Karlsruhe Institute of Technology

Hoch- und Höchstfrequenzhalbleiterschaltungen (HHHS)
Millimetre-wave monolithic integrated circuit design

Winter term 2013/2014

Switch and Phase-Shifter

INSTITUT FÜR HOCHFREQUENZTECHNIK UND ELEKTRONIK

lecture outline

- This part of the lecture is based on the lecture “Active integrated circuits for millimetre wave applications (AICMMA)”, which was given by Prof. Ingmar Kallfass, who is now with the University of Stuttgart.
- switches: applications and figures of merit
- switch design
  - diode switches
  - FET switches
- a practical switch example
- millimeter-wave phase shifters

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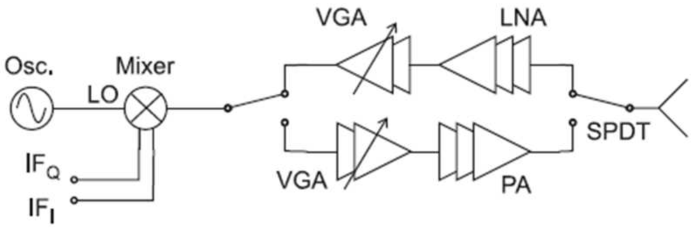
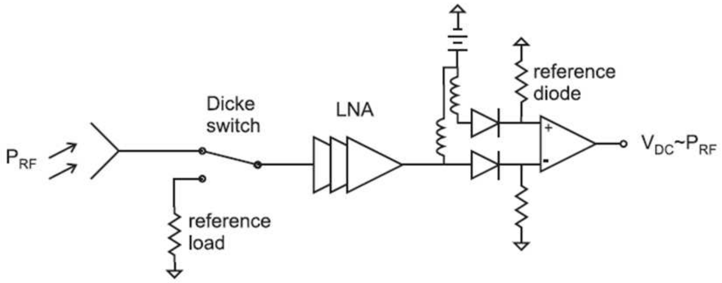
switch applications

- antenna switches
  - address a single Tx/Rx antenna: communication, mono-static (pulse) radar
  - address several Tx and/or Rx antennas (antenna diversity)
- redundancy switches
  - in space applications
- phase shifter
  - electronic beam-steering, phased arrays
- Dicke switches
  - reference load in radiometers for pixel normalisation

antenna switch



Dicke switch



switch: major figures of merit

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branch open	**insertion loss**
	reflection loss
	linearity
branch closed	isolation
	reflection loss
	linearity
control	actuation voltage
	switching speed
others	power consumption

monolithic integrated switch technologies

- integrated switches

	loss/ isolation	linearity	actuation voltage	switching speed	power cons.
Schottky diode	good	limited	low	fast	!= 0
FET channel	medium	limited	low	fast	= 0
HEMT Schottky-gate	medium	limited	low	fast	!= 0
HBT PN junction	medium	limited	low	fast	!= 0
MEMS	good	high	high	slow	= 0

- others switch technologies
  - (mechanical) waveguide switch
  - chopper wheel

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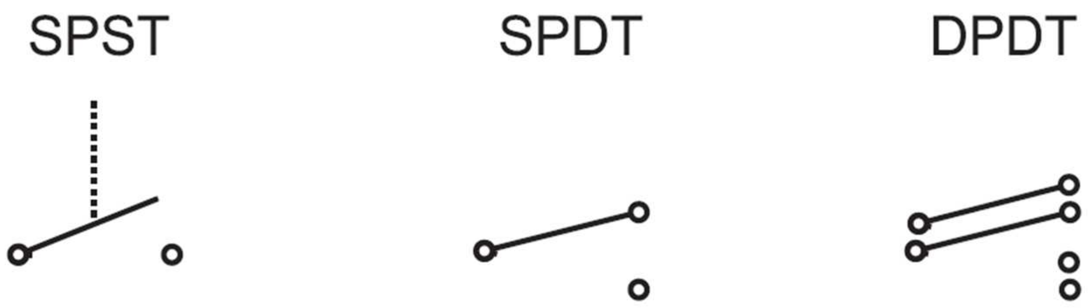
switches: terminology

- n-pole m-throw
  - single-pole single-throw (SPST), single-pole double-throw (SPDT)
  - double-pole double-throw (DPDT) etc
- power matching
  - reflective: un-matched when non-conducting
  - non-reflective: matched under all states
- operating principle
  - conductive (diodes, transistors)
  - capacitive (e.g. MEMS)



