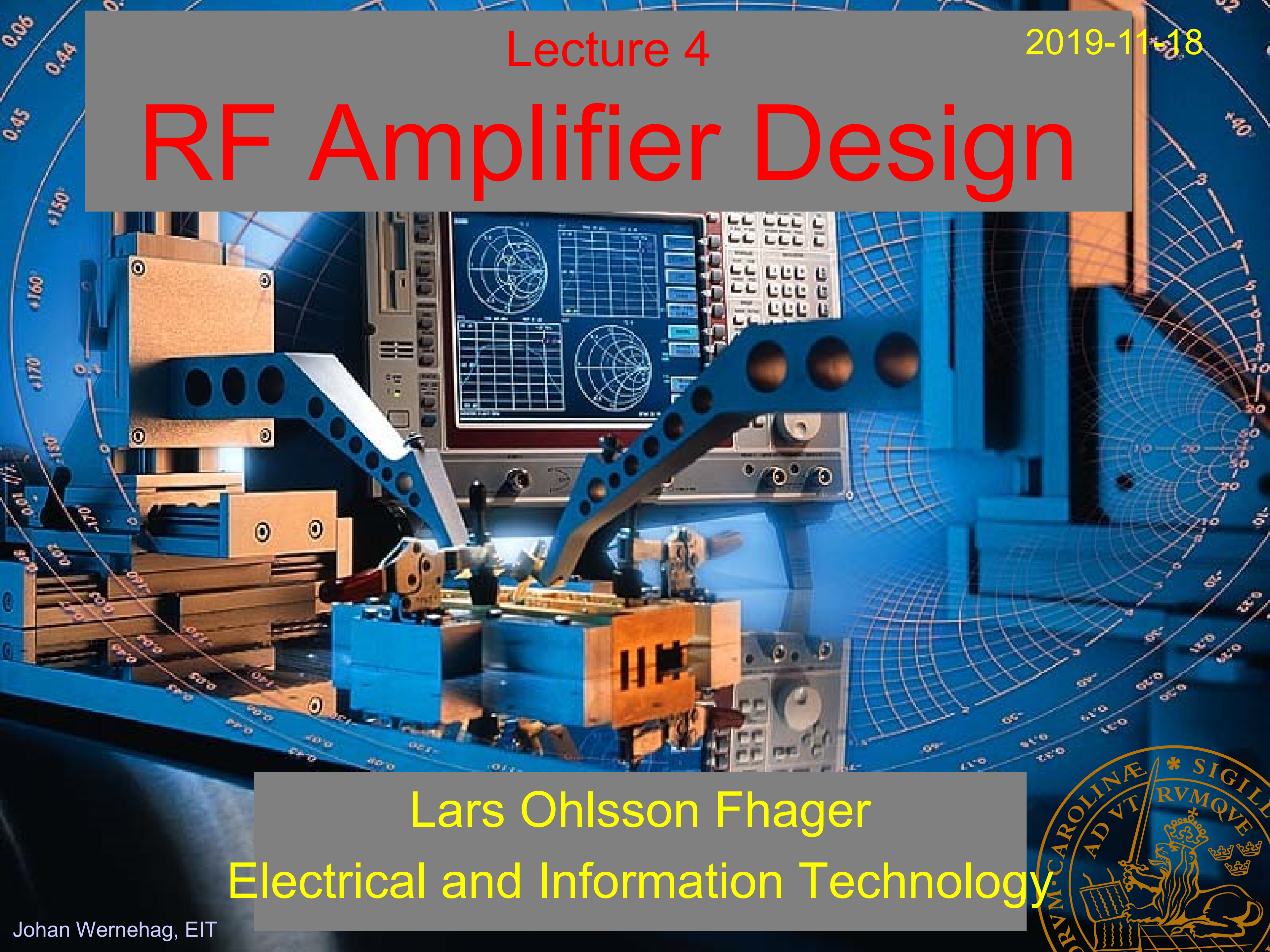
2019-11-18

Lecture 4

RF Amplifier Design



Lars Ohlsson Fhager

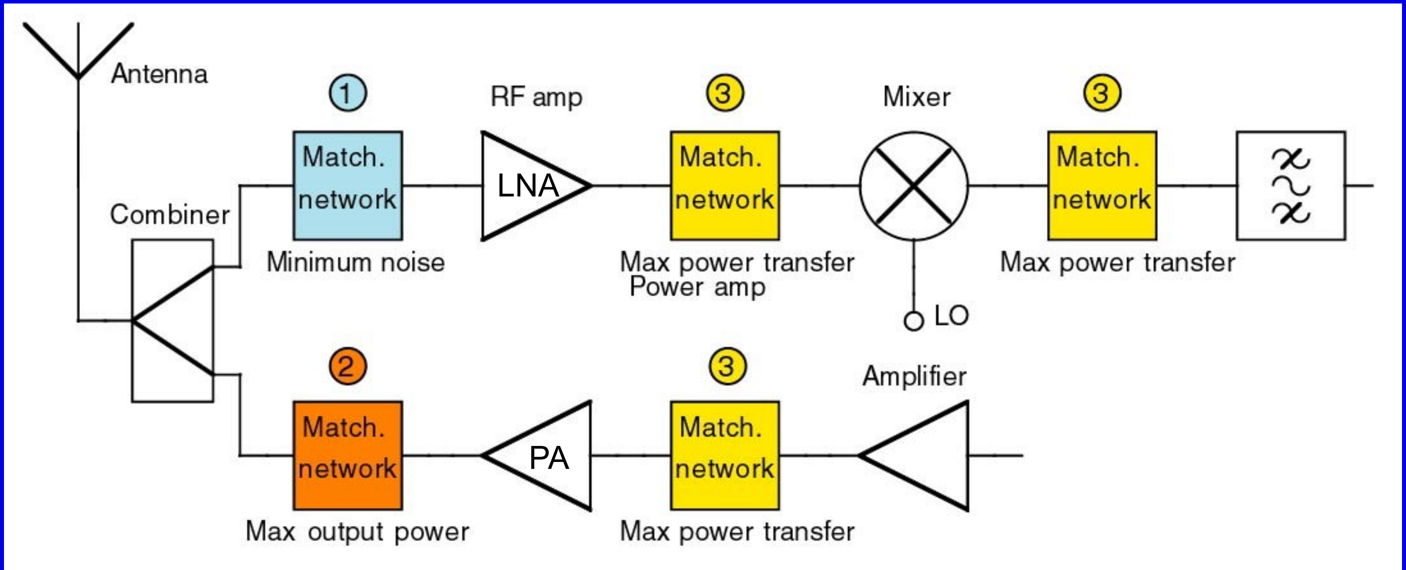
Electrical and Information Technology

Lecture 4

- Design of Matching Networks
  - Various Purposes of Matching
    - Voltage-, Current- and Power Matching
  - Design by Lumped Circuit Elements
    - L, Pi and T Networks
    - Design by using the Smith Chart
  - Design by Line Structures
    - Transformation by a Transmission Line
    - Quarter-Wave Transformer
    - Line Section with Optimised Length and Z_0
    - Stubs

- Passive Components
  - Lumped Components
    - Resistors
    - Capacitors
    - Inductors
    - Transformers
  - Substrate and Conductor Materials
  - Transmission Lines
    - Coaxial Line
    - Microstrip
    - Stripline
    - Discontinuities
      - Bends, corners

The Purpose of Matching



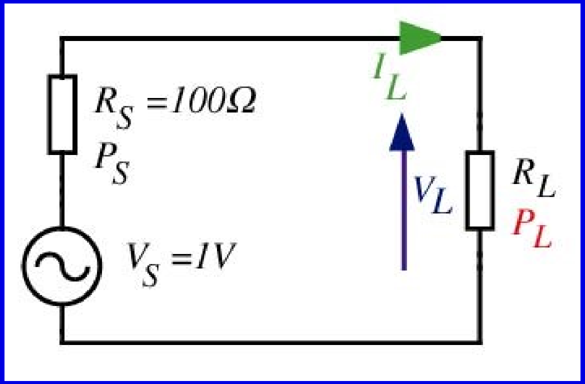
① Minimum noise power

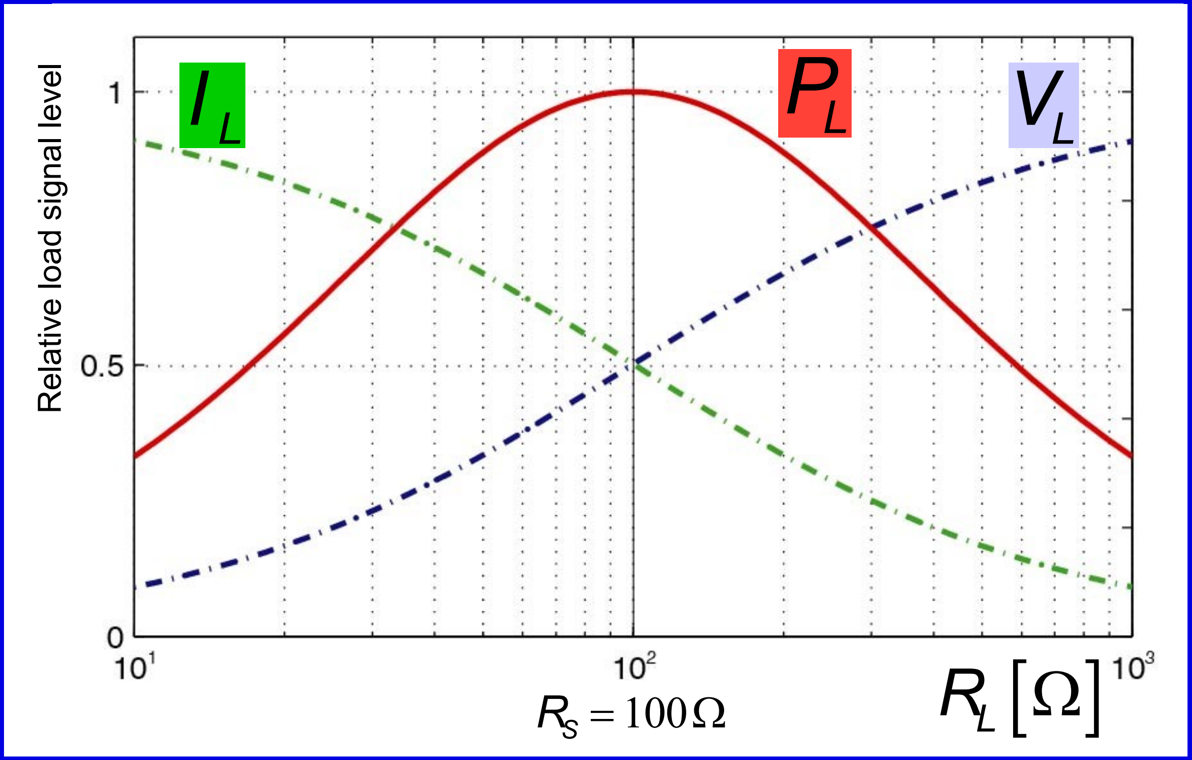
② Maximum output power

③ Maximum transfer of power

In most cases bandwidth and filtering are important parameters too

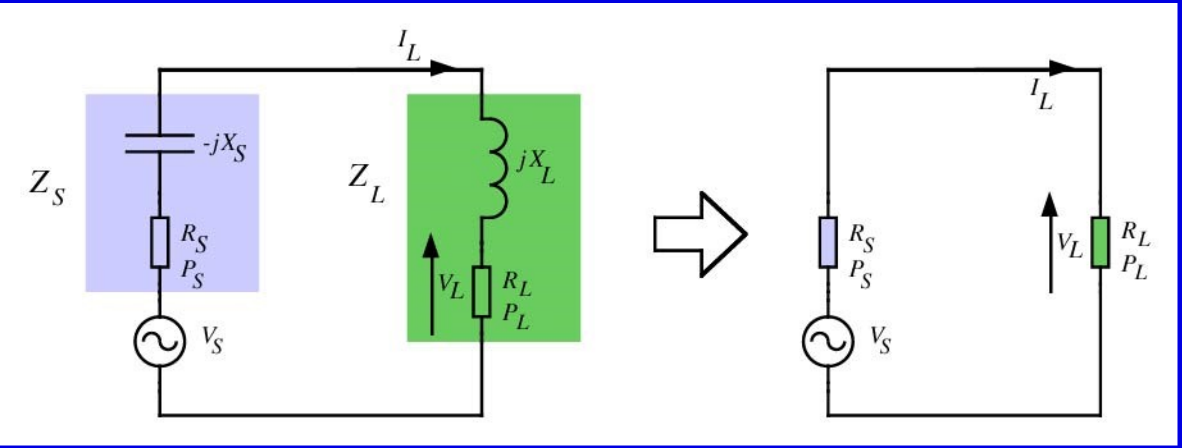
Maximum Transfer of Power





- Current matching
- Voltage matching
- Power matching

Complex Conjugate Matching

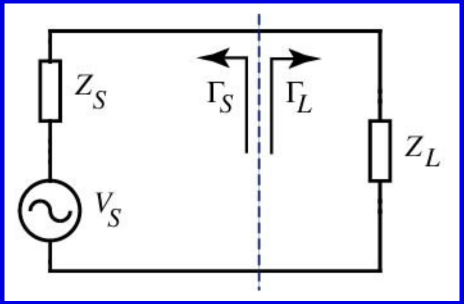


- Maximum transfer of power when

$$Z_L = Z_S^* \Rightarrow \begin{cases} R_L = R_S \\ X_L = -X_S \end{cases}$$

resonance

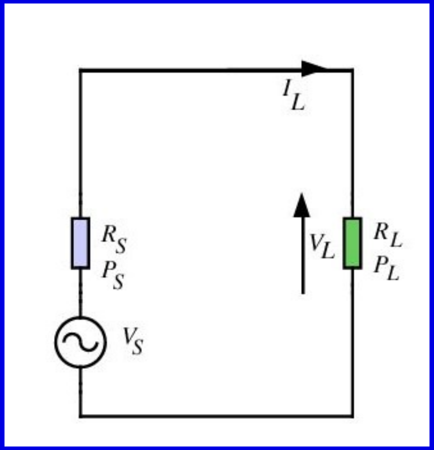
Z or Γ Representation



- Impedance $$Z_L = Z_S^* \Rightarrow \begin{cases} R_L = R_S \\ X_L = -X_S \end{cases}$$

- Reflection coefficient $$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Available Power from Source, P_{AVS}



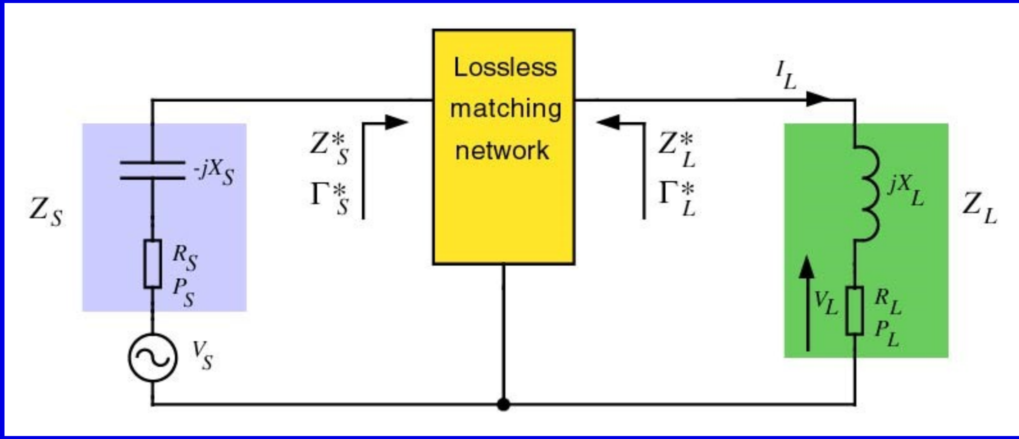
- The maximum amount of power that can be delivered from the source is defined as:

$$P_{AVS} = \frac{V_L^2}{R_L} = V_S^2 \left(\frac{R_L}{Z_S + Z_L} \right)^2 \frac{1}{R_L} \Bigg|_{Z_L = Z_S^*} = \frac{V_S^2}{4 R_S}$$

NOTE!
The unit of V_S is here V_{RMS}!

