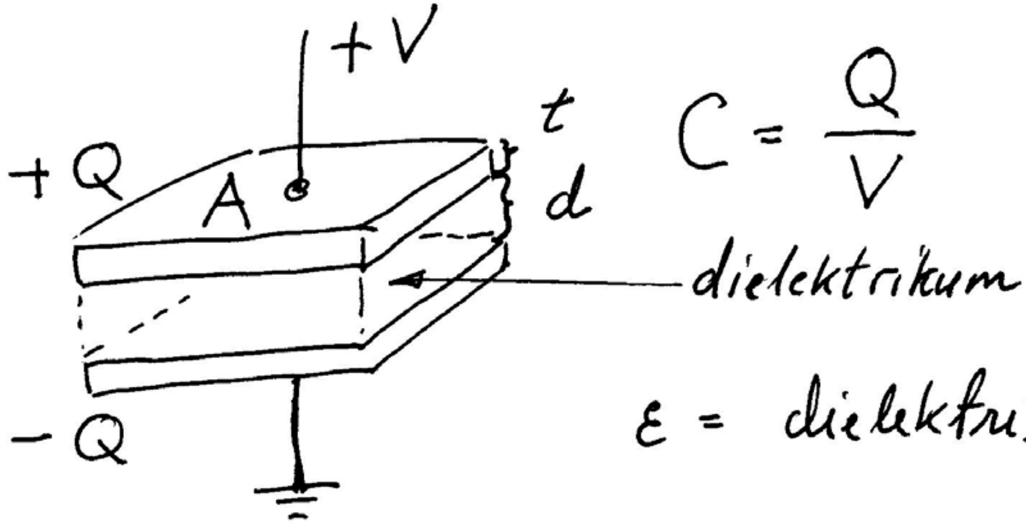
- **Electromechanical transducers**
  - Transforming
    electrical energy ←→ mechanical energy

- 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



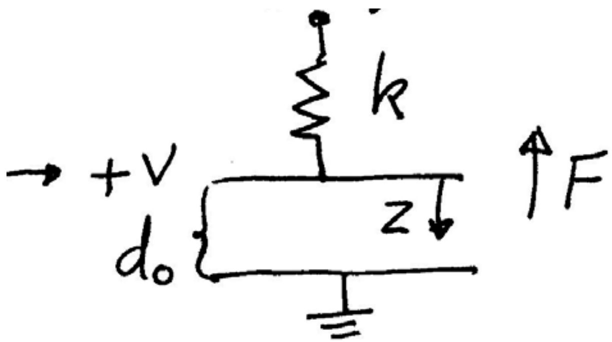
$$C = \frac{Q}{V}$$

ε = dielektrisk permittivitet

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:

$$F_{net} = -\frac{\varepsilon A V^2}{2d^2} + k\left(d_0 - d\right)$$ = 0 at equilibrium

Two equilibrium positions

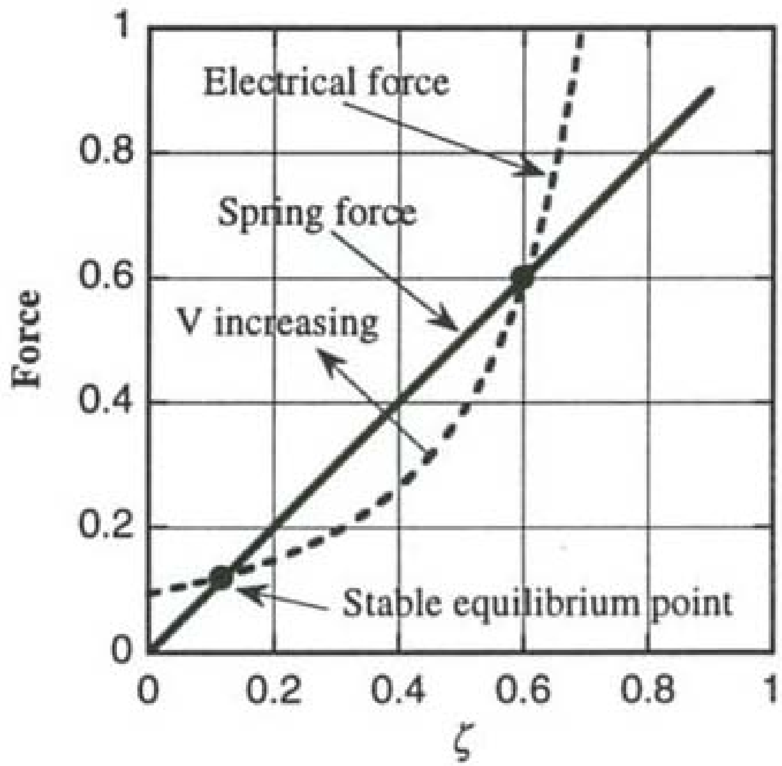


Figure 6.7. Electrical and spring forces for the voltage-controlled parallel-plate electrostatic actuator, plotted for $V/V_{PI} = 0.8$.

$\varsigma = 1 - d/d0$

Senturia

Pull-in

$$F_{net} = 0$$

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

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

Pull-in when:

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

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

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

Ex. of interconnection:

”Direct transformation”

