ECE 145a / 218 a, notes set 4: Impedance Matching

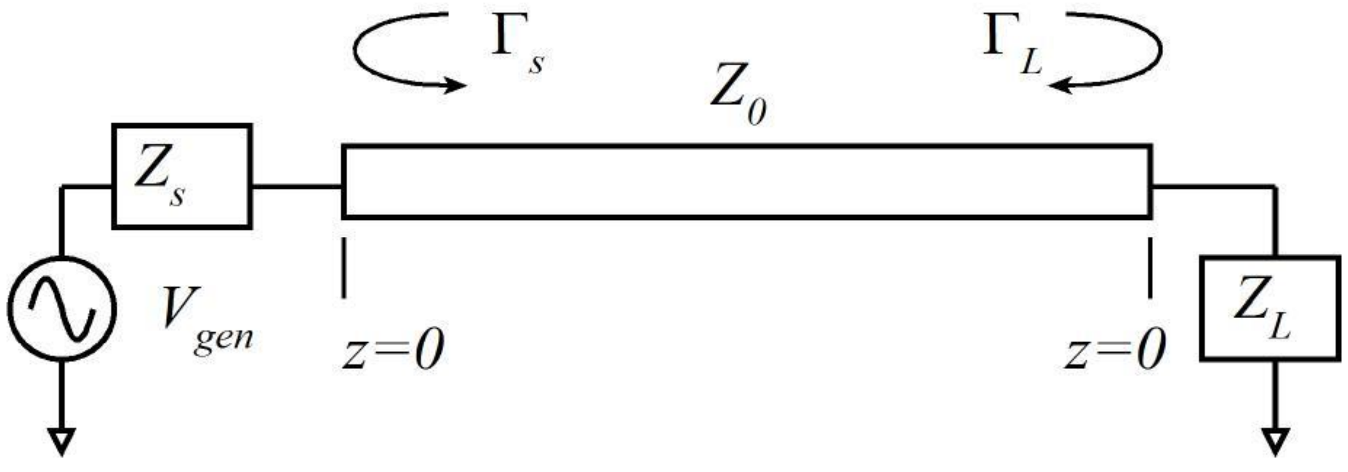
Mark Rodwell

University of California, Santa Barbara

rodwell@ece.ucsb.edu 805-893-3244, 805-893-3262 fax

Impedance-Matching: Goals

Recall: Line Reflections



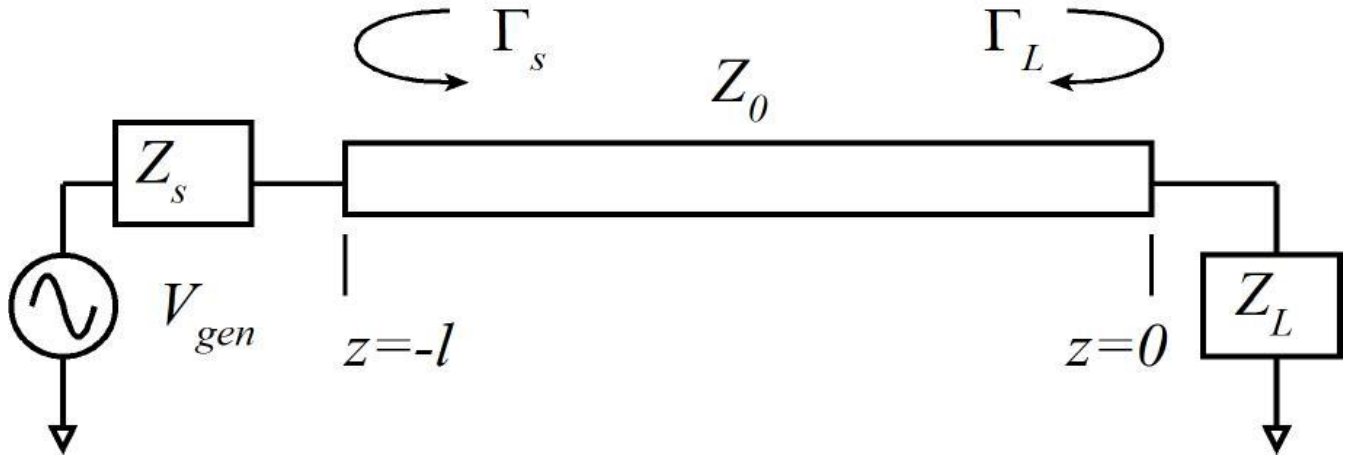
At end of line :

$$V^-(z=0)=\Gamma_L V^+(z=0) \quad \text{where } \Gamma_L = \frac{(Z_L/Z_o)-1}{(Z_L/Z_o)+1}$$

At beginning of line :

$$V^+(z=-l)=\Gamma_s V^-(z=-l)+T_s V_{gen} \quad \text{where } \Gamma_s = \frac{(Z_s/Z_o)-1}{(Z_s/Z_o)+1}$$

Line Reflections and Standing Waves



Reflections:

$$V^-(z=0)=\Gamma_L V^+(z=0) \quad \text{and} \quad V^+(z=-l)=\Gamma_s V^-(z=-l)+T_s V_{gen}$$

Waves traveling along line:

$$V^+(z=-l)=V^+(z=0)\cdot e^{j2\pi l/\lambda} \quad \text{and}\; V^-(z=-l)=V^+(z=0)\cdot e^{j2\pi l/\lambda}$$

Varying frequency, V^+ and V^- will vary from in-phase to out-of-phase...

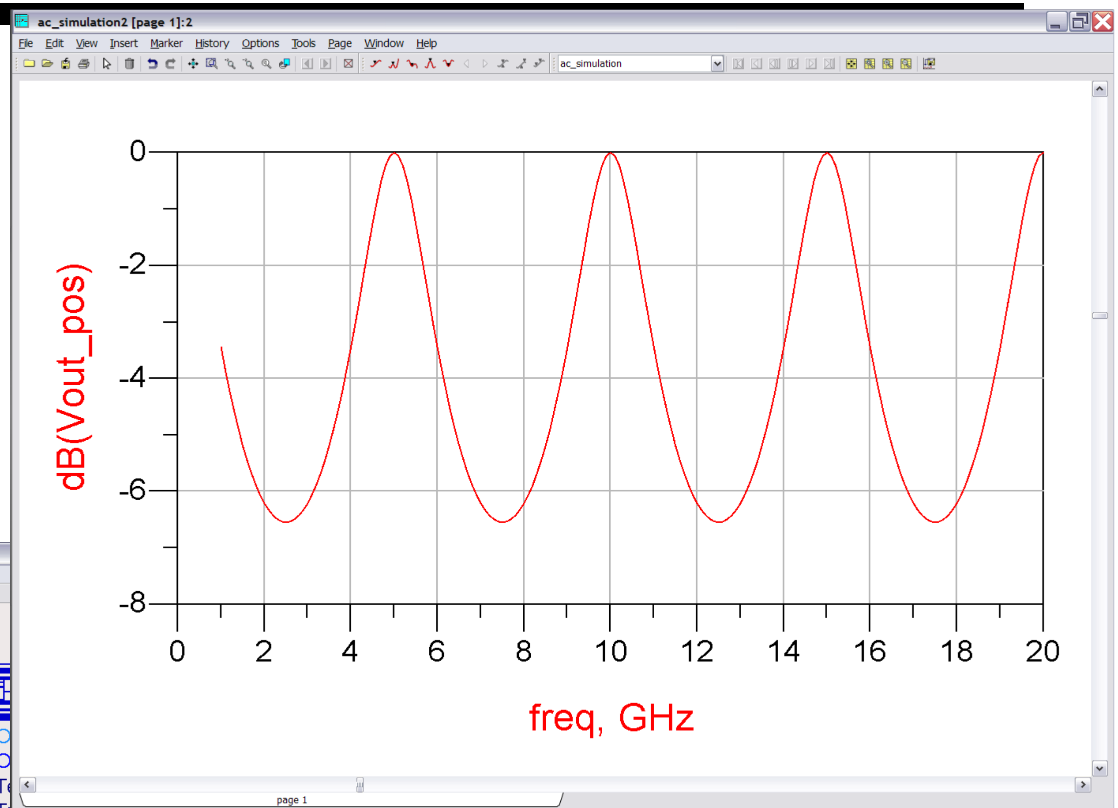
and will vary from constructive to destructive interference.

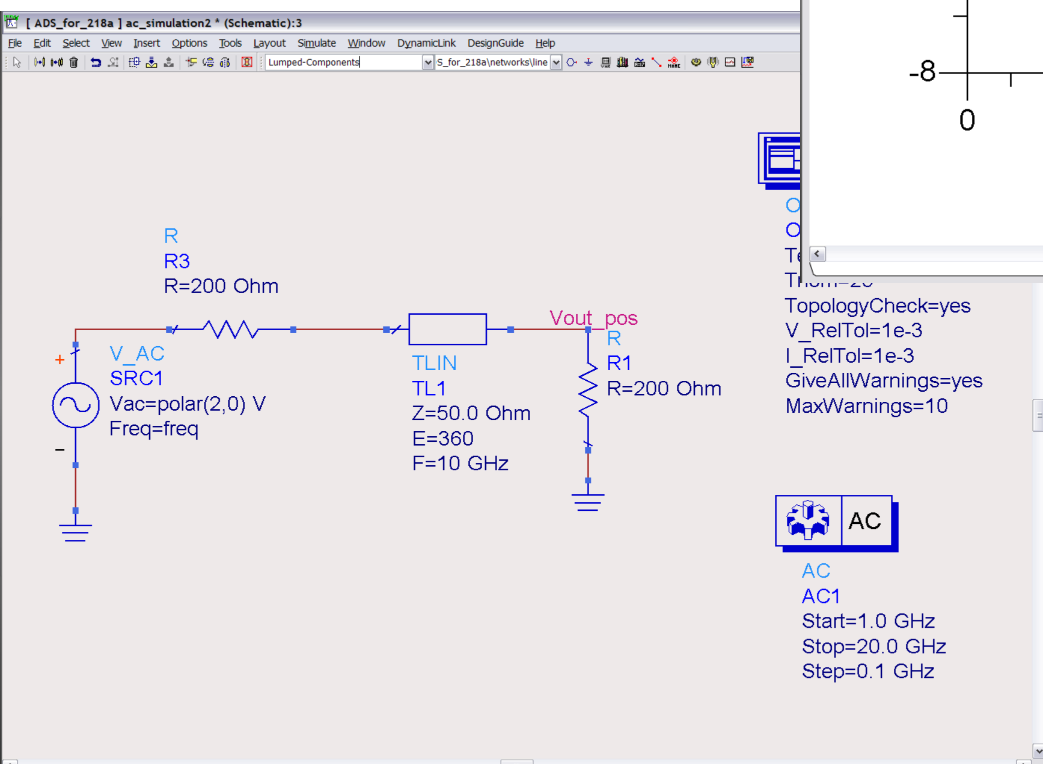
$\Rightarrow$ load voltage will vary with frequency.

Matching to Eliminate Gain Ripple

Gain ripples resulting from standing waves on line

Matching will eliminate this





One reason for impedance - matching is to eliminate gain ripple from standing waves on lines

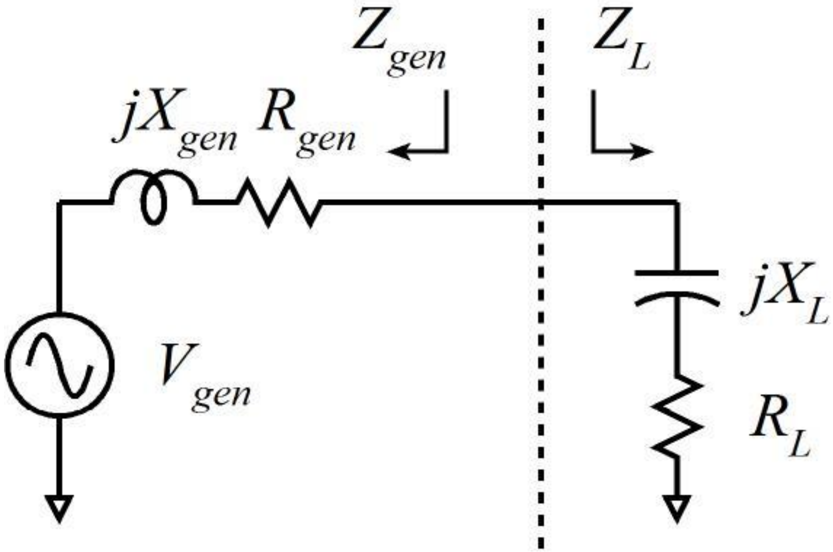
Maximum Power Transfer Theorem

(Maximum) Power Available from the Generator:

$$P_{avg} = \left\| V_{gen} \right\|^2 / 4\,\mathrm{Re}\{Z_{gen}\} \qquad \text{(RMS quantities)}$$

Load Power: $P_L = P_{AVG}$ iff $Z_L = Z_{gen}^*$;

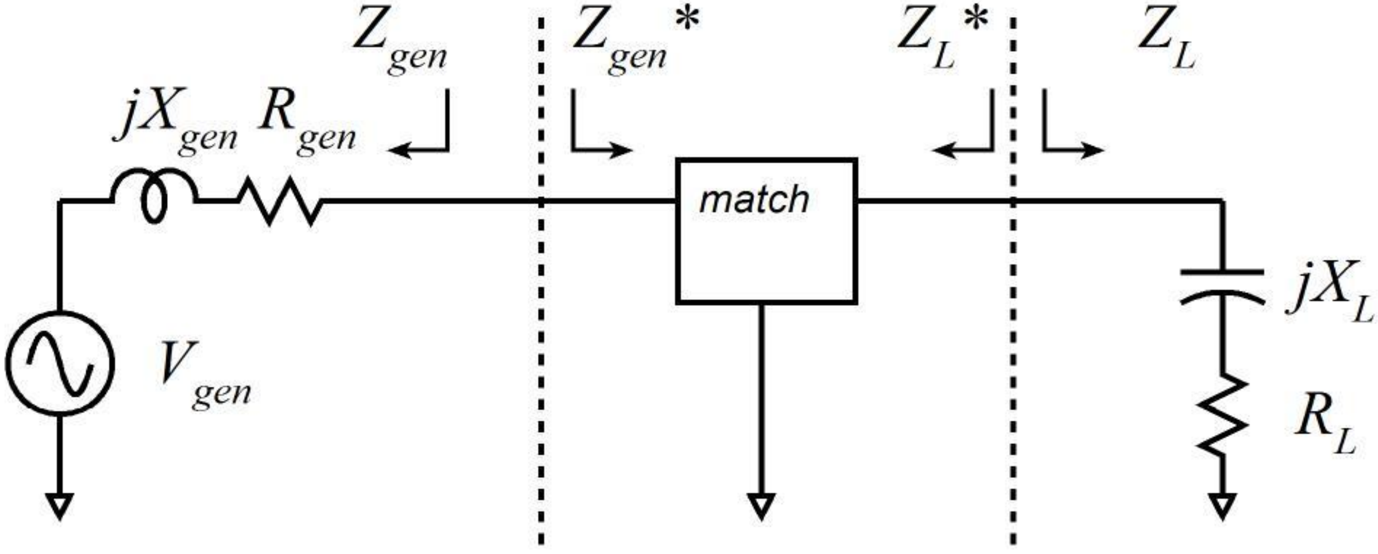
$P_L < P_{AVG}$ otherwise



Matching For Maximum Power Transfer

By adding a *lossless* matching network (no resistances) between the generator and the load, we obtain $P_L = P_{AVG}$

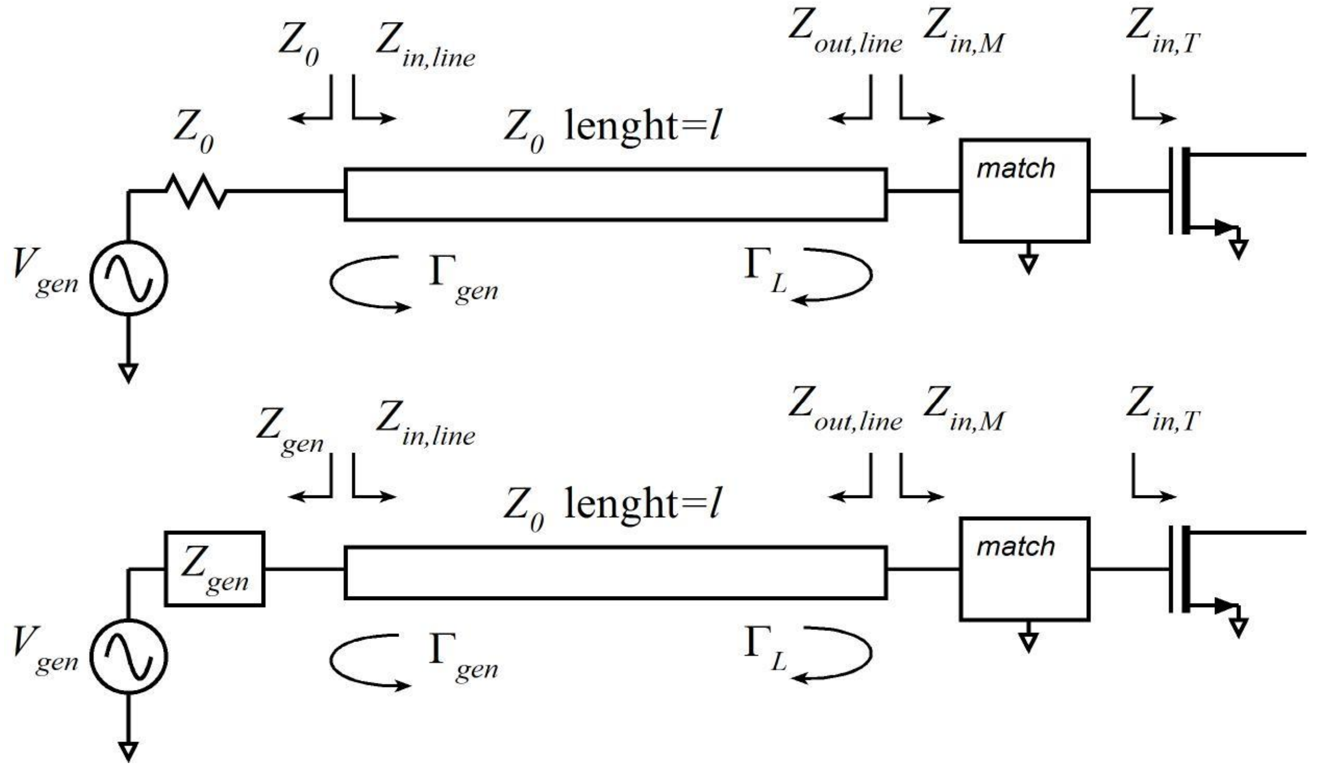
Another reason for impedance-matching is to increase signal power transferred.