Active power

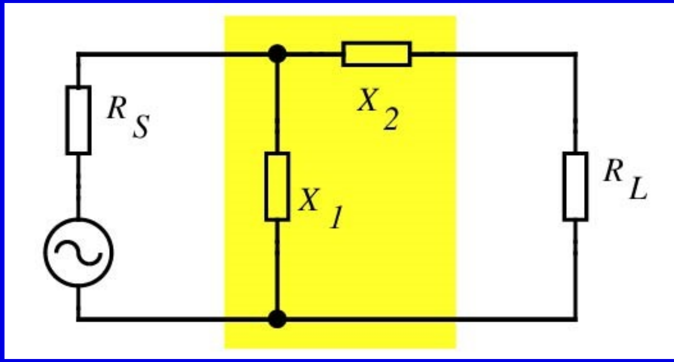
The Need of a Matching Network



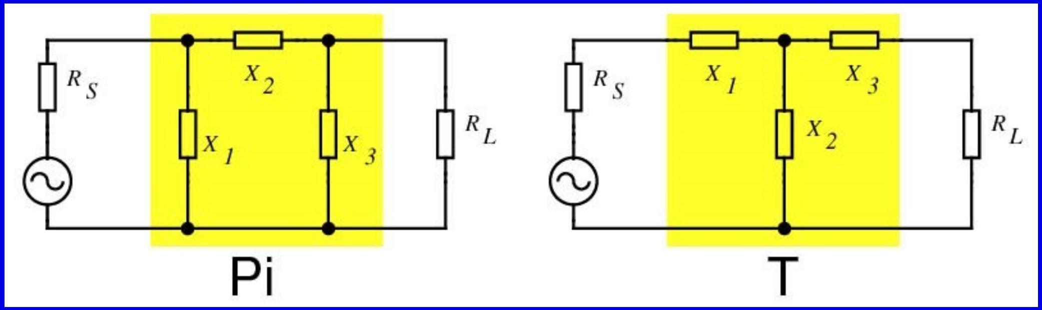
- If Z_L and/or Z_S are fixed a matching network is needed to ensure proper matching

Network Design by Lumped Circuits

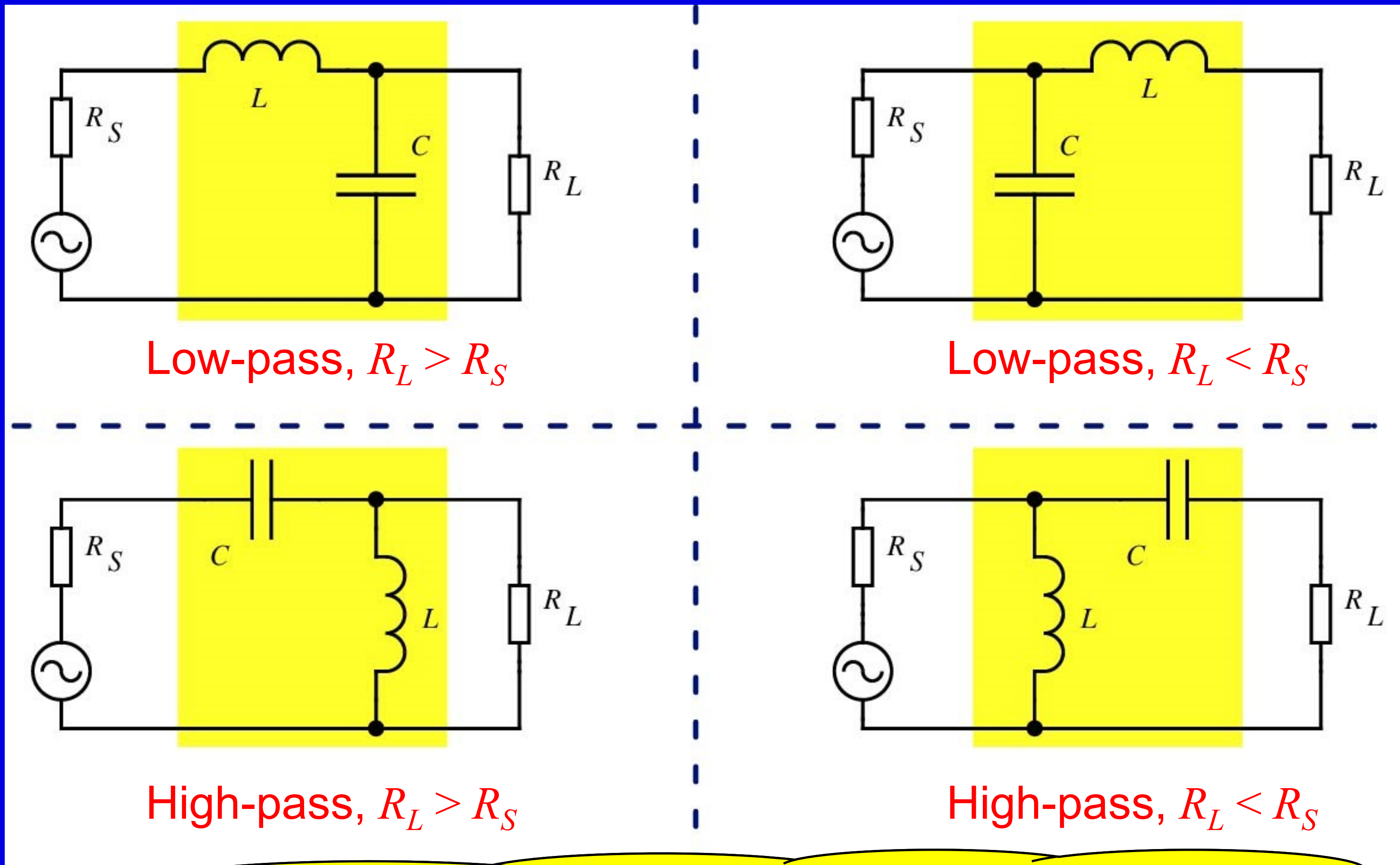
- L network
  - low-pass
  - high-pass
  - fixed circuit *Q*



- Pi and T network
  - low-pass
  - high-pass
  - desired circuit *Q*

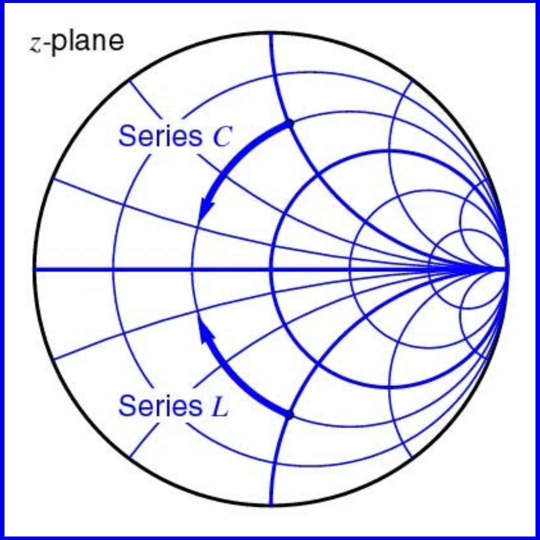


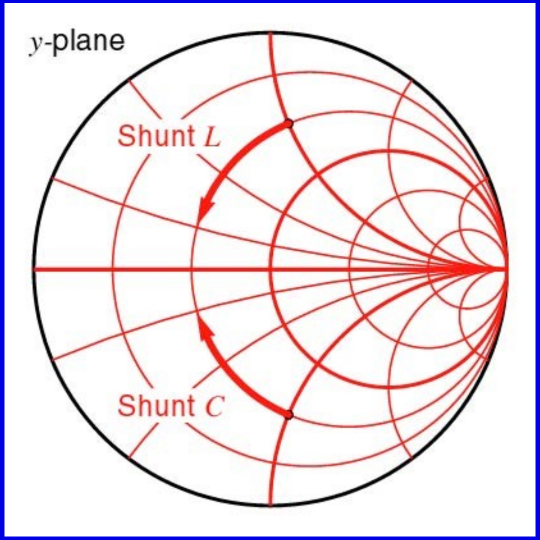
L Network, Four Different Variations

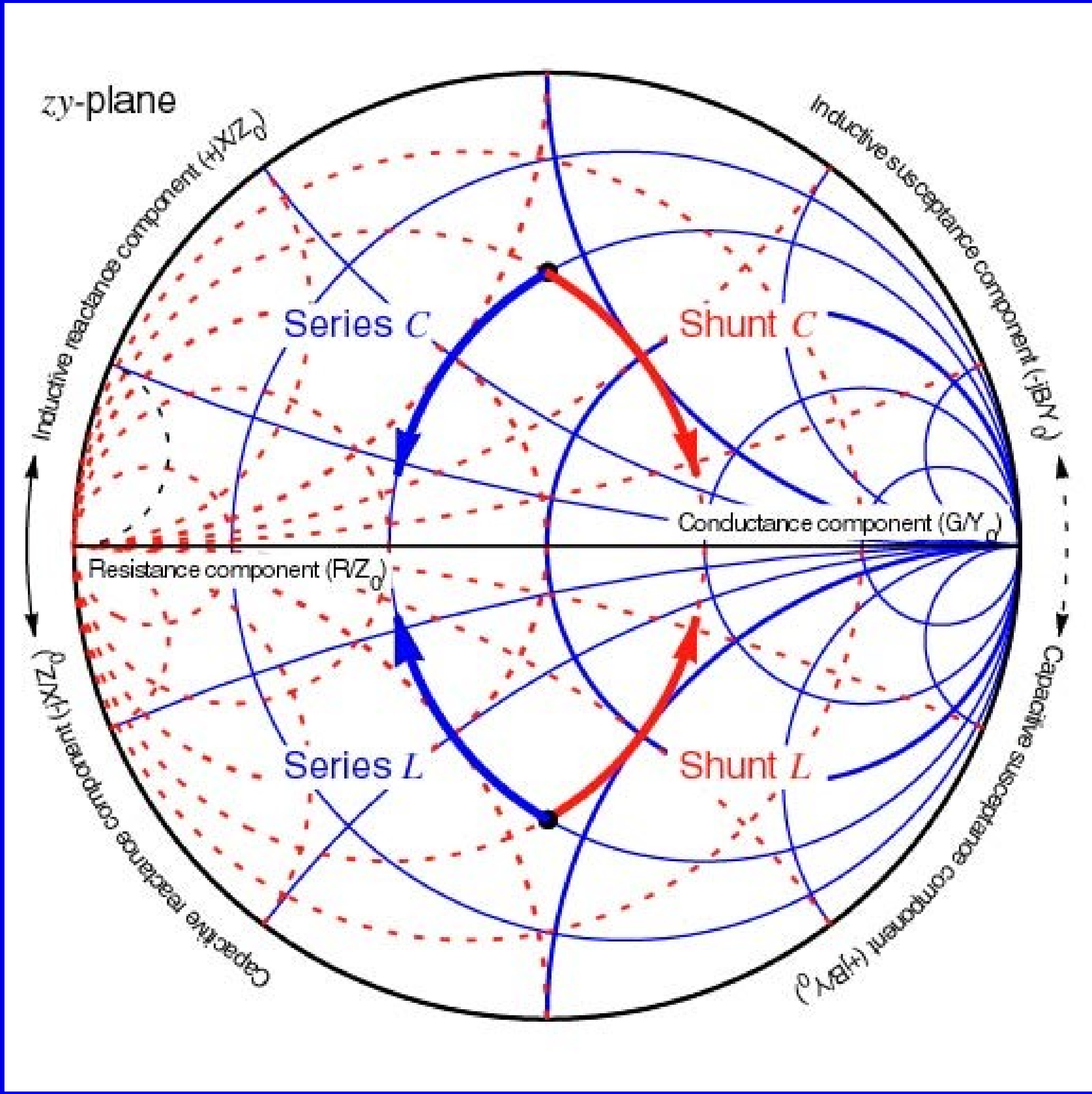


- Series component in series with the smallest impedance
- Shunt component in parallel with the largest impedance

Designing Reactive Circuit Elements in the Smith Chart

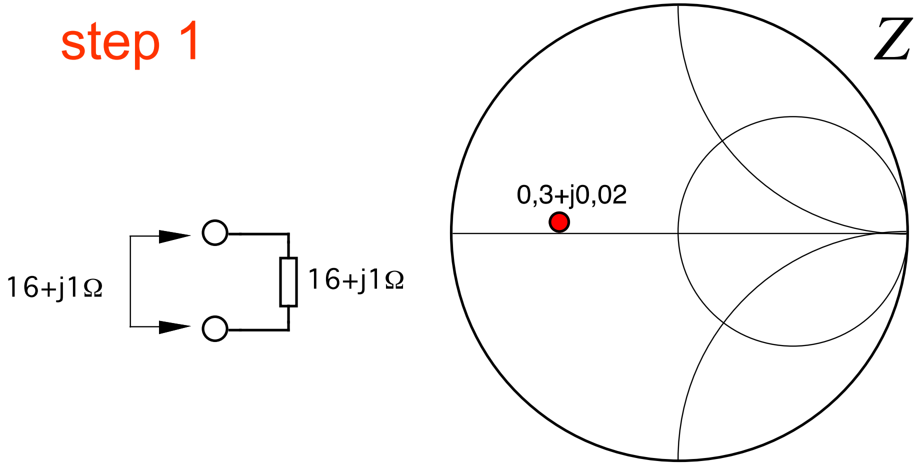






Experiment: Design a matching network by using the Smith chart and the VNA @ 775 MHz

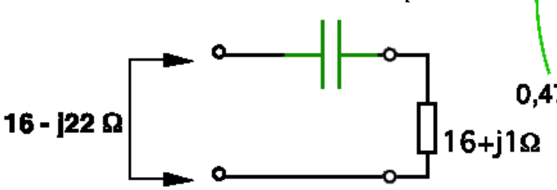
step 1

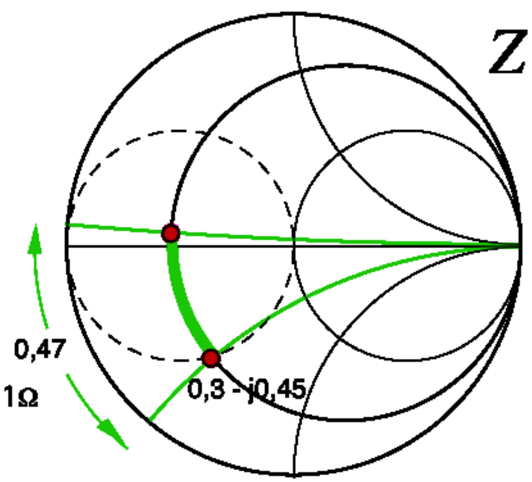


step 2

Subtract reactance (connect a capacitor in series) until you reaches the conductance circle g = 1/50 mho = 20 mS.