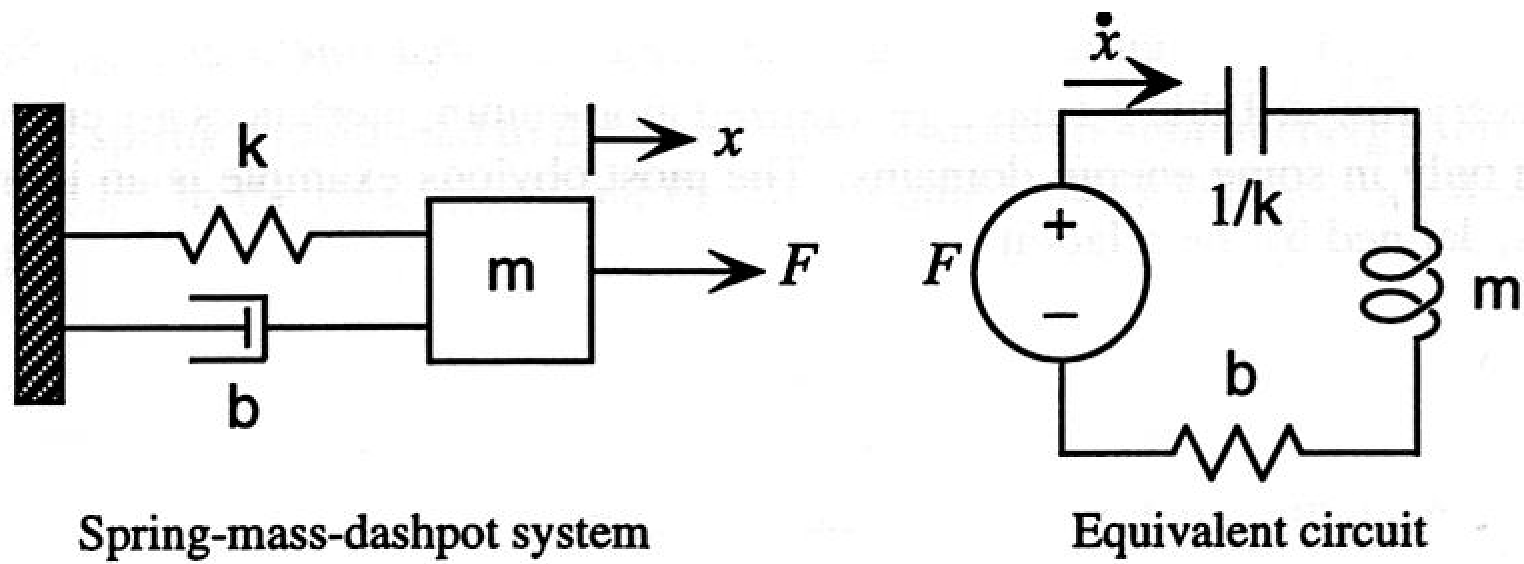
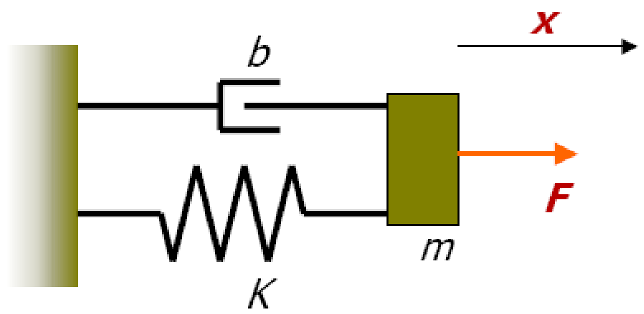
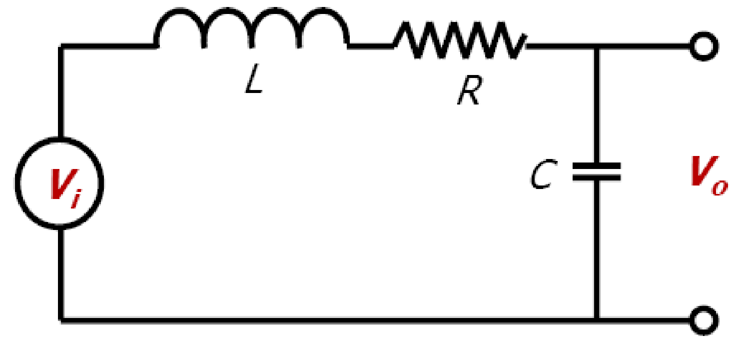


Figure 5.9. Translating mechanical to electrical representations.

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:

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

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

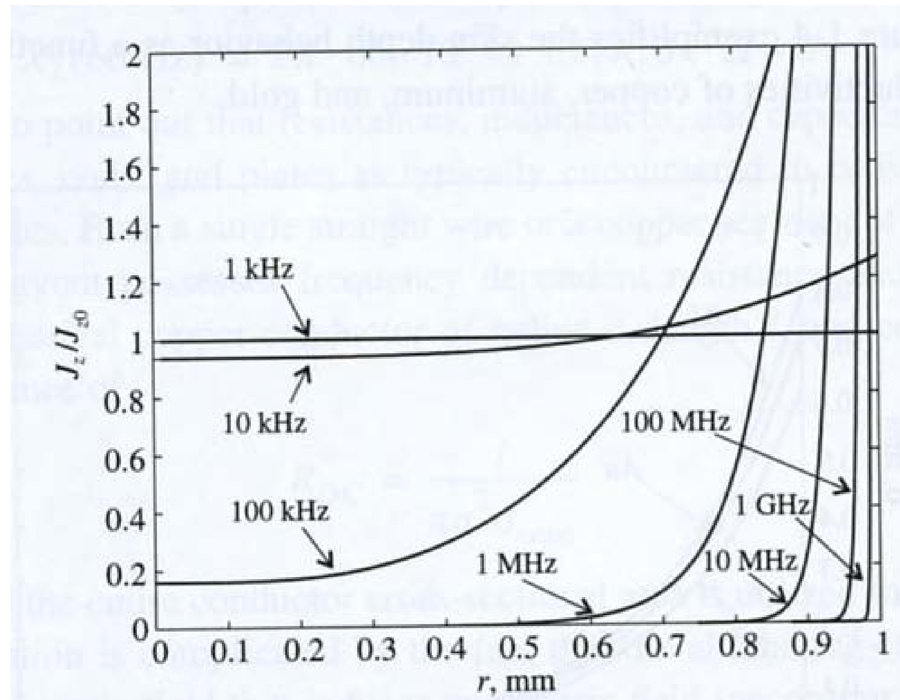
$$\omega_0 = \sqrt{\frac{K}{m}} \text{ mechanical system}, \quad \omega_0 = \sqrt{\frac{1}{LC}} \text{ electrical system}$$

$$Q \text{ quality factor}$$

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

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



- What does this mean for practical designs?

