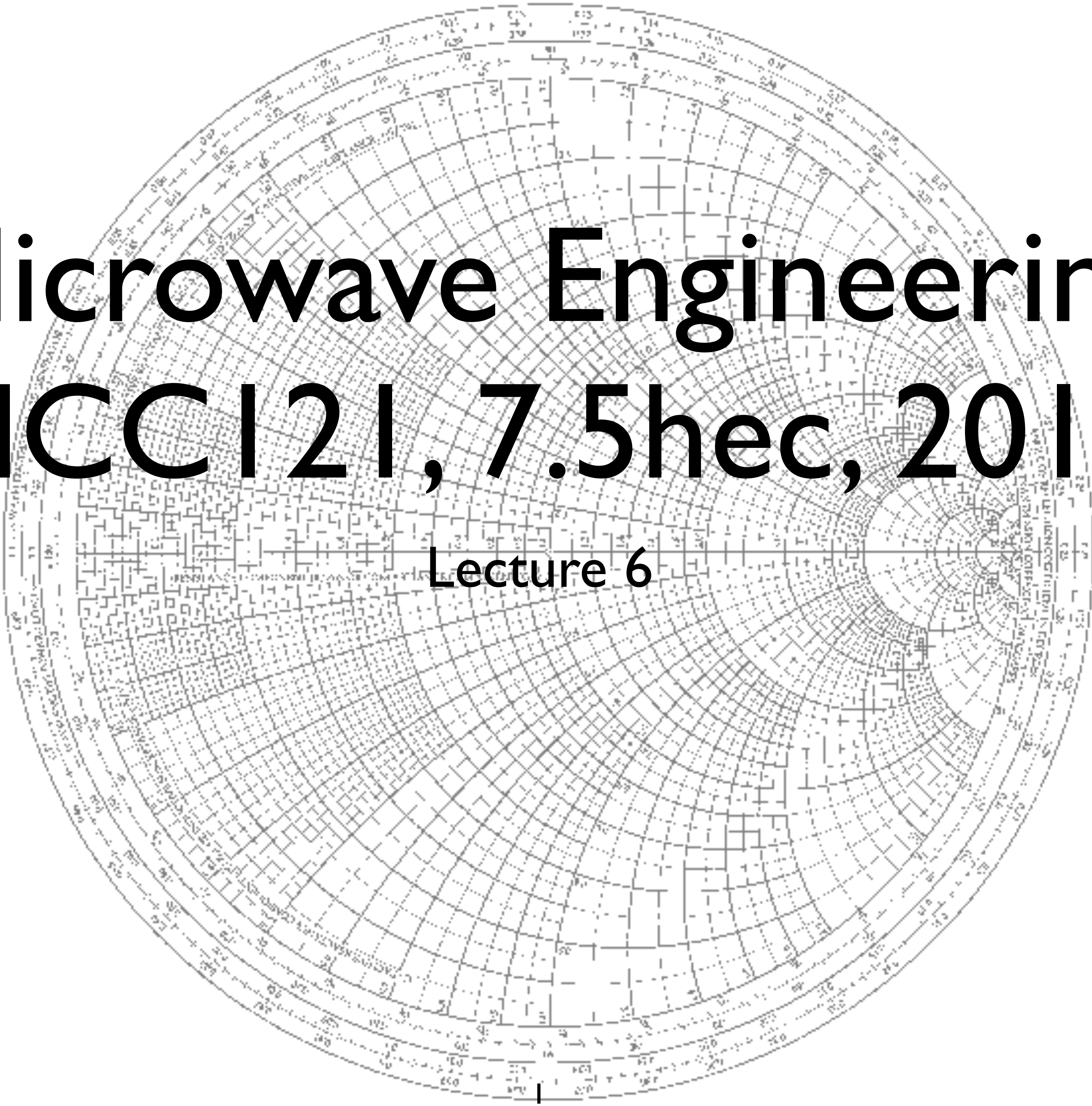
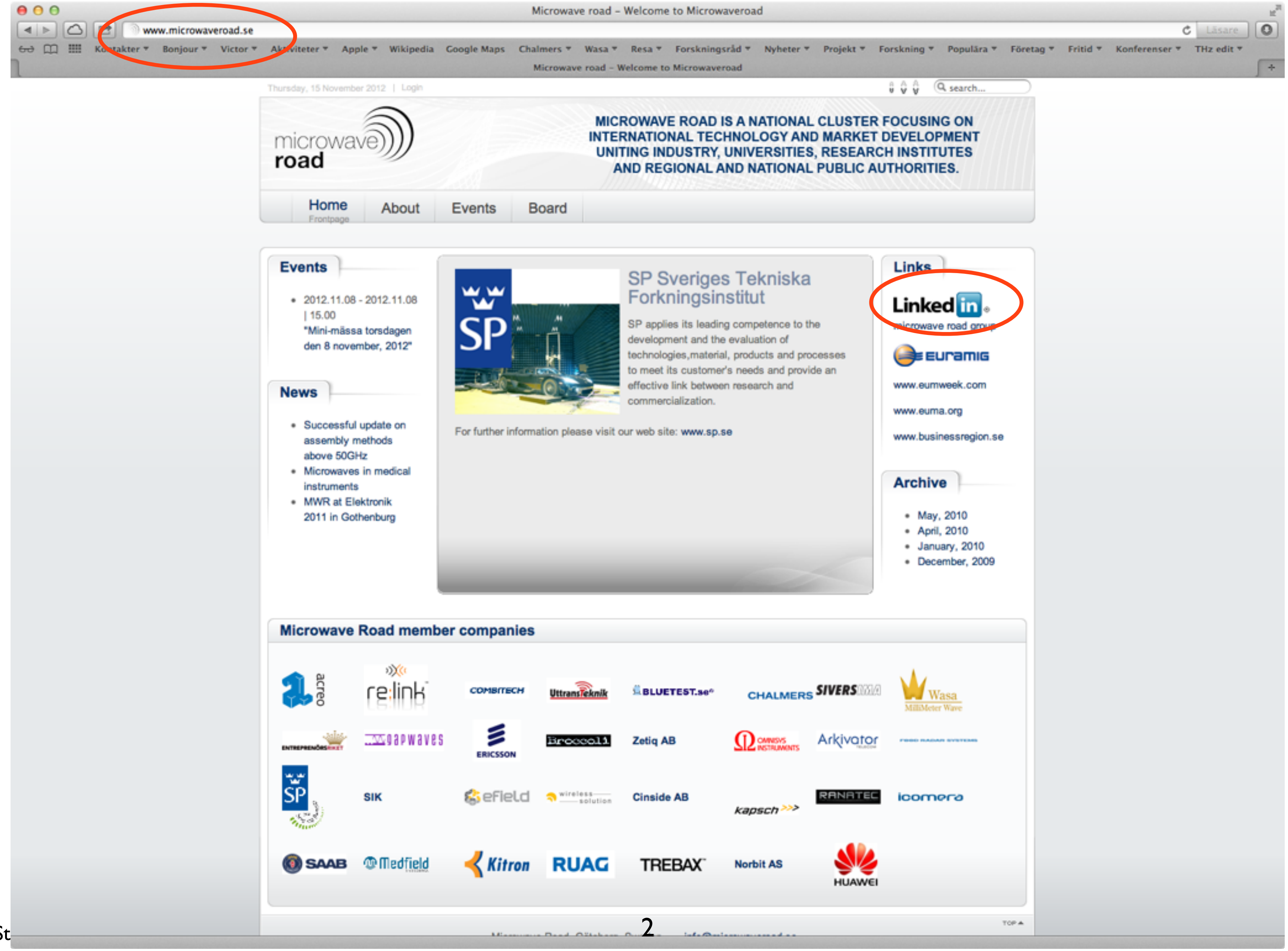


Microwave Engineering
MCC121, 7.5hec, 2014

Lecture 6

State-of-the-art
Challenging
Stimulating
Rewarding

Future?


Microwave road – Welcome to Microwaveroad
www.microwaveroad.se
microwave road
MICROWAVE ROAD IS A NATIONAL CLUSTER FOCUSING ON INTERNATIONAL TECHNOLOGY AND MARKET DEVELOPMENT UNITING INDUSTRY, UNIVERSITIES, RESEARCH INSTITUTES AND REGIONAL AND NATIONAL PUBLIC AUTHORITIES.
Home
About
Events
Board
Events
2012.11.08 - 2012.11.08 | 15.00 "Mini-mässa torsdagen den 8 november, 2012"
News
Successful update on assembly methods above 50GHz
Microwaves in medical instruments
MWR at Elektronik 2011 in Gothenburg
SP Sveriges Tekniska Forkningsinstitut
SP applies its leading competence to the development and the evaluation of technologies,material, products and processes to meet its customer's needs and provide an effective link between research and commercialization.
For further information please visit our web site: www.sp.se
Links
LinkedIn
EURAMIG
www.eumweek.com
www.euma.org
www.businessregion.se
Archive
May, 2010
April, 2010
January, 2010
December, 2009
Microwave Road member companies
acreo
re:link
COMBITECH
BLUETEST.se
CHALMERS
SIVERS
Wasa
ERICSSON
Zetiq AB
Arkivator
SP
SIK
eField
Cinside AB
kapsch
RANATEC
icomera
SAAB
Medfield
Kitron
RUAG
TREBAX
Norbit AS
HUAWEI

Outline

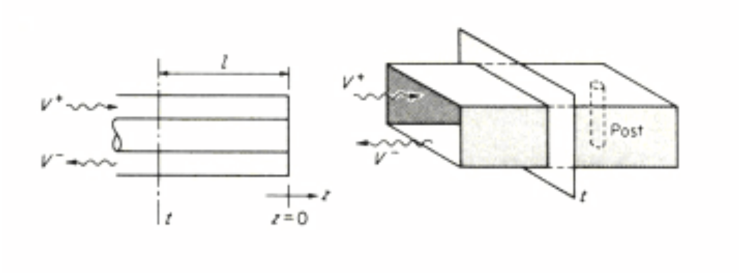
- Summary of n-port representations (Ch4)
- Impedance matching (Ch5.1-5.4)
  - Smith chart
  - Stub matching
  - Lumped element matching

Objectives

On completion of this course unit you should be able to:

- ☑ Analyse wave propagating properties of guided wave structures (TE, TM, TEM waves, microstrip, stripline, rectangular and circular waveguides, coupled lines)
- ☑ Apply N-port representations for analysing microwave circuits
- ☑ Apply the Smith chart to evaluate microwave networks
- ☐ Design and evaluate impedance matching networks
- ☐ Design, evaluate and characterise directional couplers and power dividers
- ☐ Design and analyse attenuators, phase shifters and resonators
- ☐ Explain basic properties of ferrite devices (circulators, isolators)