Matching for no reflection vs. matching for max Power Transfer

1^{st} case : $Z_{gen} = Z_0$

$\Rightarrow Z_{out,line} = Z_0$



2^{nd} case : $Z_{gen} \neq Z_0$

$\Rightarrow Z_{out,line} \neq Z_0$

If $Z_{out,line} \neq Z_0$, then

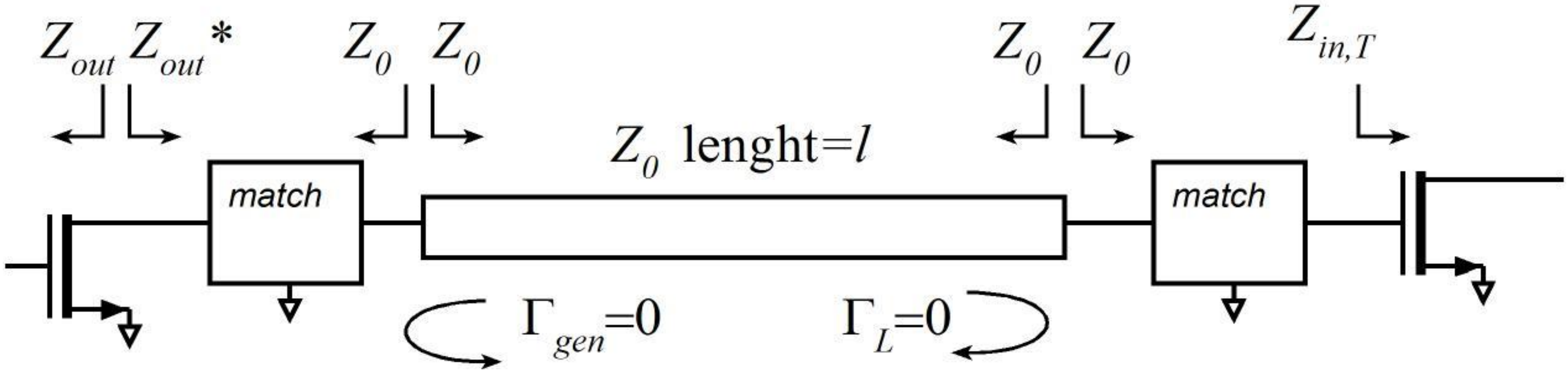
matching for zero reflection

and matching for maximum power transfer

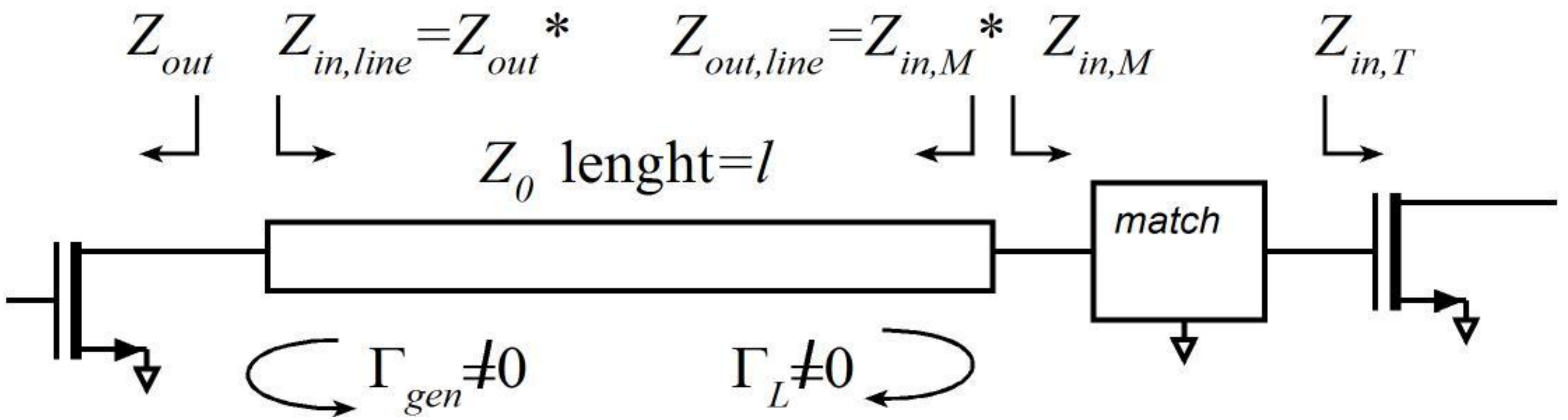
are not thesame.

Direct Interstage Matching vs. Matching Each to Z_o

Matching each to Z_0



Direct Stage - Stage Matching



Note: $Z_{in,line} = Z_o(1+\Gamma_L e^{-2j\beta l})/(1-\Gamma_L e^{-2j\beta l})$, l can be any length, including zero.

Impedance-Matching: Using Agilent / ADS in "tune" mode as a study tool.

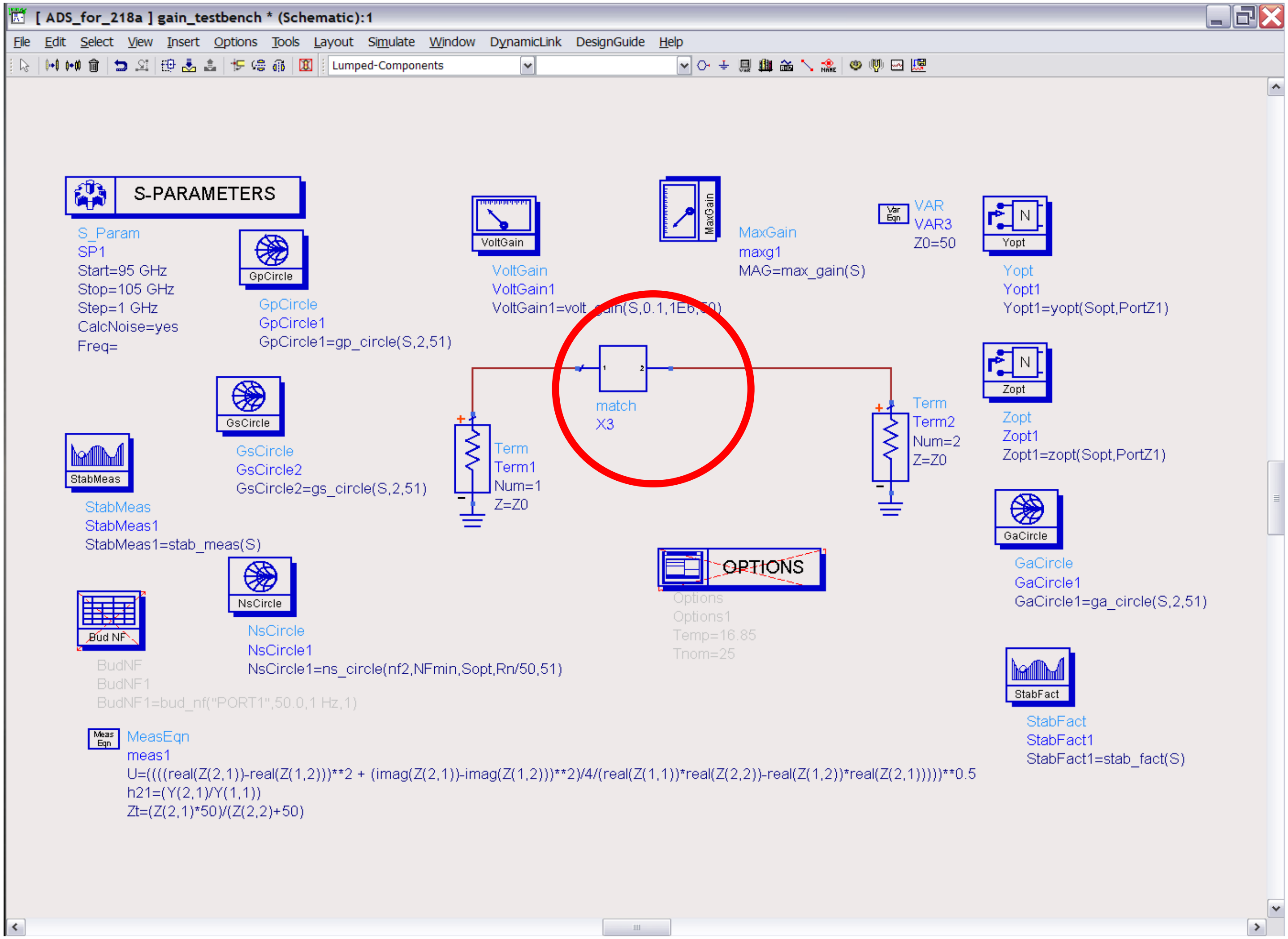
Use CAD Tool (Agilent) ADS to Explore Matching

Classic Texts: present Matching with On-Paper Smith-Chart Exercises.

Today: Matching easily presented graphically in CAD program.

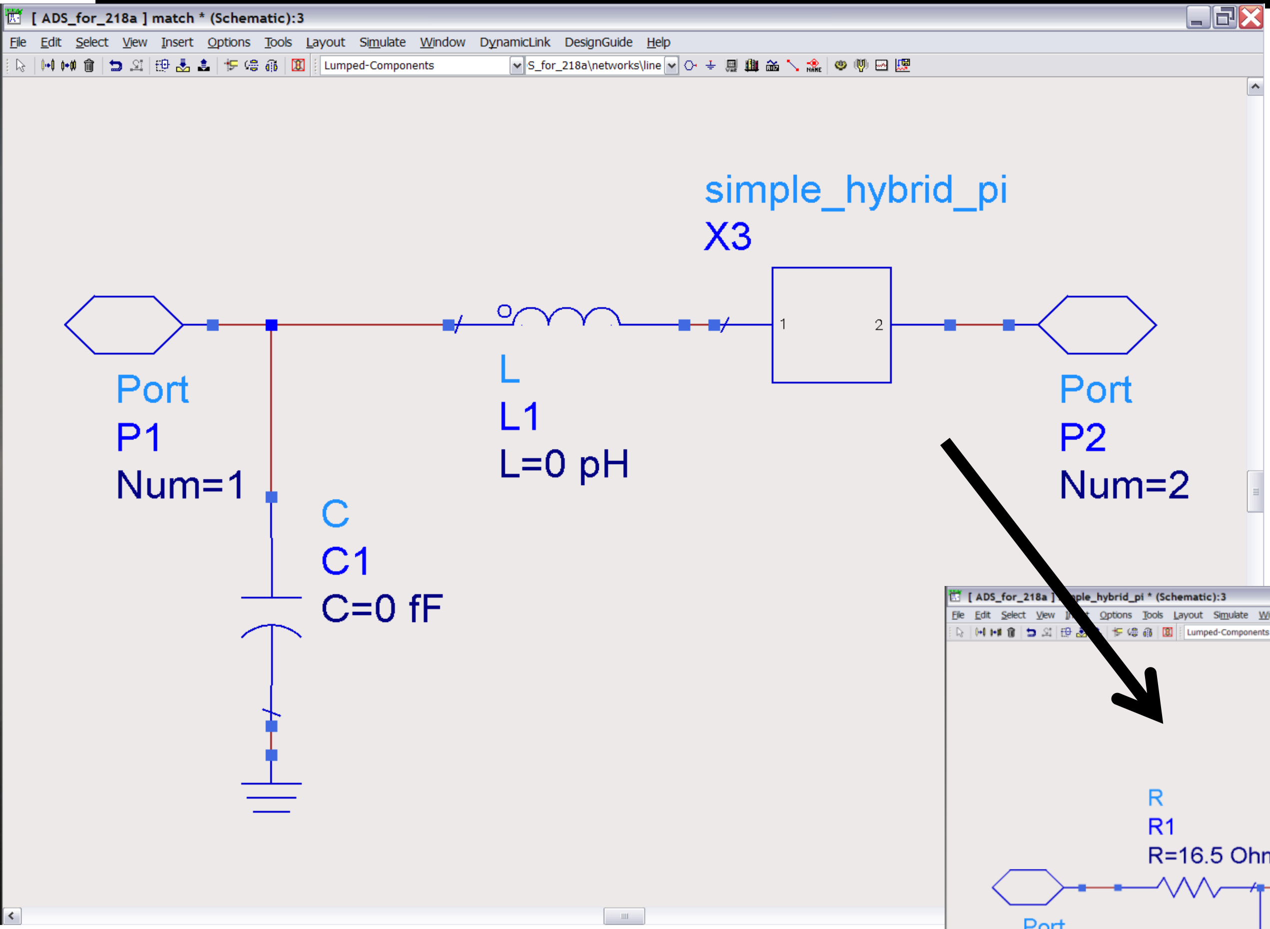
First: Show how to tune networks in ADS.
Second: Illustrate matching examples.

Tuning Elements in ADS (1)

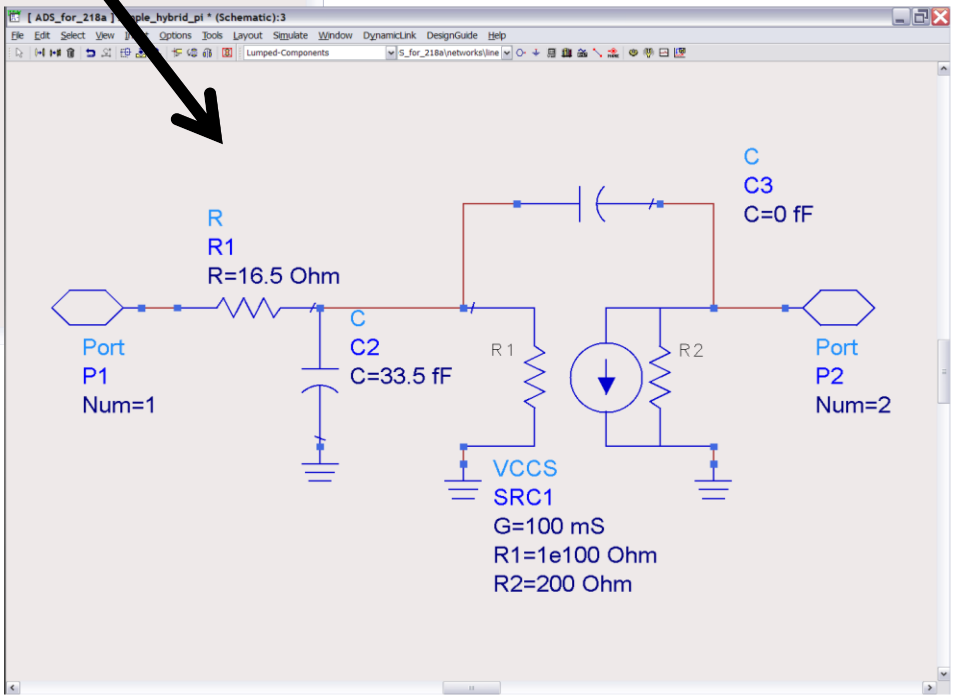


"Match" here is a circuit, having a MOSFET and an input matching network

Tuning Elements in ADS (2)



Use series L, shunt C network to match Z_{in} to Z_0.