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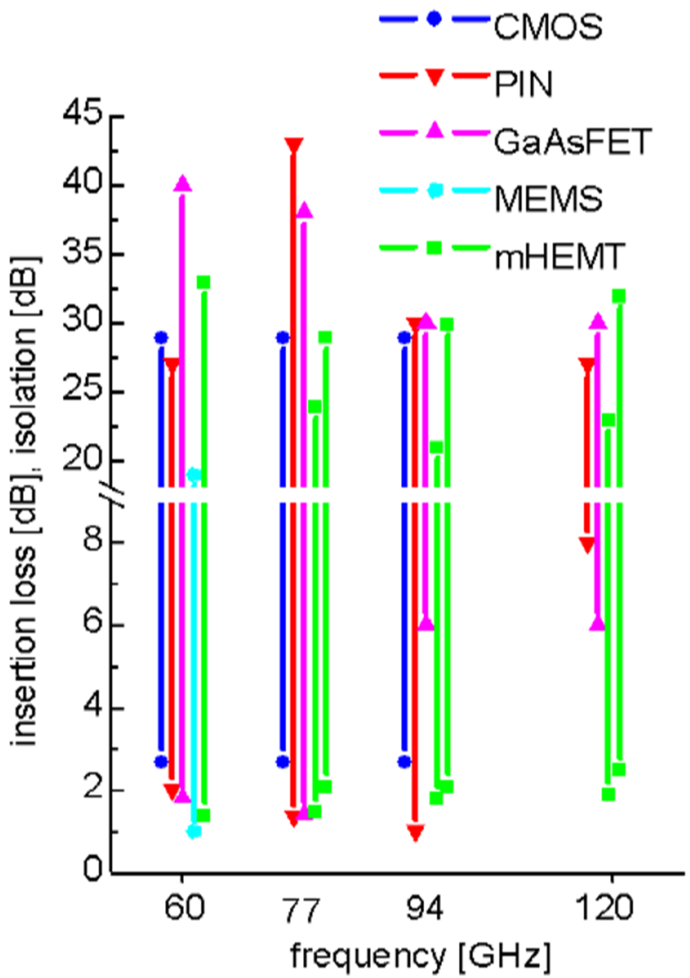
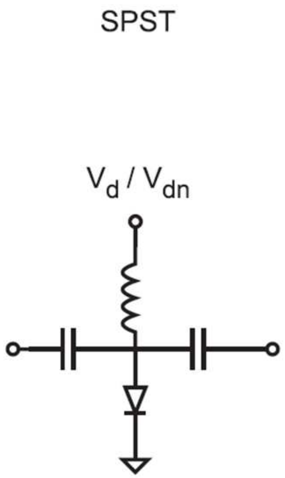
switches: state-of-the-art

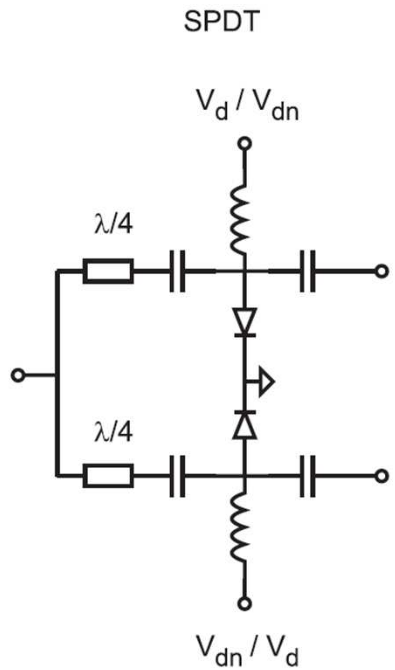
- Kallfass et.al. "Multiple-Throw Millimeter-Wave FET Switches for Frequencies from 60 up to 120 GHz," 38th European Microwave Conference, Oct. 2008



diode switch topology

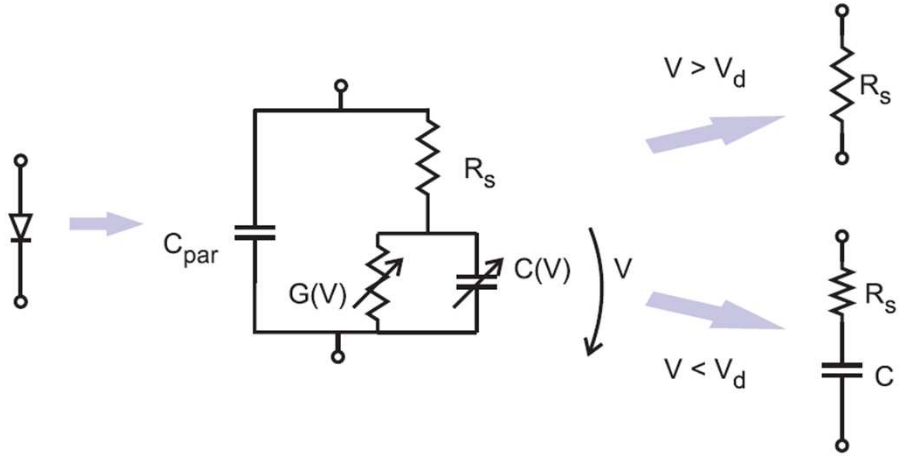
- principle of operation
  - conductive
  - requires static diode current in open mode
  - biasing inductors may be λ/4 stubs and/or used for power matching
  - in SPDT: λ/4 line for branch isolation (short → open)