Transmission line

- A conductor has to be modeled as a transmission line

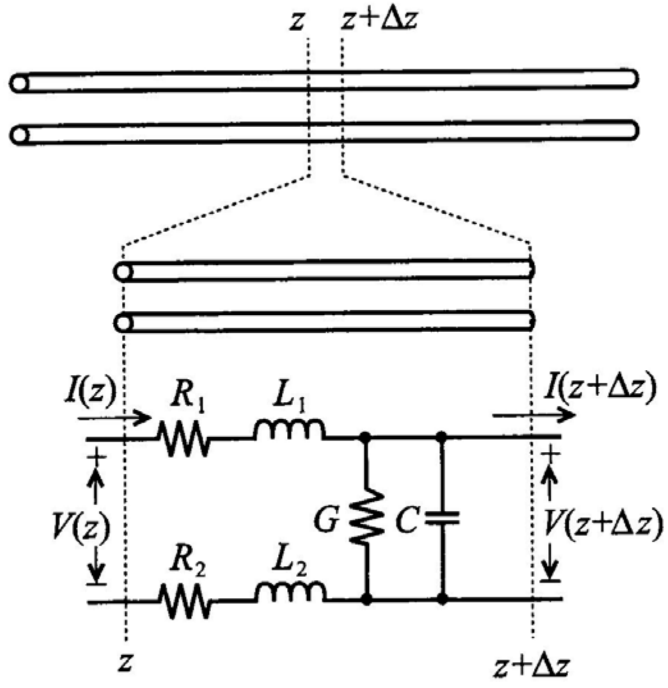


Figure 2-3 Partitioning an electric line into small elements Δz over which Kirchhoff's laws of constant voltage and current can be applied.

Solution: 2 waves

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

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

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

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

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

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

Impedance for lossless transmission line

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

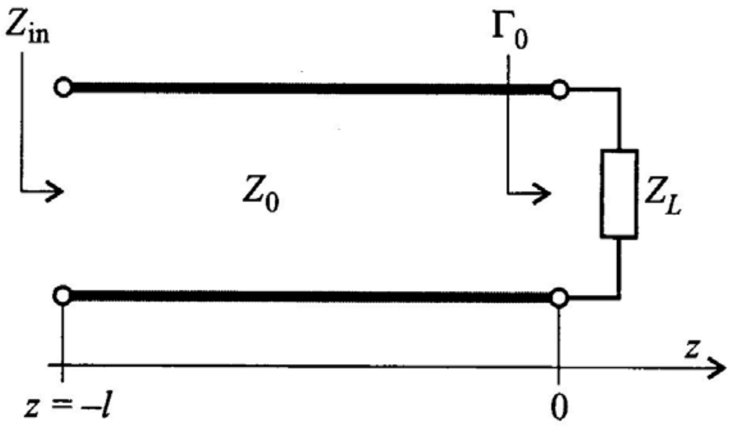


Figure 2-23 Terminated transmission line at location $z = 0$.

How to avoid reflections and have good signal propagation?

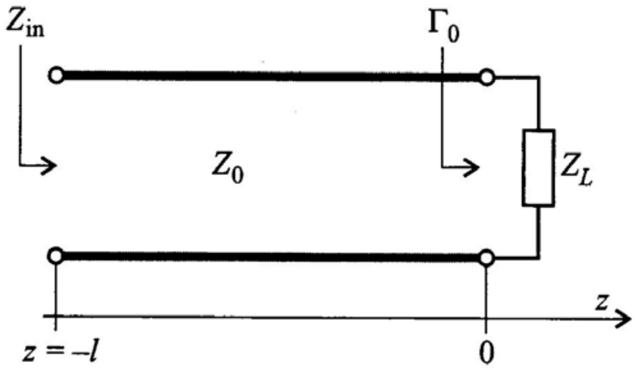
Reflection coefficient

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

← 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

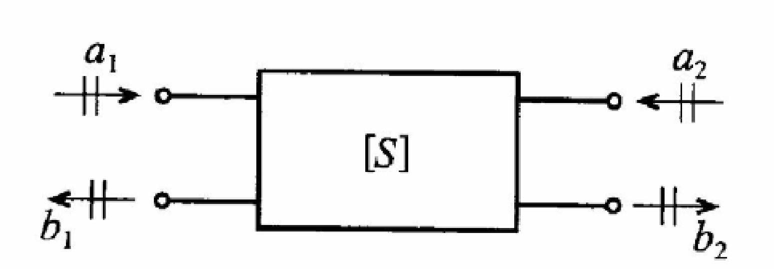
$$Z_L = 0 \Rightarrow \Gamma_0 = -1$$

No reflection when:

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

→ **”MATCHING”**

Interpretation of S-parameters



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

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

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

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

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)

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

Characterize power loss due to dissipation mechanisms in reactive elements.