One-port circuit



- energy can enter or leave through a single propagation line
- Introduce input impedance, Z_{in}

Impedance description

Assume now perfectly conductive walls, $\sigma=\infty$, $E_{tan}=0$ on all walls but t.

$$\frac{1}{2}\oint_t \bar{E}\times\bar{H}\bullet\bar{a}_z\,dS = P_{loss} + 2j\omega(W_m - W_e)$$

At the terminal plane t the transverse fields are

$$\bar{E}_t = K_1^{-1}(V^+ + V^-)\bar{e} = K_1^{-1}V\bar{e}$$
$$\bar{H}_t = K_2^{-1}(I^+ - I^-)\bar{h} = K_2^{-1}I\bar{h}$$

Thus

$$\frac{1}{2}(K_1K_2^*)^{-1}VI^*\int_t \bar{e}\times\bar{h}^*\bullet\bar{a}_z\,dS = \frac{1}{2}VI^* = P_{loss} + 2j\omega(W_m - W_e)$$

We have now $V = Z_{in}I$

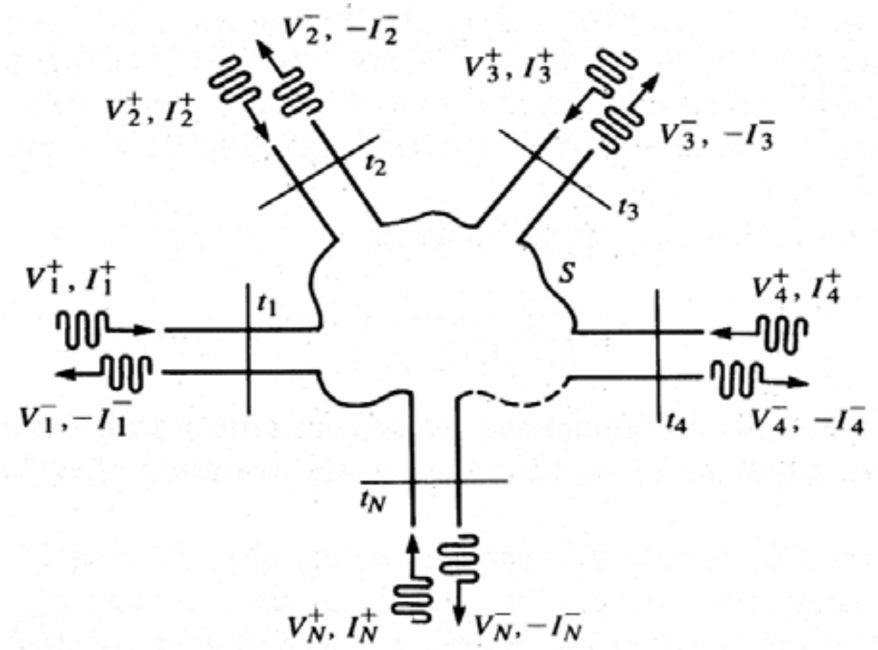
$$Z_{in} = \frac{P_{loss} + 2j\omega(W_m - W_e)}{\frac{1}{2}II^*} = R + jX$$

$$Z_{in} = f(P_{loss}, W_m - W_e)$$

If $W_m > W_e$ → $X > 0$, inductive one-port

If $W_m < W_e$ → $X < 0$, capacitive one-port

Scattering matrix [S]



$$s_{11} = \frac{V_1^-}{V_1^+}; \quad s_{n1} = \frac{V_n^-}{V_1^+}, n = 2,3,....,N$$

$$\begin{bmatrix} V_1^- \\ V_2^- \\ . \\ . \\ V_N^- \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & . & . & s_{1N} \\ s_{21} & s_{22} & . & . & s_{2N} \\ . & . & . & . & . \\ . & . & . & . & . \\ s_{N1} & s_{N2} & . & . & s_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ . \\ . \\ V_N^+ \end{bmatrix}$$

$$\left[V^-\right] = \left[S\right]\left[V^+\right] \text{ and } s_{ij} = \left.\frac{V_i^-}{V_j^+}\right|_{V_n^+=0, n\neq j}$$

[S] can be measured using a Vector Network Analyser (VNA), even at very high frequencies.

Impedance matrix

- let the terminal planes be choses sufficiently far from the junction=> only dominant incident and reflected waves. =>equivalent voltages and currents
- Use total current as independent variables and total voltages as dependent variables, hence linear combination can be written as:

$$\begin{bmatrix} V_1 \\ V_2 \\ . \\ . \\ V_N \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & . & . & z_{1N} \\ z_{21} & z_{22} & . & . & z_{2N} \\ . & . & . & . & . \\ . & . & . & . & . \\ z_{N1} & z_{N2} & . & . & z_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ . \\ . \\ I_N \end{bmatrix}$$

Properties

- Non reciprocal circuit: $Z_{ij} \neq Z_{ji}$ unsymmetrical impedance matrix ($2N^2$ parameters)
- Reciprocal circuit: $Z_{ij}=Z_{ji}$ => symmetrical impedance matrix (N(N+1) parameters)
- Lossless circuit: symmetrical and imaginary [Z] (N(N+1)/2 parameters)
- Same applies to $[Y]=[Z]^{-1}$

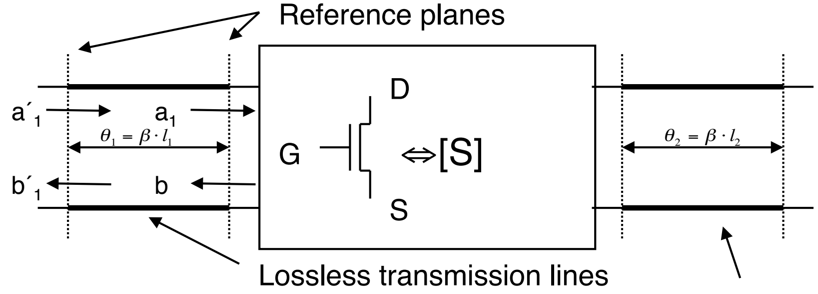
$$\begin{bmatrix} V_1 \\ V_2 \\ . \\ . \\ V_N \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & . & . & z_{1N} \\ z_{21} & z_{22} & . & . & z_{2N} \\ . & . & . & . & . \\ . & . & . & . & . \\ z_{N1} & z_{N2} & . & . & z_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ . \\ . \\ I_N \end{bmatrix}$$

Properties of the S-matrix

- Reciprocal if ([S] symmetric) $[S]=[S]^t$
- Lossless if: ([S] is unitary, [U] is the unit diagonal matrix) $[S]^t[S]^*=[U]$

Shift of the reference plane

- Two port case:



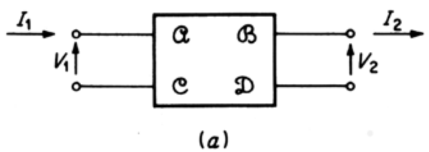
$$[S'] = [\Phi]\cdot[S]\cdot[\Phi],\ [\Phi] = \begin{bmatrix} e^{-j\cdot\beta\cdot l_1} & 0 \\ 0 & e^{-j\cdot\beta\cdot l_2} \end{bmatrix}$$

$$\text{or } [S] = [\Phi]^{-1}\cdot[S']\cdot[\Phi]^{-1}$$

$$[S] = \begin{bmatrix} e^{j\cdot\beta\cdot l_1} & 0 \\ 0 & e^{j\cdot\beta\cdot l_2} \end{bmatrix}\cdot[S']\cdot\begin{bmatrix} e^{j\cdot\beta\cdot l_1} & 0 \\ 0 & e^{j\cdot\beta\cdot l_2} \end{bmatrix}$$

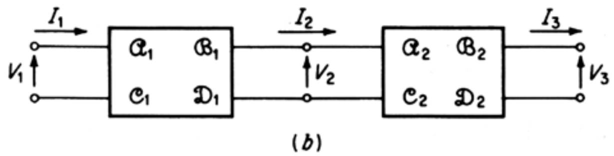
Cascaded components

- For cascaded components a convenient way to describe the connection is to use transmission matrices (sometimes called ABCD matrices)



$$V_1 = AV_2 + BI_2$$
$$I_1 = CV_2 + DI_2$$

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_2 \\ I_2 \end{pmatrix}$$



$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} \begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix}$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \dfrac{z_{11}}{z_{12}} & \dfrac{\left(z_{11}z_{22} - z_{12}^2\right)}{z_{12}} \\ \dfrac{1}{z_{12}} & \dfrac{z_{22}}{z_{12}} \end{pmatrix}$$