diode characteristics

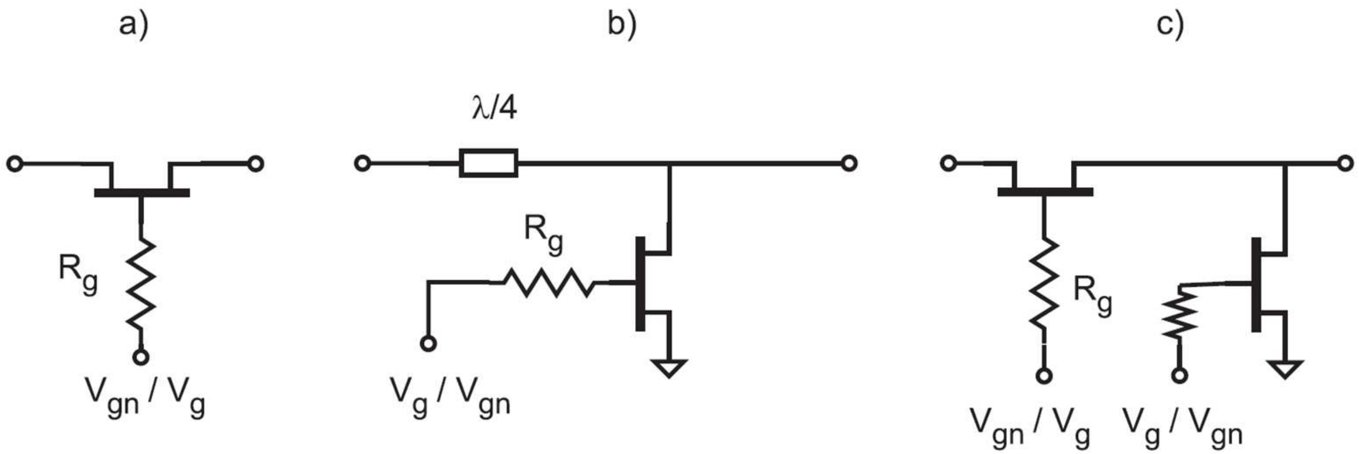
- parasitic elements
  - R_s → finite series resistance
  - C_{par} → geometrical fringing capacitance



- diode conductive: V >> V_{on}
  - conductance limited by R_s → attenuation in open switch branch
  - $I_s \neq 0$ → DC power consumption!
- diode in reverse-bias: V << V_{on}
  - finite coupling capacitance → finite isolation of closed switch branch

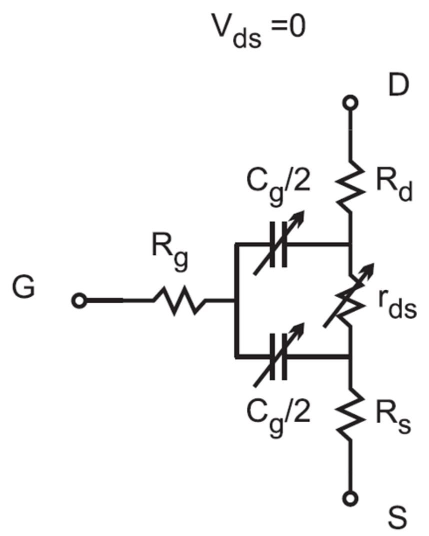
FET switches

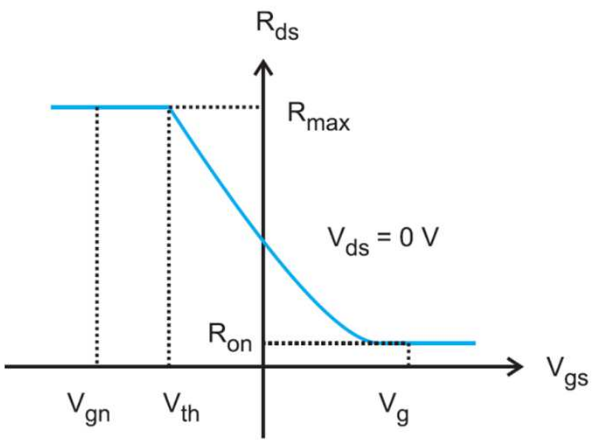
- FET switch configurations
  - a) series, R_g for reduced (parasitic) FET capacitance
  - b) shunt, λ/4 line for branch isolation (short → open)
  - c) combined series/shunt, for better isolation



FET switch: operating point

- FET as voltage-controlled resistor ($V_{ds} = 0$)
  - $C_{gs} = C_{gd} = C_g/2$
  - no power consumption, since $I_g \approx 0$ A
  - switching time: $t = R_g C_g$
- on-state
  - minimum achievable resistance: $R_{on} = R_d + R_c + R_s$
- off-state
  - parasitic capacitance
    - low impedance gate termination $C_{off} = C_{gs} + C_{gd} = C_g$
    - high impedance gate termination $1/C_{off} = 1/C_{gs} + 1/C_{gd} = 4/C_g \rightarrow C_{off} = C_g/4$