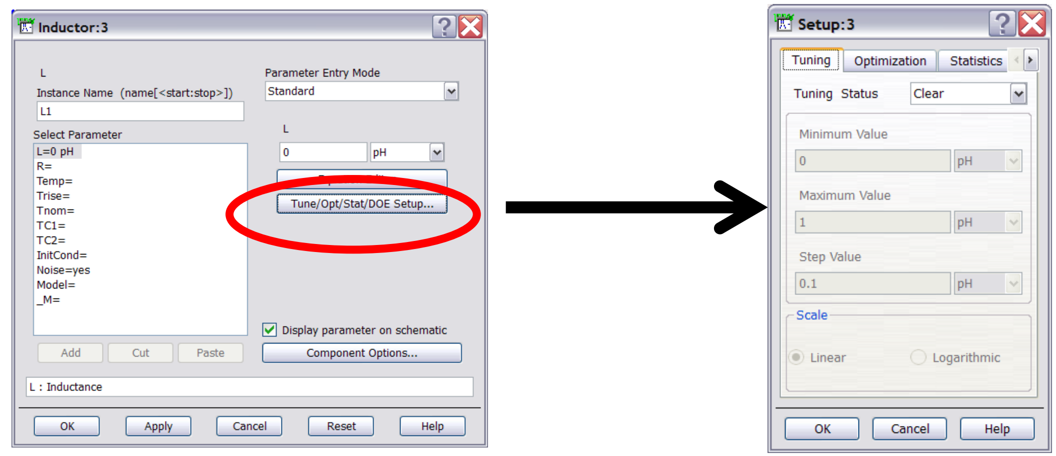


Very simple MOSFET small-signal model

Setting Up Element Tuning in ADS:

Double-click on L_1 ,

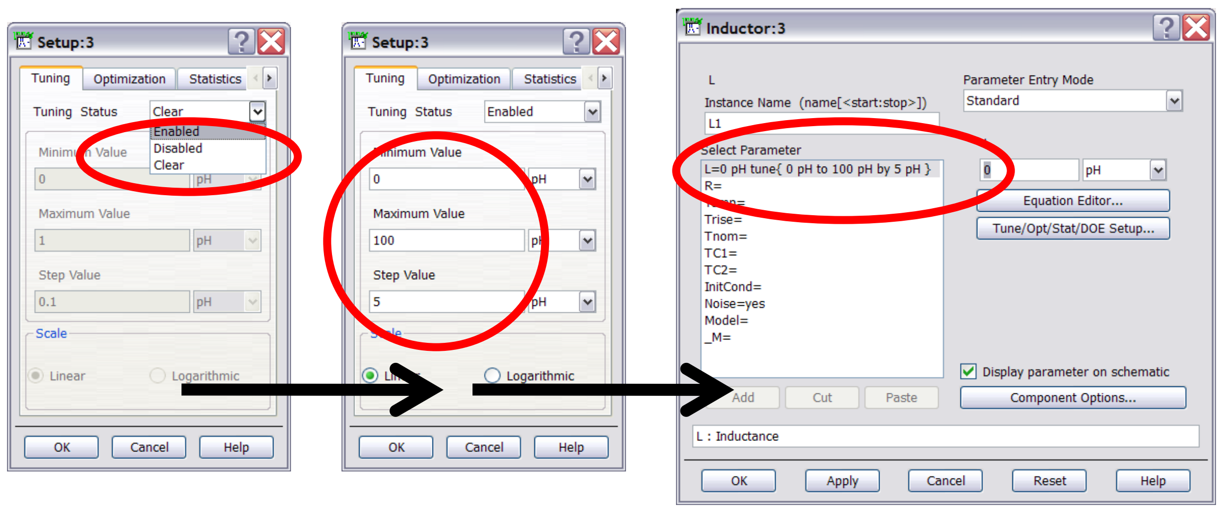
then press Tune/Opt/Stat...:



Enable tuning,

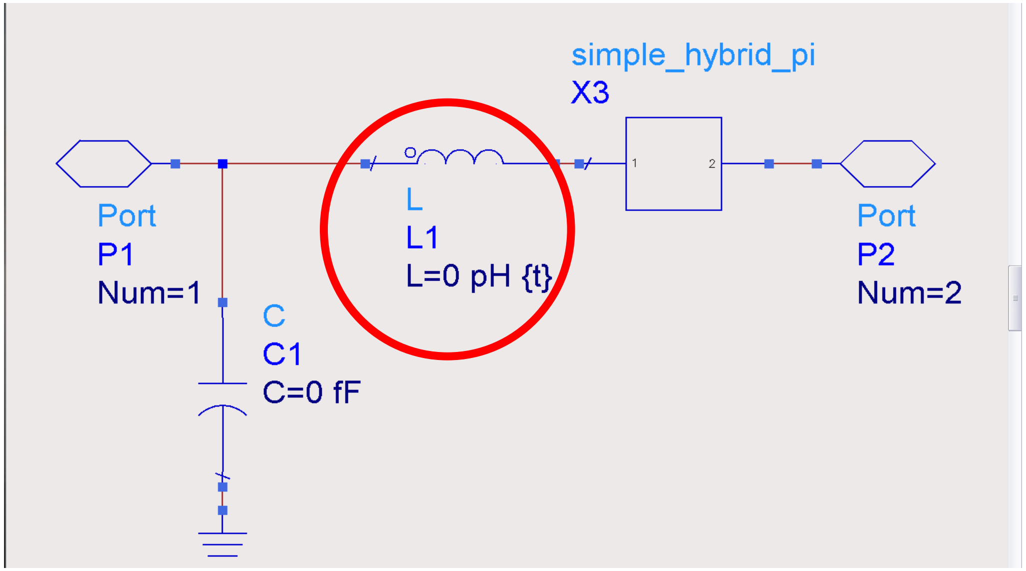
then set min, max,

step values...

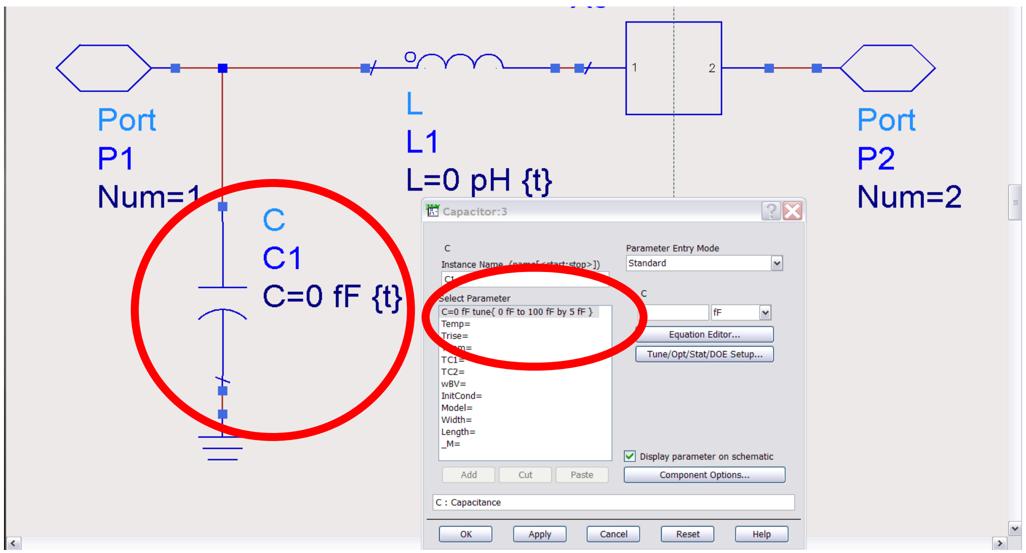


Setting Up Element Tuning in ADS:

L_1 is now a tunable element :

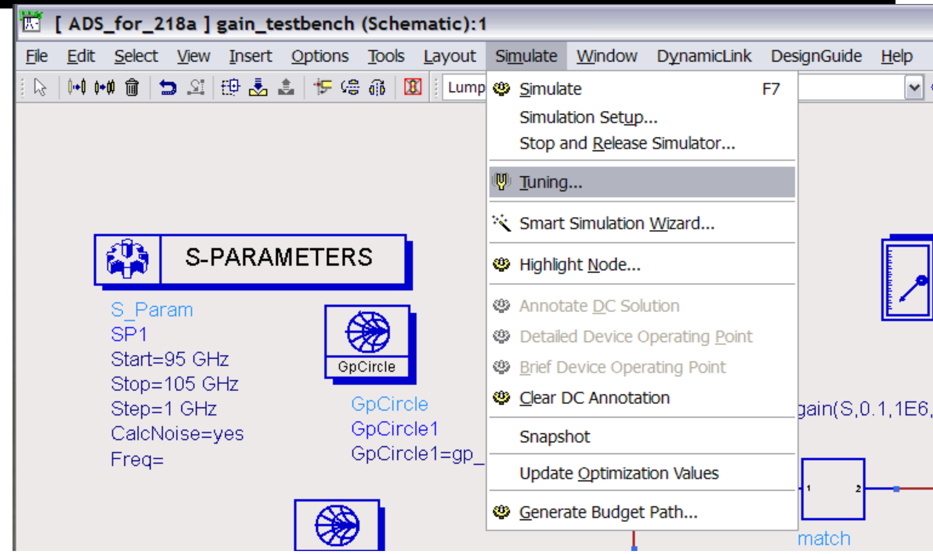


Do the same for C_1 :

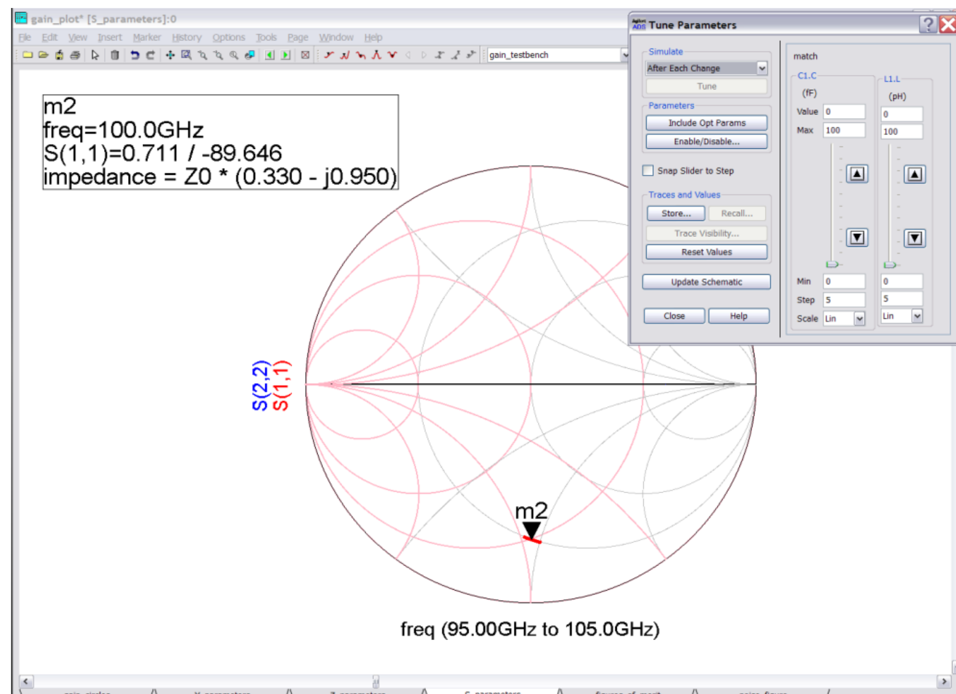


Setting Up Element Tuning in ADS:

Go to the main testbench and select tuning :

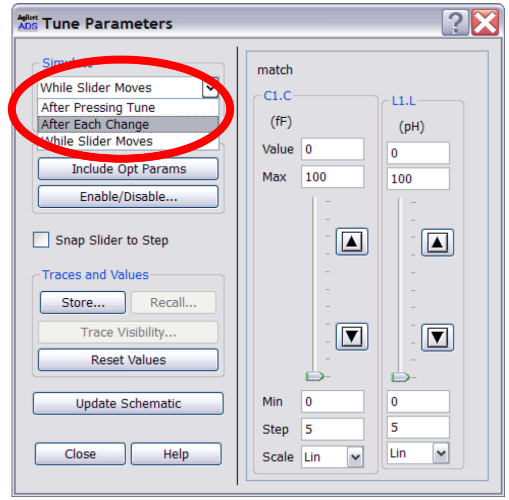


Then manipulate windows until you can see both the "Tune Parameters" window and the Plot window

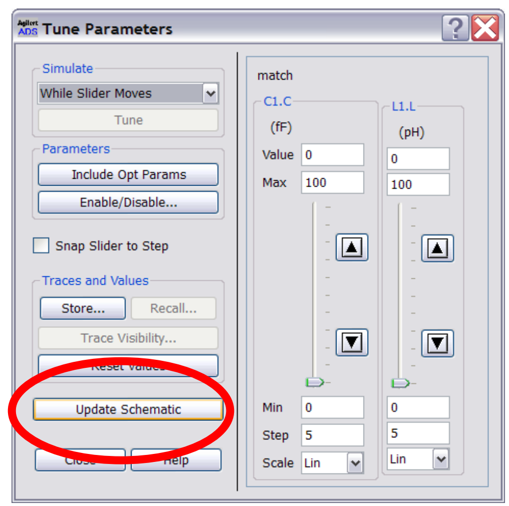


Setting Up Element Tuning in ADS:

Usually easiest to make the plot update after every tuning change :



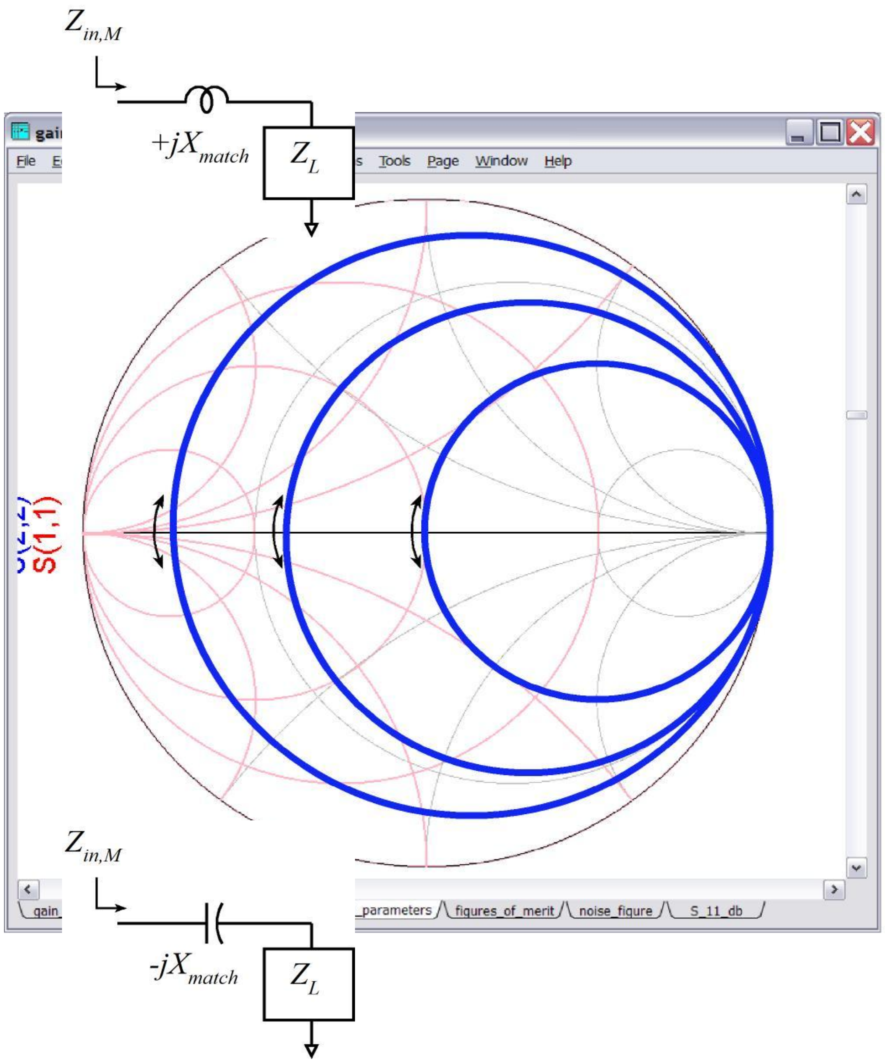
Need to update Schematic after tuning : otherwise, you will lose the changes made.