For reciprocal junctions $AD\text{-}BC=1$

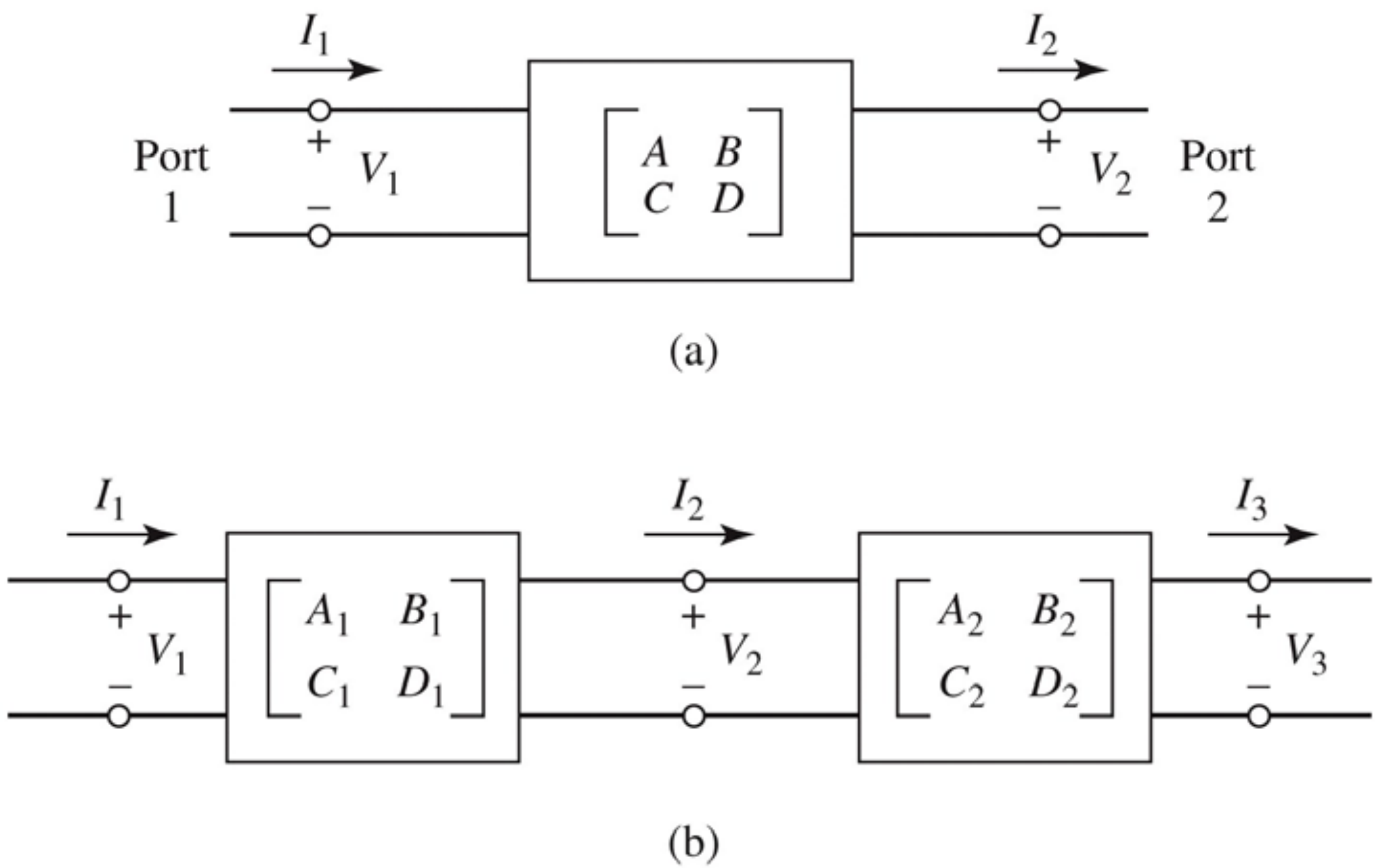

I_1
I_2
Port
1
+
V_1
–
A B
C D
+
V_2
–
Port
2
(a)
I_1
I_2
I_3
+
V_1
–
A_1 B_1
C_1 D_1
+
V_2
–
A_2 B_2
C_2 D_2
+
V_3
–
(b)

Figure 4.11

TABLE 4.1 ***ABCD* Parameters of Some Useful Two-Port Circuits**

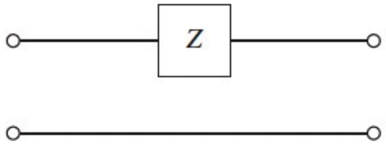
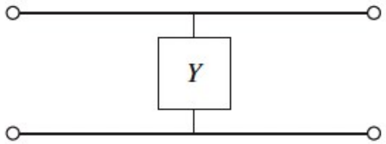
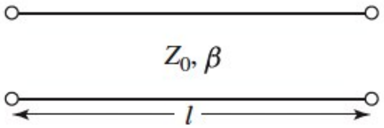
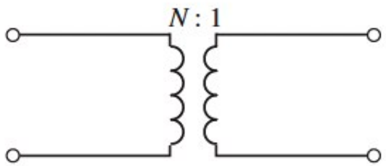
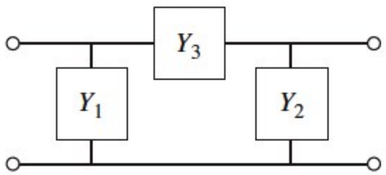
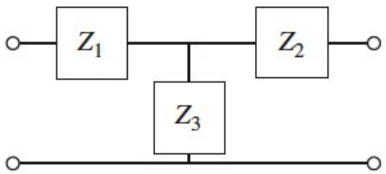
Circuit	*ABCD* Parameters	
	$A = 1$ $C = 0$	$B = Z$ $D = 1$
	$A = 1$ $C = Y$	$B = 0$ $D = 1$
	$A = \cos \beta\ell$ $C = jY_0 \sin \beta\ell$	$B = jZ_0 \sin \beta\ell$ $D = \cos \beta\ell$
	$A = N$ $C = 0$	$B = 0$ $D = \frac{1}{N}$
	$A = 1 + \frac{Y_2}{Y_3}$ $C = Y_1 + Y_2 + \frac{Y_1 Y_2}{Y_3}$	$B = \frac{1}{Y_3}$ $D = 1 + \frac{Y_1}{Y_3}$
	$A = 1 + \frac{Z_1}{Z_3}$ $C = \frac{1}{Z_3}$	$B = Z_1 + Z_2 + \frac{Z_1 Z_2}{Z_3}$ $D = 1 + \frac{Z_2}{Z_3}$

Table 4.1

Conversion table

	S	z	y	h	$ABCD$
S	S_{11} S_{12} S_{21} S_{22}	$S_{11}=\frac{(z'_{11}-1)(z'_{22}+1)-z'_{12}z'_{21}}{\Delta_1}$ $S_{12}=\frac{2z'_{12}}{\Delta_1}$ $S_{21}=\frac{2z'_{21}}{\Delta_1}$ $S_{22}=\frac{(z'_{11}+1)(z'_{22}-1)-z'_{12}z'_{21}}{\Delta_1}$	$S_{11}=\frac{(1-y'_{11})(1+y'_{22})+y'_{12}y'_{21}}{\Delta_2}$ $S_{12}=\frac{-2y'_{12}}{\Delta_2}$ $S_{21}=\frac{-2y'_{21}}{\Delta_2}$ $S_{22}=\frac{(1+y'_{11})(1-y'_{22})+y'_{12}y'_{21}}{\Delta_2}$	$S_{11}=\frac{(h'_{11}-1)(h'_{22}+1)-h'_{12}h'_{21}}{\Delta_3}$ $S_{12}=\frac{2h'_{12}}{\Delta_3}$ $S_{21}=\frac{-2h'_{21}}{\Delta_3}$ $S_{22}=\frac{(1+h'_{11})(1-h'_{22})+h'_{12}h'_{21}}{\Delta_3}$	$\frac{A'+B'-C'-D'}{\Delta_4}$ $\frac{2(A'D'-B'C')}{\Delta_4}$ $\frac{2}{\Delta_4}$ $\frac{-A'+B'-C'+D'}{\Delta_4}$
z	$z'_{11}=\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{\Delta_5}$ $z'_{12}=\frac{2S_{12}}{\Delta_5}$ $z'_{21}=\frac{2S_{21}}{\Delta_5}$ $z'_{22}=\frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{\Delta_5}$	z_{11} z_{12} z_{21} z_{22}	$\frac{y_{22}}{\|y\|}$ $\frac{-y_{12}}{\|y\|}$ $\frac{-y_{21}}{\|y\|}$ $\frac{y_{11}}{\|y\|}$	$\frac{\|h\|}{h_{22}}$ $\frac{h_{12}}{h_{22}}$ $\frac{-h_{21}}{h_{22}}$ $\frac{1}{h_{22}}$	$\frac{A}{C}$ $\frac{\Delta_8}{C}$ $\frac{1}{C}$ $\frac{D}{C}$
y	$y'_{11}=\frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{\Delta_6}$ $y'_{12}=\frac{-2S_{12}}{\Delta_6}$ $y'_{21}=\frac{-2S_{21}}{\Delta_6}$ $y'_{22}=\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{\Delta_6}$	$\frac{z_{22}}{\|z\|}$ $\frac{-z_{12}}{\|z\|}$ $\frac{-z_{21}}{\|z\|}$ $\frac{z_{11}}{\|z\|}$	y_{11} y_{12} y_{21} y_{22}	$\frac{1}{h_{11}}$ $\frac{-h_{12}}{h_{11}}$ $\frac{h_{21}}{h_{11}}$ $\frac{\|h\|}{h_{11}}$	$\frac{D}{B}$ $\frac{-\Delta_8}{B}$ $\frac{-1}{B}$ $\frac{A}{B}$
h	$h'_{11}=\frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{\Delta_7}$ $h'_{12}=\frac{2S_{12}}{\Delta_7}$ $h'_{21}=\frac{-2S_{21}}{\Delta_7}$ $h'_{22}=\frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{\Delta_7}$	$\frac{\|z\|}{z_{22}}$ $\frac{z_{12}}{z_{22}}$ $\frac{-z_{21}}{z_{22}}$ $\frac{1}{z_{22}}$	$\frac{1}{y_{11}}$ $\frac{-y_{12}}{y_{11}}$ $\frac{y_{21}}{y_{11}}$ $\frac{\|y\|}{y_{11}}$	h_{11} h_{12} h_{21} h_{22}	$\frac{B}{D}$ $\frac{-\Delta_8}{D}$ $\frac{-1}{D}$ $\frac{C}{D}$
$ABCD$	$A'=\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}}$ $B'=\frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}}$ $C'=\frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}}$ $D'=\frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}}$	$\frac{z_{11}}{z_{21}}$ $\frac{\|z\|}{z_{21}}$ $\frac{1}{z_{21}}$ $\frac{z_{22}}{z_{21}}$	$\frac{-y_{22}}{y_{21}}$ $\frac{-1}{y_{21}}$ $\frac{-\|y\|}{y_{21}}$ $\frac{-y_{11}}{y_{21}}$	$\frac{-\|h\|}{h_{21}}$ $\frac{-h_{11}}{h_{21}}$ $\frac{-h_{22}}{h_{21}}$ $\frac{-1}{h_{21}}$	A B C D

$\Delta_1=(z'_{11}+1)(z'_{22}+1)-z'_{12}z'_{21}$
$\Delta_2=(1+y'_{11})(1+y'_{22})-y'_{12}y'_{21}$
$\Delta_3=(h'_{11}+1)(h'_{22}+1)-h'_{12}h'_{21}$
$\Delta_4=A'+B'+C'+D'$
$\Delta_5=(1-S_{11})(1-S_{22})-S_{12}S_{21}$
$\Delta_6=(1+S_{11})(1+S_{22})-S_{12}S_{21}$
$\Delta_7=(1-S_{11})(1+S_{22})+S_{12}S_{21}$
$\Delta_8=AD-BC$

$z'_{11}=z_{11}/Z_o,\ z'_{12}=z_{12}/Z_o,\ z'_{21}=z_{21}/Z_o,\ z'_{22}=z_{22}/Z_o$
$y'_{11}=y_{11}Z_o,\ y'_{12}=y_{12}Z_o,\ y'_{21}=y_{21}Z_o,\ y'_{22}=y_{22}Z_o$
$h'_{11}=h_{11}/Z_o,\ h'_{12}=h_{12},\ h'_{21}=h_{21},\ h'_{22}=h_{22}Z_o$
$A'=A,\ B'=B/Z_o,\ C'=CZ_o,\ D'=D$
$|z|=z_{11}z_{22}-z_{12}z_{21}$
$|y|=y_{11}y_{22}-y_{12}y_{21}$
$|h|=h_{11}h_{22}-h_{12}h_{21}$

See Gonzalez, page 62.