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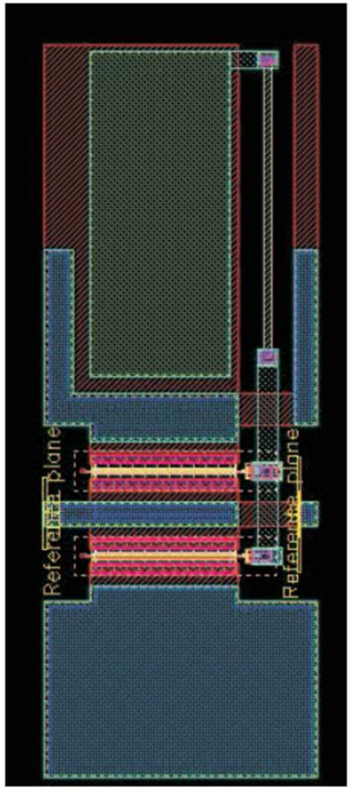
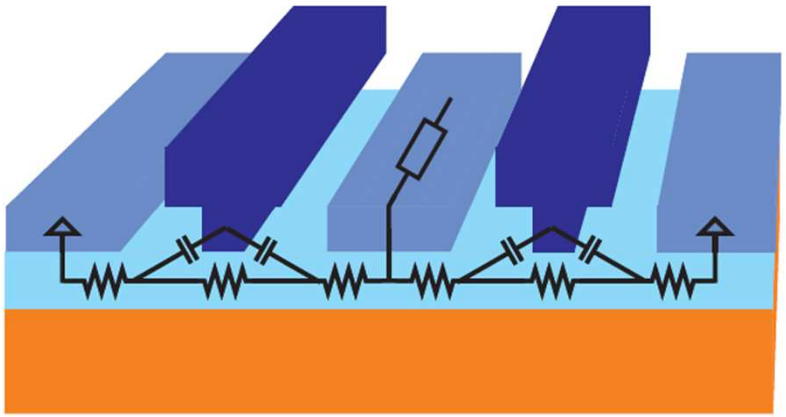
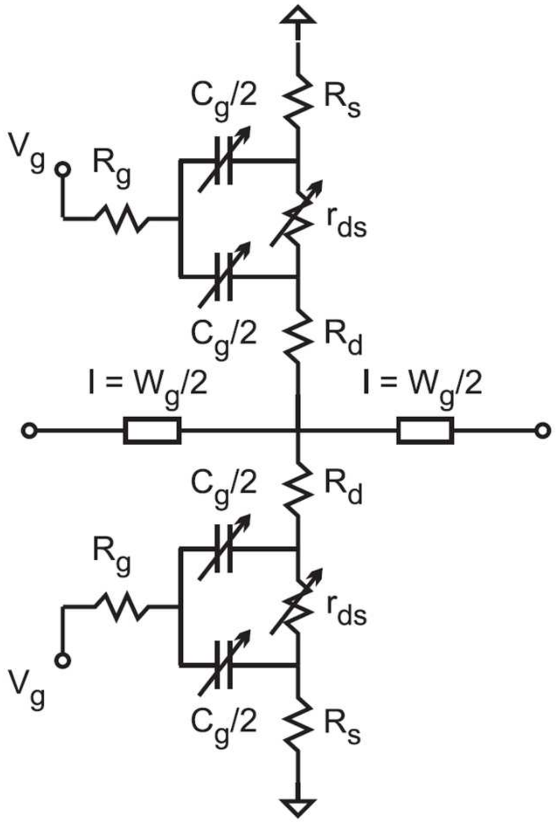
FET switch: shunt configuration

- shunt FET in coplanar transmission line environment
  - 2-finger FET: symmetry
  - switch model has to include phase shift along gate finger width

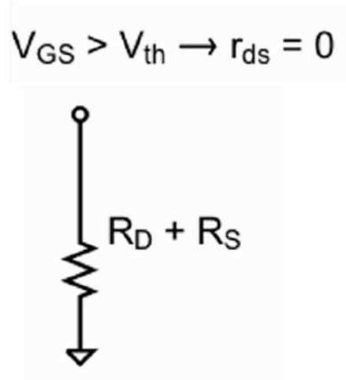


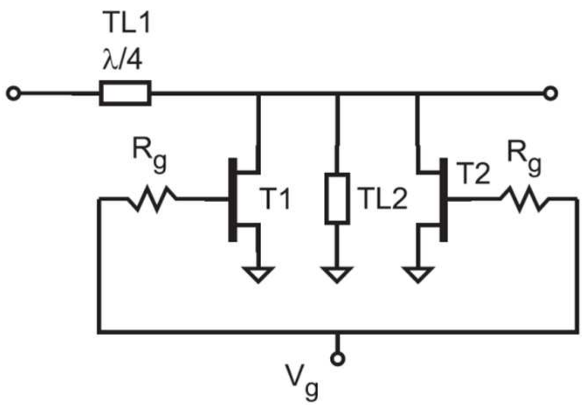


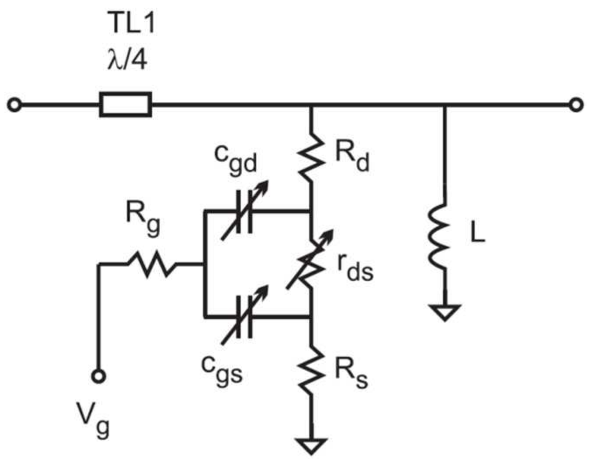


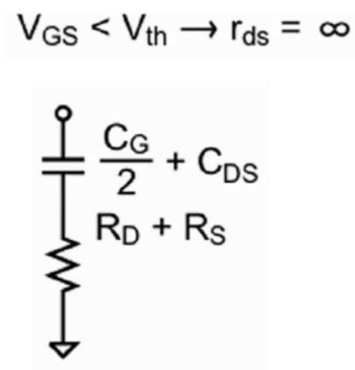
a practical switch example: 60 GHz SPDT

- use FET in shunt configuration
- shorted stub (TL2)
  - compensate for parasitic FET capacitance
    - imaginary parts cancel out at resonance
  - provide zero drain bias