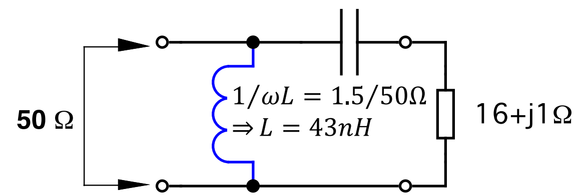
$1/\omega C = 0.47 \cdot 50\Omega \Rightarrow C \approx 55pF$

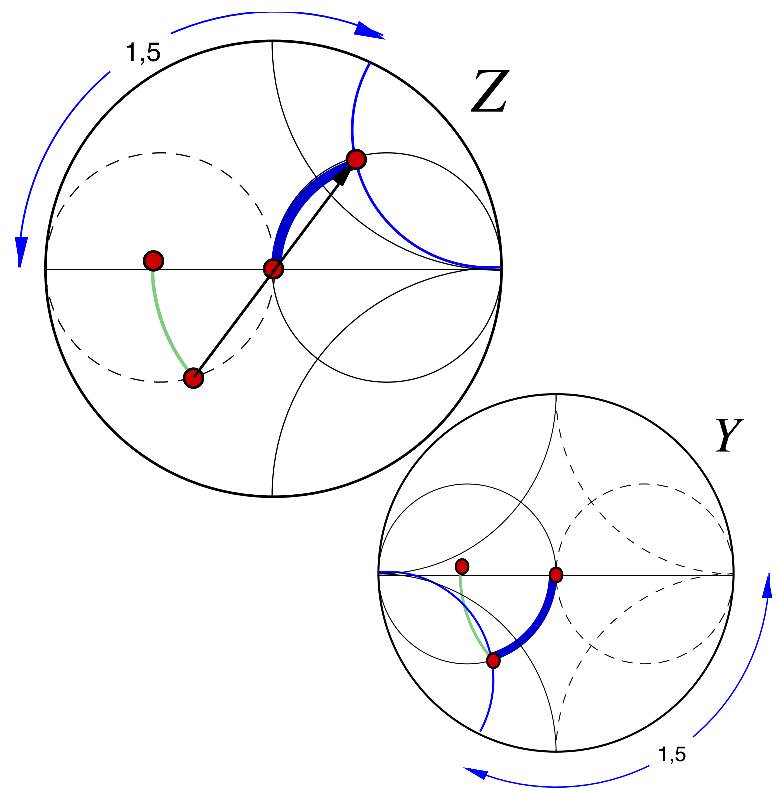




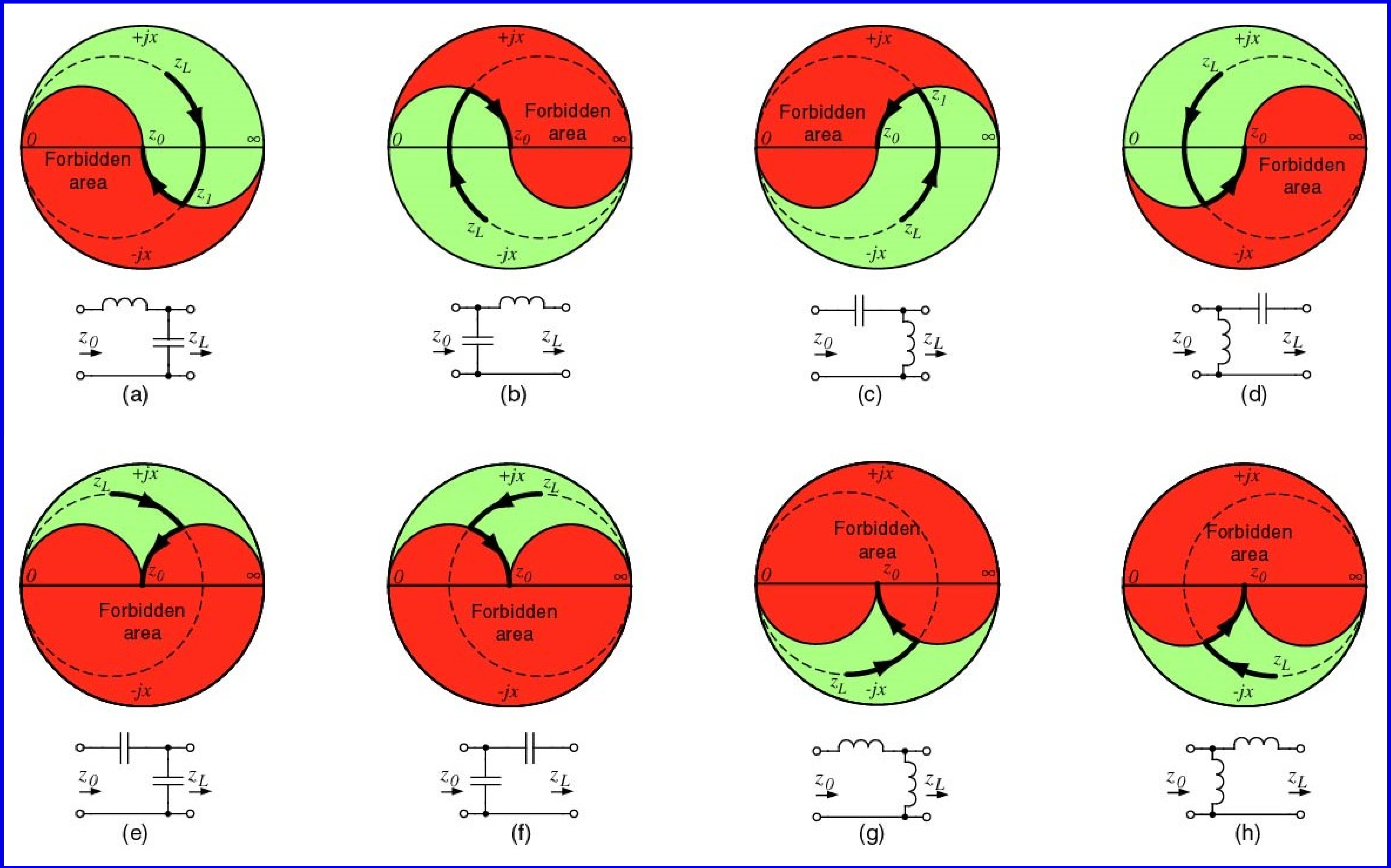
step 3

Add susceptance (connect an inductor in parallel) until you end up in $Y = Y_0$ = 1/50 mho = 20 mS.





Eight possible L-type Networks

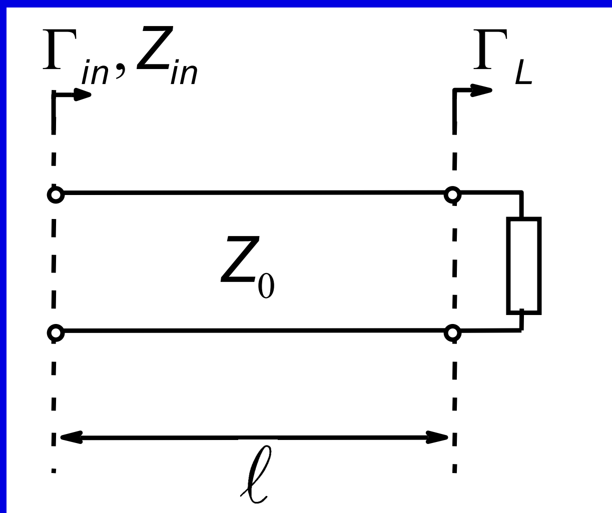


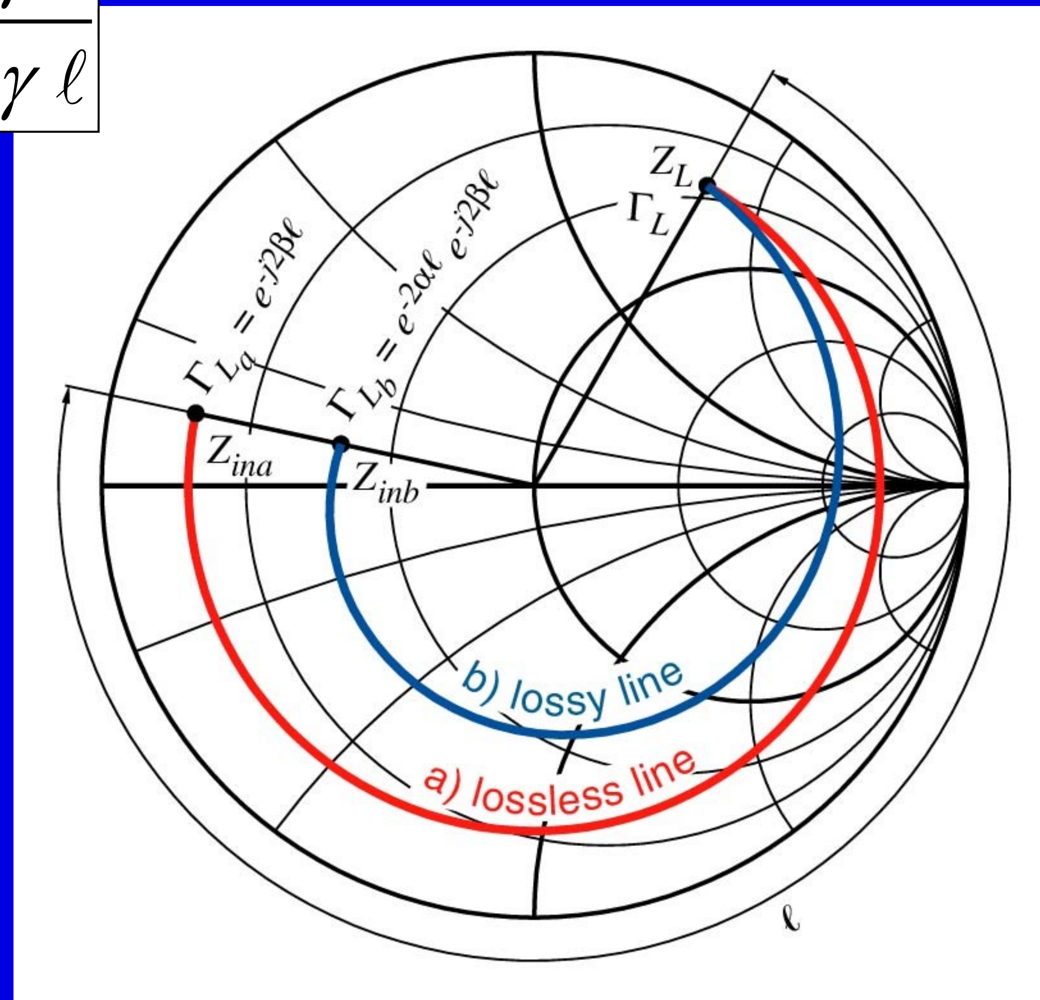
Matching Networks by Line Structures

- Transformation by a cascaded transmission line
  - line section with optimised length and Z_0
  - quarter-wave transformer
  - matching by multiple sections
- Stubs
  - short-circuited and open-circuited stubs
  - symmetrical stubs

Impedance Transformation by a Single Serial Line

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh \gamma \ell}{Z_0 + Z_L \tanh \gamma \ell}$$





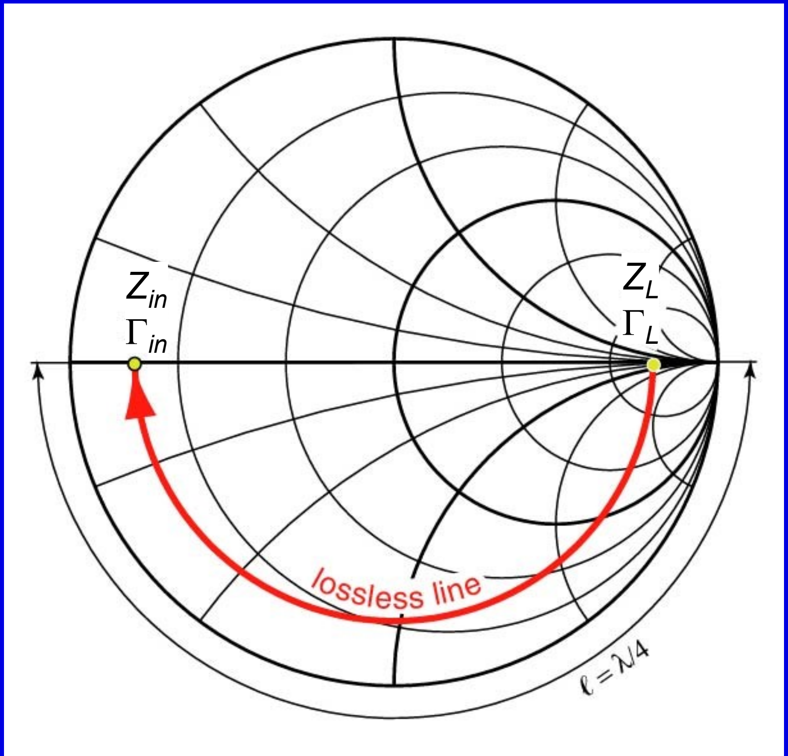
a) lossless line

b) lossy line

The Quarter-Wave Transformer

- For a line at the length λ/4 is

$$Z_{in} = \frac{Z_0^2}{Z_L}$$ if Z_L is resistive



- may be used for matching between arbitrary resistive source and load impedances.

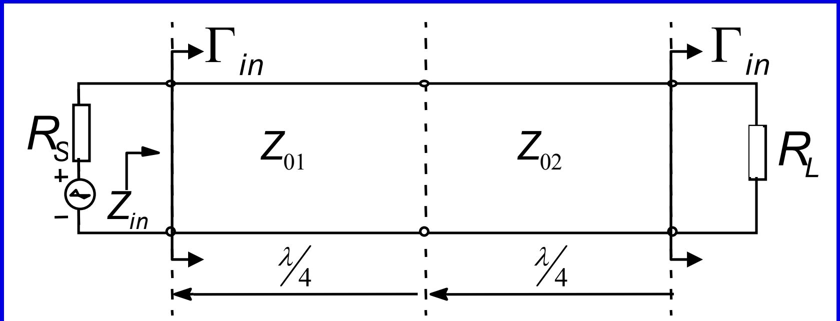
$$Z_0 = \sqrt{Z_L Z_{in}}$$

Geometric mean value of source and load!

Quarter-Wave Transformer at Multiple Sections

- Transformation in several and minor impedance steps may provide a larger bandwidth

- If the characteristic impedances are distributed according to binomial coefficients maximum-flatness is achieved.



n ↓ k →	0	1	2	3	4	5
0	1					
1	1	1				
2	1	2	1			
3	1	3	3	1		
4	1	4	6	4	1	
5	1	5	10	10	5	1

Binomial coefficients

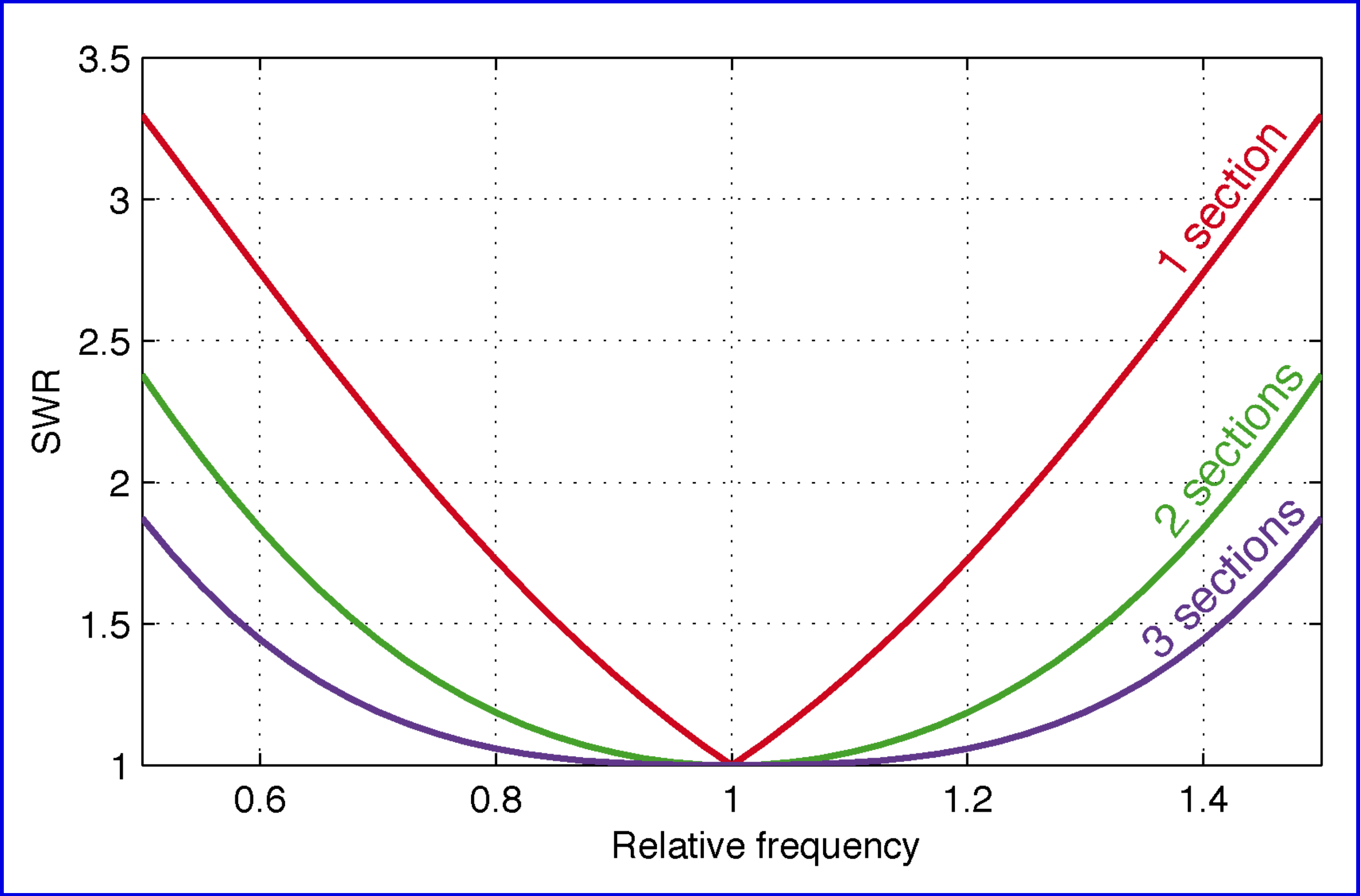
Ex. three sections:

$$Z_{01} = R_S\left(\frac{R_L}{R_S}\right)^{\frac{1}{8}}$$

$$Z_{02} = Z_{01}\left(\frac{R_L}{R_S}\right)^{\frac{3}{8}} = R_S\left(\frac{R_L}{R_S}\right)^{\frac{4}{8}}$$