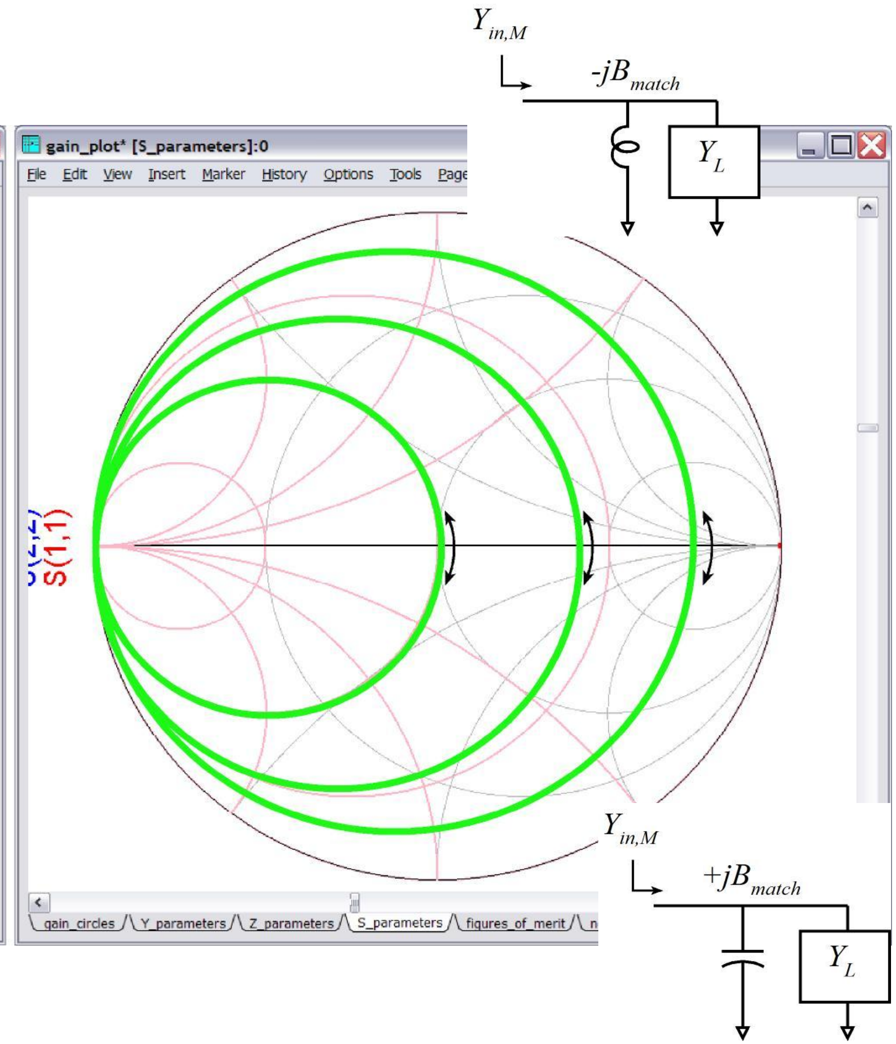
Impedance-Matching: Methods/Examples

Trajectories for adding series / shunt L and C

Adding Series L or C

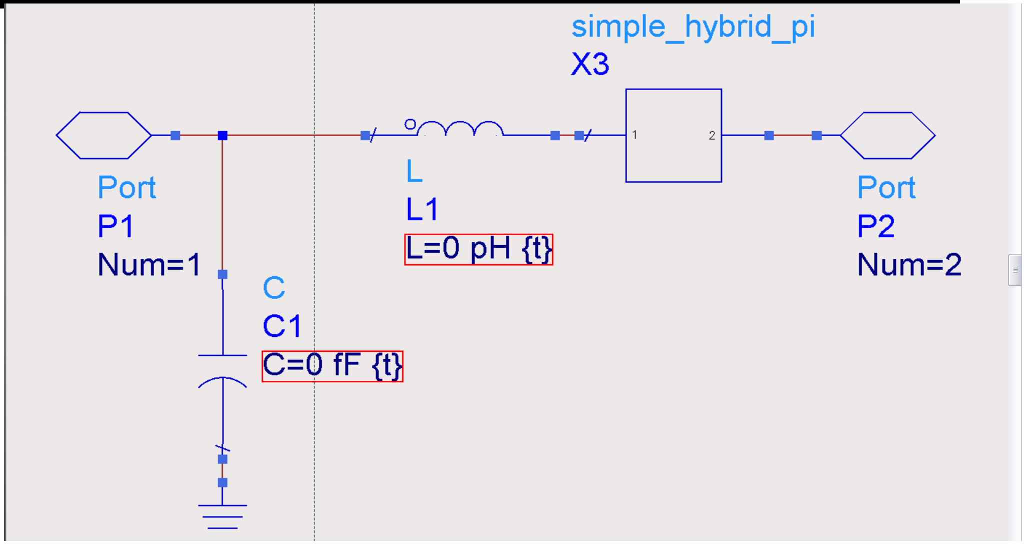


Adding Shunt (Parallel) L or C

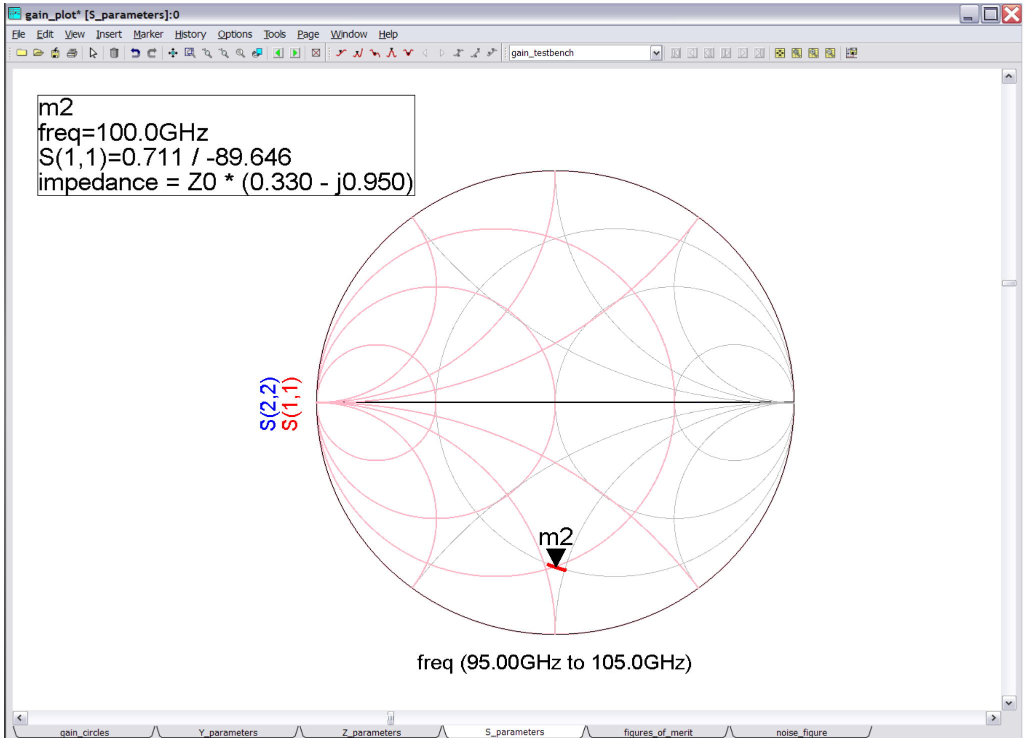


1st Lumped L-C Matching Network:

Network Topology

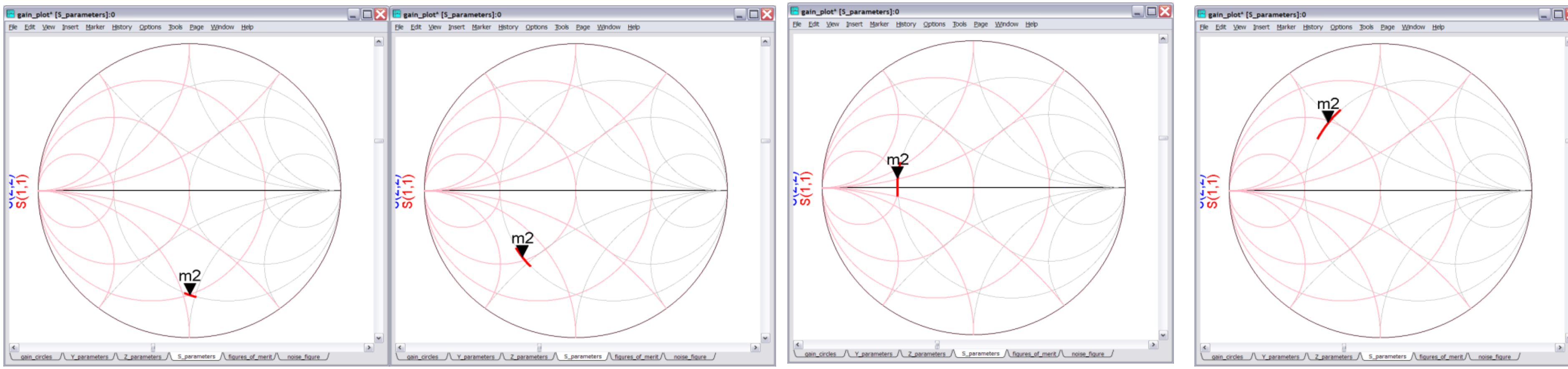


S_{11} before matching at 100 GHz



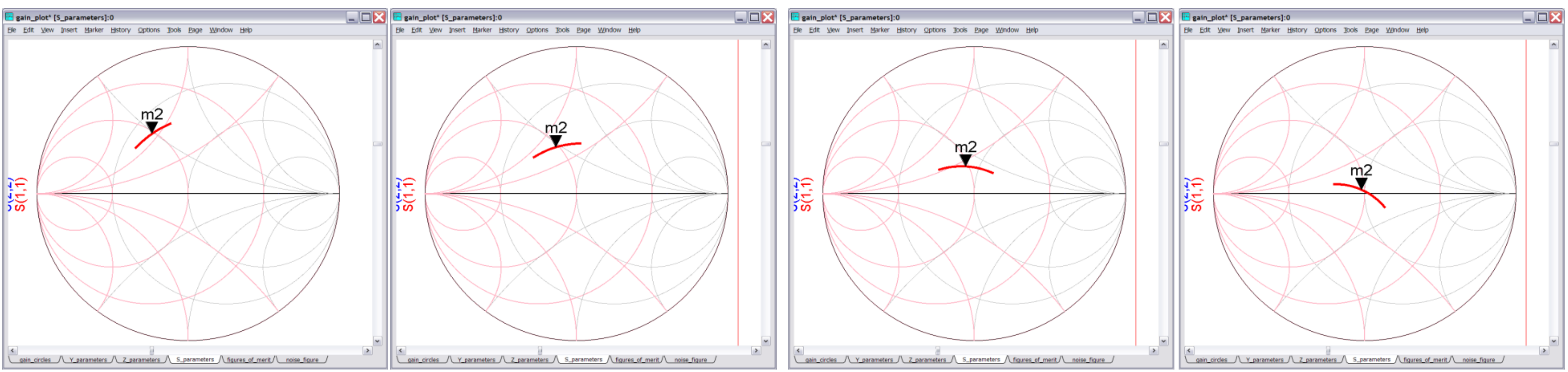
1st Lumped L-C Matching Network:

Increase L until $Y_{in}/Y_0 = 1.0 + jB$: Reached when $L_1 = 112$ pH



We have moved on a constant-r circle towards values of higher reactance jx.

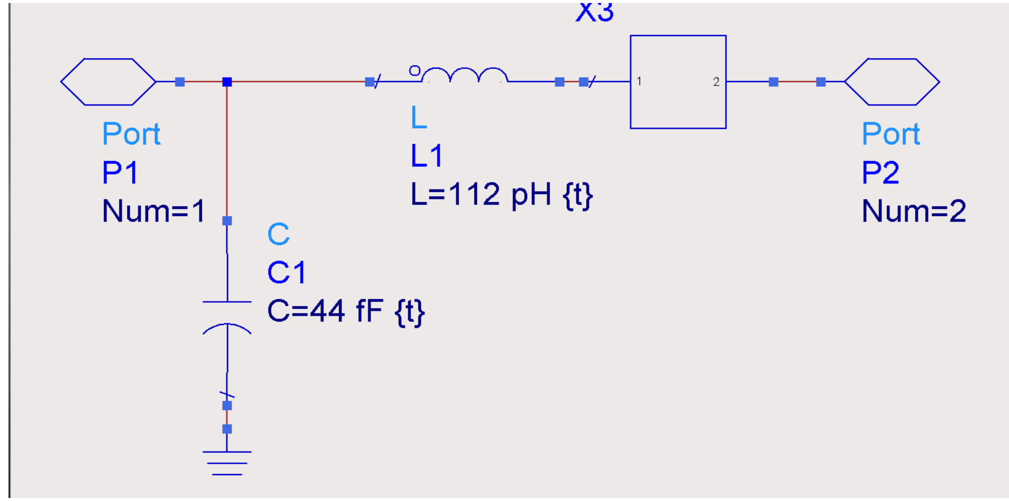
Increase C until $Z_{in}/Z_0 = 1.0 + j0$: Reached when $C_1 = 44$ fF



We have moved on a constant-g circle towards values of higher susceptance jb.

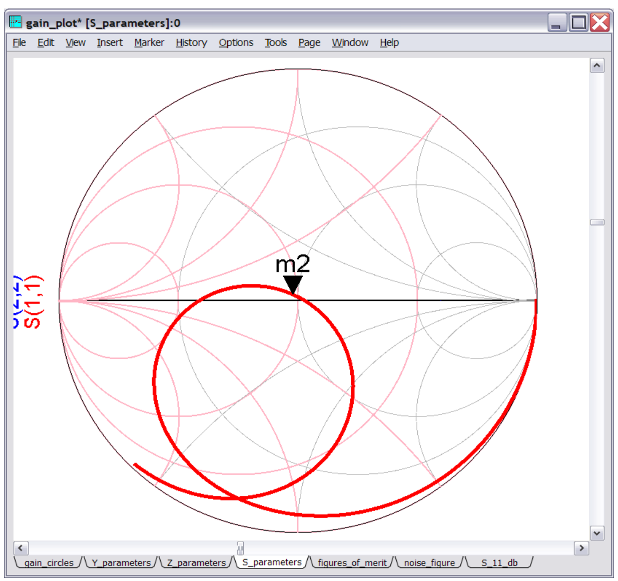
1st Lumped L-C Matching Network:

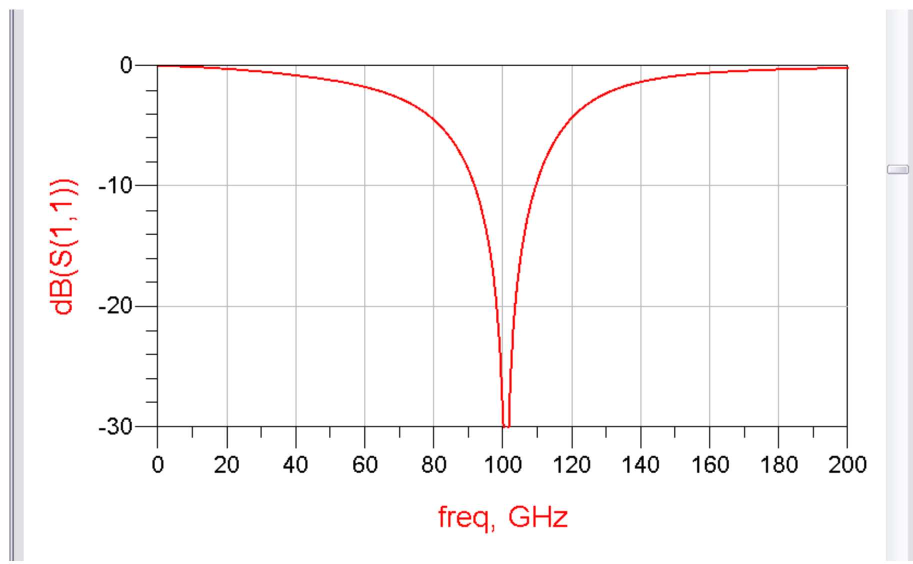
Final Values



Performance vs Frequency

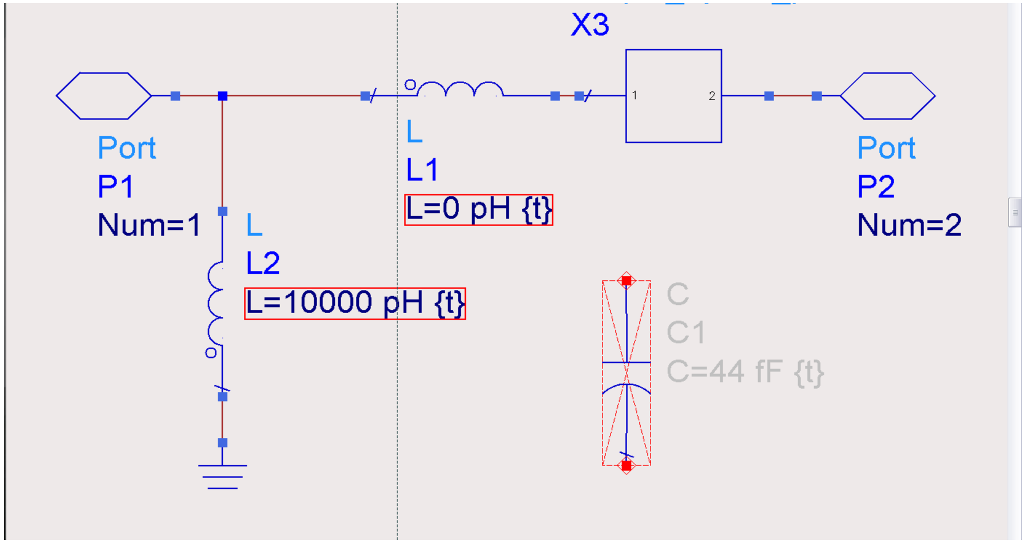
(DC - 200 GHz frequency sweep, marker at 100 GHz)



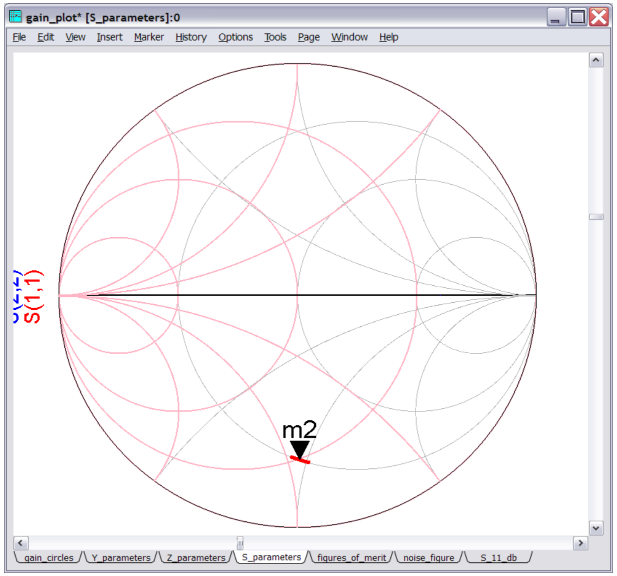


2nd Lumped L-C Matching Network:

Network Topology

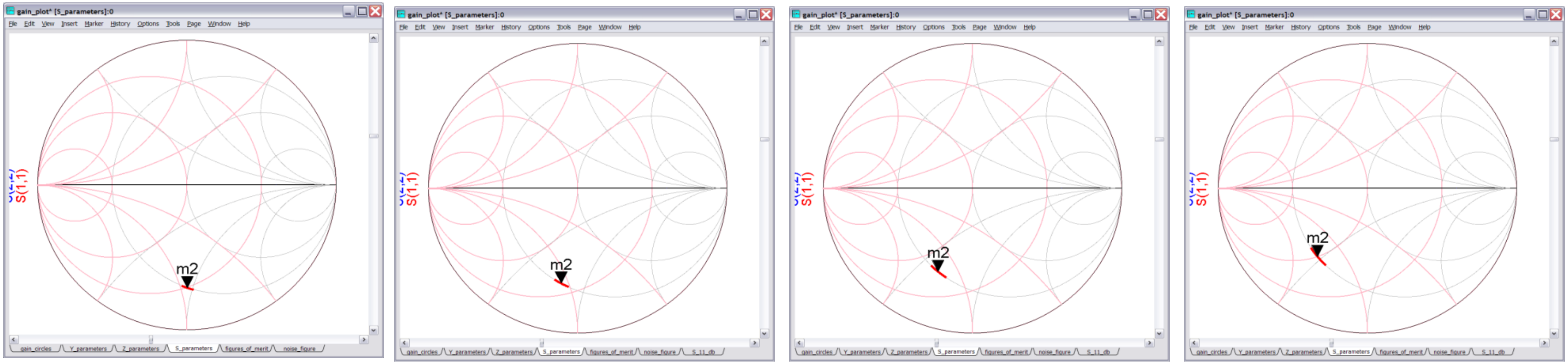


S_{11} before matching at 100 GHz



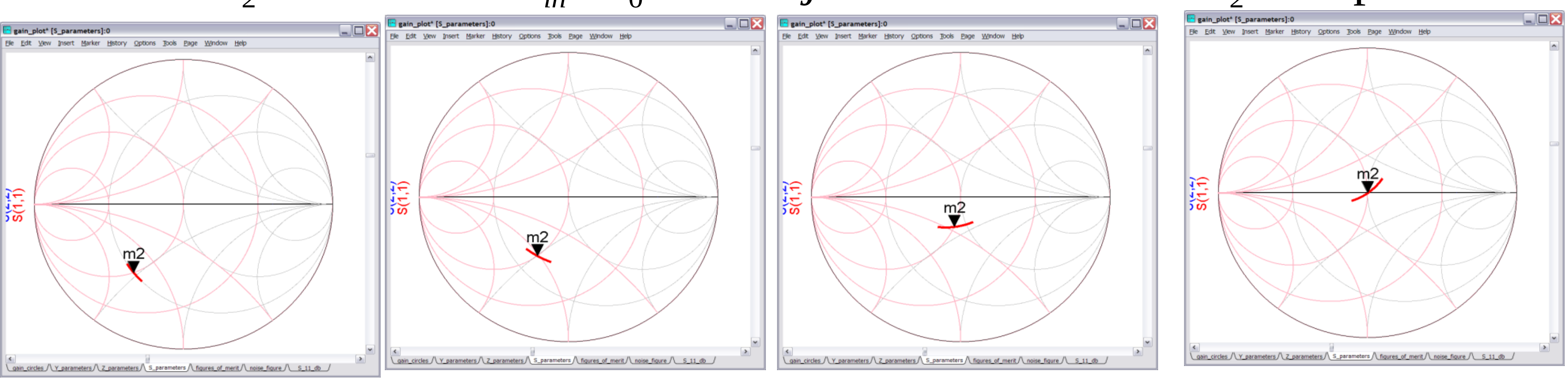
2nd Lumped L-C Matching Network:

Increase L_1 until $Y_{in}/Y_0 = 1.0 - jB$: Reached when $L_1 = 38$ pH



We have moved on a constant-r circle towards values of higher reactance jx.