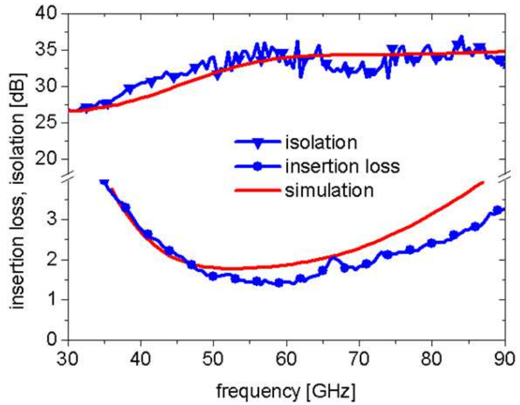


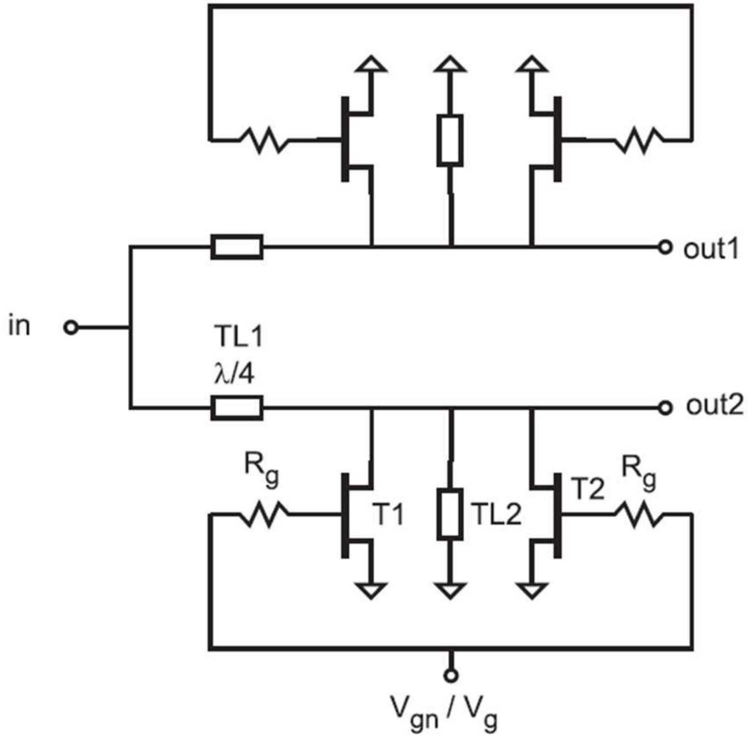


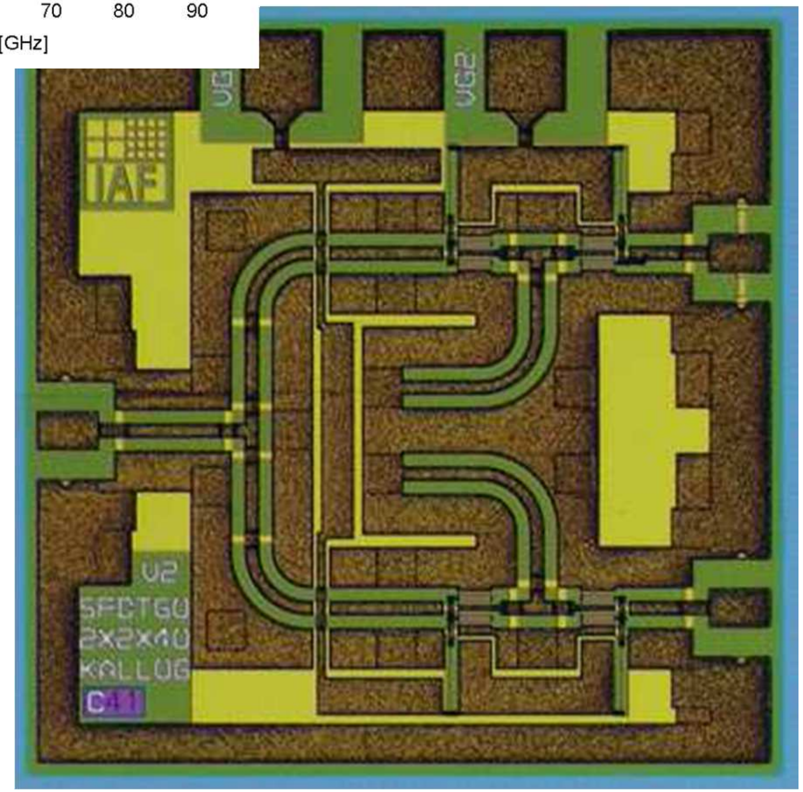


a practical switch example: 60 GHz SPDT

- SPDT layout
  - chip size 1 × 1 mm2







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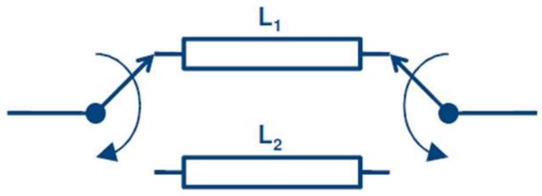
  - diode switches
  - FET switches
- a practical switch example
- millimeter-wave phase shifters