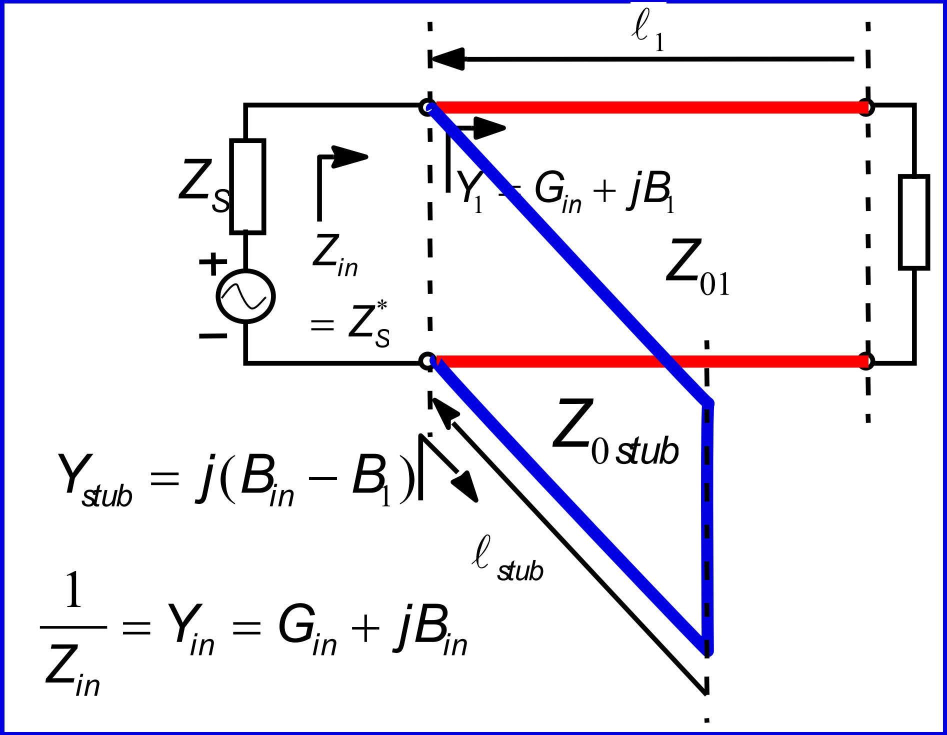
$$Z_{03} = Z_{02}\left(\frac{R_L}{R_S}\right)^{\frac{3}{8}} = R_S\left(\frac{R_L}{R_S}\right)^{\frac{7}{8}}$$

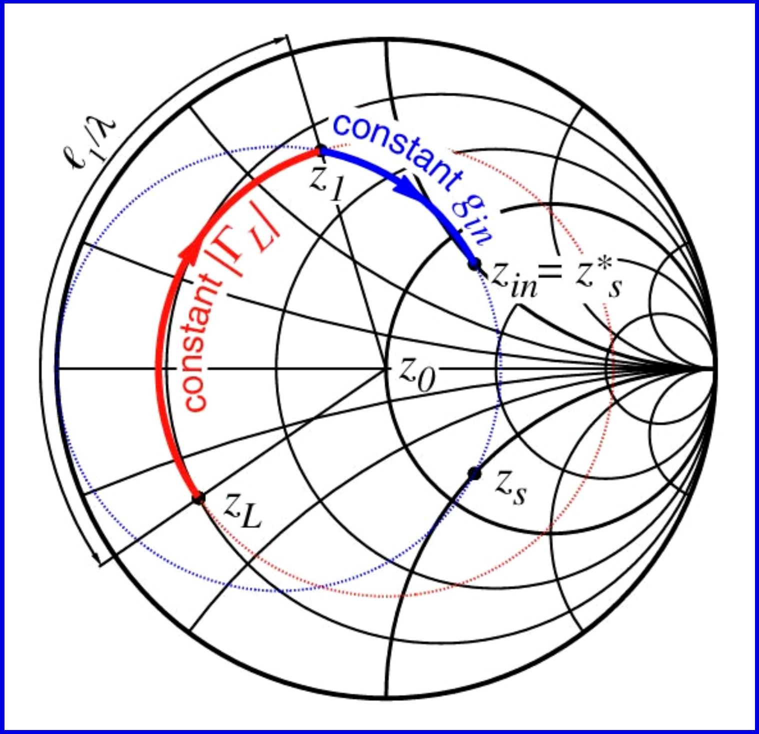
Quarter-Wave Transformer at Multiple Sections (cont.)



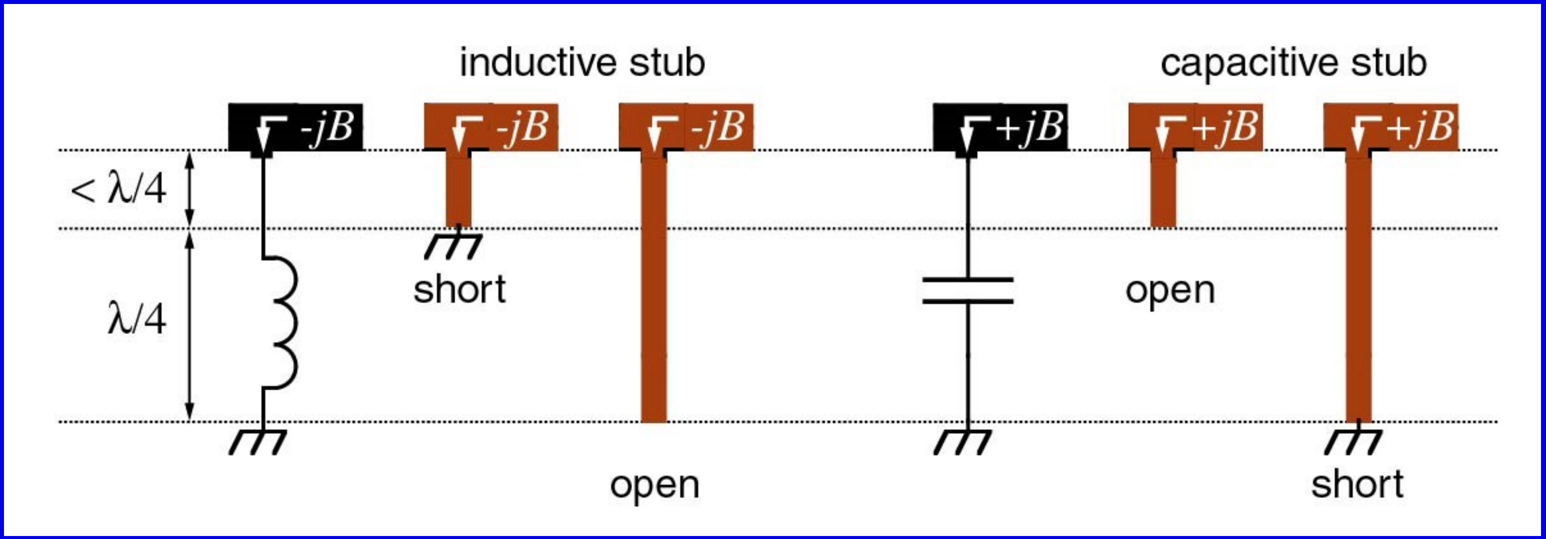
Matching by Stubs and Cascaded Lines

- Short-circuited or open line sections may be used as reactive shunt elements.
- Combined with cascaded line, matching can be achieved between arbitrary loci in the Smith chart.

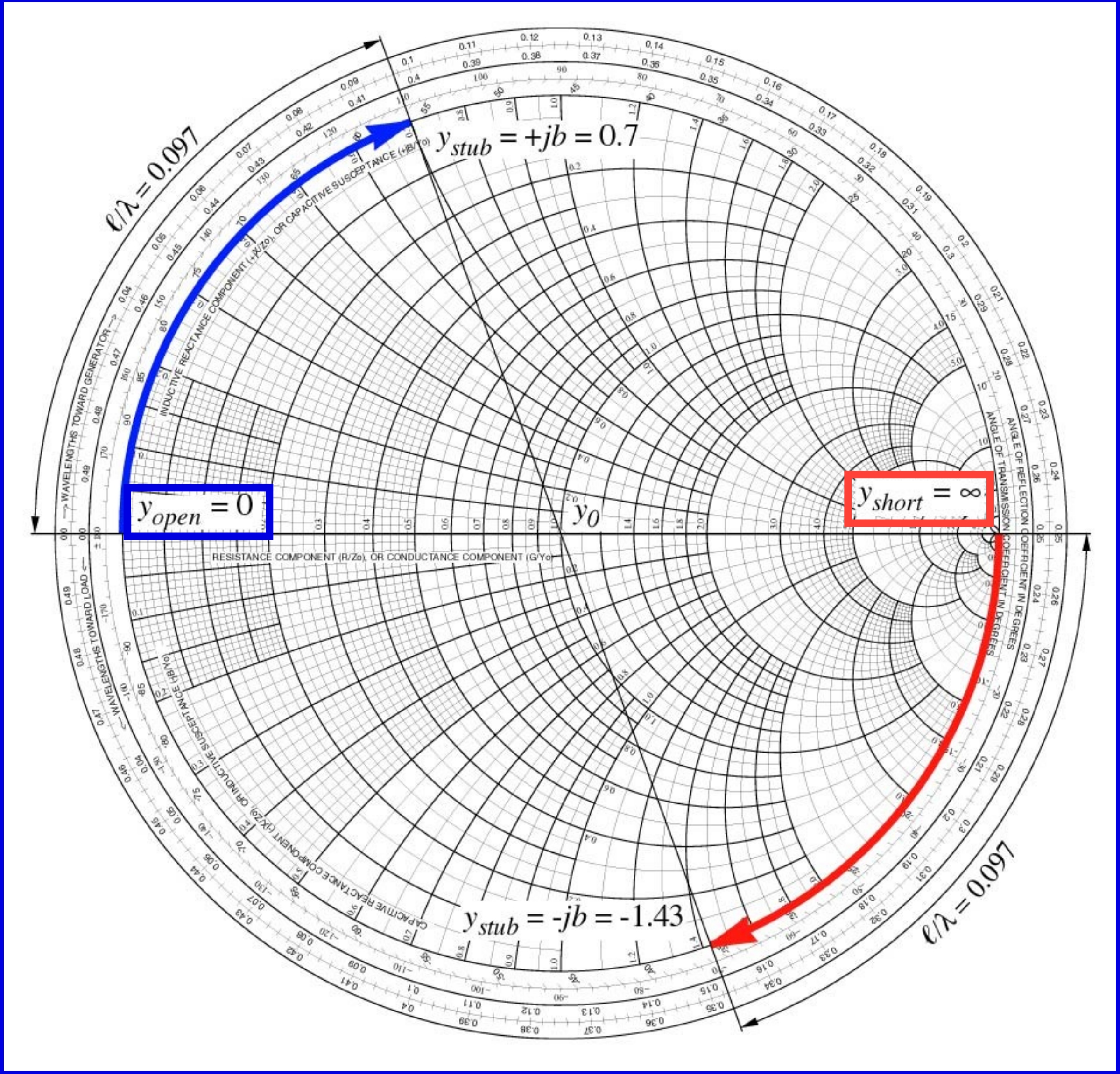




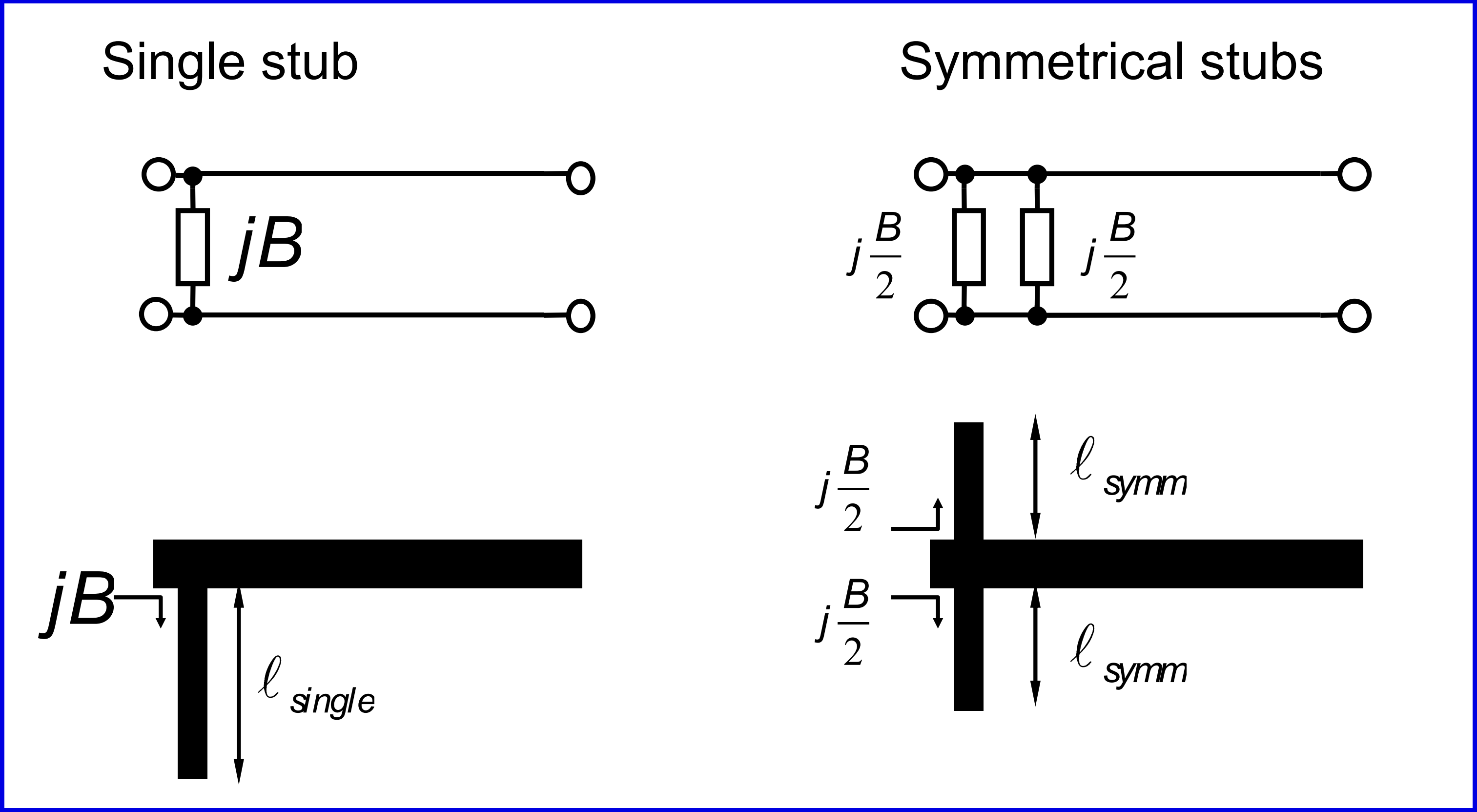
Length and Termination of the Stubs



Designing the Length of the Stub



Symmetrical Stubs

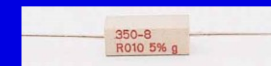


- Note: $l_{single} \neq 2 \cdot l_{symm}$
- The length of the symmetrical stubs is designed to individually provide the half value of the requested susceptance.