Smith chart

Impedance transformation and matching

- to match an arbitrary load to a given transmission line
- to present a certain impedance to a device (embedding impedances)

For low VSWR, energy transfer or design goals

Low VSWR results in better power handling capability

Distributed components

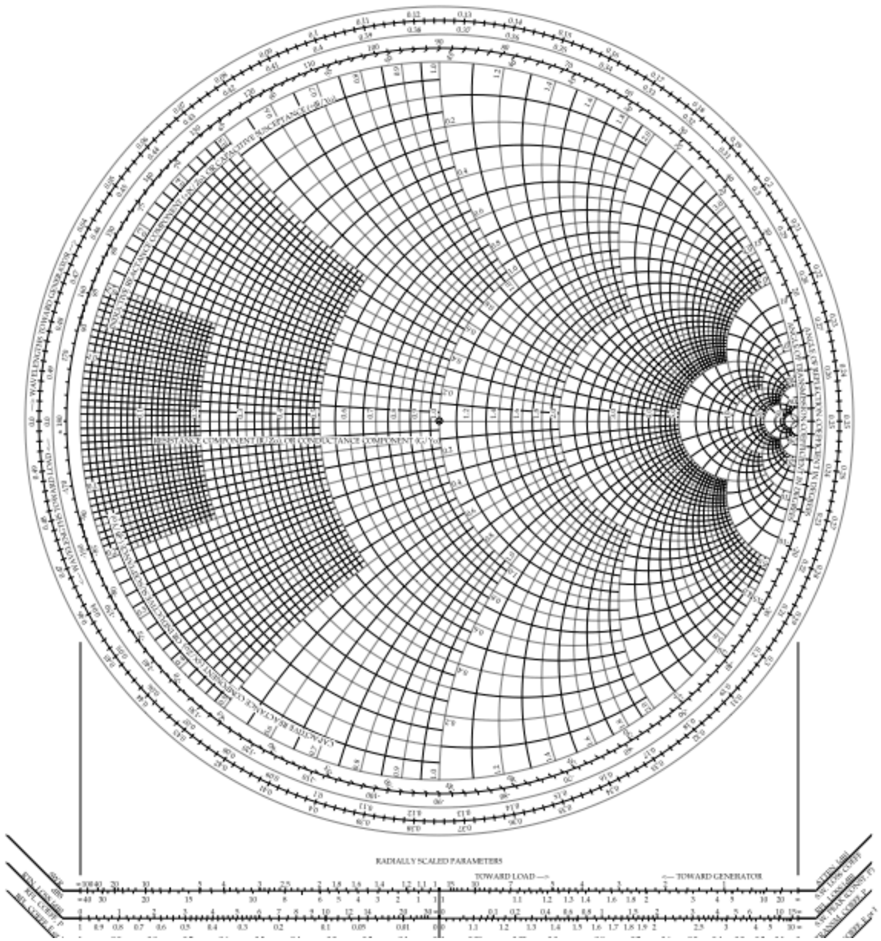
- Single, double or triple stubs
- Transformers

Discrete components

The Smith Chart (SC)

- Proposed 1939 by Philip H. Smith as a graphical aid to analyse and design matching networks
- Mr. Smith worked at Bell Telephone labs with impedance matching of antennas (for AM broadcasting)
- Today, still a powerful tool as part of the design process in order to find suitable circuit topologies etc

Z or impedance SC

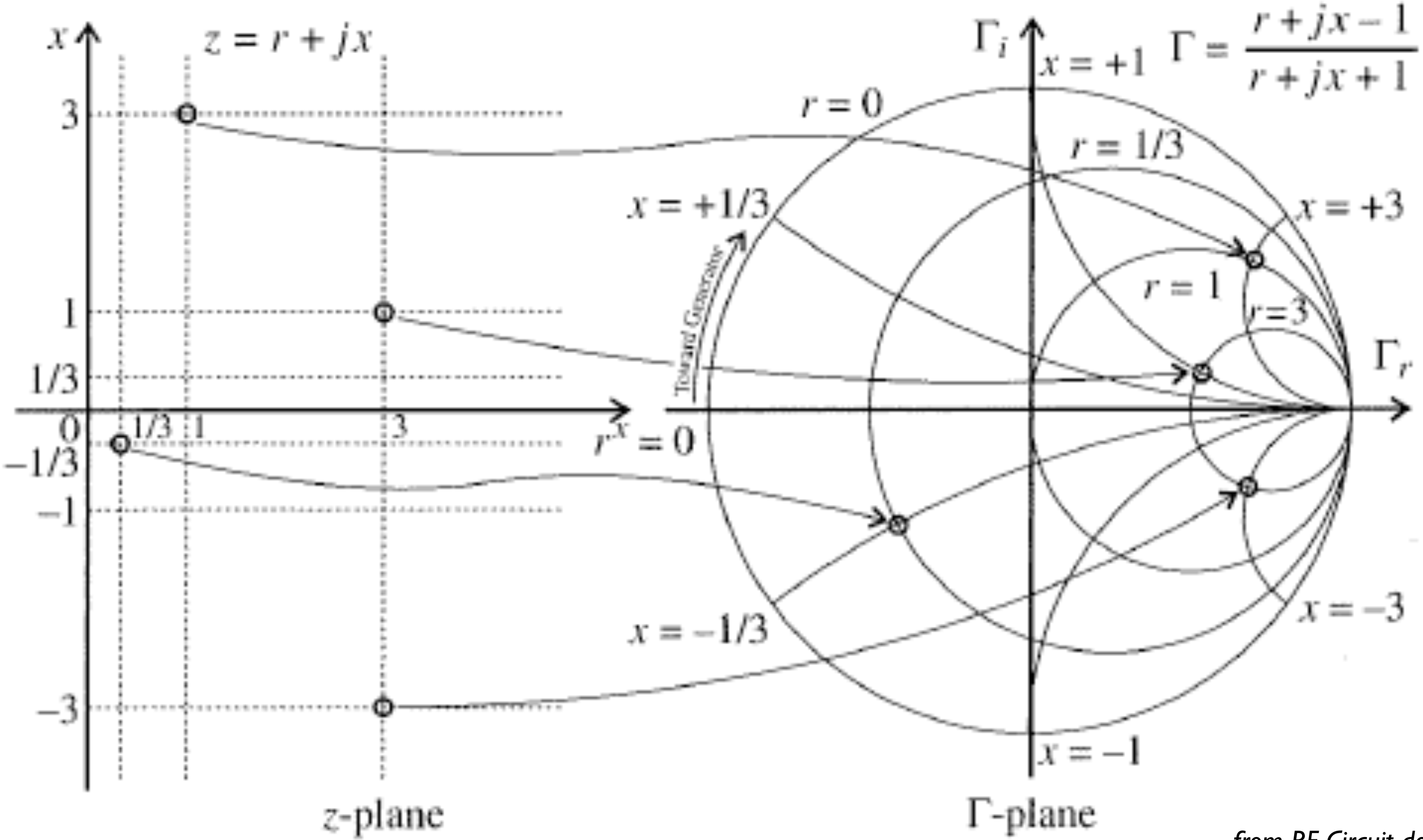


Conformal mapping (Möbius)

- Z Smith chart: $$\Gamma = \frac{z-1}{z+1}$$

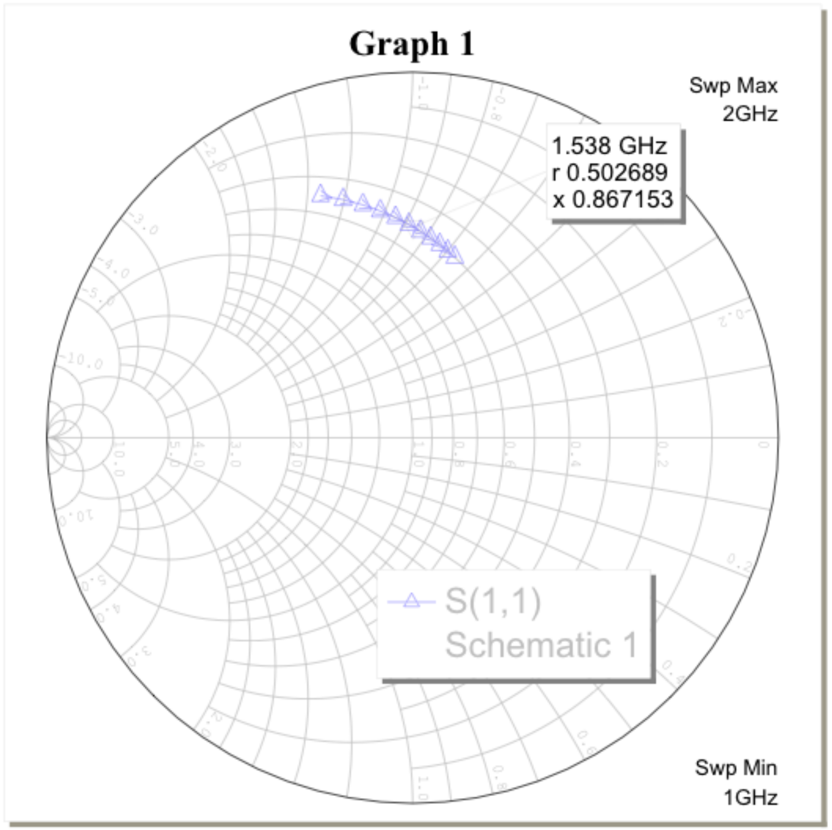
- Y Smith chart: $$\Gamma = \frac{1-y}{1+y}$$