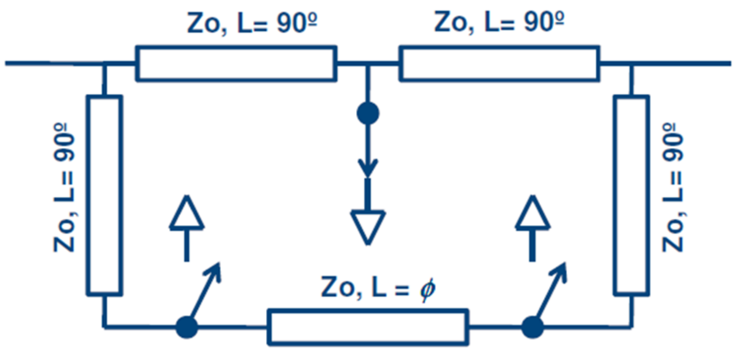
phase shifter topologies: series lines

- series switch phase bit topology
  - transmission lines of different length
  - disadvantages
    - insertion loss = 2 x switches loss + TRL loss
    - amplitude imbalances due to different line loss



$$\Delta\varphi = \frac{2\pi f}{v}(L_2 - L_1)$$

- shunt switch phase bit topology
  - advantages
    - switches in shunt configuration
  - disadvantages
    - amplitude imbalances due to different line loss



$$\Delta\varphi = \frac{2\pi f}{v} L_\varphi$$

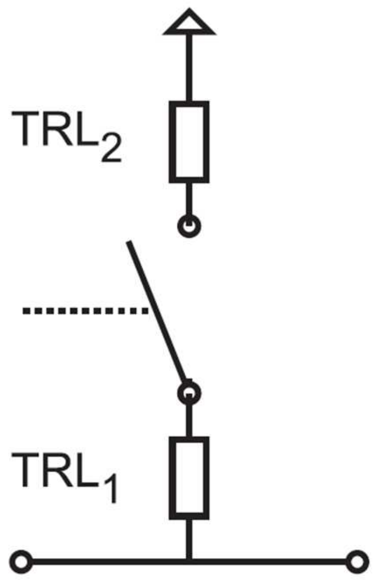
Source: Charles F. Campbell “Linear Phase Shifter Design”, 2010 IEEE CSICS

phase shifter topologies: filter-type

- phase shift by parallel lines
  - phase shift through reflection
  - $\Delta\Phi = 2\beta\,(l_1 + l_2) - 2\beta\, l_1 = 2\beta\, l_2$

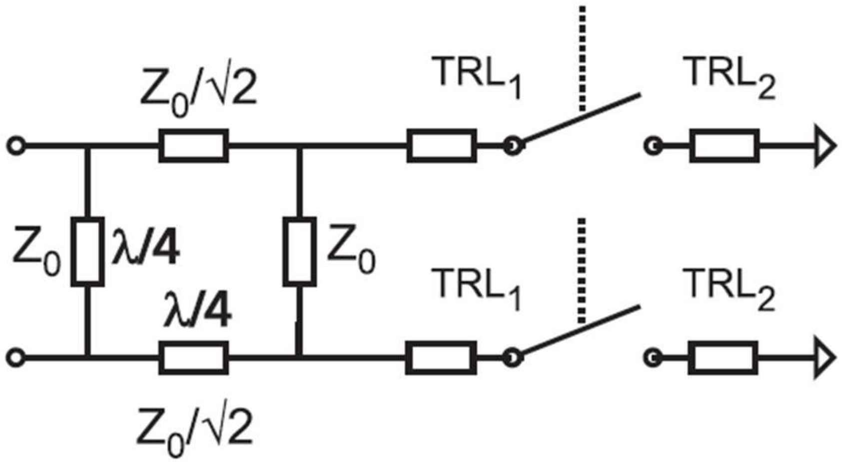
- advantages
  - no switch in series connection

- disadvantages
  - amplitude imbalance
  - impedance matching required
  - only small phase shifts realisable (impedance transformation → mismatch)