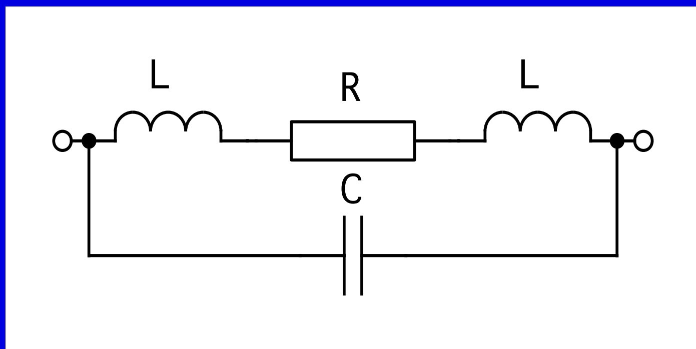
Resistors

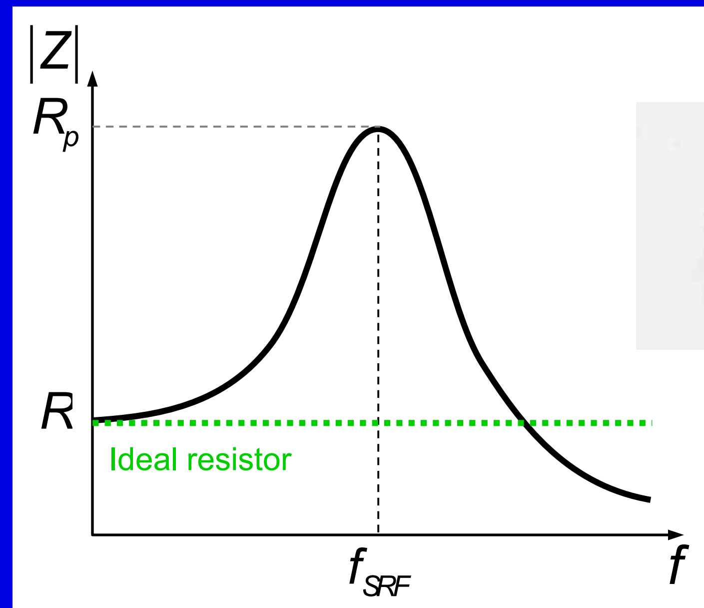


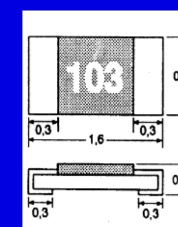


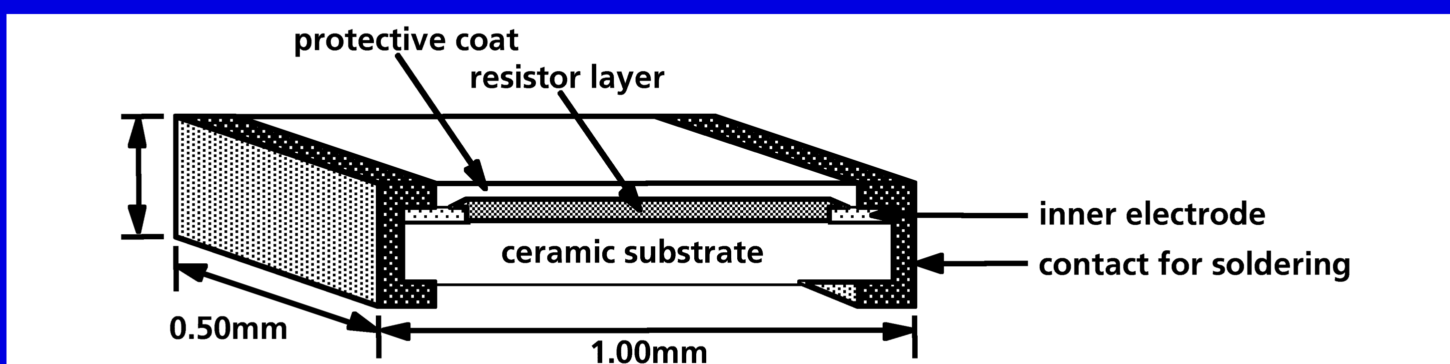
high-frequency model





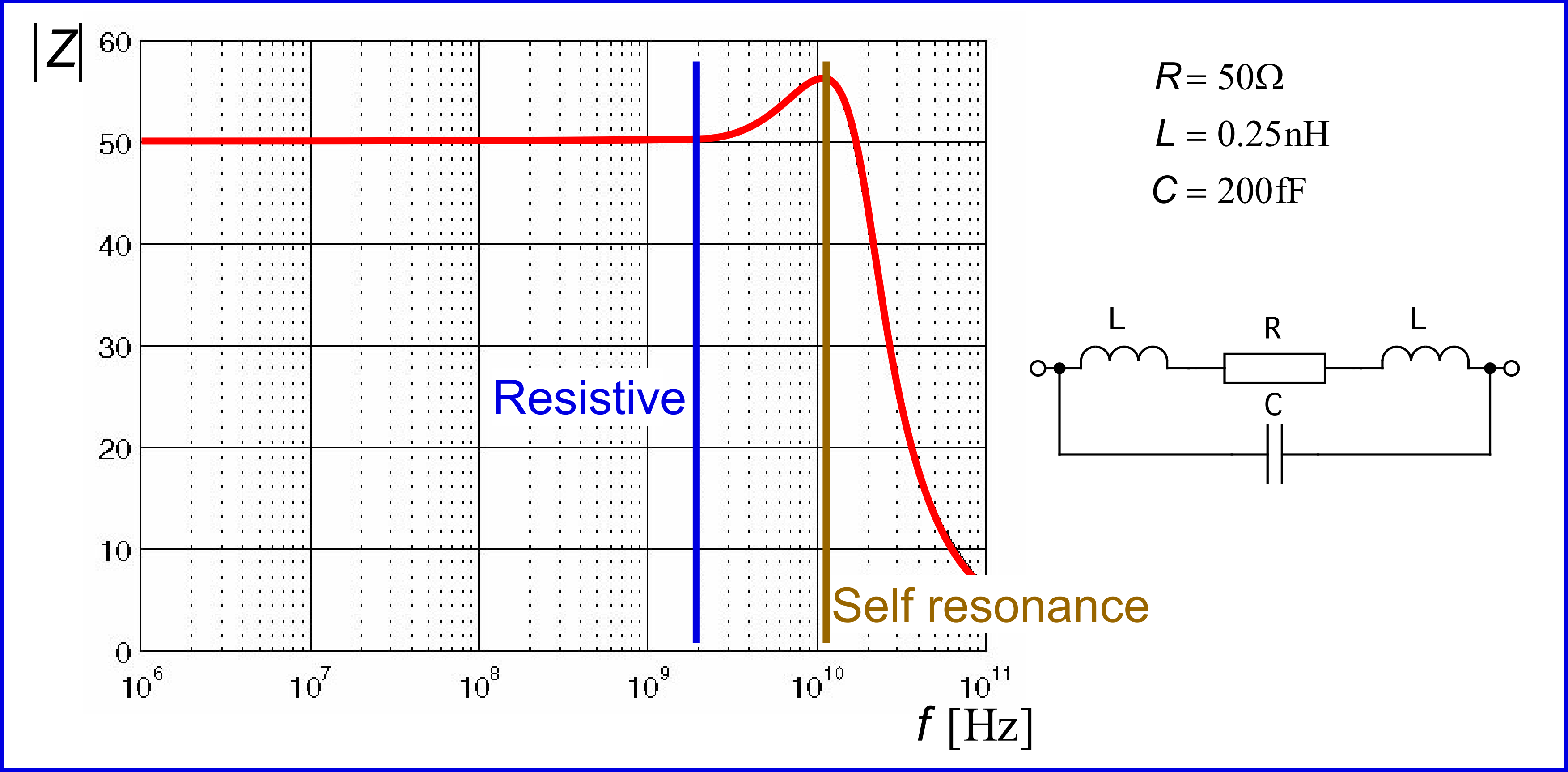


f_{SRF} = Self Resonance Frequency



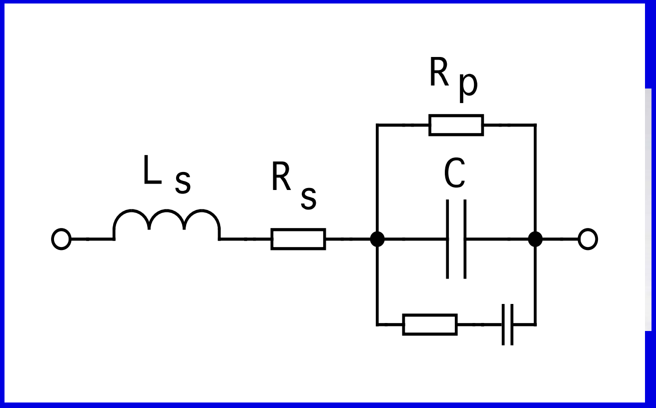
Resistor

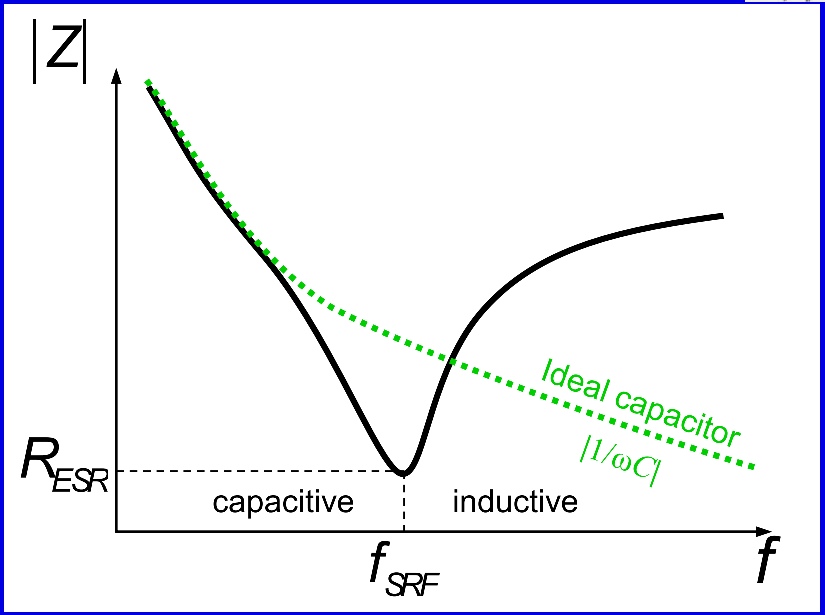
Frequency characteristics - example

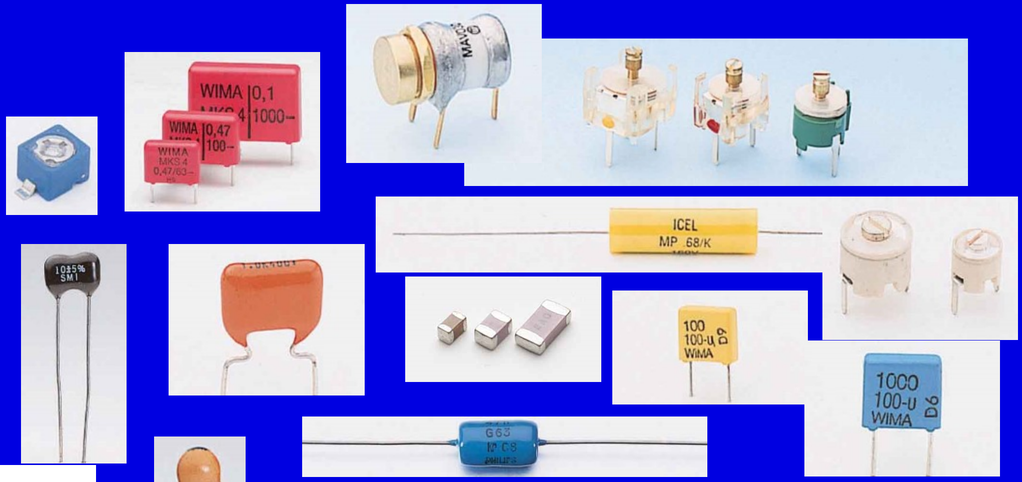


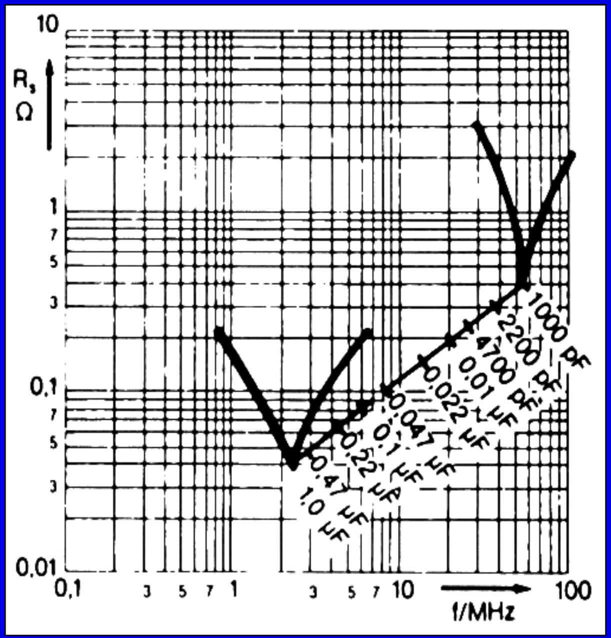
Capacitors

high-frequency model





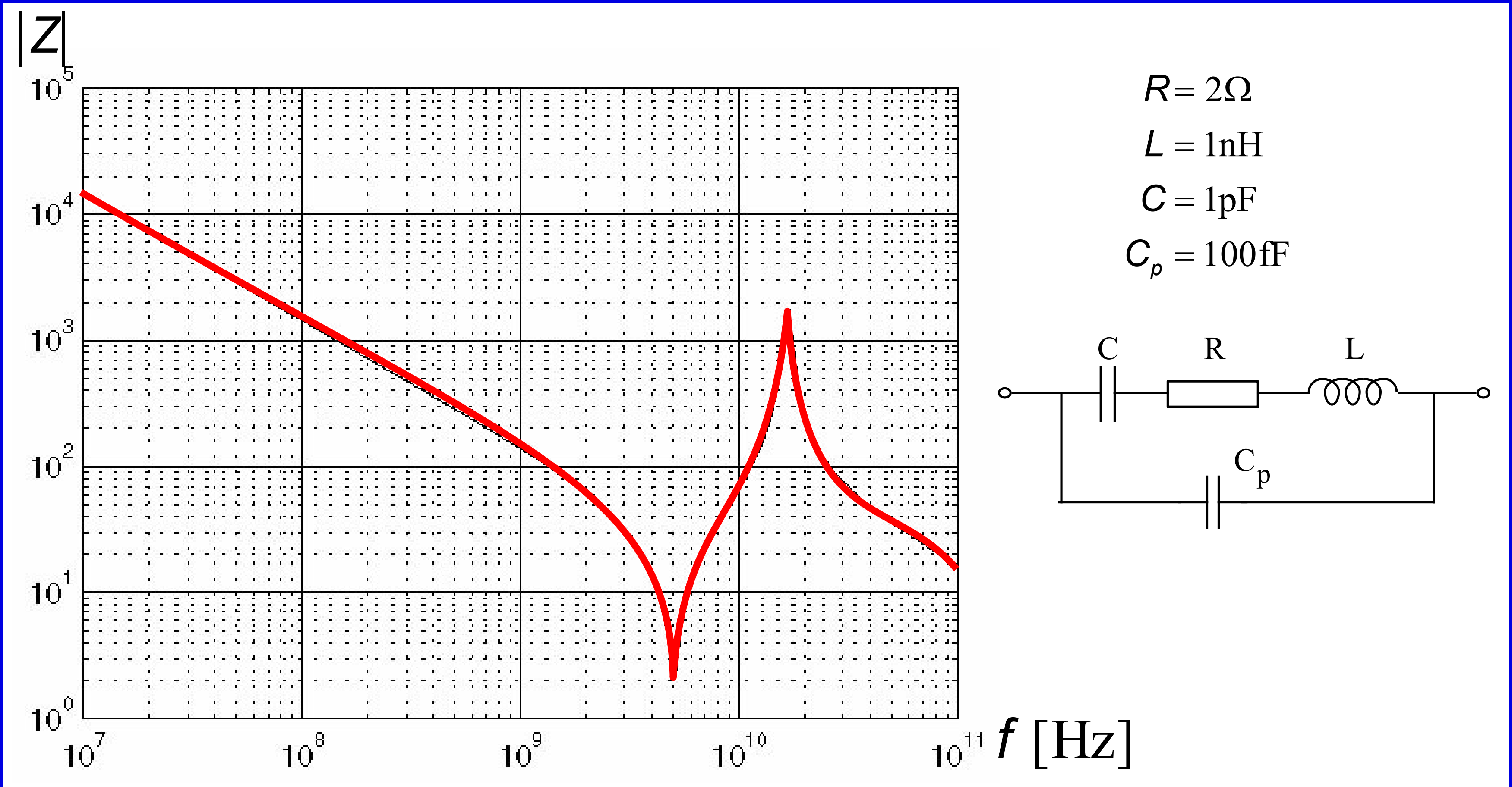