Complex impedance transformed to complex reflection plane



from RF Circuit design, Ludvig and Bogdanov

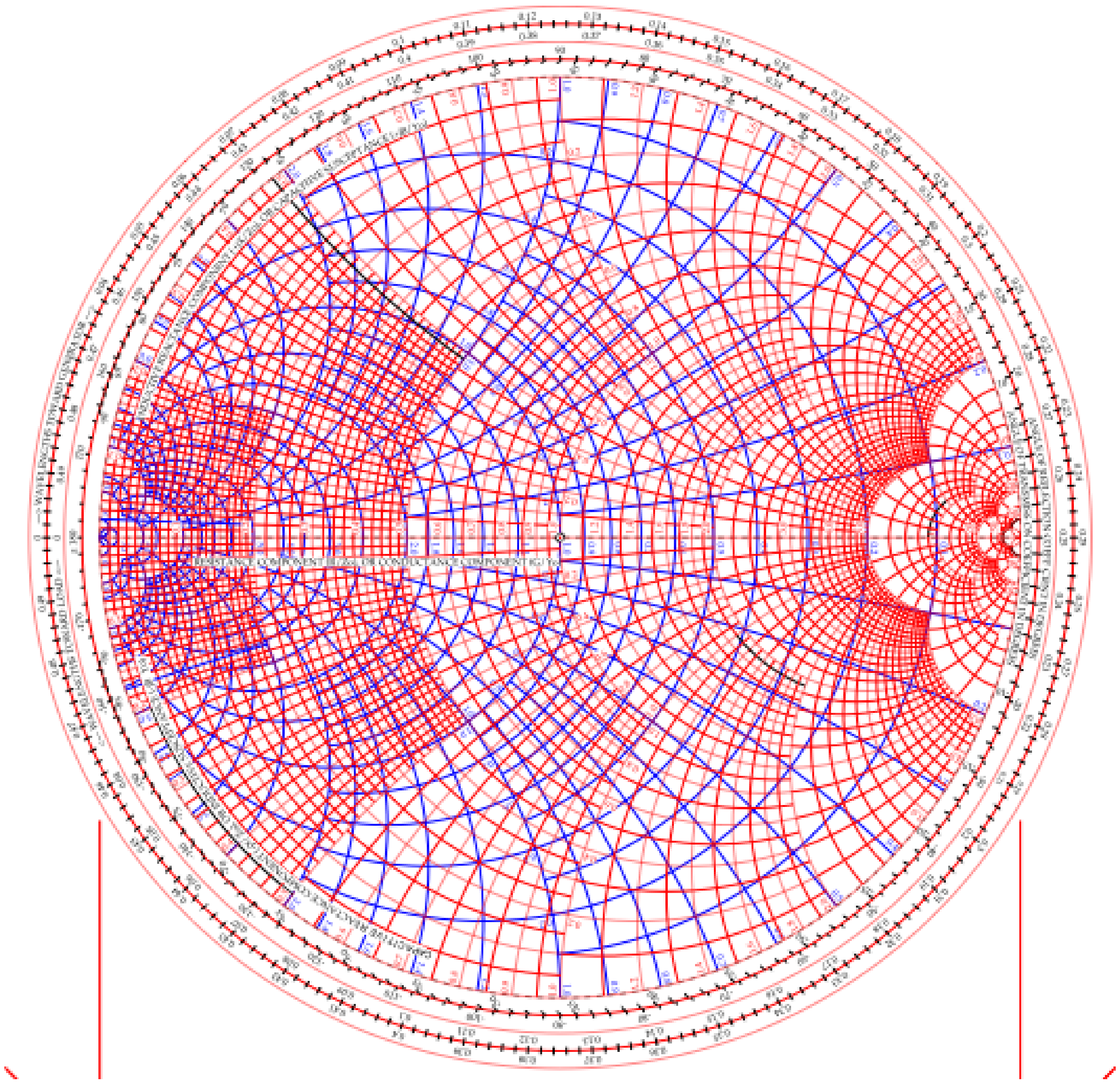
Y or admittance SC



The Smith Chart

- Complex plane for the reflection coefficient.
  - Normalised contours for resistances/ conductances and reactances/susceptances
  - Upper half->inductive, lower half->capacitive

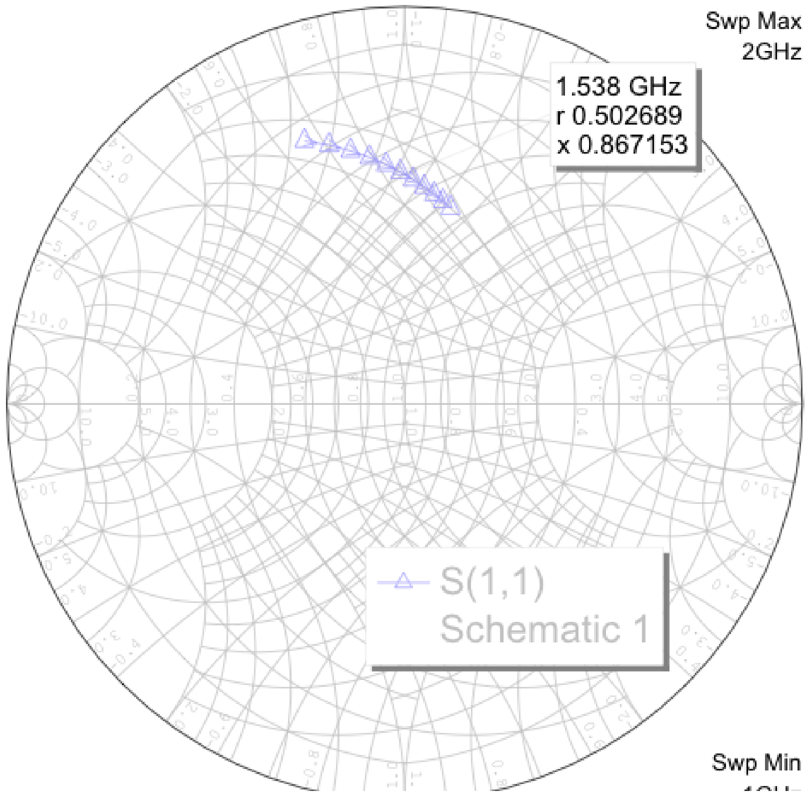
- Common practice to plot S-parameters in Smith charts. E.g. Vector network analysers or design tools



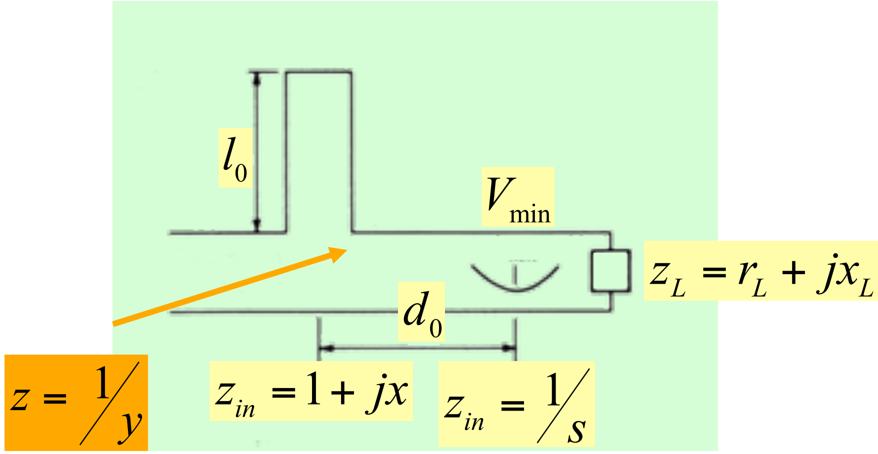
ZY Smith Chart

- Z for series connections

- Y for parallel connections



Single stub matching (series)



$$y = \frac{(g_L + jb_L) + jt}{1 + jt(g_L + jb_L)}; \quad t = \tan \beta d$$

$$z = 1/y = r + jx$$

$$r = \frac{g_L(1+t^2)}{g_L^2 + (b_L + t)^2}; \quad x = \frac{g_L^2 t - (1 - tb_L)(b_L + t)}{g_L^2 + (b_L + t)^2}$$

To get the match we need the real part of the equation, $r = 1$

$$t = \frac{b_L \pm \sqrt{g_L\left[(1-g_L)^2 + b_L^2\right]}}{g_L - 1}; \quad g_L \neq 1$$

If $g_L = 1 \rightarrow t = -b_L/2$

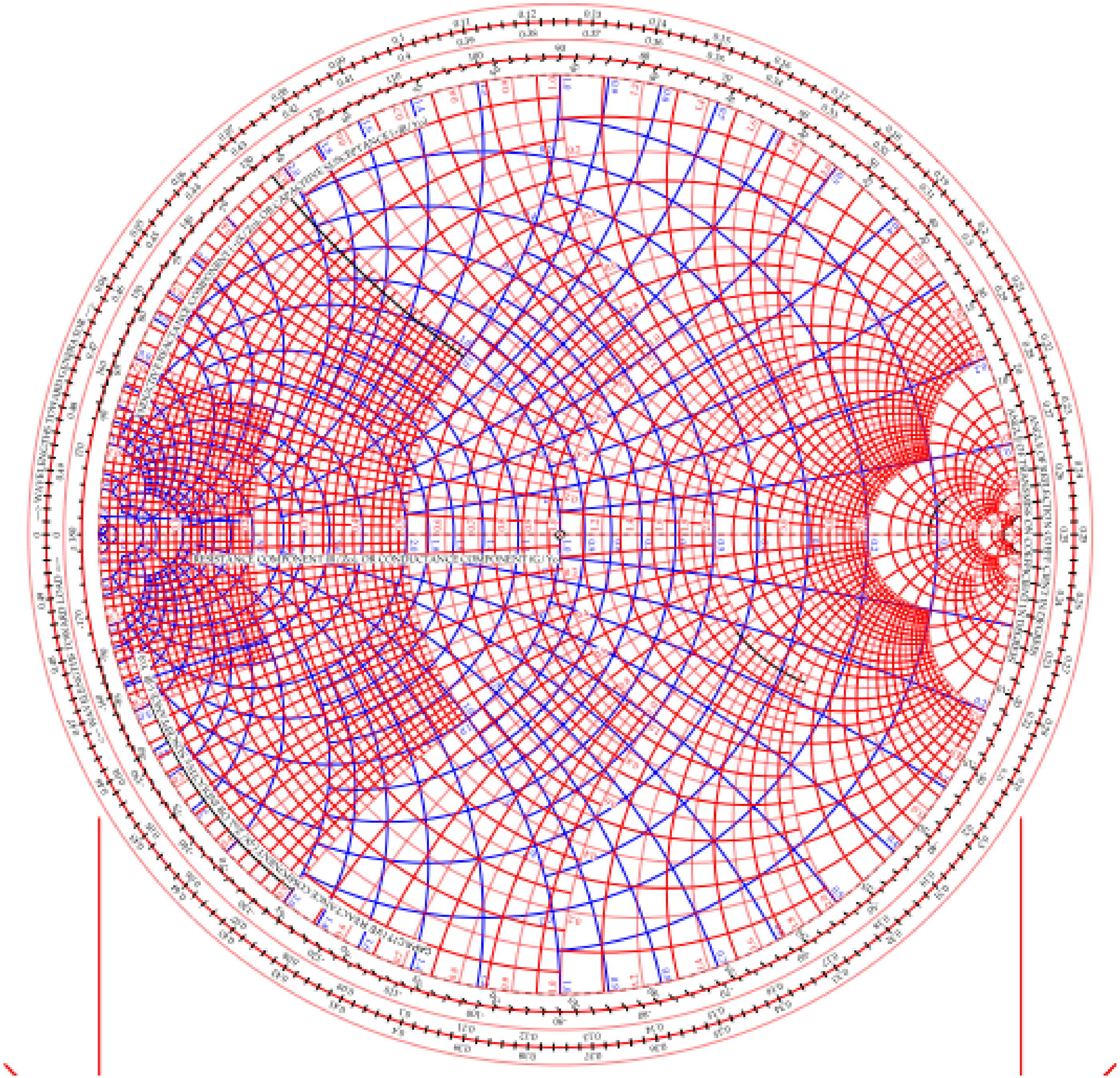
$$d = \frac{\lambda}{2\pi}\arctan t, \; t \geq 0$$