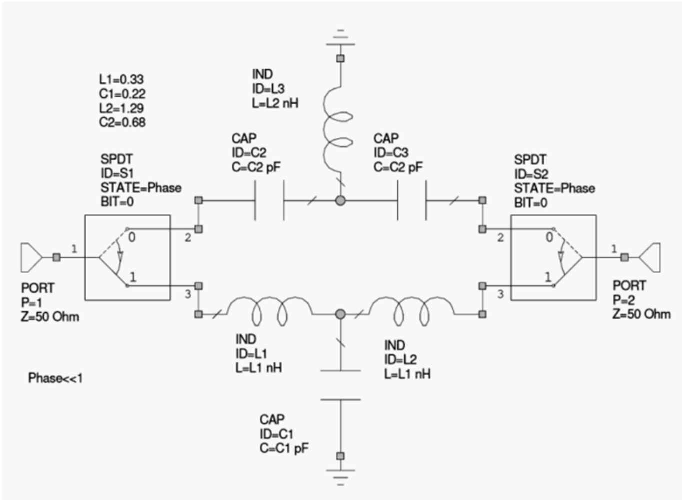
phase shifter topologies: 90° hybrid

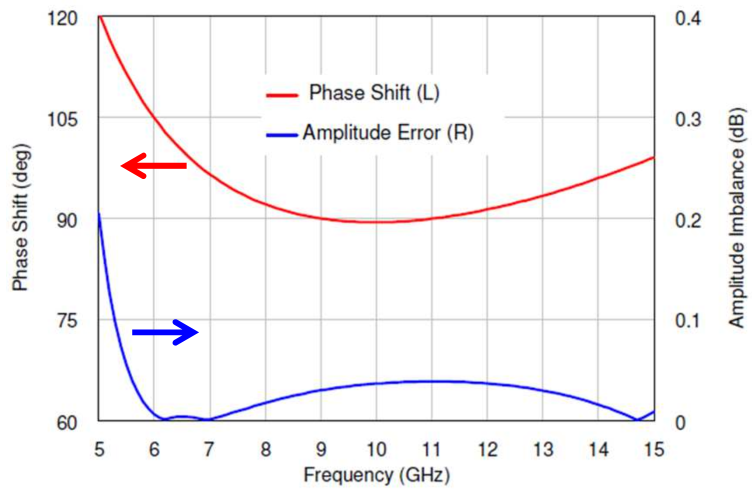
- 90° hybrid coupler with full reflection
  - signal transmission to normally isolated port
  - phase shift through reflection
  - $\Delta\Phi = 2\beta\,(l_1 + l_2) - 2\beta\, l_1 = 2\beta\, l_2$
- advantages
  - no switch in series connection
  - inherent and broadband impedance match → large phase shifts realisable
- disadvantages
  - amplitude imbalance
  - circuit size



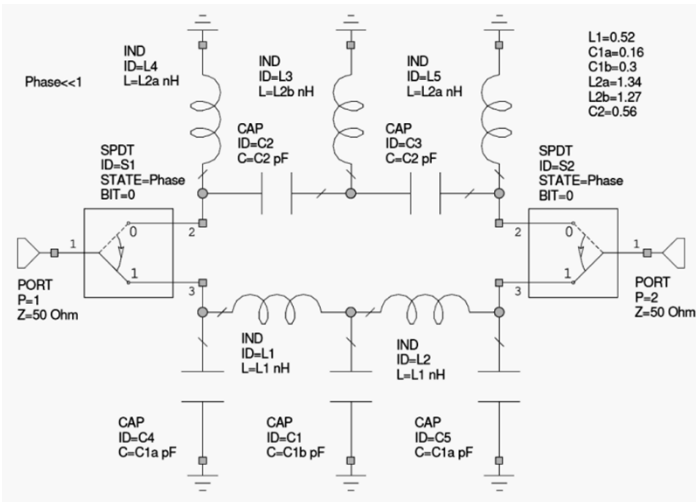
phase shifter topologies – switched filter

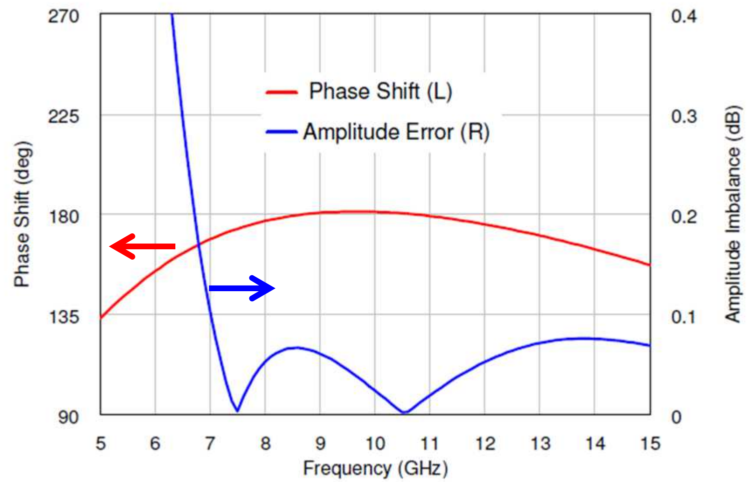
- switch the signal between low pass and high pass filters
- 90˚





- 180˚



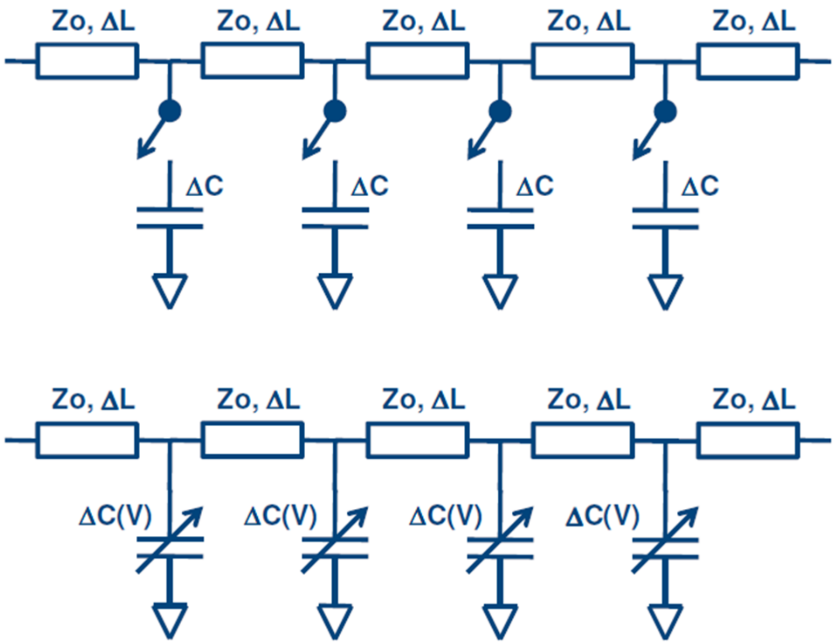


Source: Charles F. Campbell “Linear Phase Shifter Design”, 2010 IEEE CSICS

phase shifter topologies – loaded line

- change of TRL phase velocity by periodically loading the TRL with capacitance
  - switch in lumped capacitors or use varactors
  - disadvantage
    - C has an effect on impedance and velocity
      → VSWR changes