R_{ESR} = equivalent series resistance

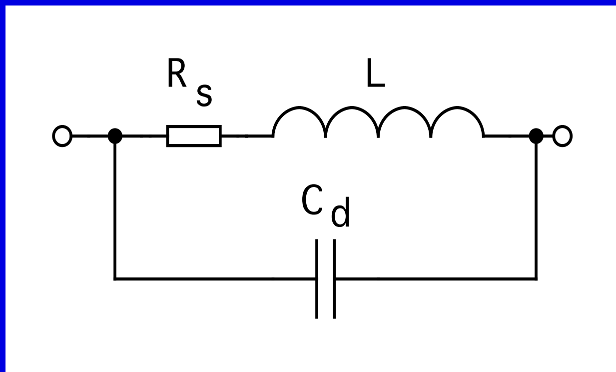
Capacitor

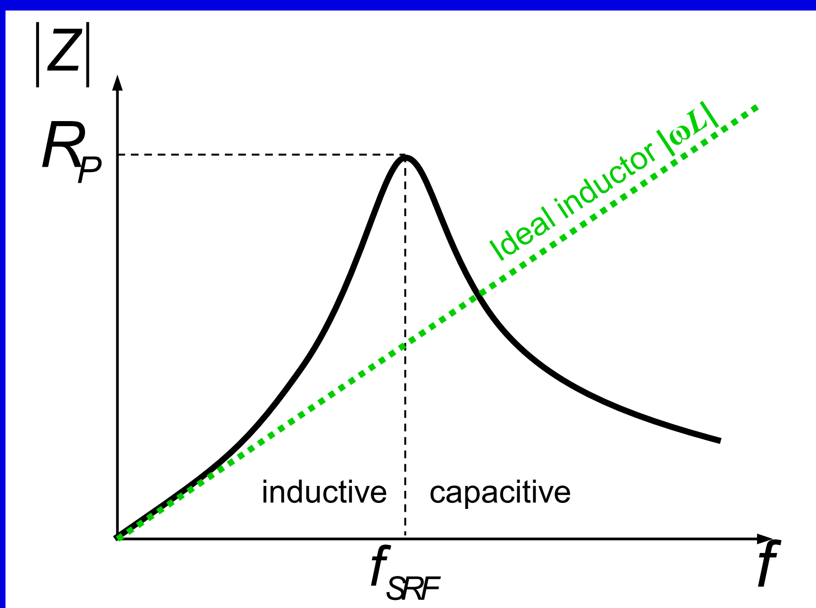
Frequency characteristics - example

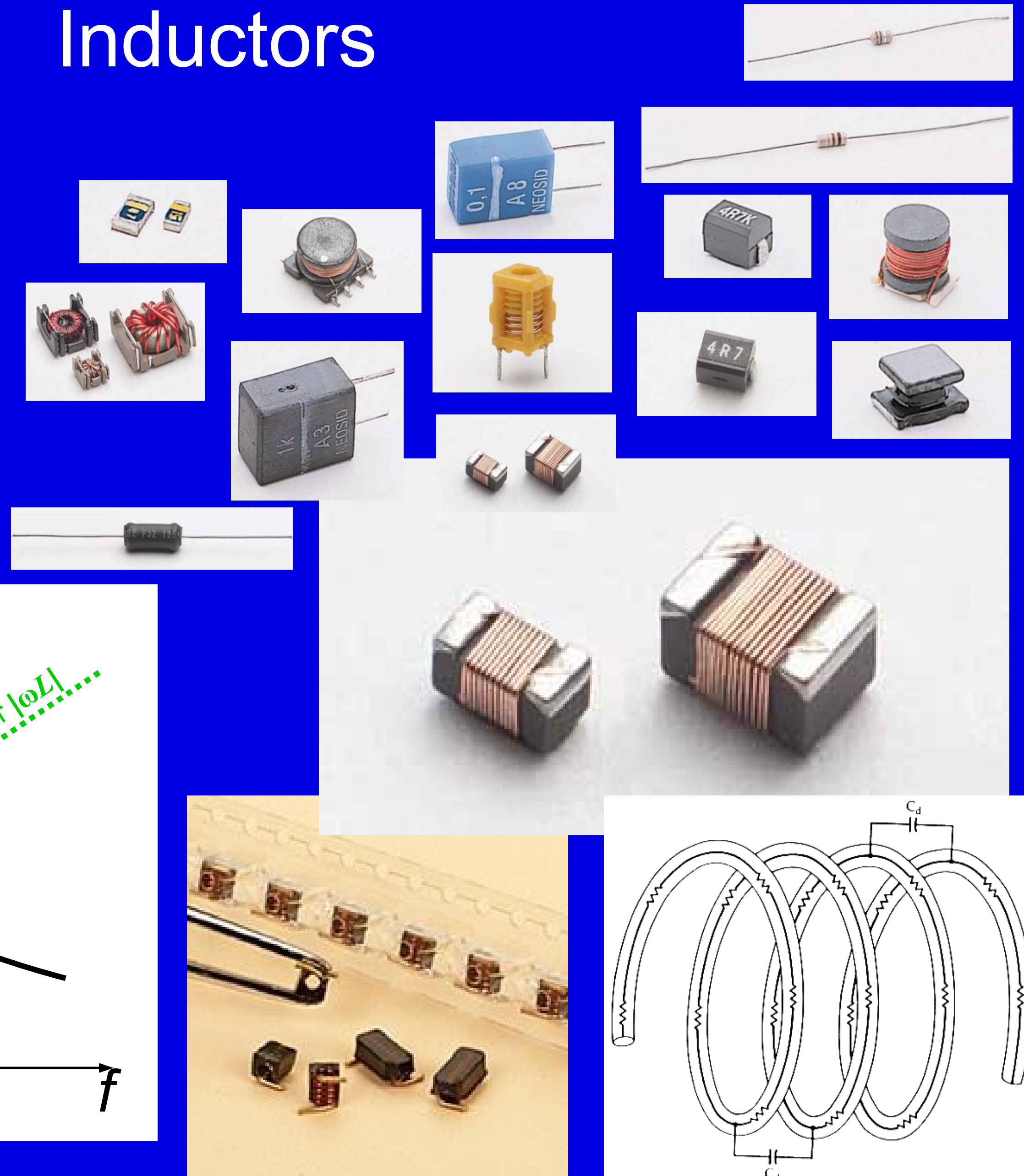


Inductors

high-frequency model



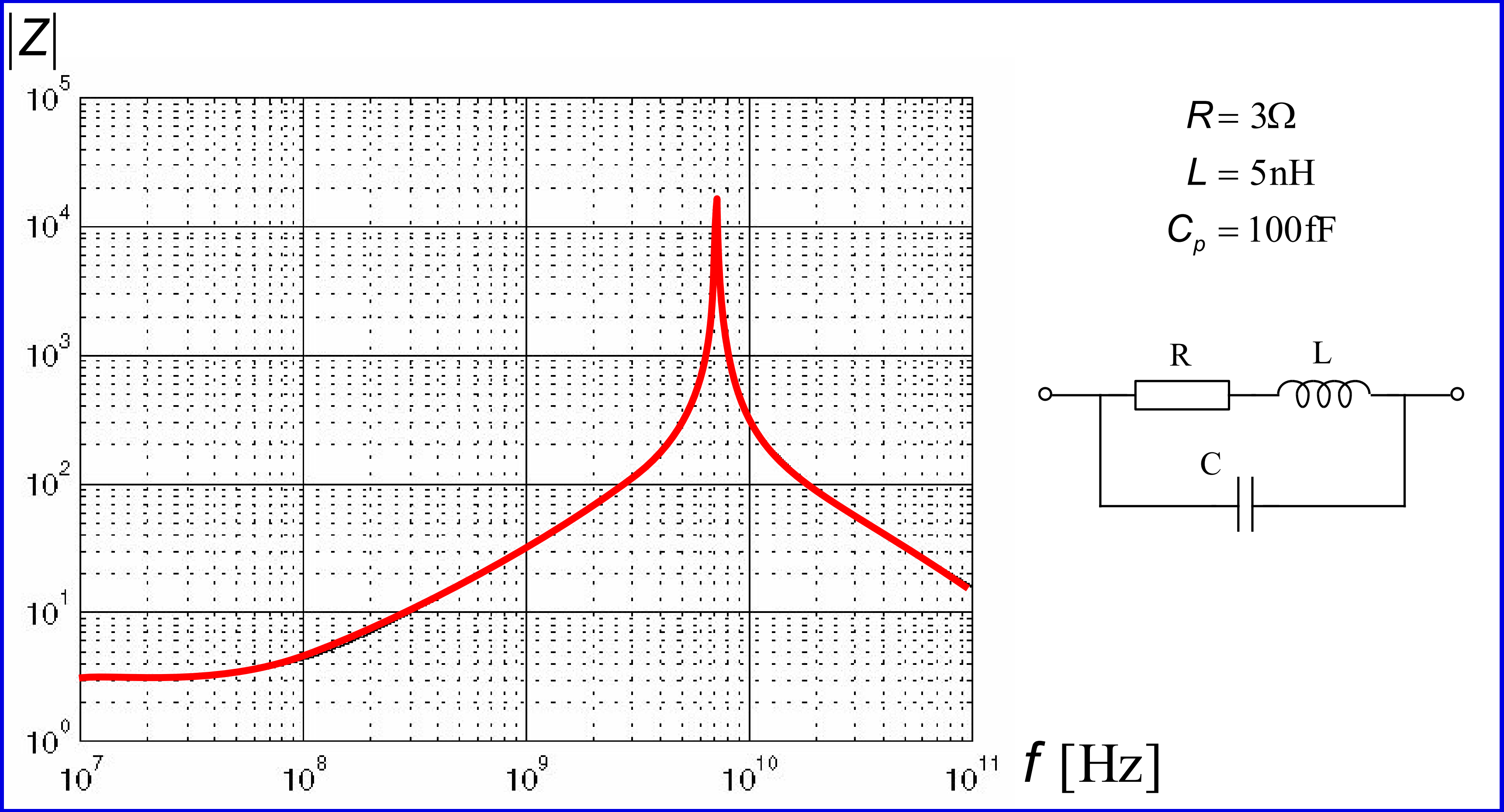




R_P = equivalent parallel resistance

Inductor

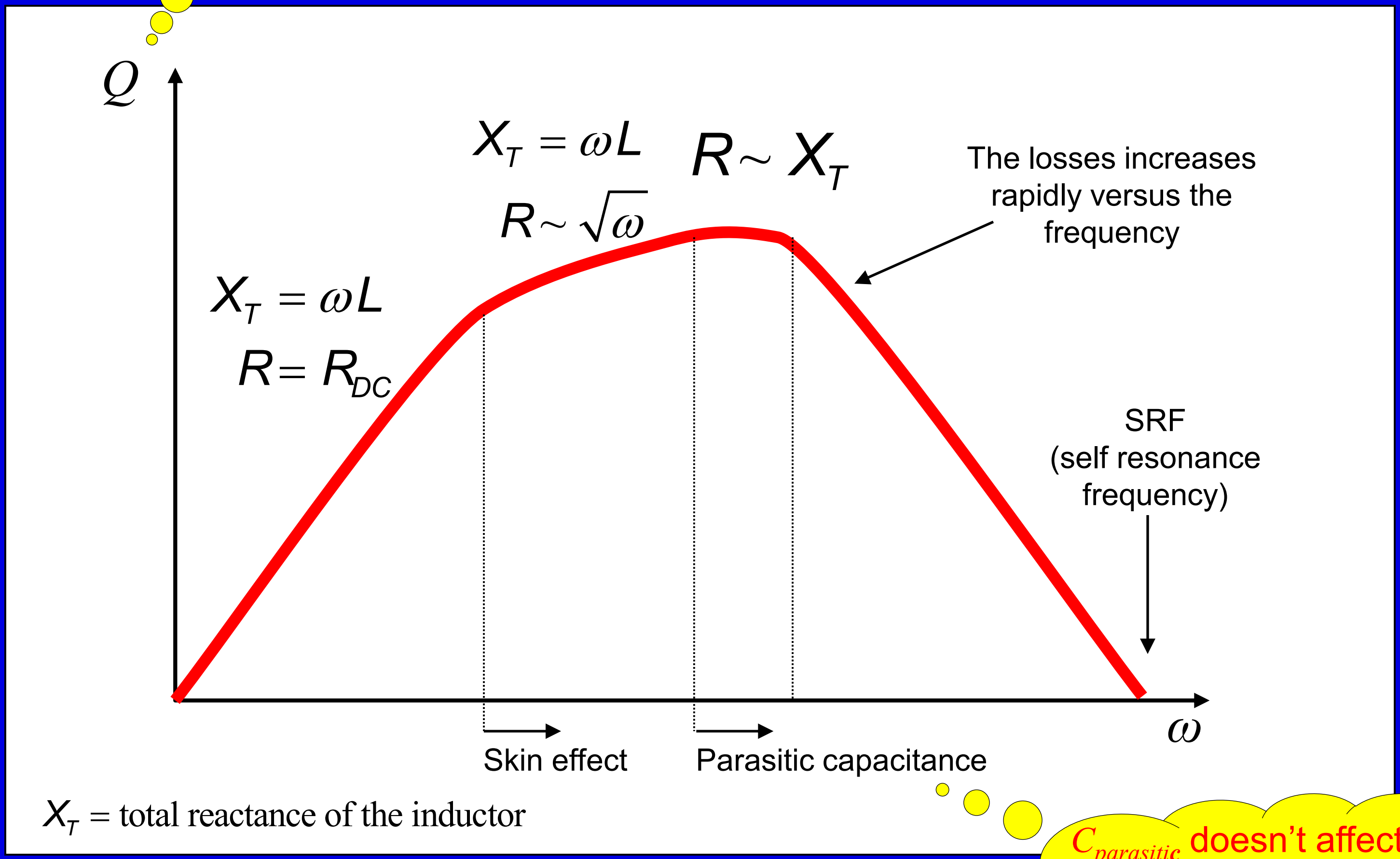
Frequency characteristics - example



Inductor

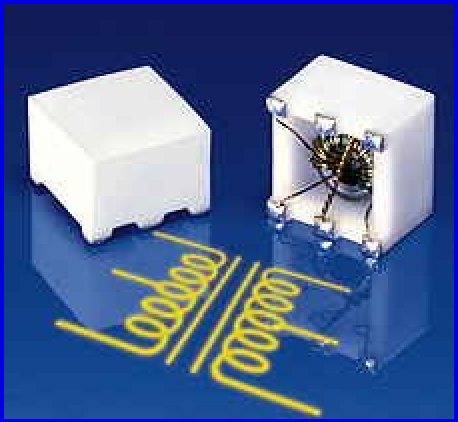
$$Q = \frac{X}{R_S}$$

The Q-factor frequency dependence



$C_{parasitic}$ doesn't affect the Q if the inductor is used in a resonant circuit!