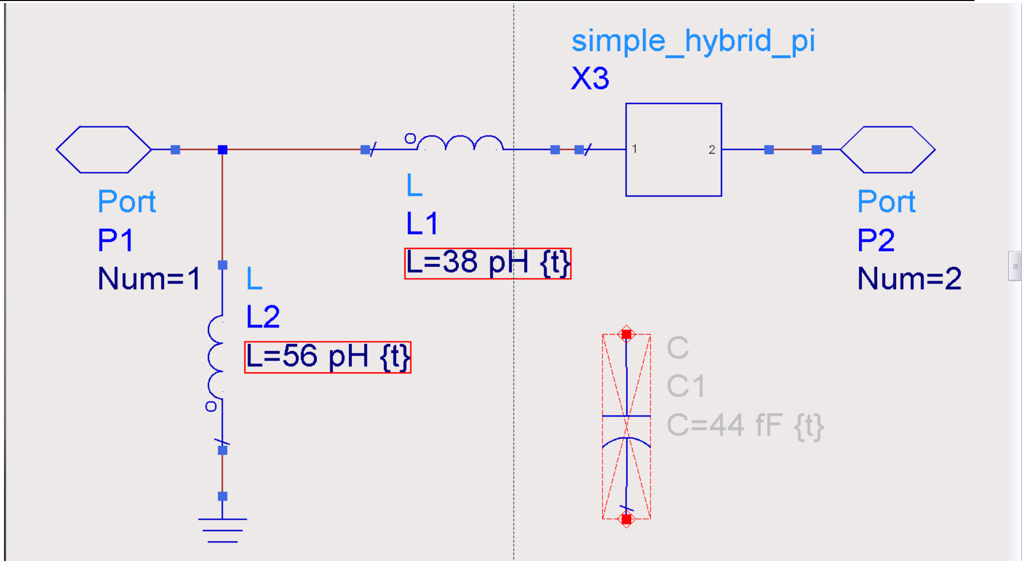
Increase L_2 from ∞ until $Z_{in}/Z_0 = 1.0 + j0$: Reached when $L_2 = 56$ pH



We have moved on a constant-g circle towards values of higher susceptance jb.

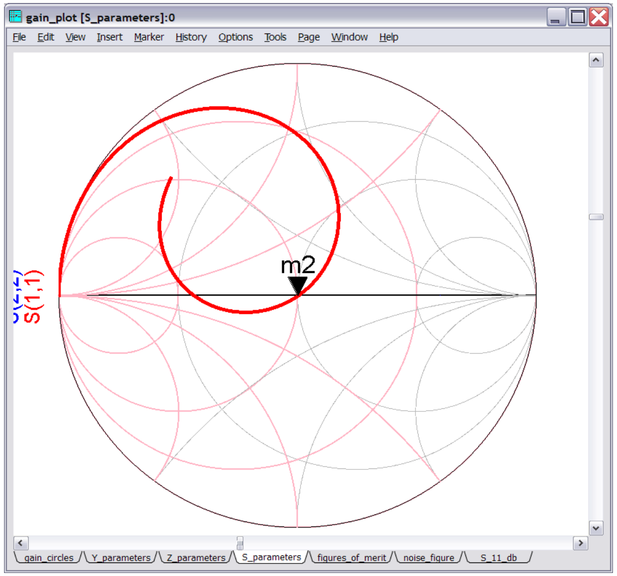
2nd Lumped L-C Matching Network:

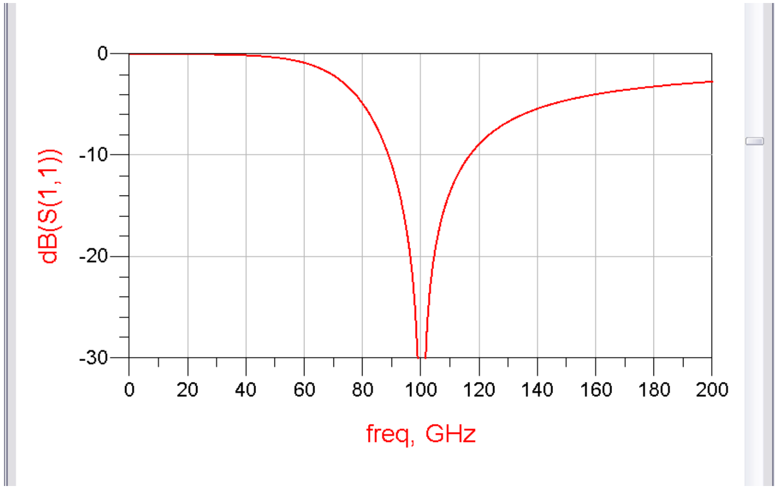
Final Values



Performance vs Frequency

(DC - 200 GHz frequency sweep, marker at 100 GHz)

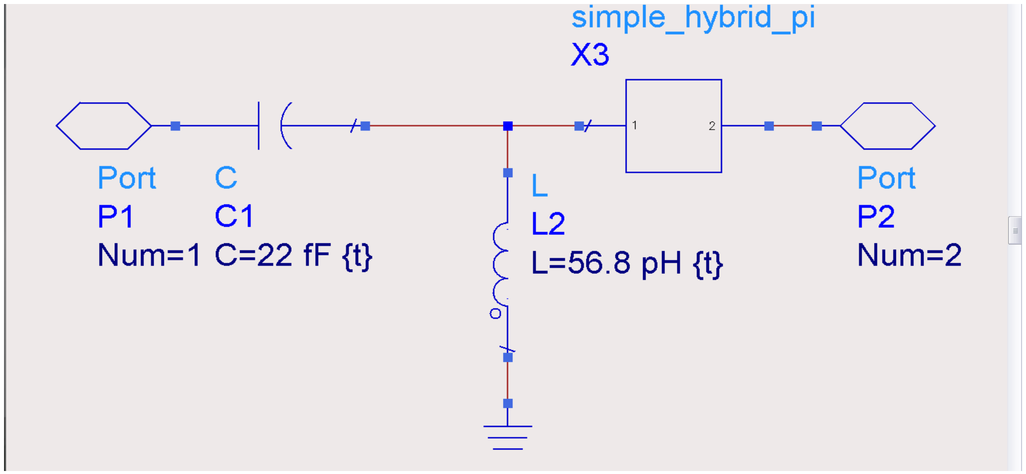




More direct matching trajectory → broader bandwidth

3rd Lumped L-C Matching Network:

Matching network with values

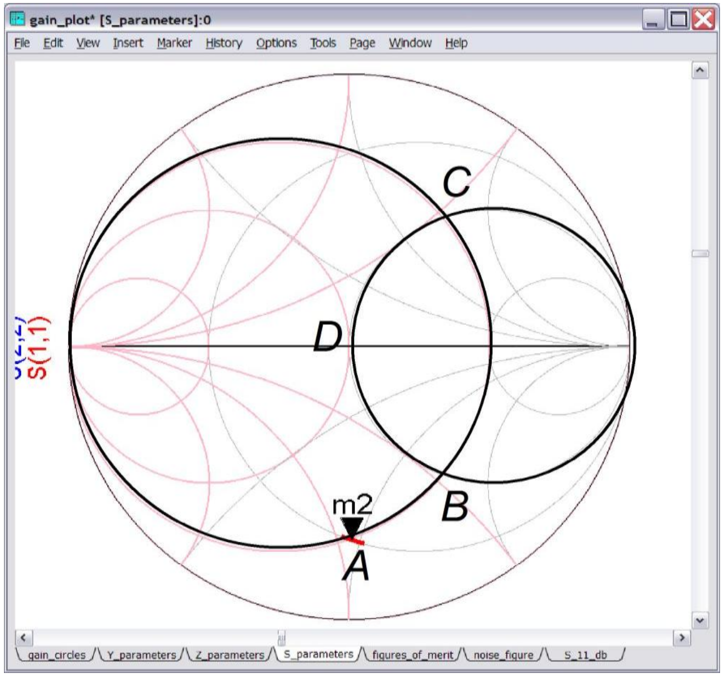


S_{11} matching trajectory at 100 GHz

A : original Z_{in}

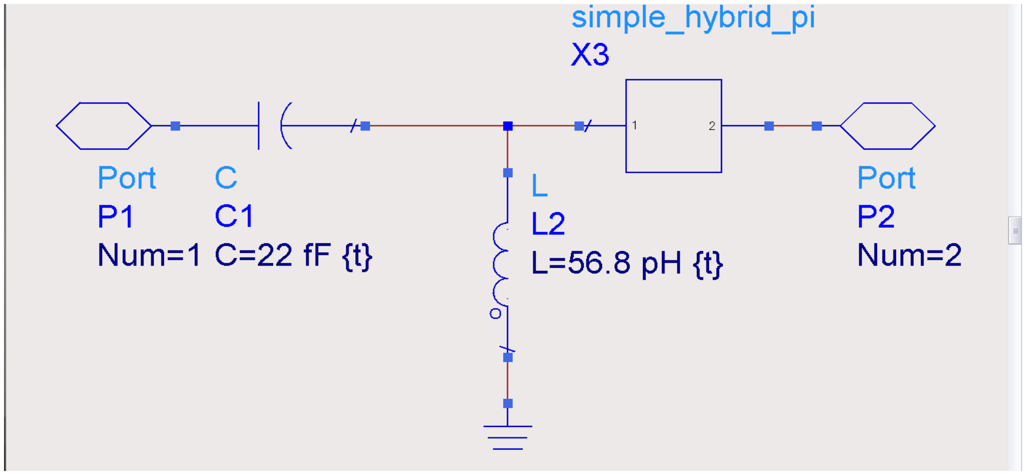
C : after adding L_2 in parallel

D : after adding C_1 in series



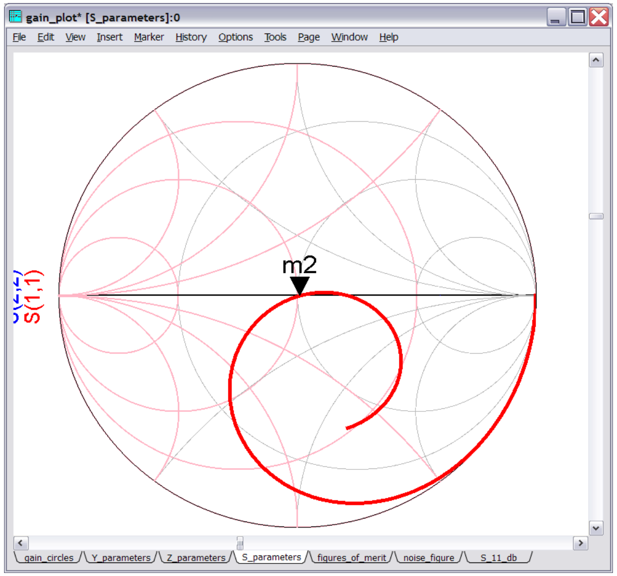
3rd Lumped L-C Matching Network:

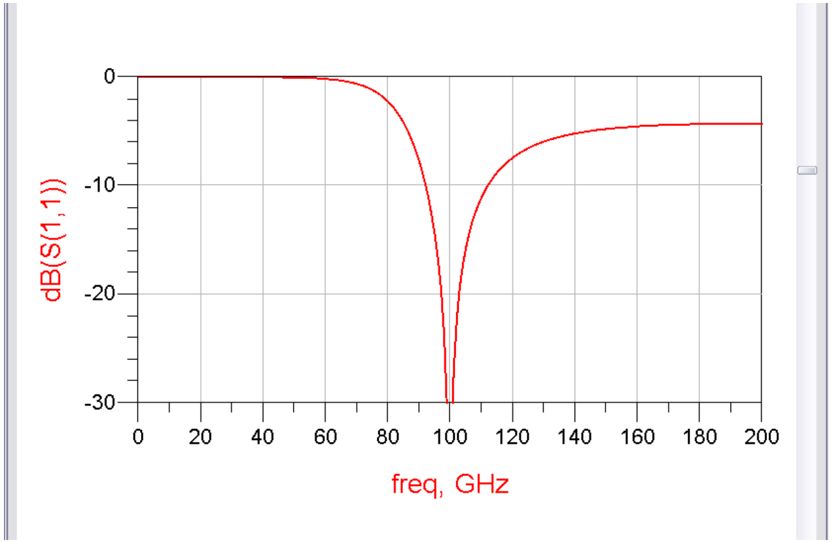
Final Values



Performance vs Frequency

(DC - 200 GHz frequency sweep, marker at 100 GHz)

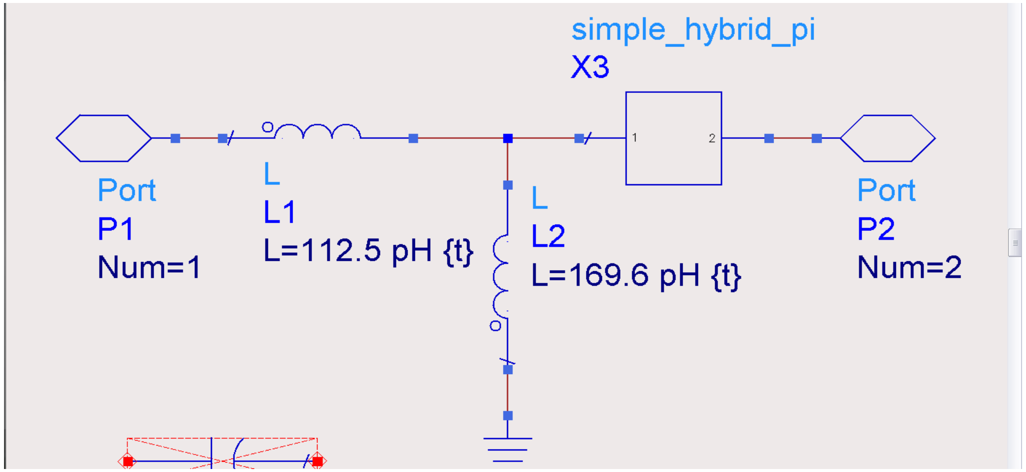




Long matching trajectory → narrower bandwidth

4th Lumped L-C Matching Network:

Matching network with values

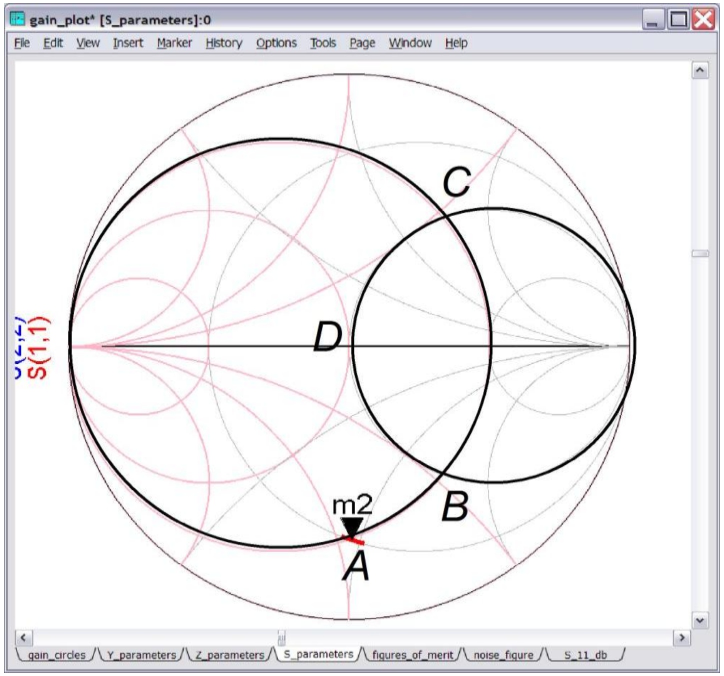


S_{11} matching trajectory at 100 GHz

A : original Z_{in}

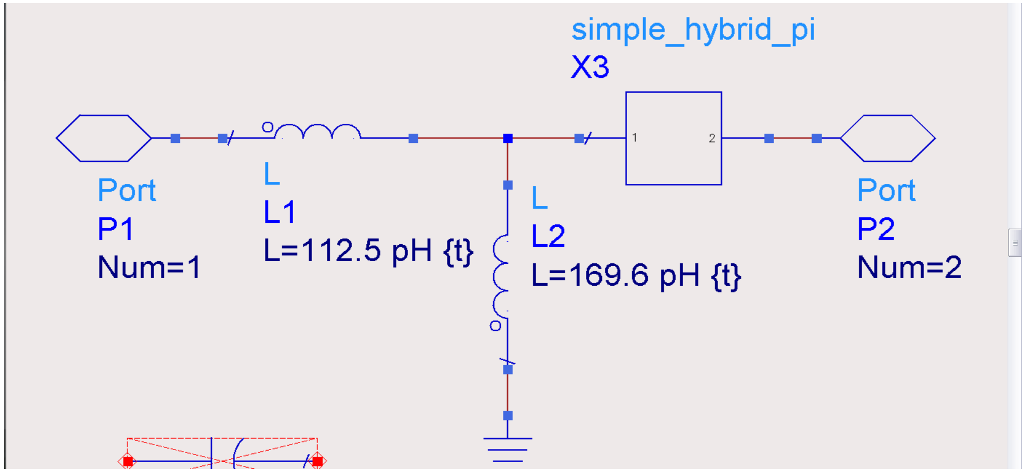
B : after adding L_2 in parallel

D : after adding L_1 in series



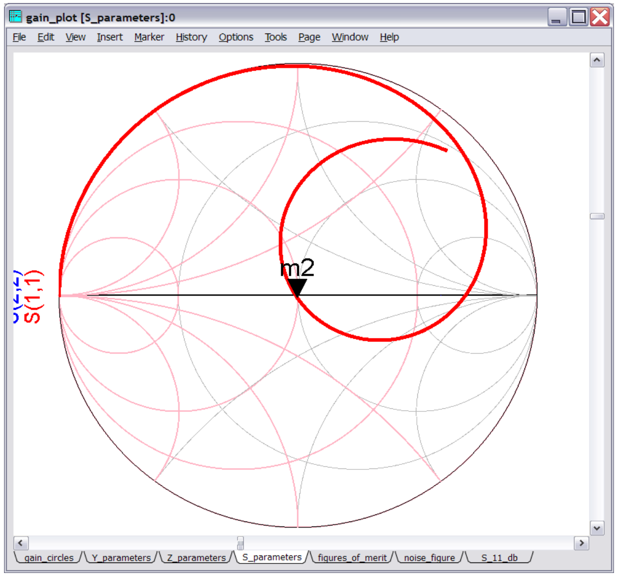
4th Lumped L-C Matching Network:

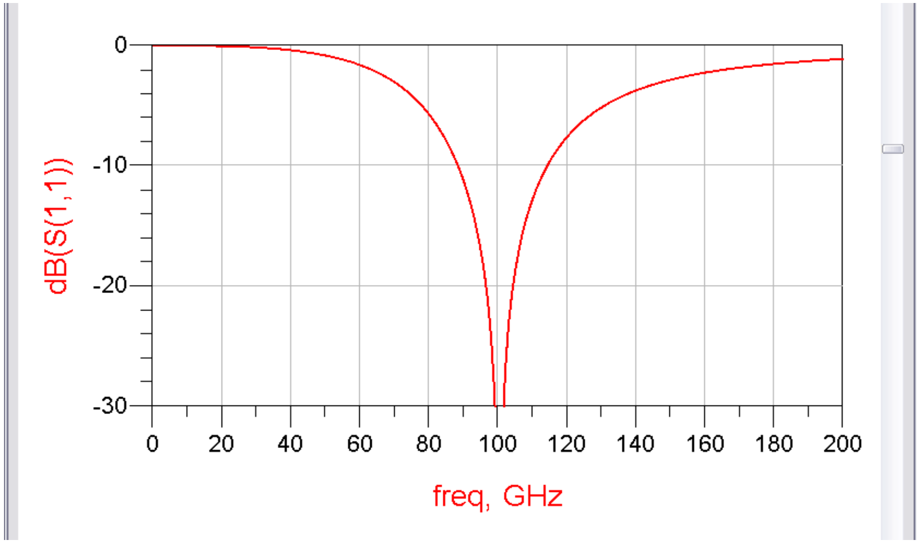
Final Values



Performance vs Frequency

(DC - 200 GHz frequency sweep, marker at 100 GHz)

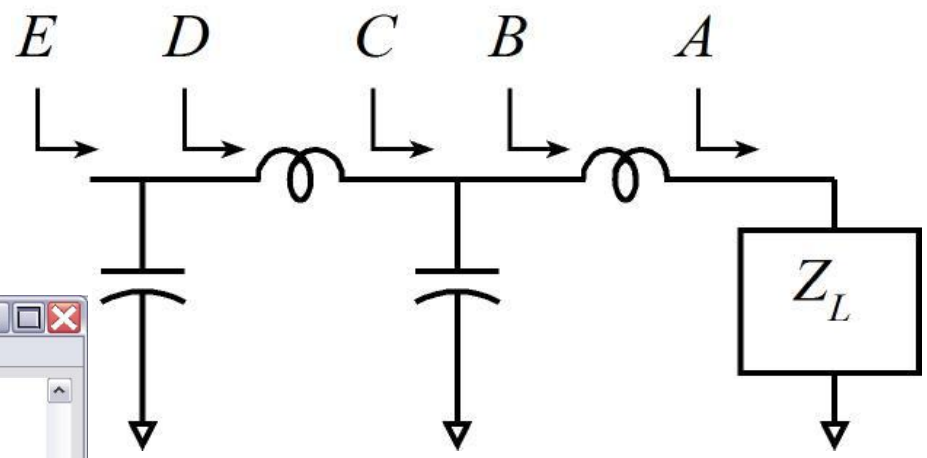


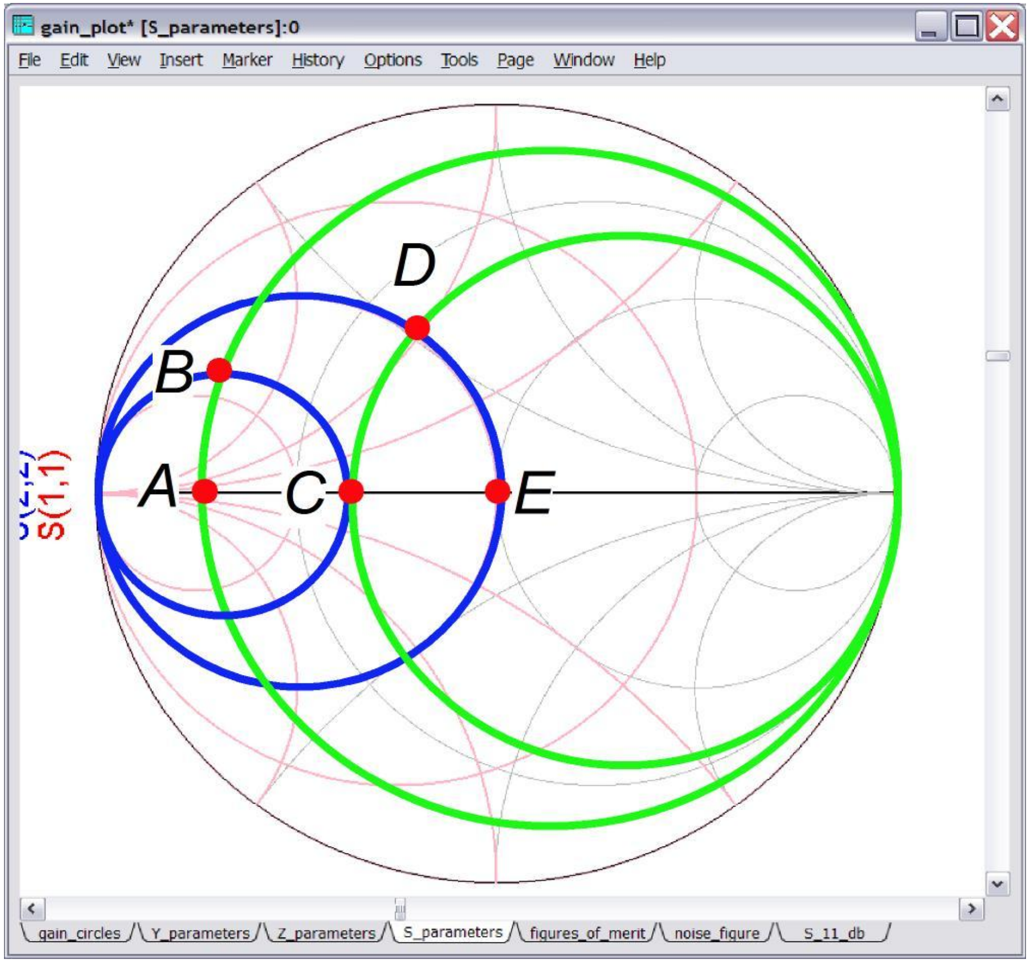


short matching trajectory → wider bandwidth

Multi-Section L-C Matching Network:

Tuning with
multiple series/shunt elements





infinite # of possible
matching networks.

Lines of Constant Q:

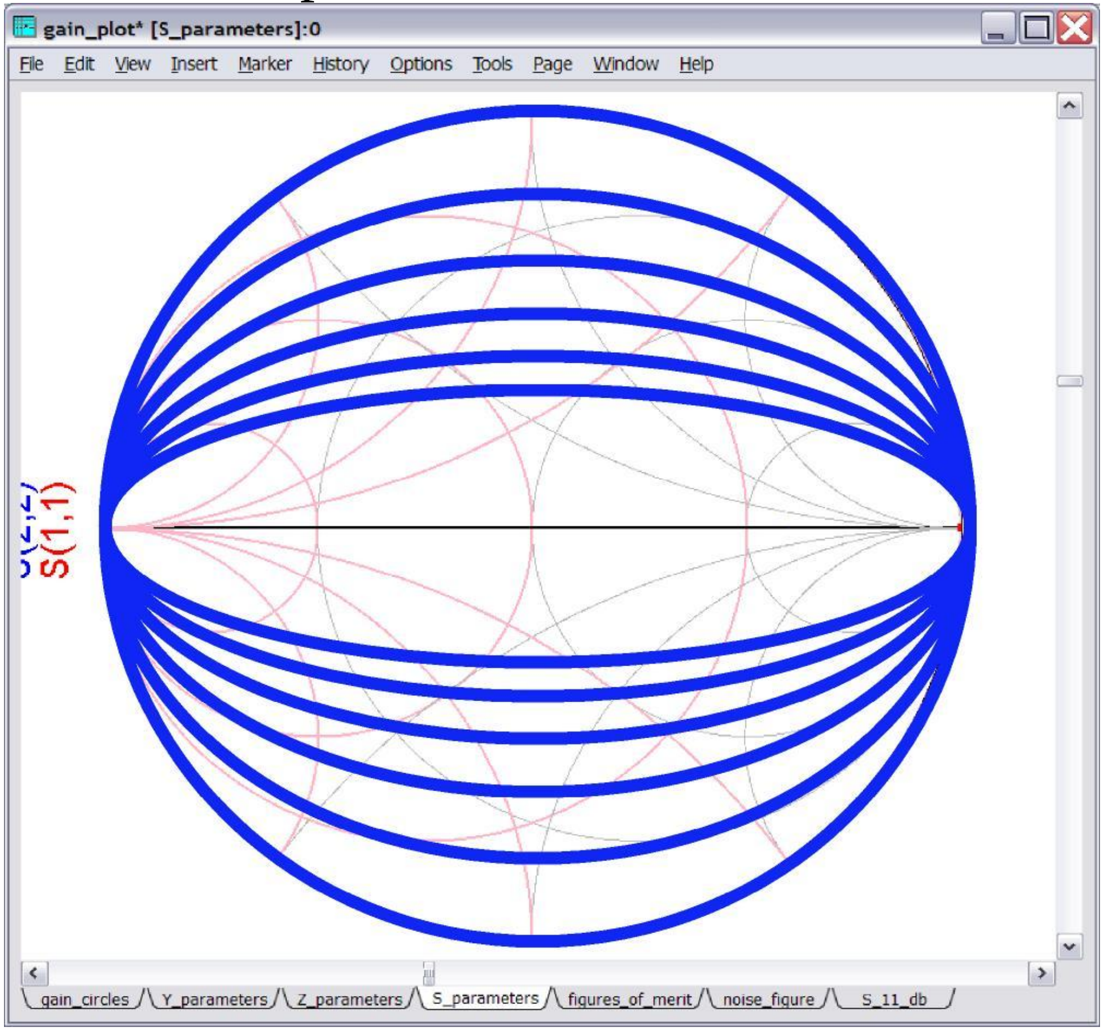
$$Q = \text{(maximum energy stored)/(energy dissipated per radian)}$$

$$= \| X_{series} \| / R_{series}$$

$$= \| B_{series} \| / G_{series} \text{ for simple 2-element impedances}$$

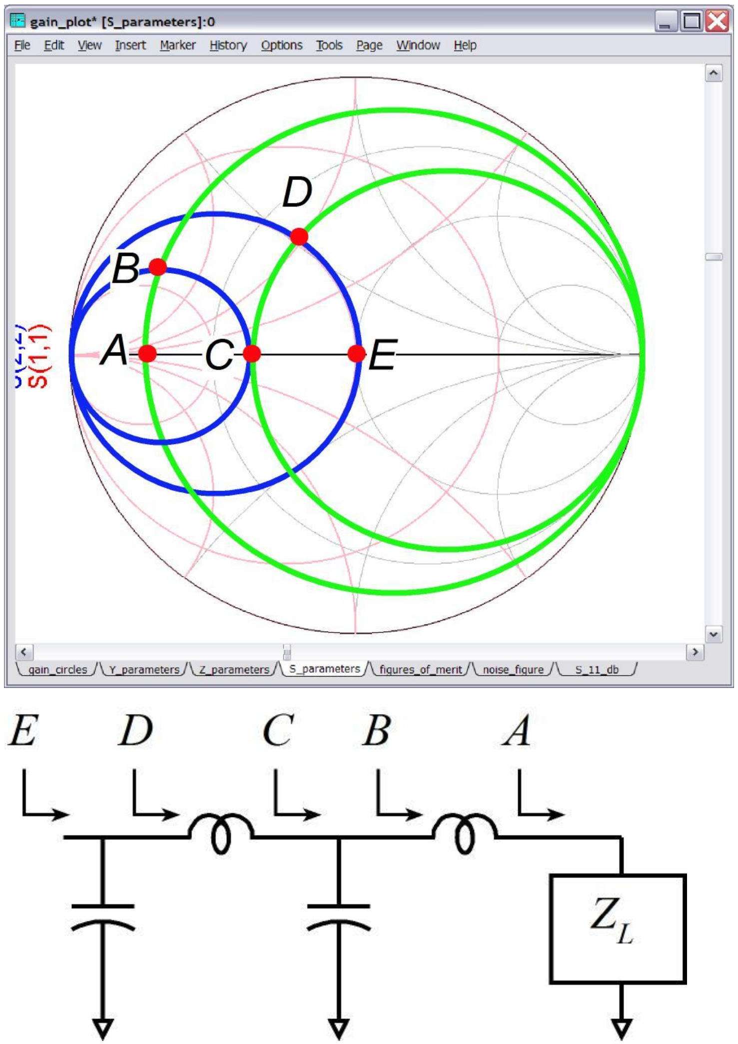
curves of constant Q look roughly like this.

Matching networks passing through high-Q points will have narrow bandwidth.