$$v = 1/\sqrt{LC} \qquad Z_o = \sqrt{L/C}$$

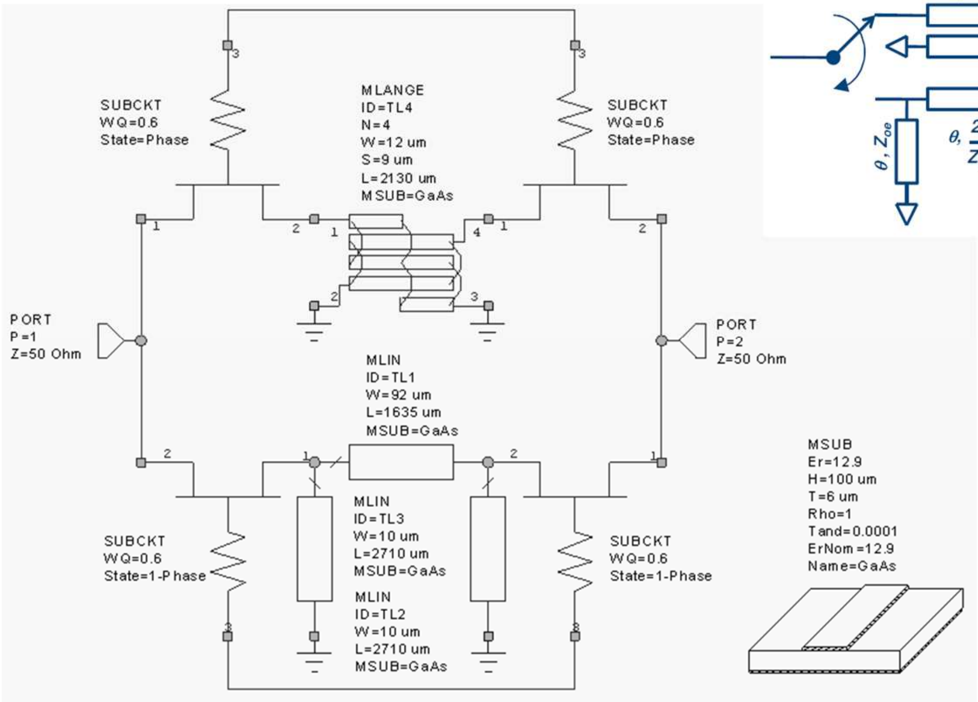


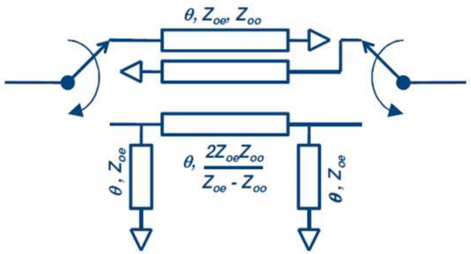
$$\Delta\varphi = 2\pi f L_\varphi \left(\sqrt{L(C+\Delta C)} - \sqrt{LC}\right)$$

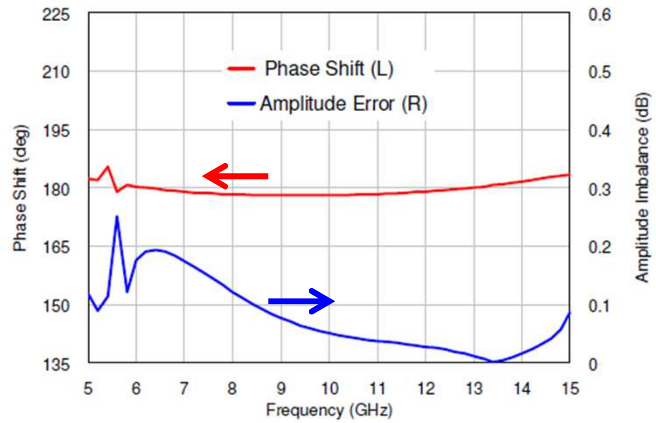
Source: Charles F. Campbell “Linear Phase Shifter Design”, 2010 IEEE CSICS

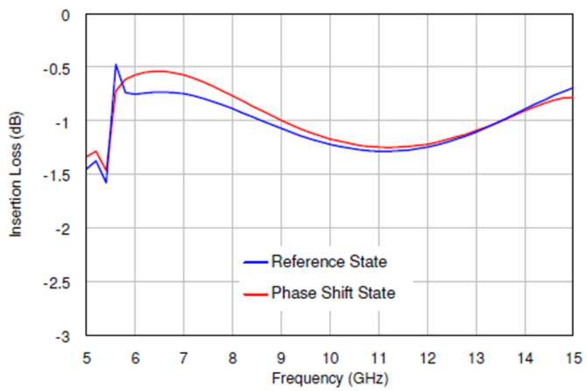
phase shifter topologies – coupler based

- phase shifting properties of couplers are utilized
  - 180° phase bit is difficult to realize with the previous topologies
  - → use wideband coupler
- phase shift = 180° independent of frequency









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