Transformer



- Windings on a ferrite rod or toroid core
- These materials provides a high permeability that unfortunately decreases at higher frequencies
- Usable at best up to a few GHz

Loss in Substrate Materials

- For dielectric materials often the loss tangent used to specify the losses:

$$\tan\delta = \frac{\sigma}{\omega\varepsilon}$$

- for material with low loss $\tan\delta \;\square\; \delta$ where δ is the loss angle

- The loss tangent is also related to the quality factor or Q-factor of the material: $\tan\delta = \frac{1}{Q_d}$

Properties of some Substrate Materials

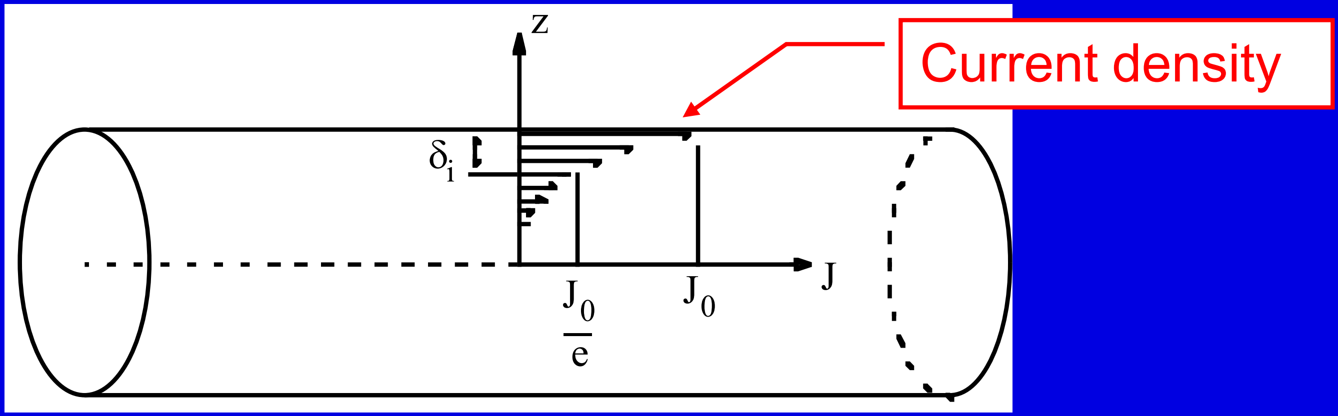
Material	ε_r	tanδ
Ceramic	10	0.004
Beryllium oxide	6	0.0003
Duorid	2.6	0.0001
Teflon fibre-glass	2.3	0.0015
Silicon	11.7	0.004
Quarz	3.8	0.0001
Epoxy fibre-glass	4	0.02
Aluminium oxide	10	0.0003

Properties of some Metals

Metal	σ [S/m]
Aluminium	$3.816 \cdot 10^7$
Copper	$5.813 \cdot 10^7$
Gold	$4.098 \cdot 10^7$
Iron	$1.03 \cdot 10^7$
Silver	$6.173 \cdot 10^7$

Skin Effect

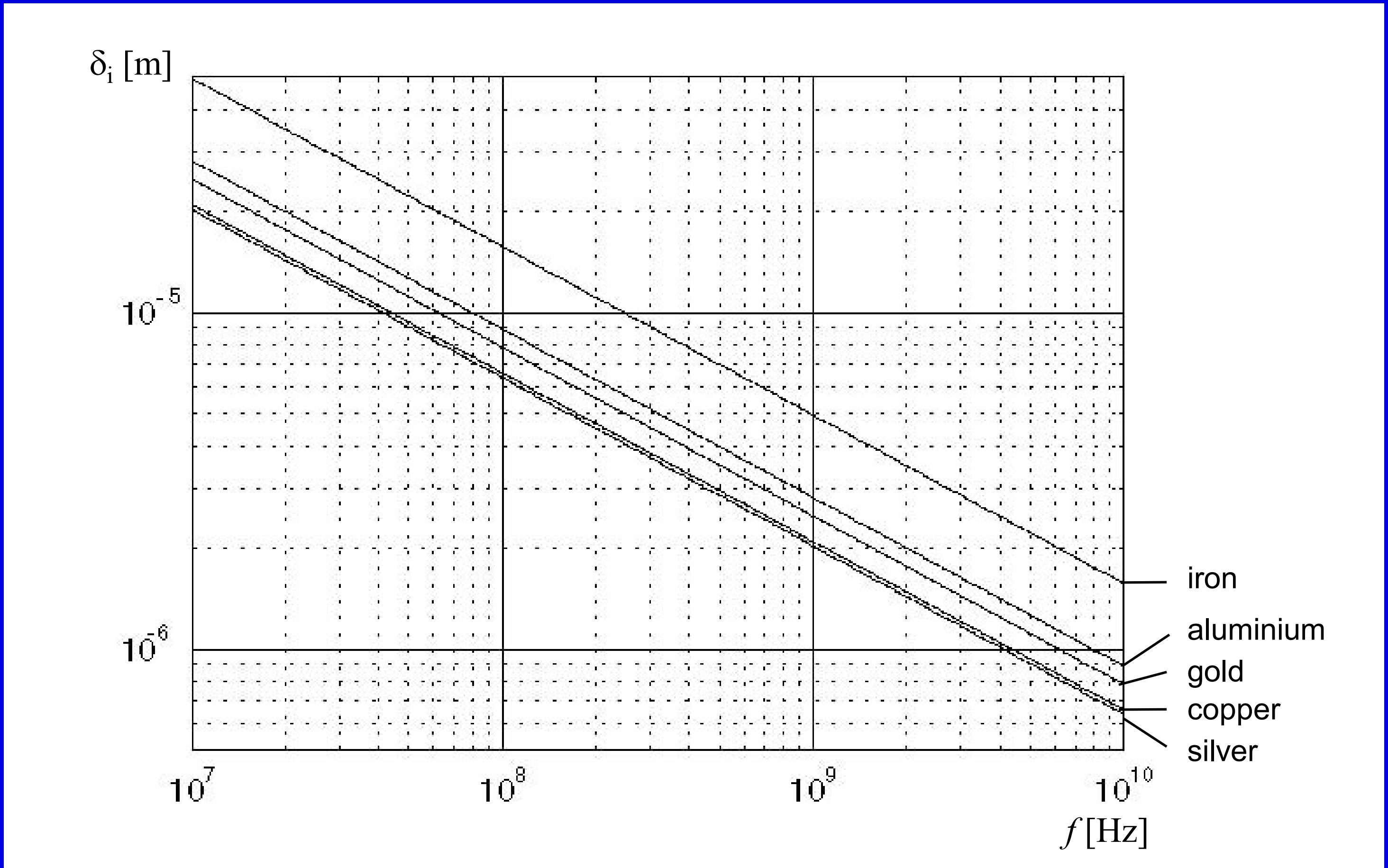
- The magnetic flux inside the conductor will effectively push the current to a narrow region close to the surface



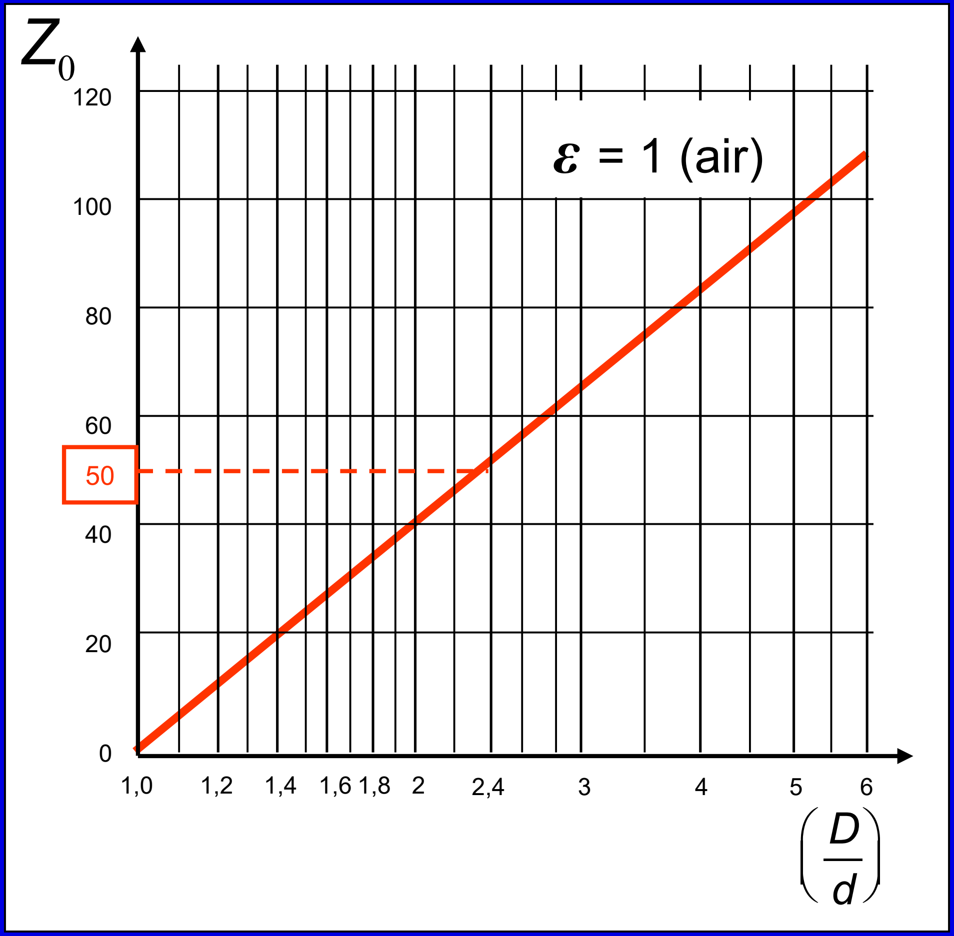
- Skin depth: $\delta_i = \sqrt{\frac{2}{\omega\mu\sigma}}$ = the distance were the current density has decreased by a factor e

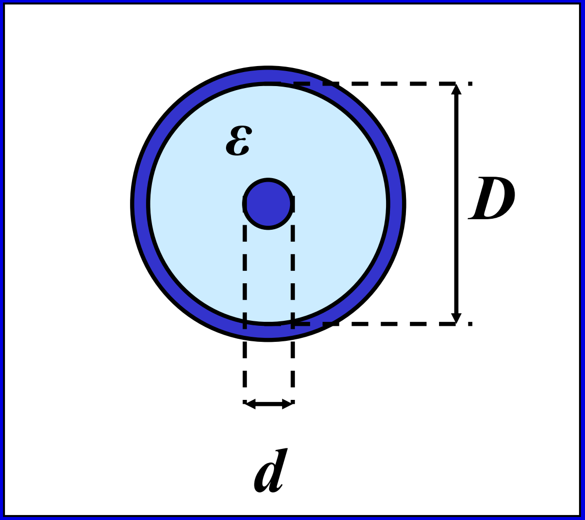
- A large circumference is more essential than a large cross section area of the conductor!

Example of Skin Depth



Coaxial Cable Design: Char. Impedance

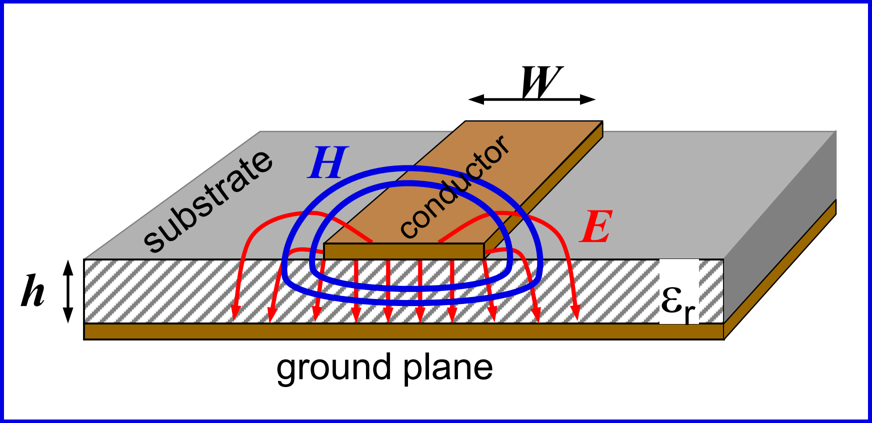




$$Z_0 = \frac{138}{\sqrt{\varepsilon_r}} \log^{10}\left(\frac{D}{d}\right) = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right)$$

Microstrip

Cross section of a microstrip structure



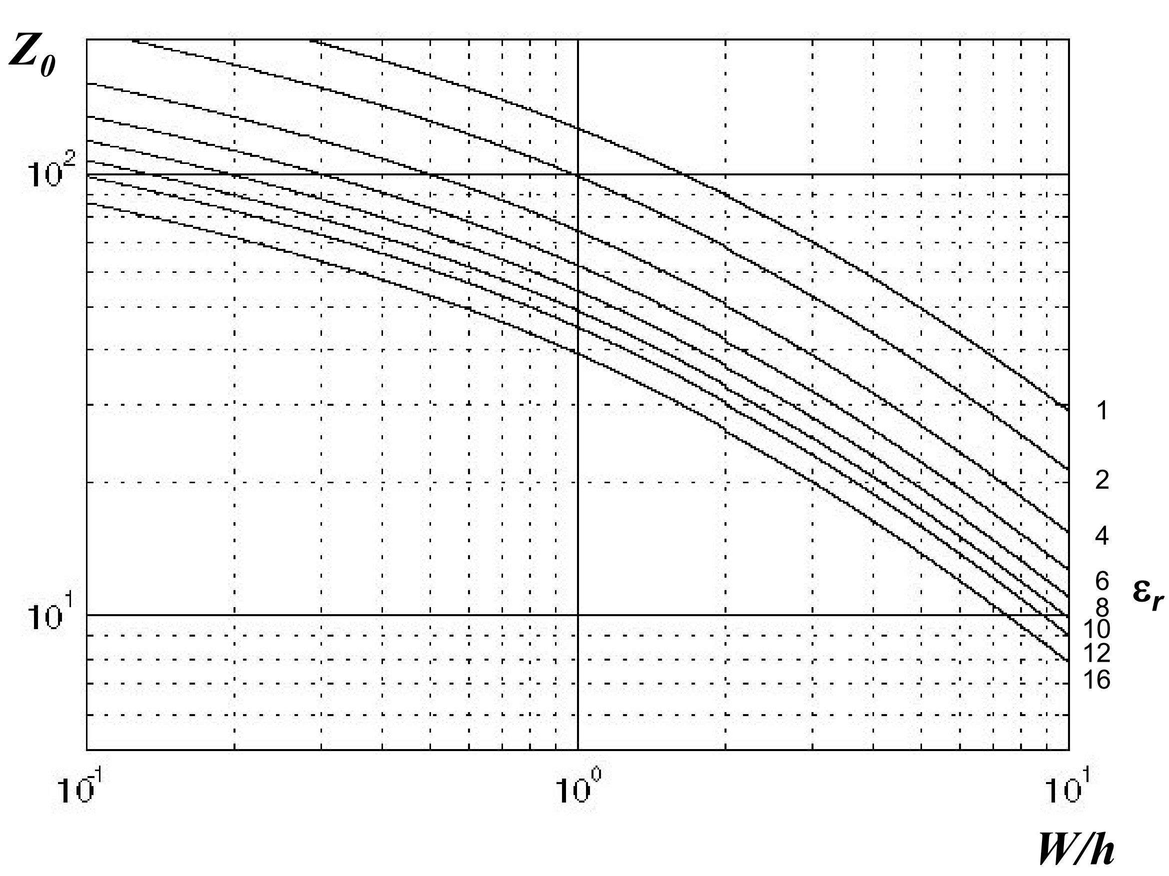
Complex geometry and non-uniform fields makes a complicated flux image.

ε_r in the substrate is therefore not usable for calculation of for example electrical length in the line structure.