$$d = \frac{\lambda}{2\pi}(\pi + \arctan t), \; t<0$$

For shorted stub $l_0 = -\frac{\lambda}{2\pi}\arctan\left(\frac{X}{Z_0}\right)$

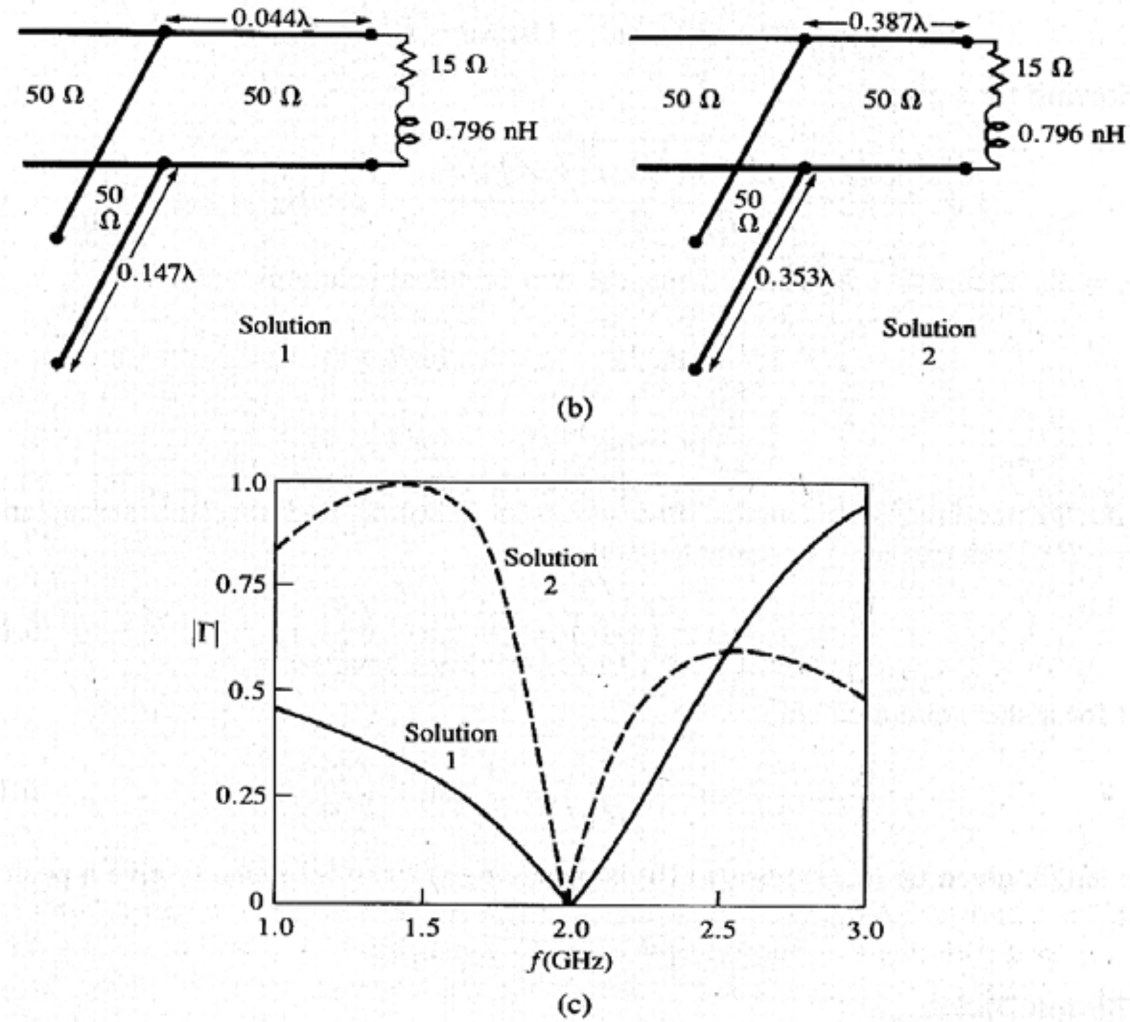
For open stub $l_0 = \frac{\lambda}{2\pi}\arctan\left(\frac{Z_0}{X}\right)$

- *On white board: Use SC to match z=2+j1.6 using an open series stub*



- *On white board: Use SC to match z=0.3+j0.2 using an open parallel stub*

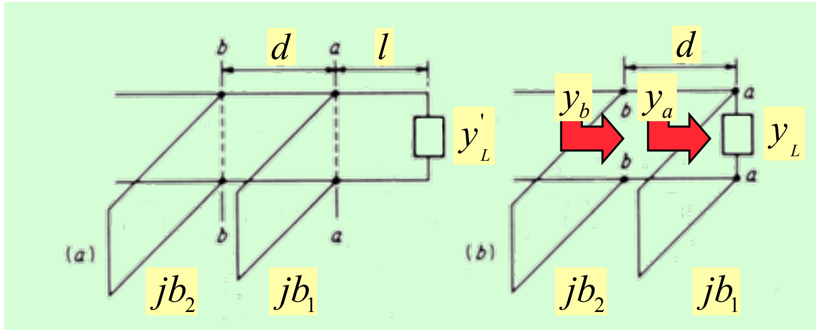
Transmission line matching

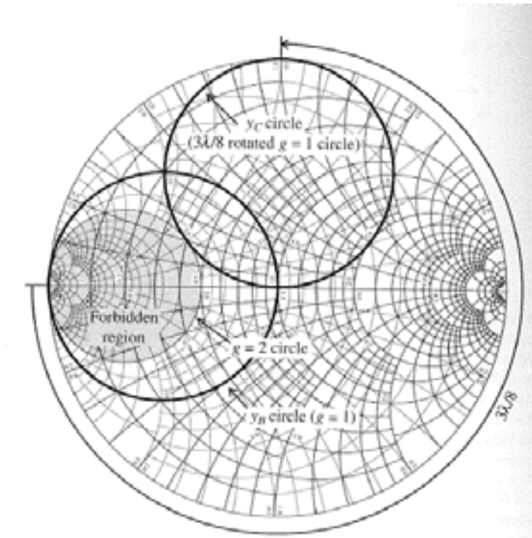


Electrically small circuit->wider bandwidth!

Double-stub tuner

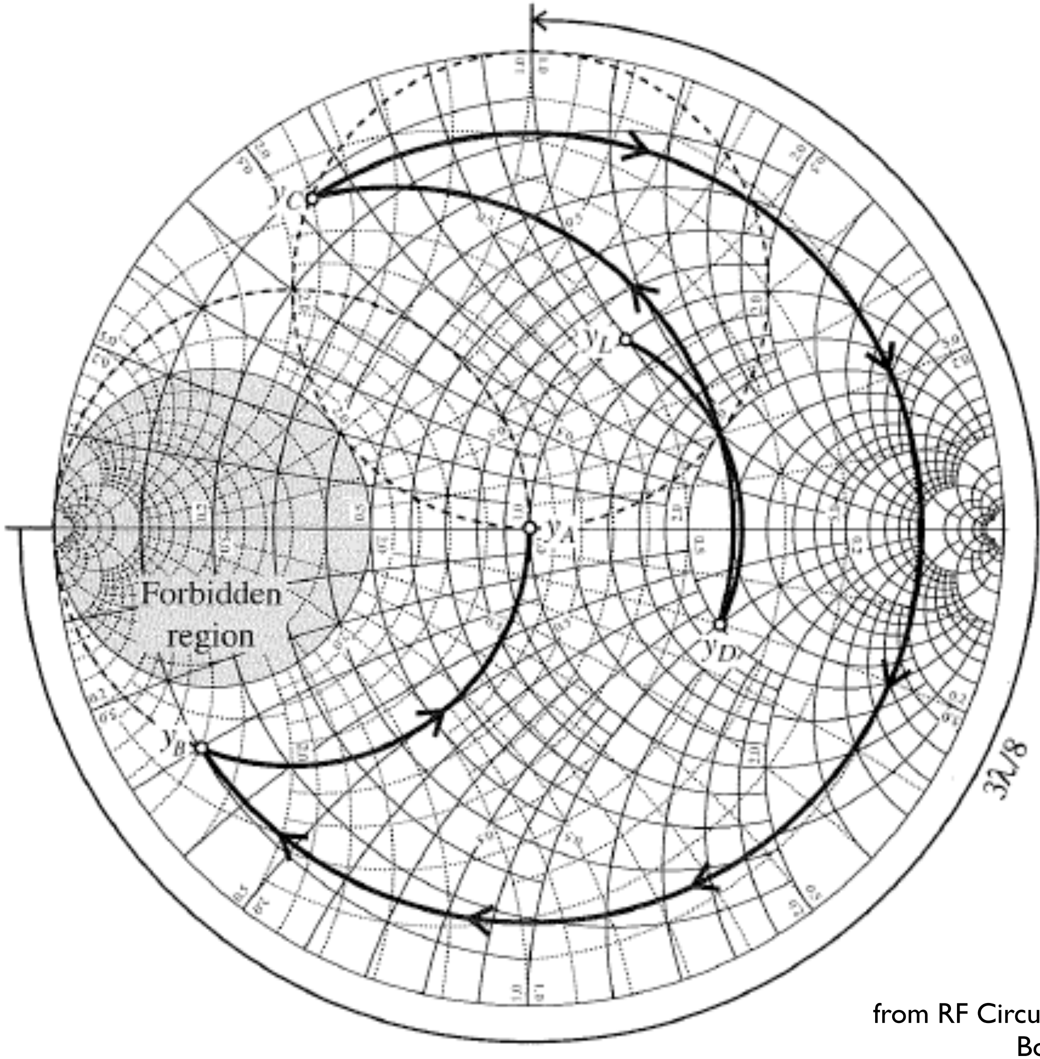
- Rotate g=1 circle counter clock wise, so the first stub (jb_1) can transform your load to the rotated circle
- require no variable length between load and stubs
- But!, forbidden region