$$Q_{\text{Tuned Circuit}} = \frac{f_0}{B}$$

$$Q_{\text{Capacitor}} = \frac{\omega_0 C}{G}$$

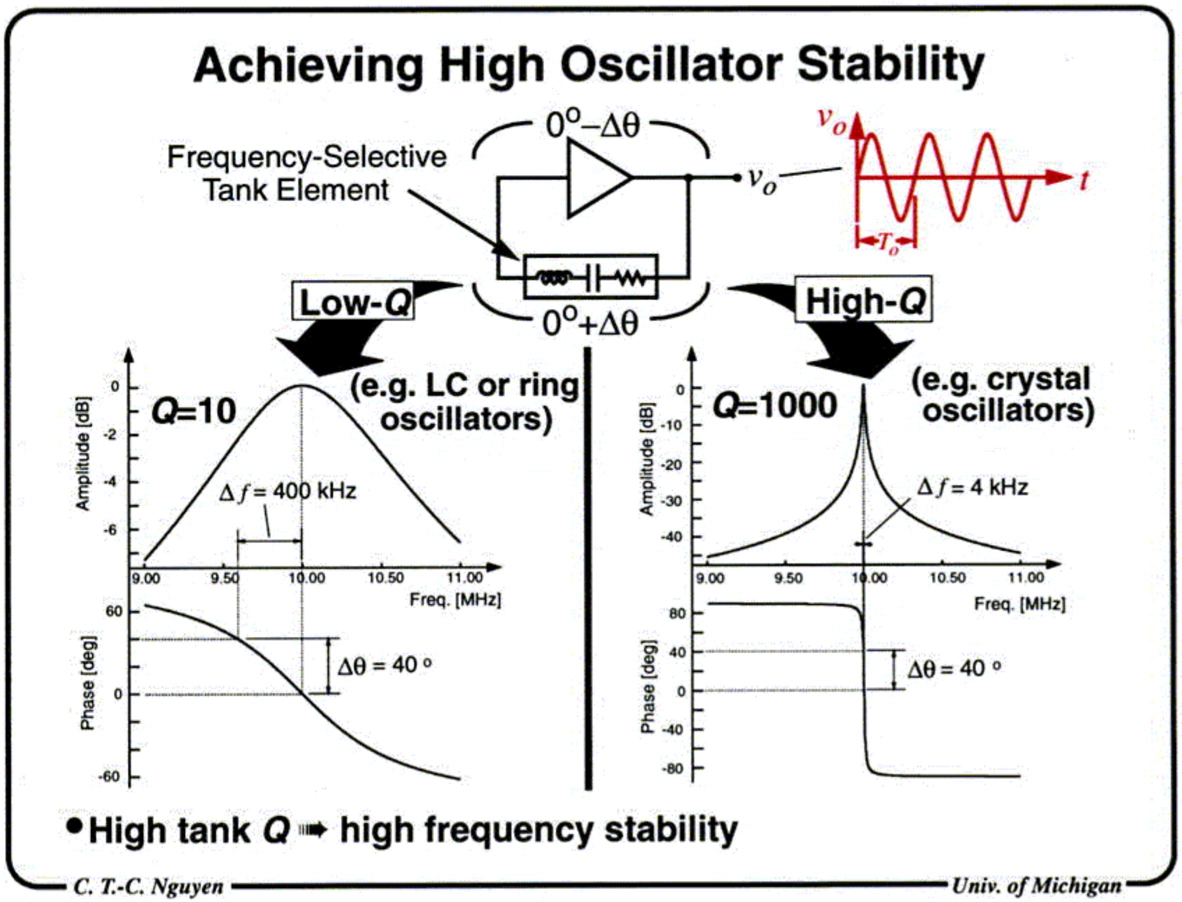
$$Q_{\text{Inductor}} = \frac{\omega_0 L}{R}$$

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

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

Relation between Q-factor and oscillator stability

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



Benefits and typical characteristics of RF MEMS switches

FSRM

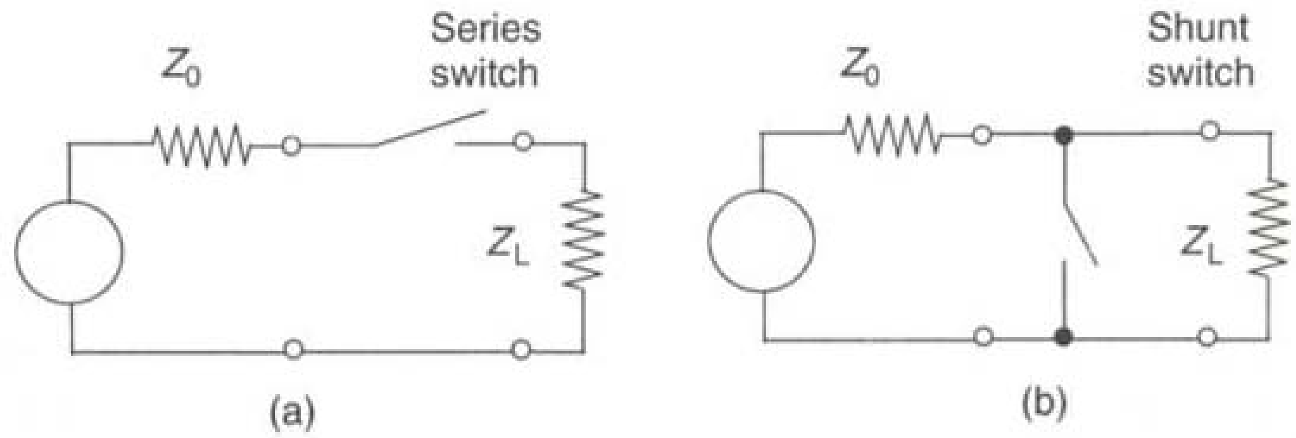
RF MEMS switch: key advantages and issues