Instead the effective permittivity, ε_{eff} , based on the dimensions of the microstrip structure, may be used.

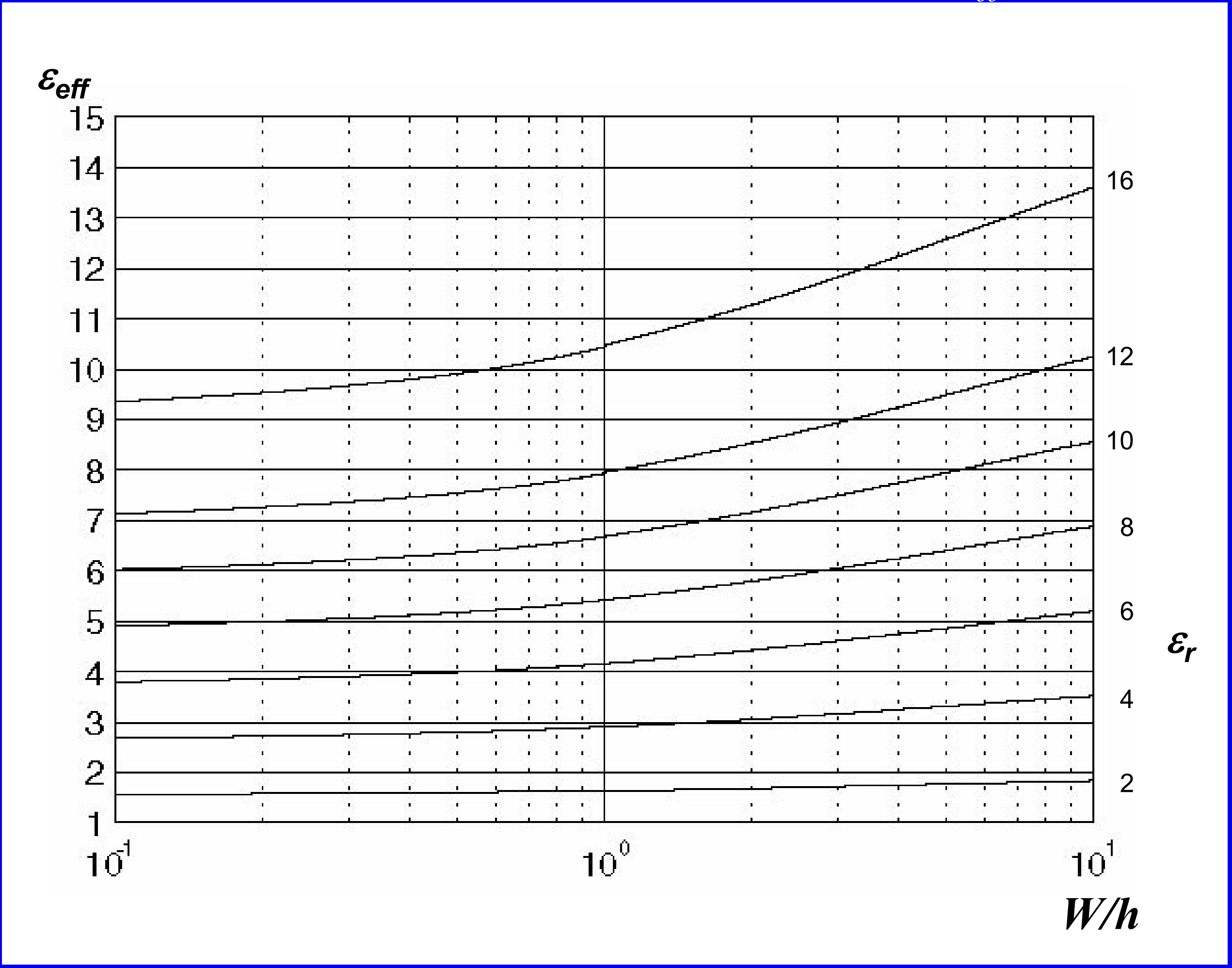
Microstrip Design: Char. Impedance

Determine the proper W for a specified Z_0 and h



Microstrip Design: Eff. Permittivity

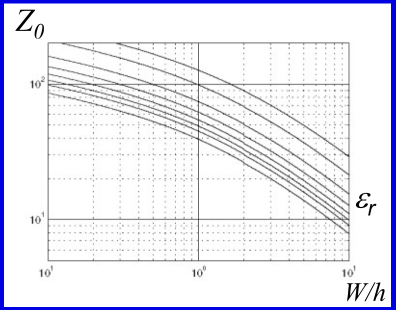
Determine the effective permittivity ε_{eff}



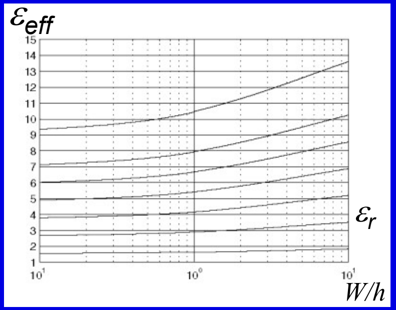
Microstrip Design: Summary

Specified Z_0, substrate height h and permittivity ε_r:

1. Select the width W in diagram 1



2. Select the effective permittivity ε_{eff} in diagram 2

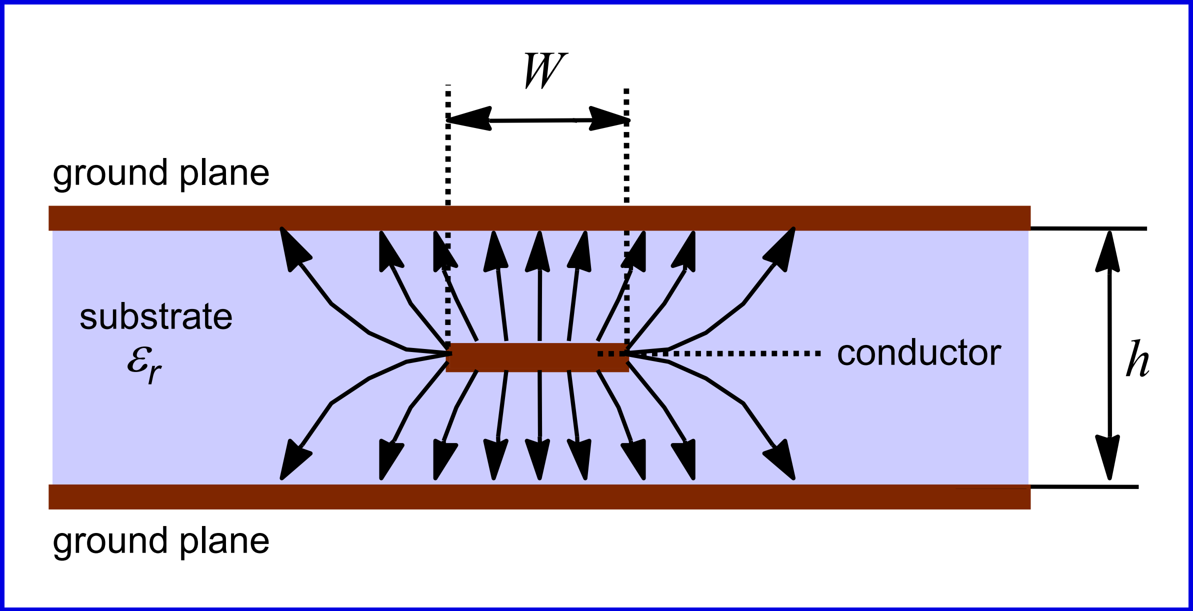


3. Calculate the effective wavelength $\lambda_{eff} = \dfrac{\lambda_0}{\sqrt{\varepsilon_{eff}}}$

Specified electrical length ℓ_{el}

4. Calculate the physical length $\ell = \ell_{el} \cdot \lambda_{eff}$

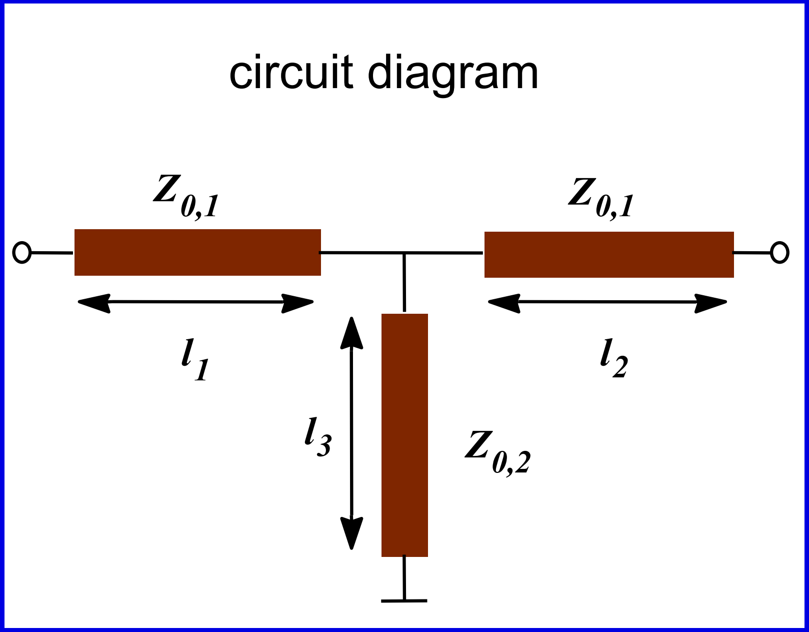
Stripline

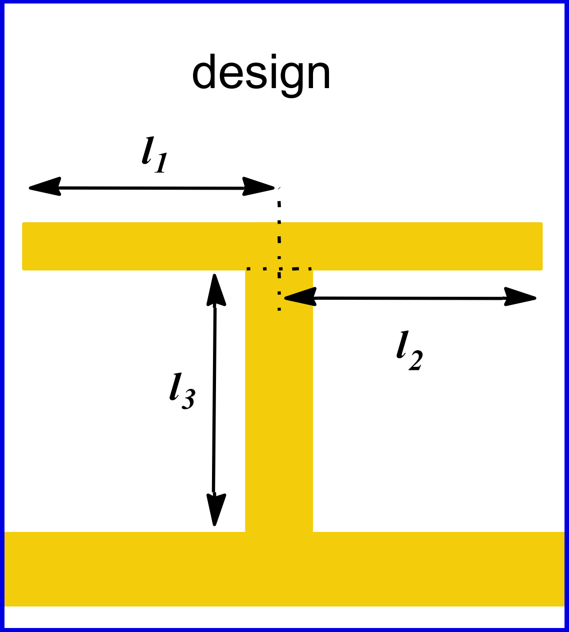


W
ground plane
substrate
ε_r
conductor
h
ground plane

Discontinuities

- The design of circuits containing transmission lines must take into account the impact of junctions and transitions between different line widths.

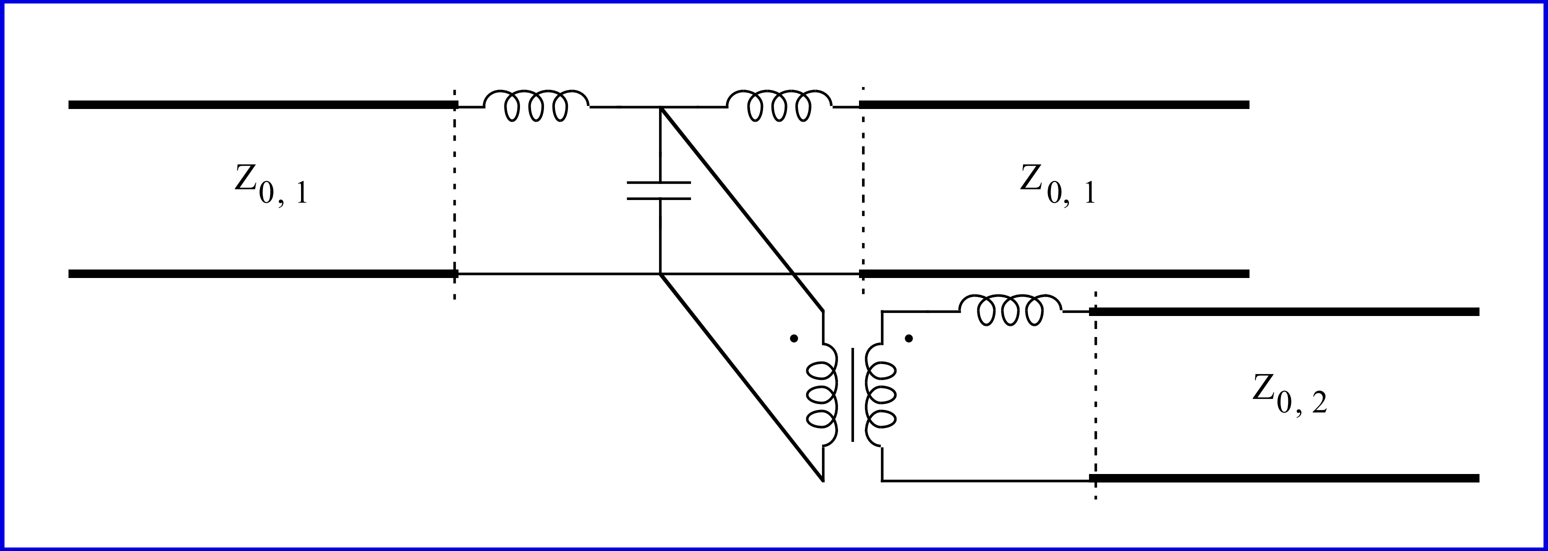




- How to model such a geometry?

Discontinuities (cont.)

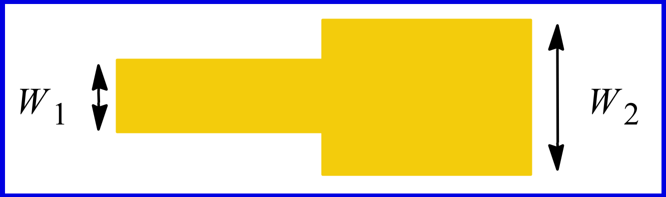
- T-junction, equivalent model

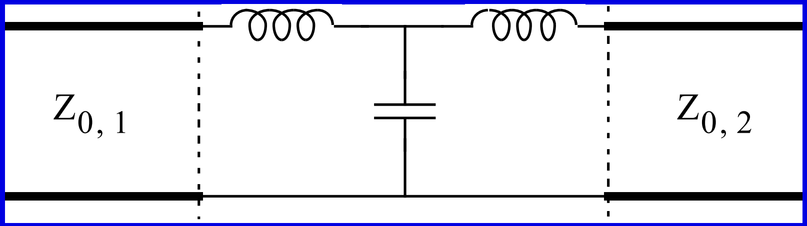


- Methods for manual calculation of the circuit elements in the equivalent model may be found in handbooks.

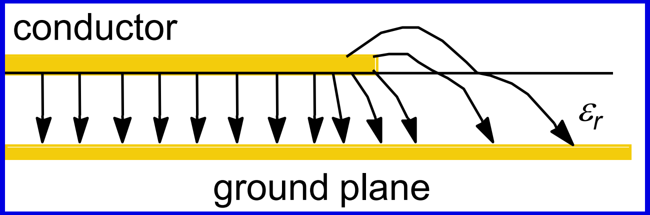
Discontinuities (cont.)

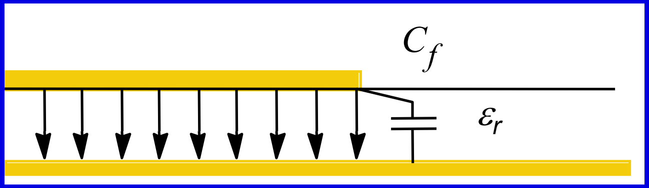
- Symmetrical step, an abrupt transition between two different line widths





- Transmission line, open-circuit termination





Discontinuities (cont.)

- Some other cases are
  - corners and bends
  - serial gap (to realize a serial capacitance)
  - undesired coupling between nearby structures
    - Crosstalk
- CAD tools are necessary for analysis and design of more complex circuits
  - ADS and others
- In worst case a complete structure may be simulated by the finite element method and Maxwell's equations which is both time and memory consuming