from RF Circuit design, Ludvig and Bogdanov

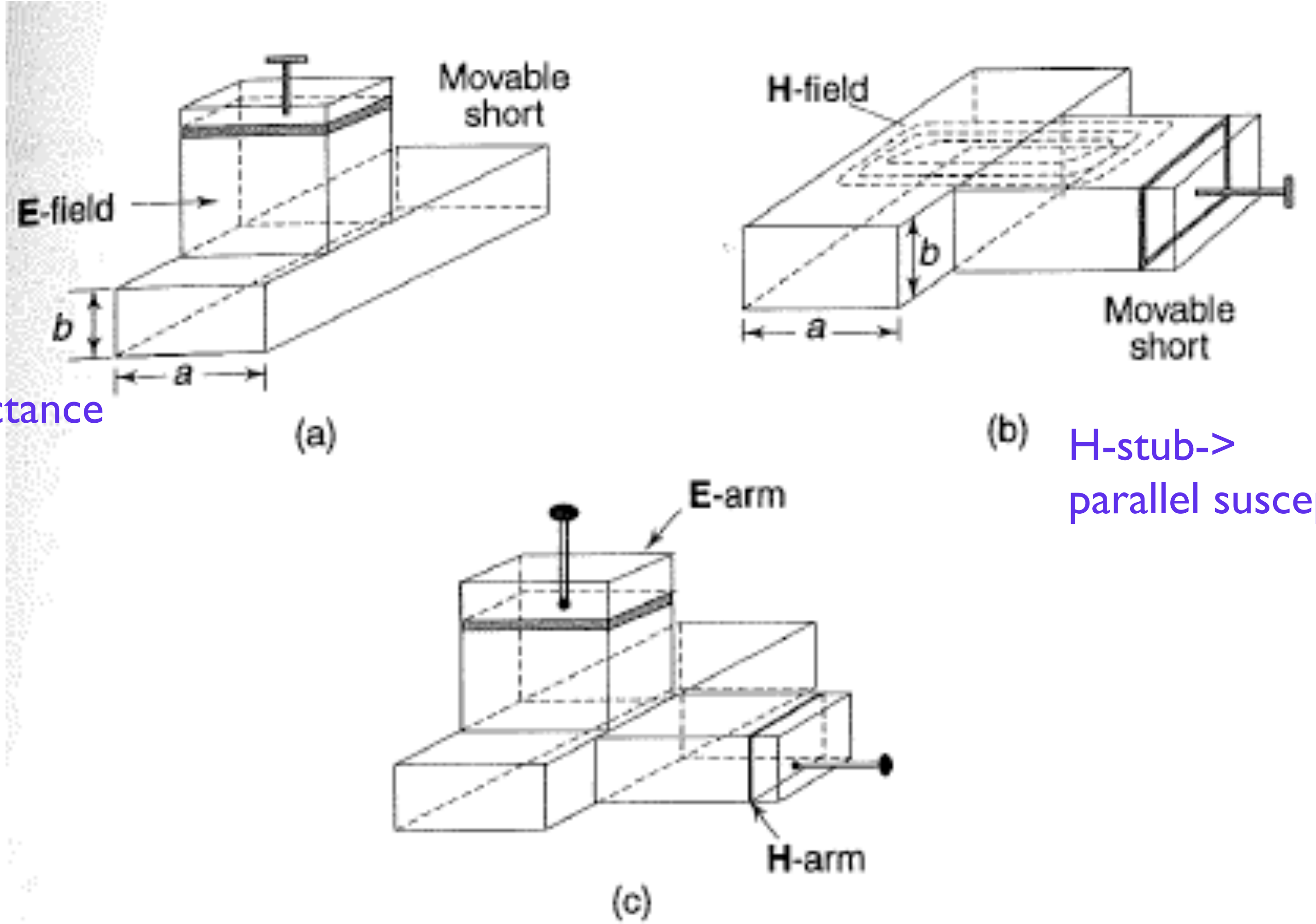
- *On white board: Use SC to match 1+j using double, shorted stubs. Distance between stubs 3/8 wavelengths, and 1/8 wavelength between load and first stub.*



from RF Circuit design, Ludvig and Bogdanov

E-H Tuners

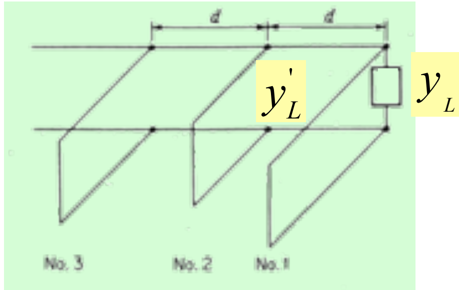
E-stub->
series reactance



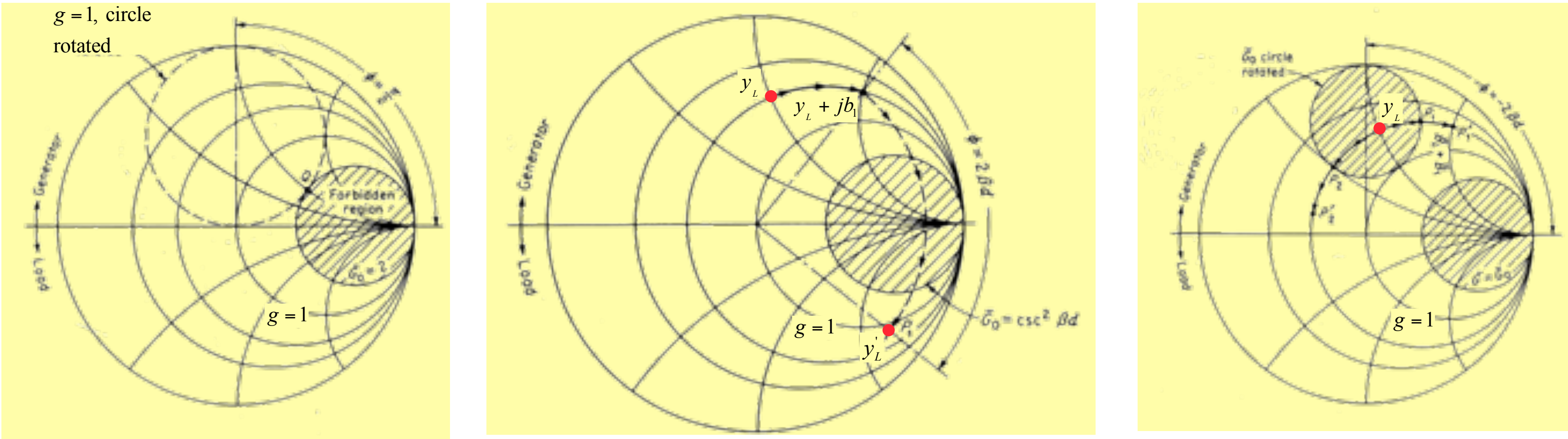
(a) (b) (c)

H-stub->
parallel susceptance

Triple-stub tuner

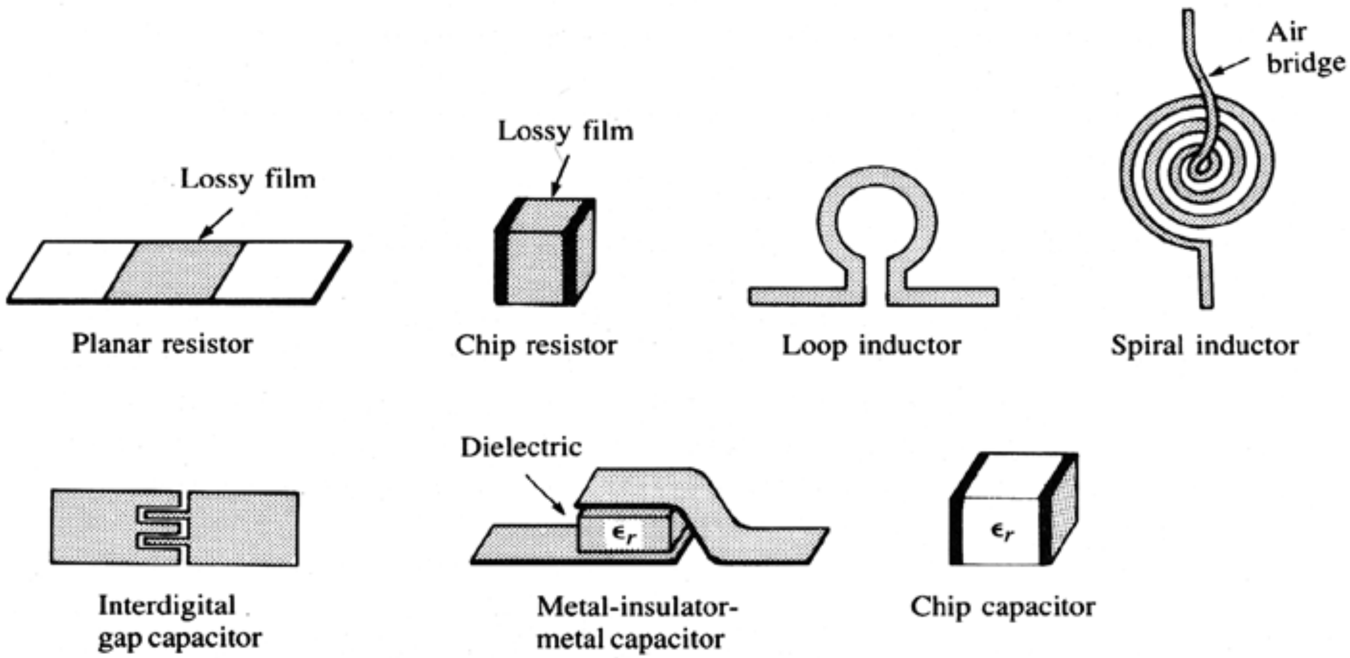


Why?