+ • **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



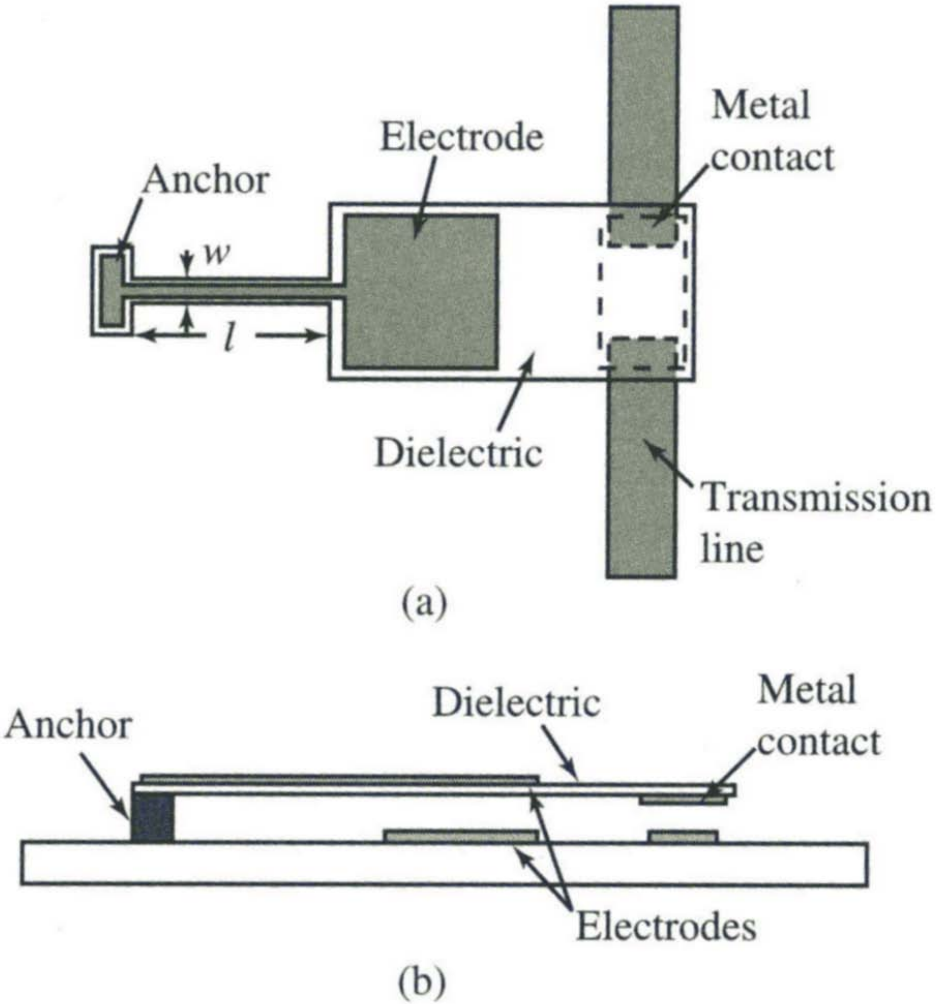
Varadan fig. 3.2

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

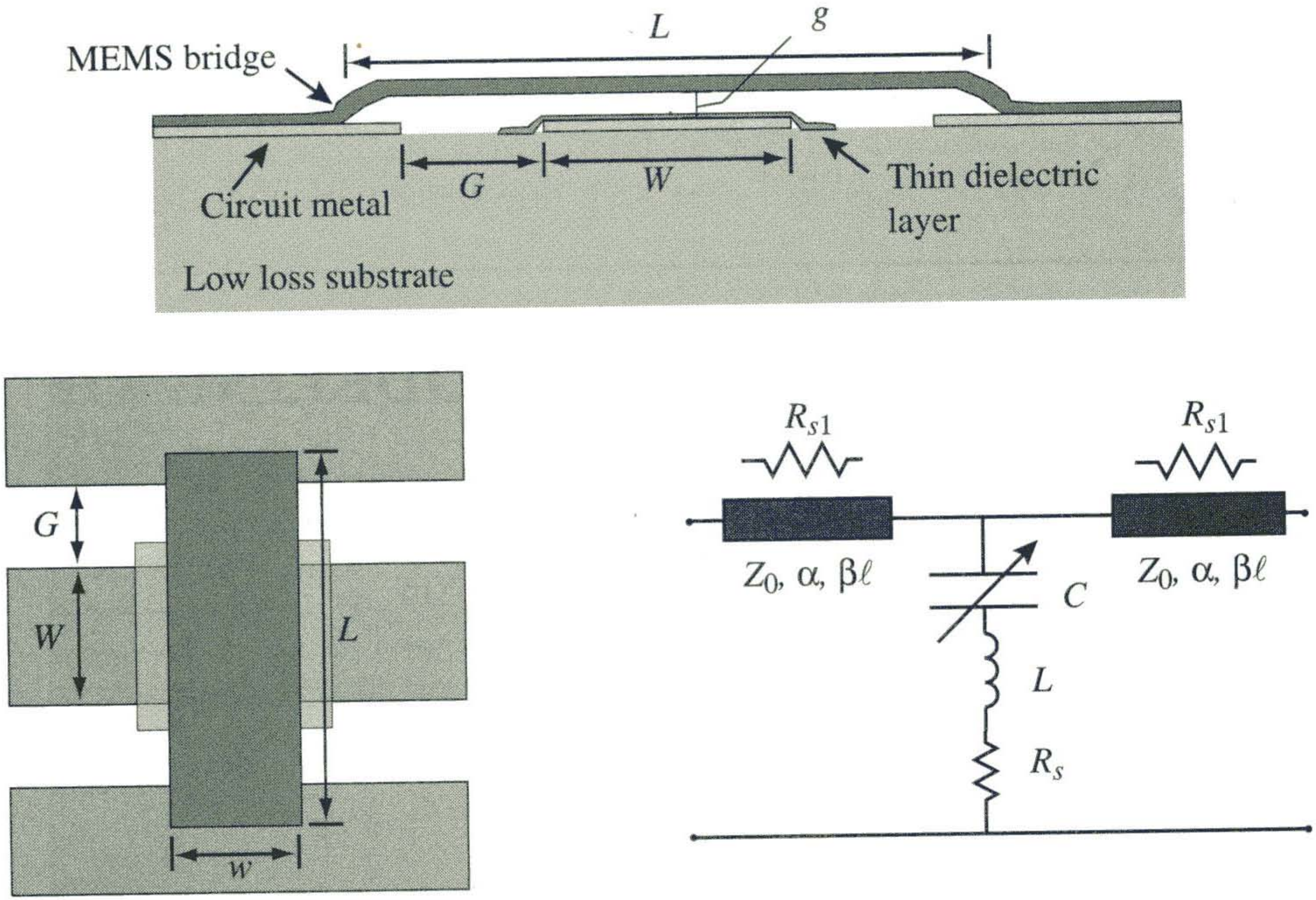


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

Rebeiz

Electromechanical operation

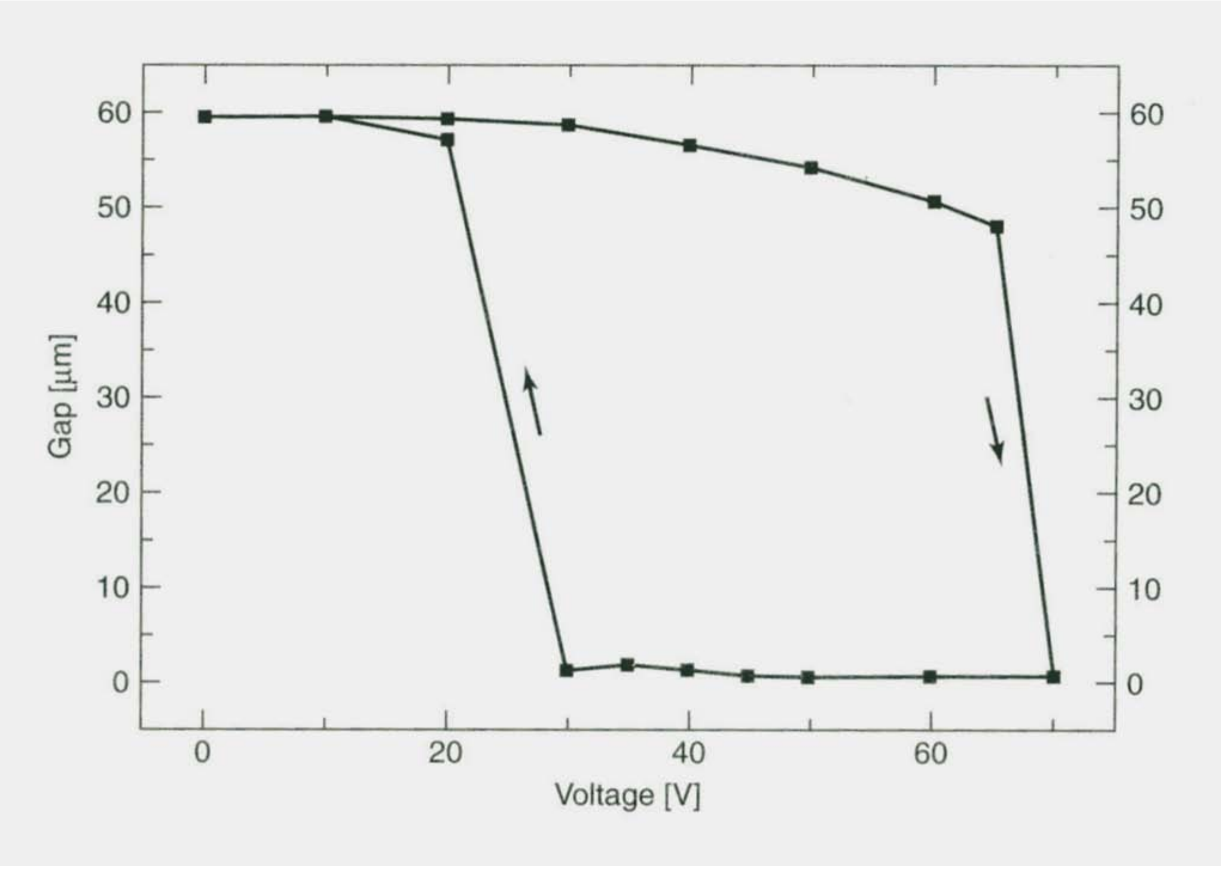
- The operation is based on the **pull-in** effect
  - Characteristics at pull-in
    - Membrane/beam pulls in at 1/3 of gap
    - Pull-in voltage:

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

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

Hysteresis

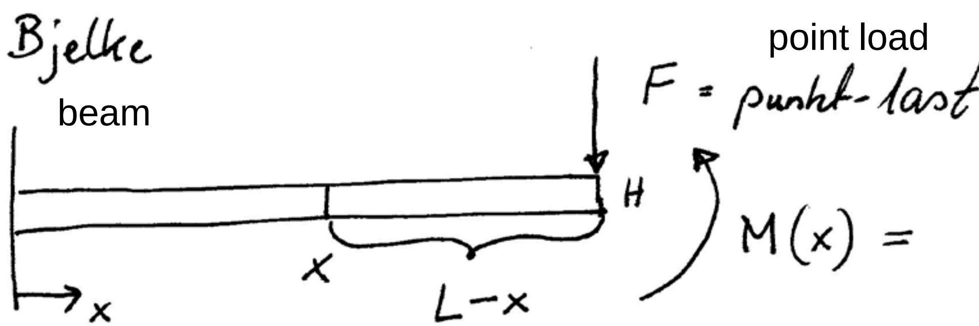
- A capacitive switch shows hysteresis when being switched on/off