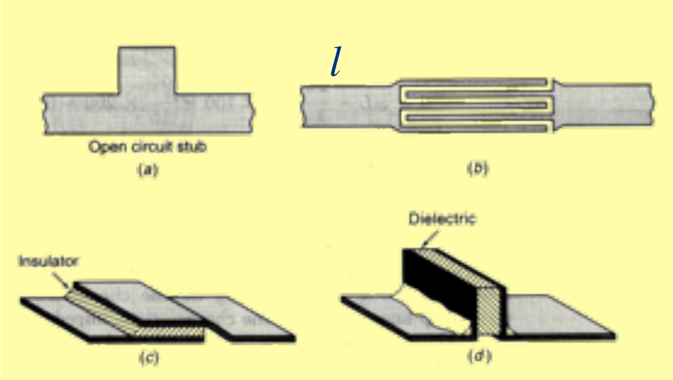
Function of stub 1 is to ensure, that the $y_L' = g_L' + jb_L'$ has $g_L' < \csc^2 bd$

Matching with lumped elements



Capacitors

$l = \lambda/4$, C<1pF

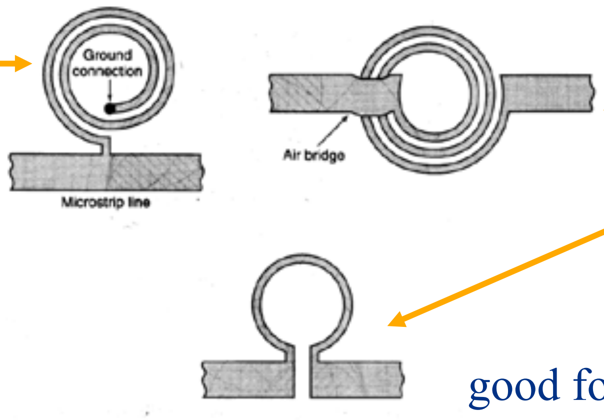


Interdigital capacitor, MMIC compatible, C<5-6 pF

MIM(metal-insulator-metal), MMIC compatible, C<20−30 pF

Inductors

shunt



series

good for small values

We assume $l = \lambda$ and TEM wave

$$Z_c = \sqrt{\frac{L}{C}}, \beta = \omega\sqrt{LC}$$

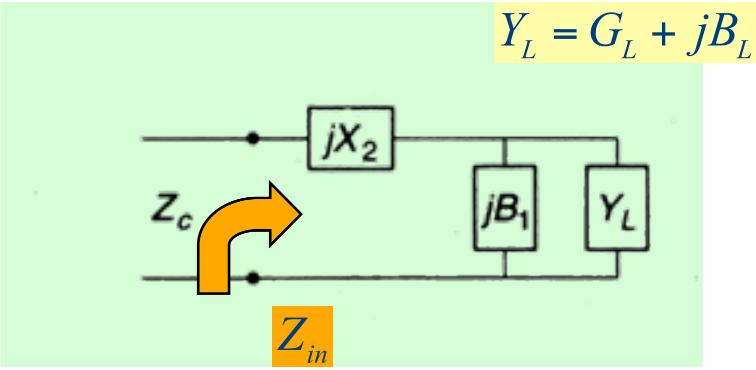
$$X_L = \omega L = \beta Z_c = k_0 Z_{c0} \ \Omega / m \quad (1)$$

Eq (1) shows that narrow lines (high impedance) should be used for inductors since

$$L \nearrow \text{ if } Z_{c0} \nearrow$$

Matching circuits

$R_L > Z_c$

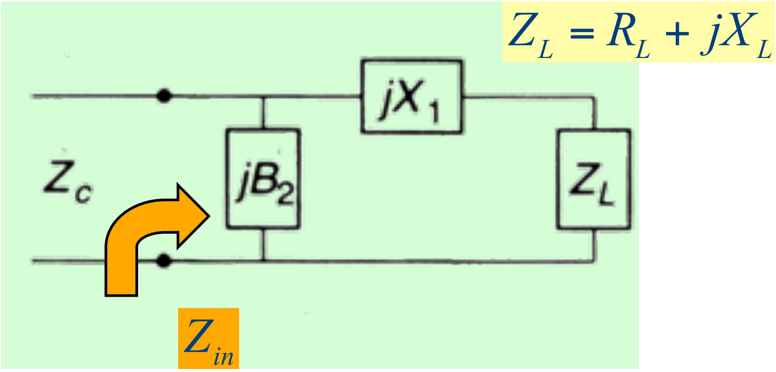


$$Z_{in} = Z_c$$

$$X_2 = \pm\left(\frac{Z_c}{G_L}(1 - Z_c G_L)\right)^{1/2}$$

$$B_1 = -B_L \pm \left(\frac{G_L}{Z_c}(1 - Z_c G_L)\right)^{1/2}$$

$R_L < Z_c$



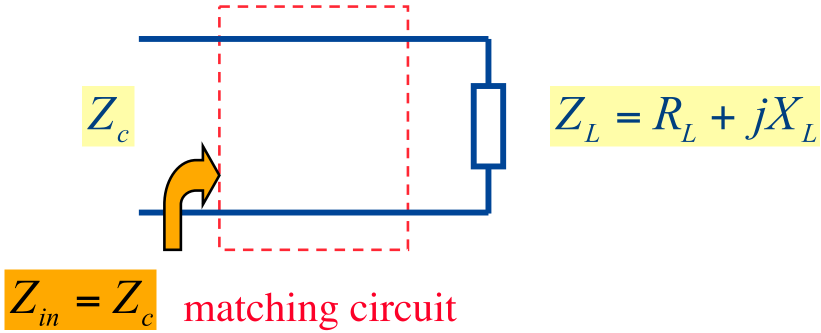
$$Z_{in} = Z_c$$

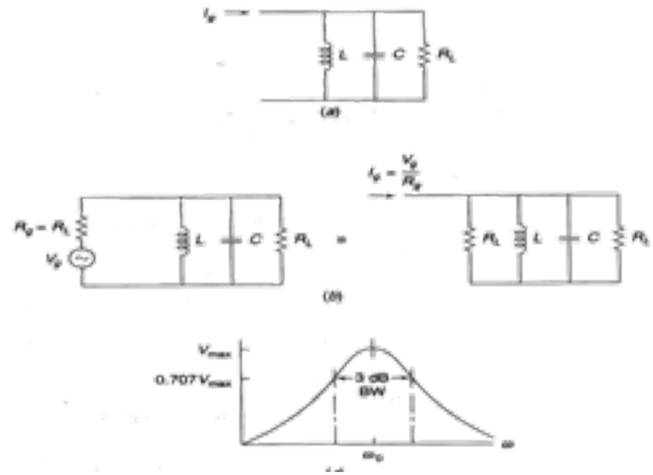
$$X_1 = \pm\left(R_L(Z_c - R_L)\right)^{1/2} - X_L$$

$$B_2 = \pm\frac{1}{Z_c}\left(\frac{Z_c - R_L}{R_L}\right)^{1/2}$$

- *On white board: Use SC to match 100 + j100 ohm using L and C, to a 50 ohm transmission line.*

Circuit Q and bandwidth





Reactive components in Z_L and matching circuit form a resonance circuit loaded with R_L and Z_c with a quality factor Q:

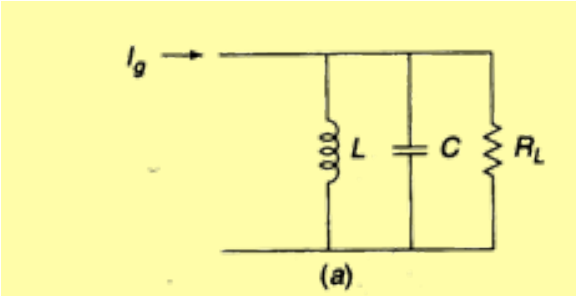
$$Q = \frac{\omega(\text{average stored electric and magnetic energy})}{\text{power loss}}$$

At resonance:

$$W_m = W_e$$

$$Q = \omega\frac{2W_e}{P_{loss}} = \omega\frac{2W_m}{P_{loss}}$$

The bandwidth of the circuit is the frequency band, Δf over which ½ or more (3 dB) of the maximum power is delivered to the load (it is inversely proportional to the loaded Q)



$$V_{R_L} = \frac{I_g}{Y_{in}} = \frac{I_g}{G_L + j\omega C - j/\omega L}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Y_{in} = G_L + j\omega C\left(\frac{\omega^2 - \omega_0^2}{\omega^2}\right)$$

At resonance $\omega=\omega_0$

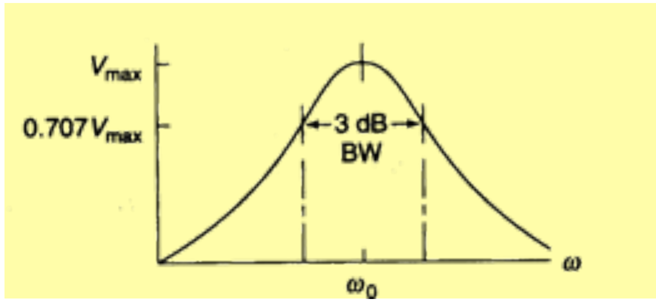
$$V_{R_L} = \frac{I_g}{G_L} \rightarrow V_{\max}\big|_{load} \rightarrow P_{\max}$$

At the band edges

$$j\omega C g\frac{\omega^2 - \omega_0^2}{\omega^2} = jG_L$$

$$\left|V_{R_L}\right| = \frac{I_g}{\sqrt{2}G_L} \rightarrow P = 1/2\,P_{\max}$$

$$Q = \frac{R_L}{\omega_0 L} = R_L\omega_0 C = \frac{\omega_0 C}{G_L}$$



Q>10

$$Y_{in} = G_L + j\omega C\left(\frac{\omega^2 - \omega_0^2}{\omega^2}\right) \approx G_L + j\omega C\frac{2\omega(\omega - \omega_0)}{\omega^2} =$$
$$= G_L + j\omega_0 C\frac{2(\omega - \omega_0)}{\omega_0} = G_L\left(1 + 2jQ\,{}^{\Delta\omega}\!/_{\omega_0}\right)$$

The 3-dB fractional BW:

$$2Q\frac{\Delta\omega}{\omega_0} = 2Q\frac{BW}{2} = 1 \rightarrow BW = {}^{1}\!/_{Q}$$

In the matching problems there are generally two solutions possible:

- narrowband design ⟹ high Q-value
- broadband design ⟹ low Q-value

Summary of lecture 6

- Read chapter 5 (impedance matching).
  - Smith chart
  - Single, double and triple stub matching
  - Discrete elements for matching
- Next: Impedance transformation (ch5)

Further reading

- A. Inan, "Remembering Phillip H. Smith on his 100th birthday," Antennas and Propagation Society International Symposium, 2005 IEEE, vol. 3, pp. 129–132 vol. 3B, Jun. 2005.
- R. M. Fano, Theoretical limitations on the broadband matching of arbitrary impedances, no. 41. 1948.