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



$M(x) =$ 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

Gap vs. Time for various Q-factors

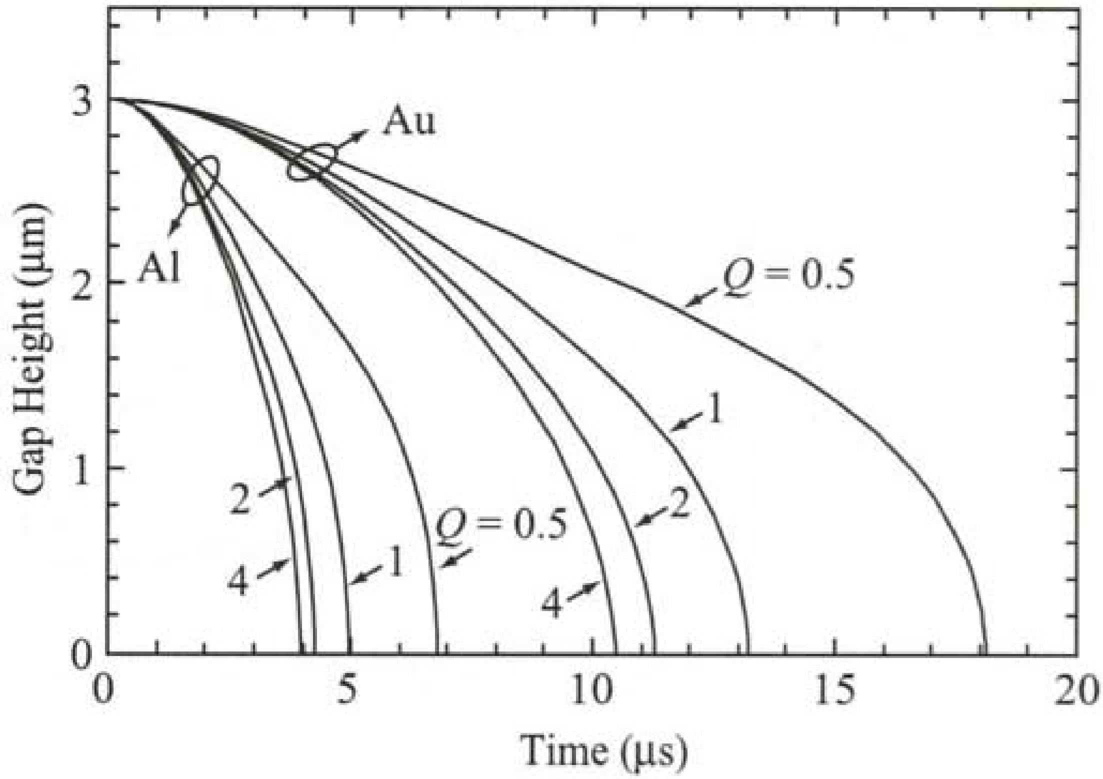


Figure 3.3. Pull-down simulations for the Au and Al beams of Table 3.1 for an applied voltage of 42 V ($V_s = 1.4V_p$).

Acceleration limited switch

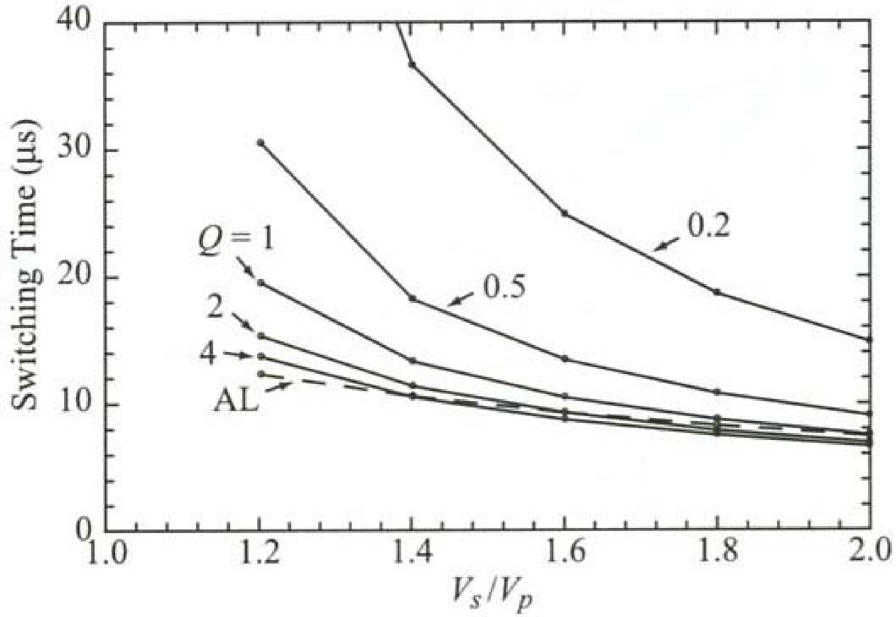


Figure 3.5. Simulated switching times for the Au beam given in Table 3.1. "AL" means acceleration-limited and is given by Eq. (3.23).

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

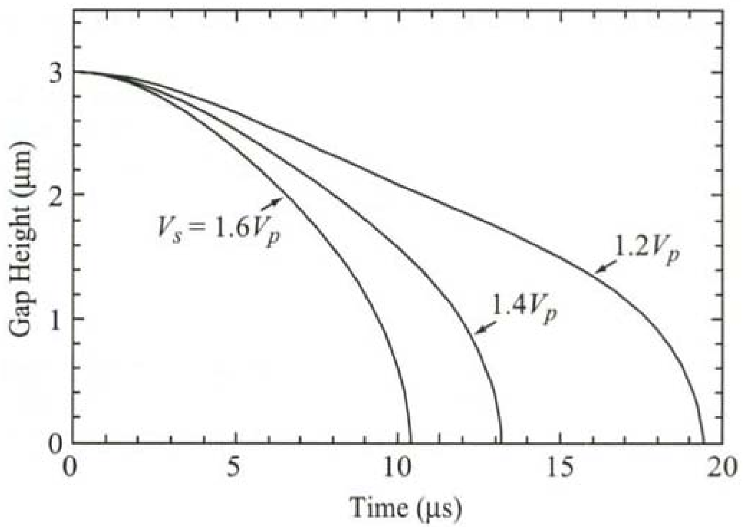
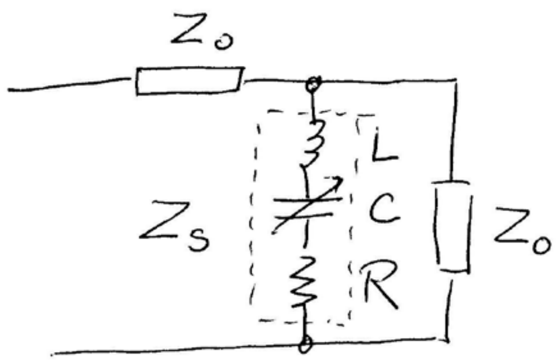


Figure 3.4. Pull-down simulations for the Au beam of Table 3.1 versus the applied voltage, and $Q = 1$.

RF modeling: Shunt configuration



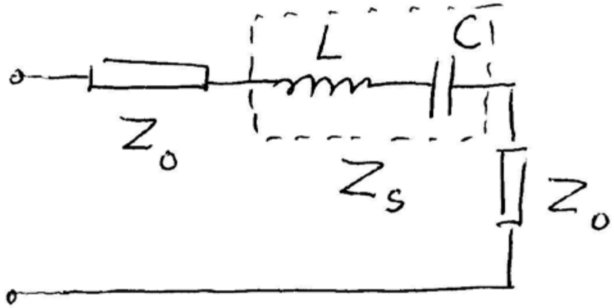
$$Z_s = R + j\omega L + \frac{1}{j\omega C}$$

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

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

Series contact cantilever switch

OFF (up-state)



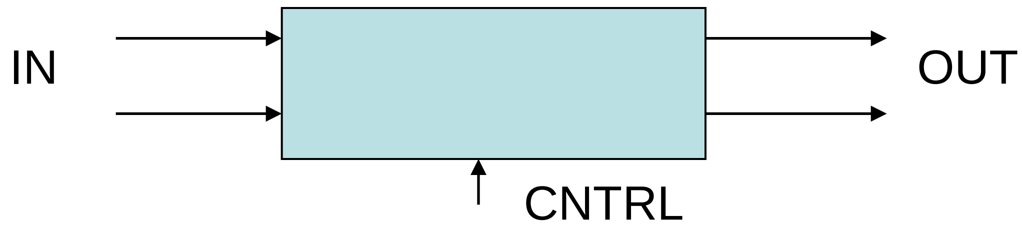
$$Z_s = j\omega L + \frac{1}{j\omega C}$$

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

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

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**

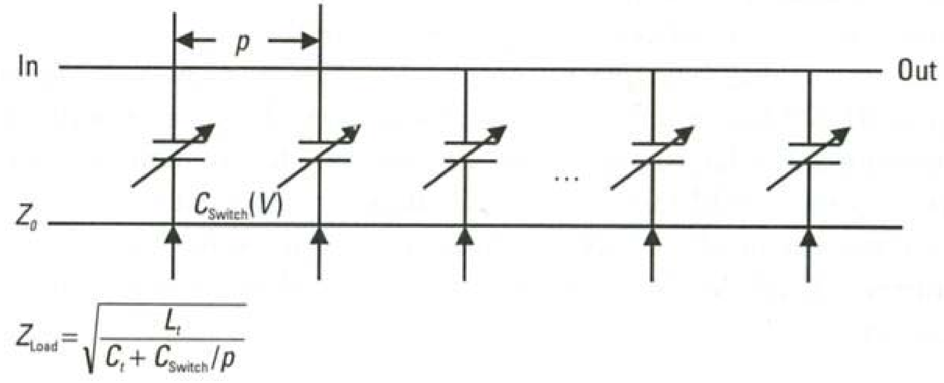
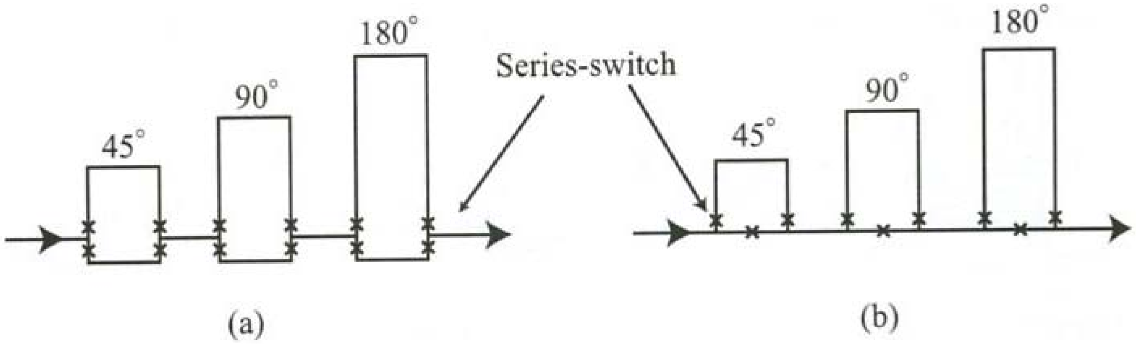


Figure 5.1 Schematic of analog phase shifter.

De Los Santos

C_t = line capacitance

Digital phase shifters with series-switches



- 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

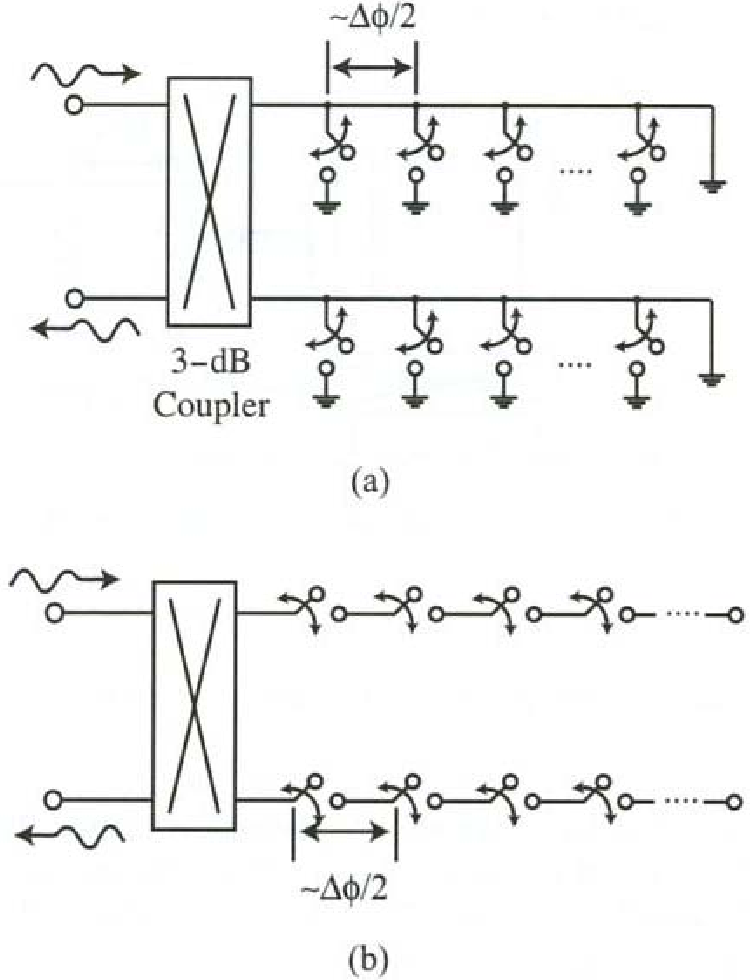


Figure 9.1. A reflect-line N-bit phase shifter using (a) shunt and (b) series switches.