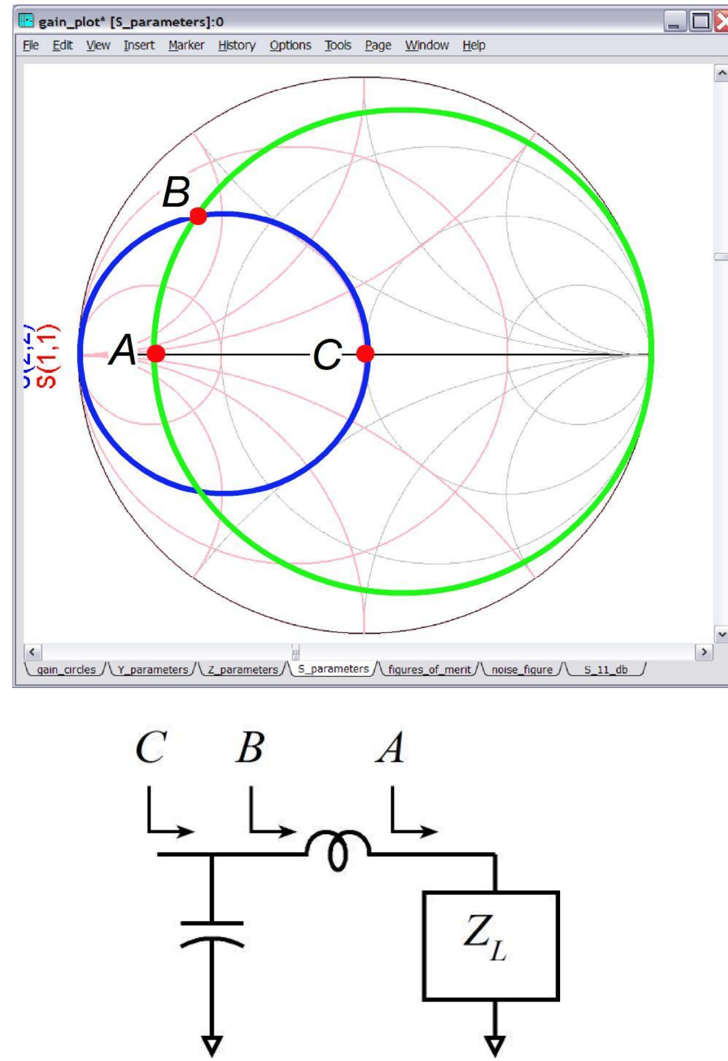


Narrowband vs. Wideband Matching Networks

4 - element : wideband

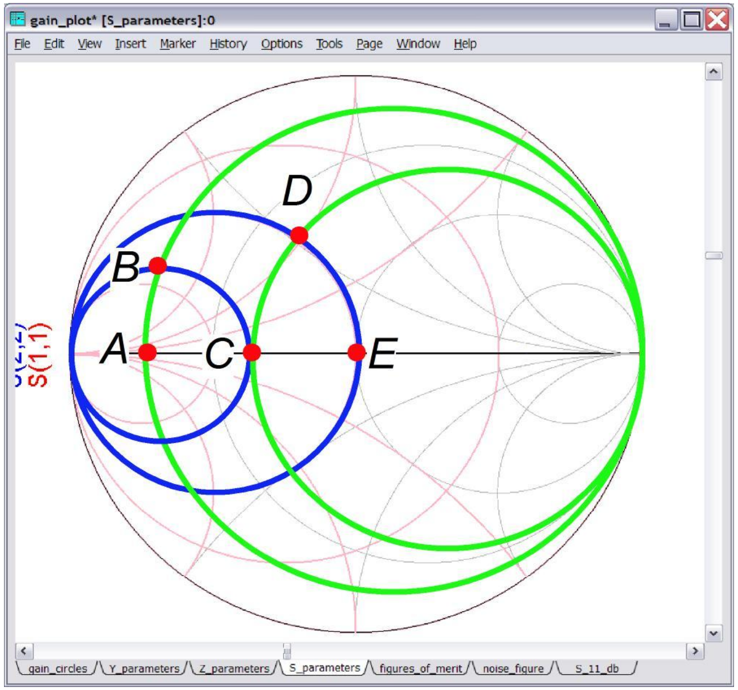


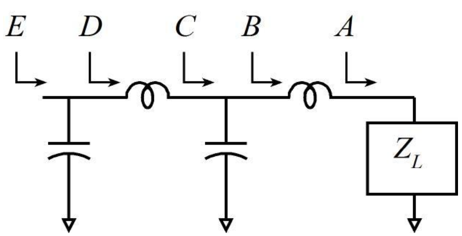
2 - element : narrowband



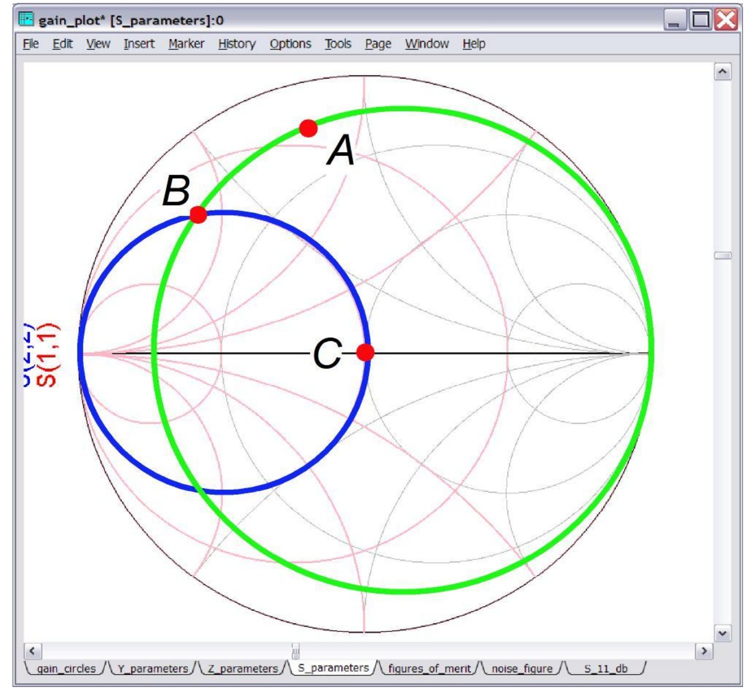
Limits to Matching Network Bandwidth

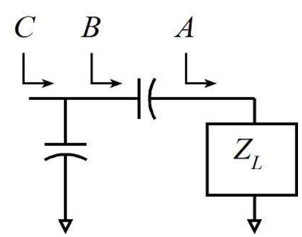
Low-Q load Z_L





High-Q load Z_L





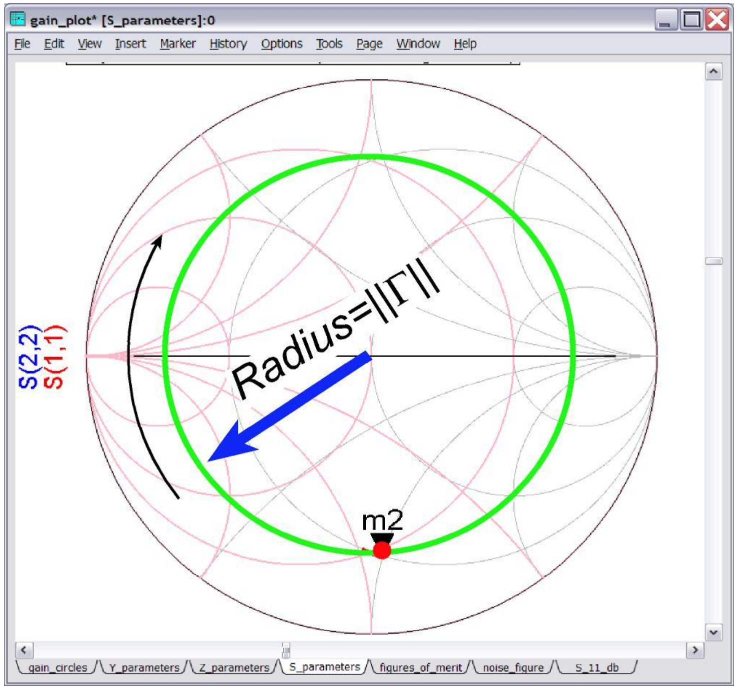
Starting point (Z_L) is low-Q
$\rightarrow$ match can be made wide or narrow

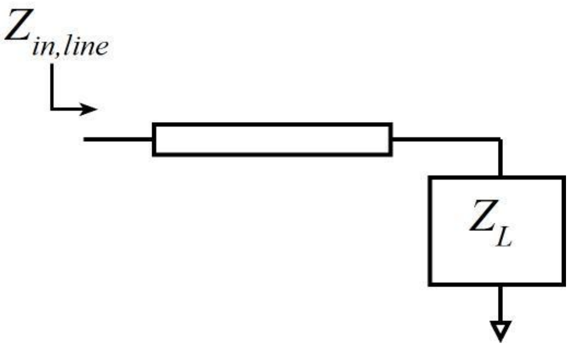
Starting point (Z_L) is high-Q
$\rightarrow$ match cannot be made wide

Shunt-Stub Matching Networks

Trajectories for Adding a Series Line of Impedance Zo

Adding Series TRX line :





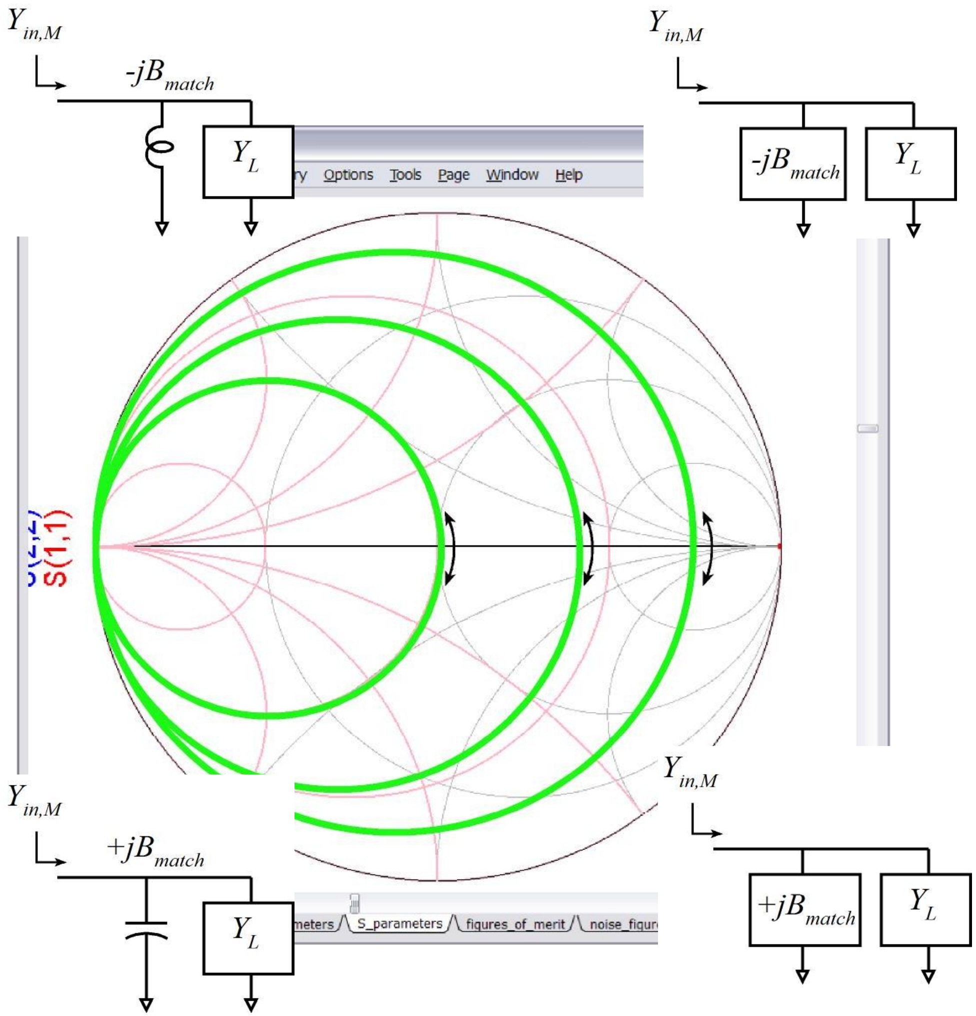
increasing the line length rotates the load reflection coefficient : $\Gamma_{in} = \Gamma_L e^{-2jl/\lambda}$

Series line : $Z_{line} = Z_{\text{system\_standard}} = Z_0$

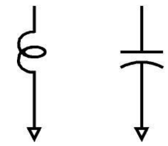
(if the standard impedance is 50Ω, the line is 50Ω)

Recall: Trajectory for adding Shunt Susceptance

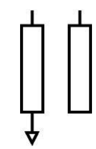
Adding Shunt (Parallel) Susceptance



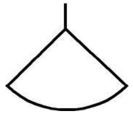
Susceptance can be an ideal $\{L \text{ or } C\}$.



Susceptance can be a shunt transmission-line stub.

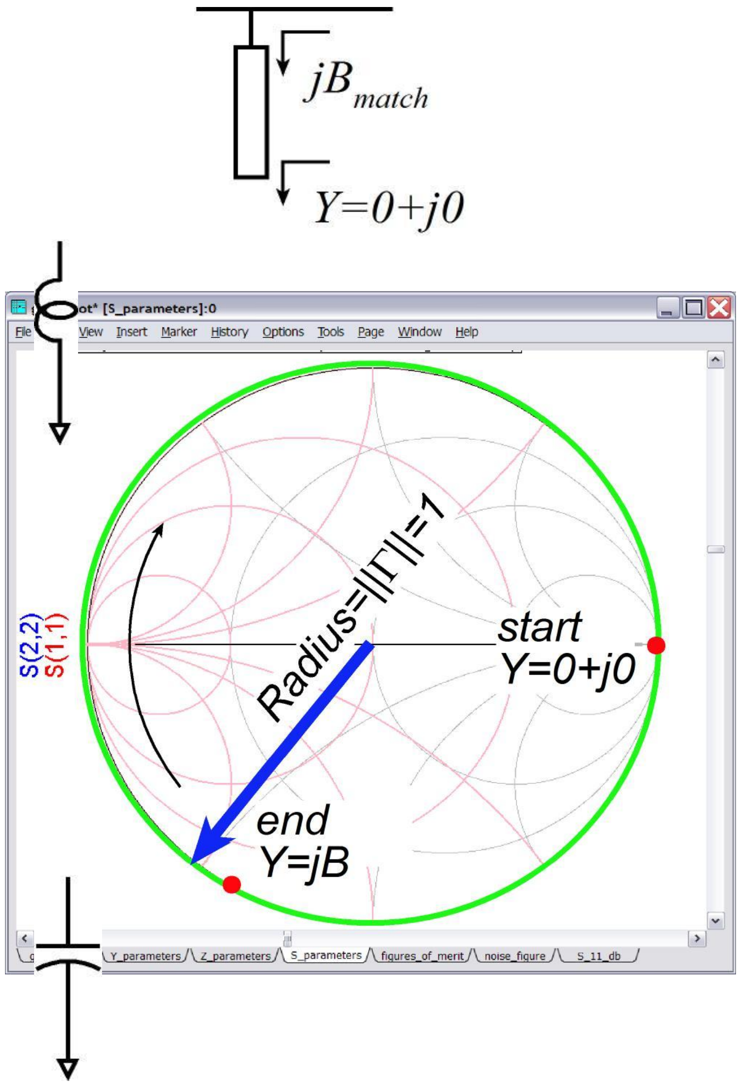


Susceptance can be a shunt radial stub.

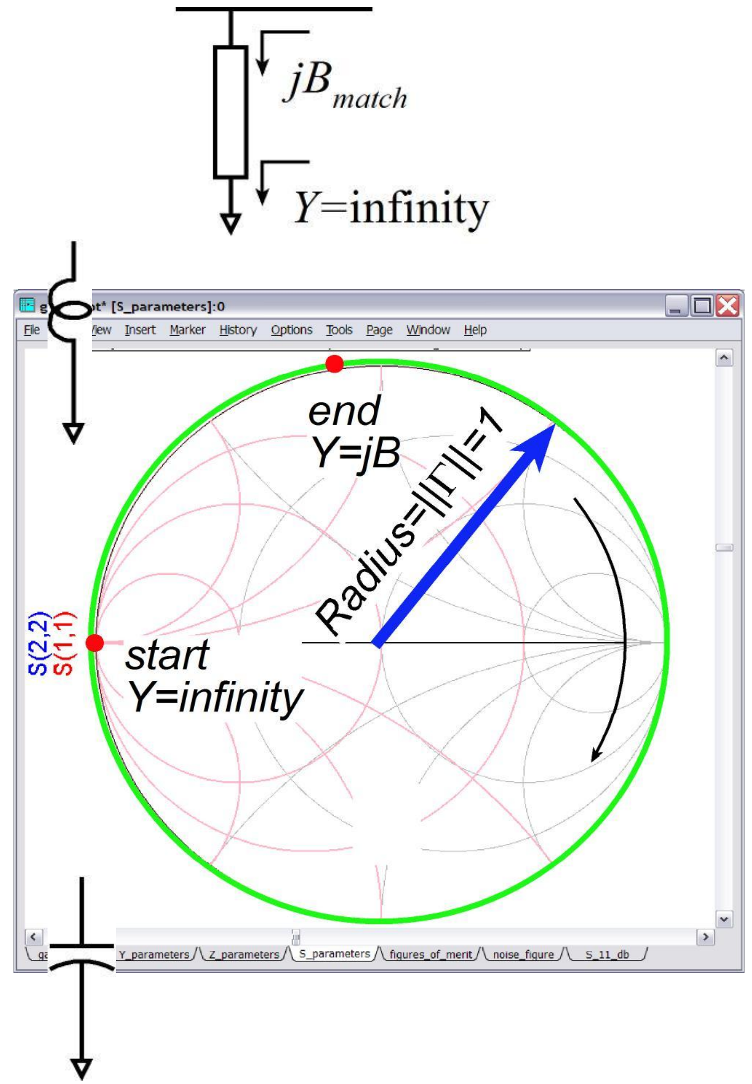


Susceptance of Shunt Stub (Open-Terminated)

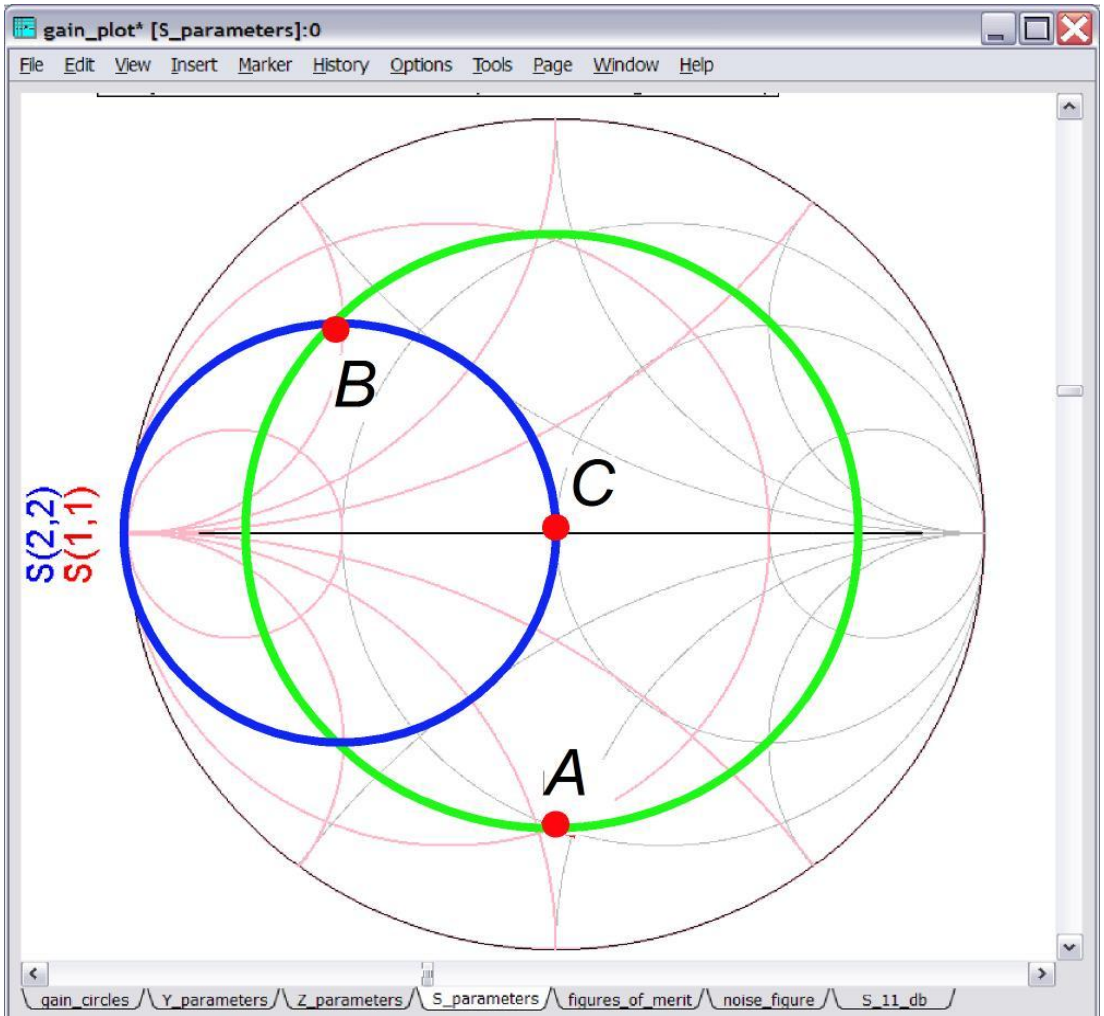
Open-Terminated

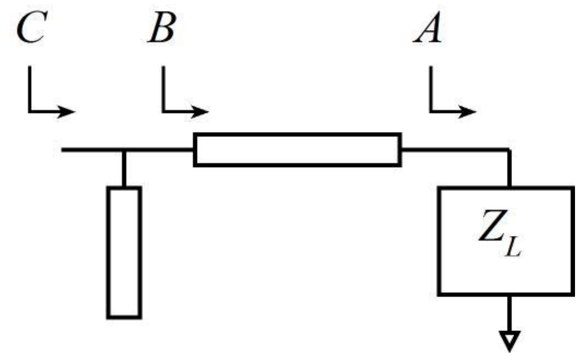


Short-Terminated



Shunt-Stub Matching Network:





Series line brings load

to $Y/Y_0 = 1 \pm jB$

Shunt stub adds

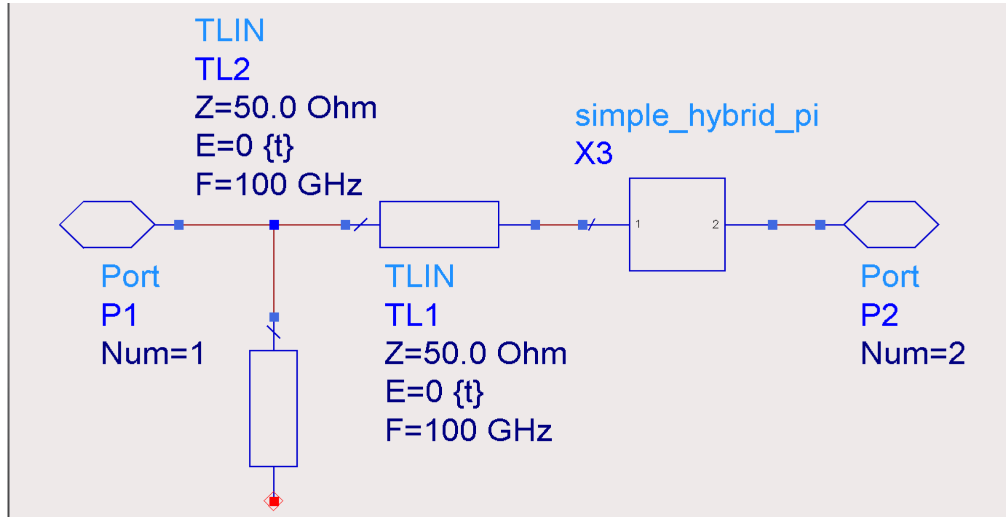
$Y_{stub}/Y_0 = \mp jB$

Combination brings load

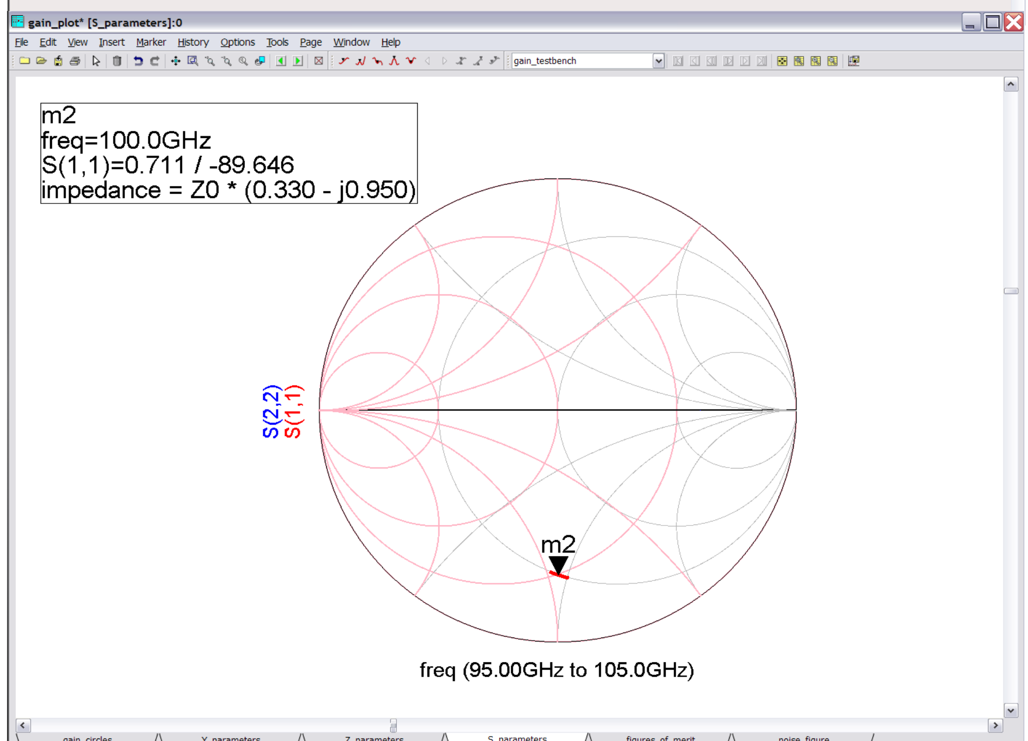
to $Y/Y_0 = 1 + j0$

1st Shunt-Stub Matching Network

Network Topology

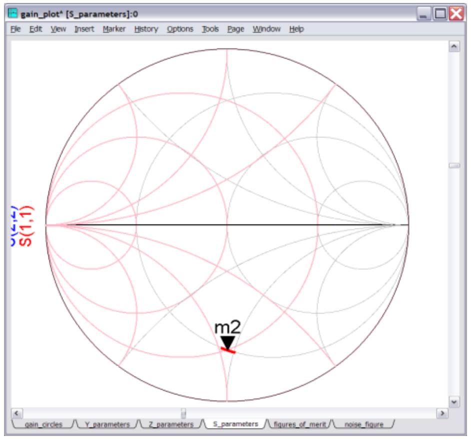


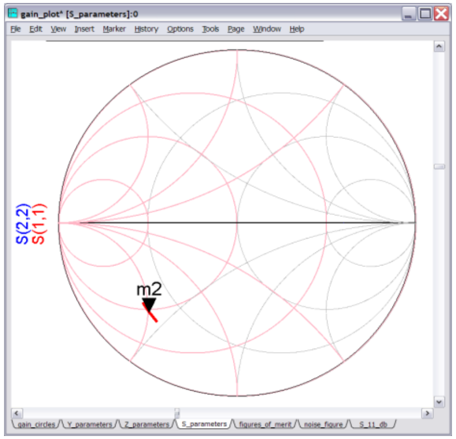
S_{11} before matching at 100 GHz

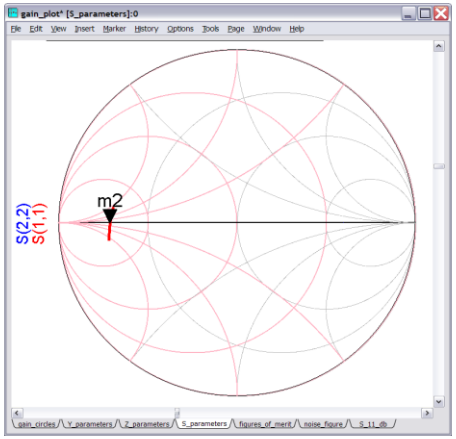


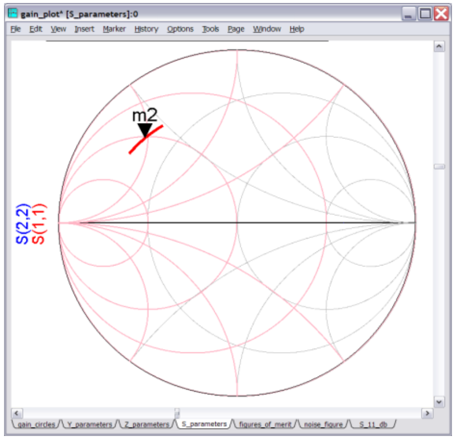
1st Shunt-Stub Matching Network

Increase TL_1 length until $Y_{in}/Y_0 = 1.0 + jB$: Reached when $2\pi l_1/\lambda = 68$ degrees



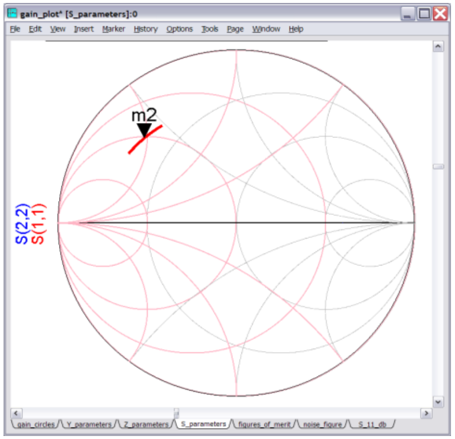


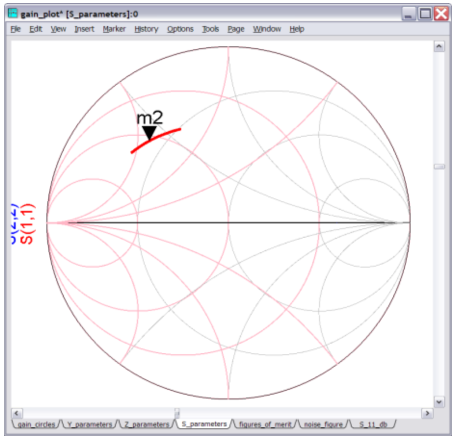


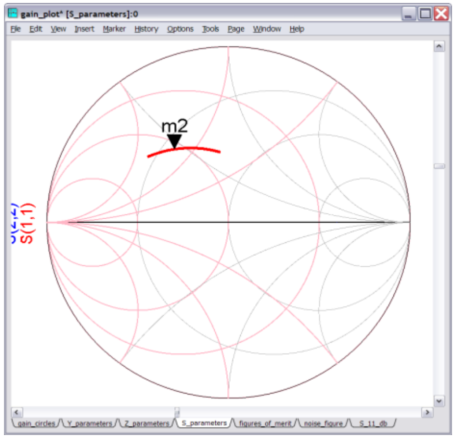


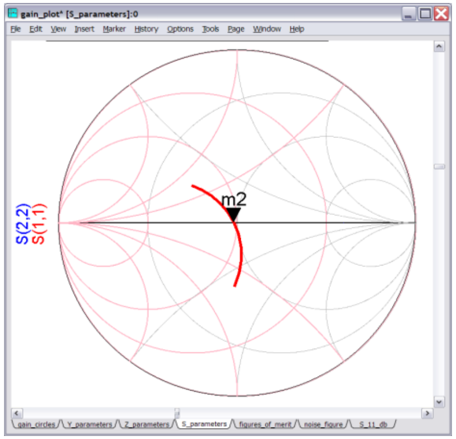
We have moved on a constant $-\Gamma$ circle.

Increase TL_2 length until $Y_{in}/Y_0 = 1.0 + j0$: Reached when $2\pi l_2/\lambda = 65$ degrees





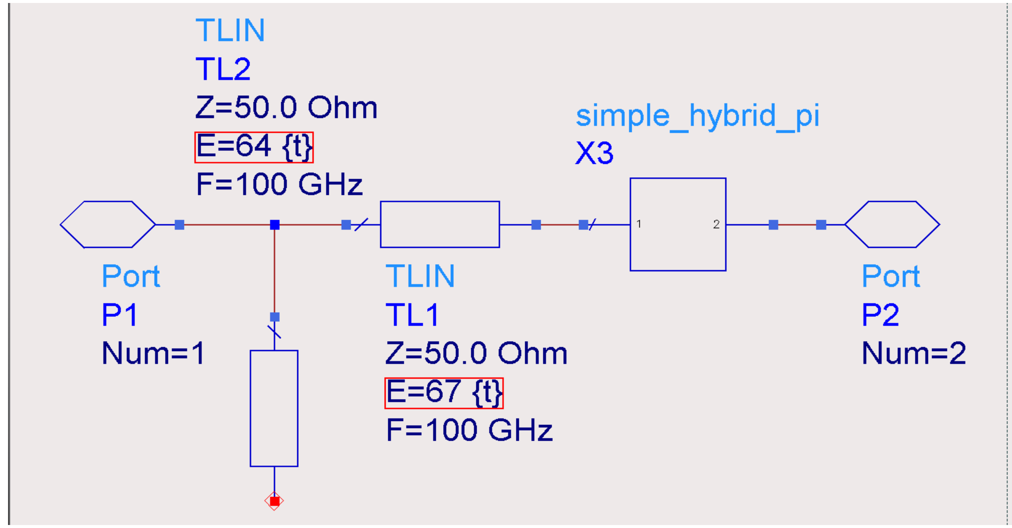




We have moved on a constant - g circle towards values of higher susceptance jb.

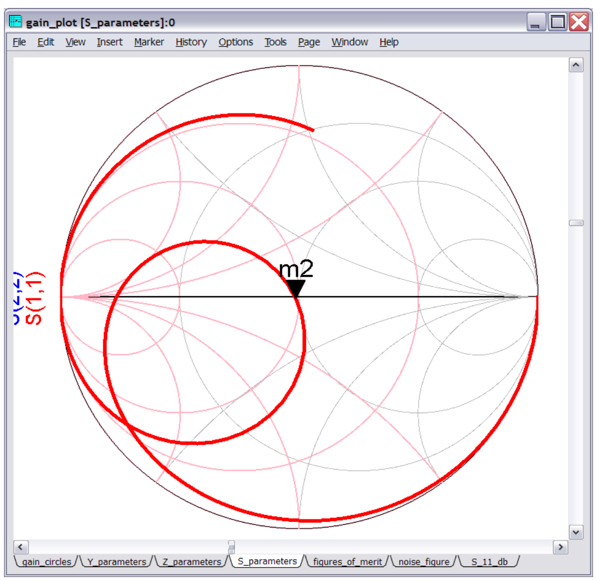
1st Shunt-Stub Matching Network

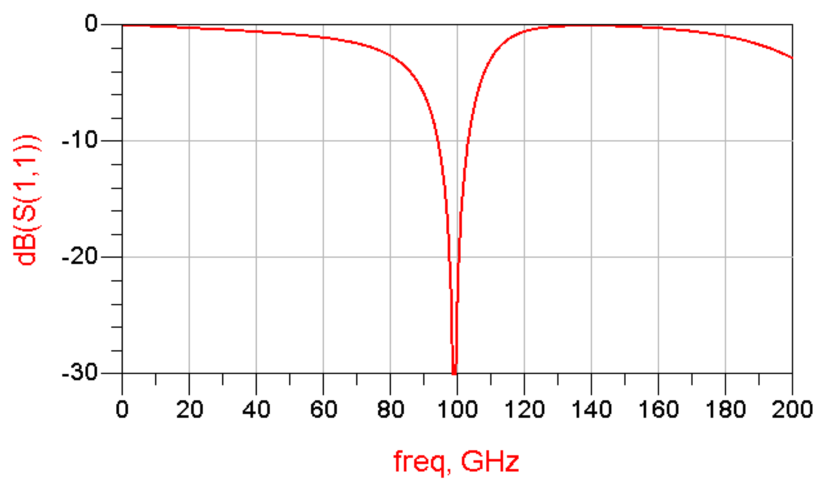
Final Values



Performance vs Frequency

(DC - 200 GHz frequency sweep, marker at 100 GHz)

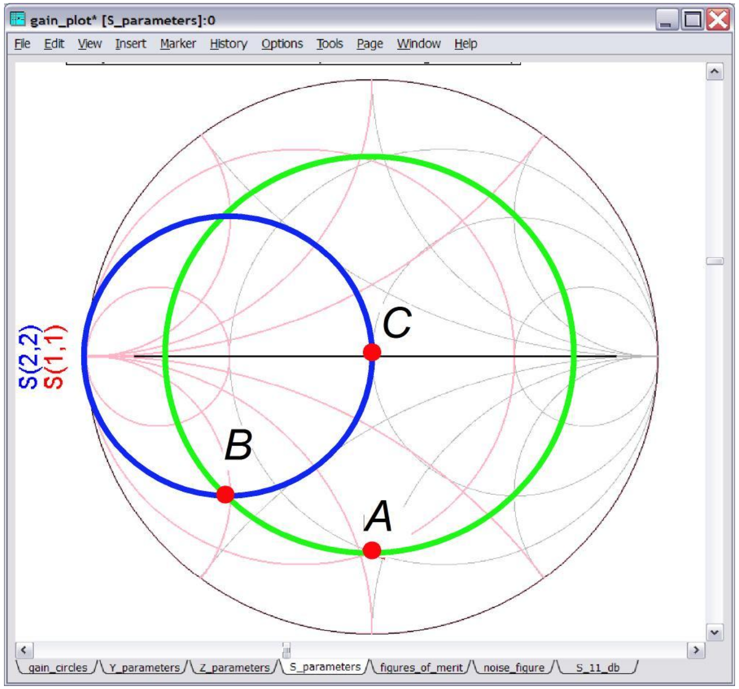


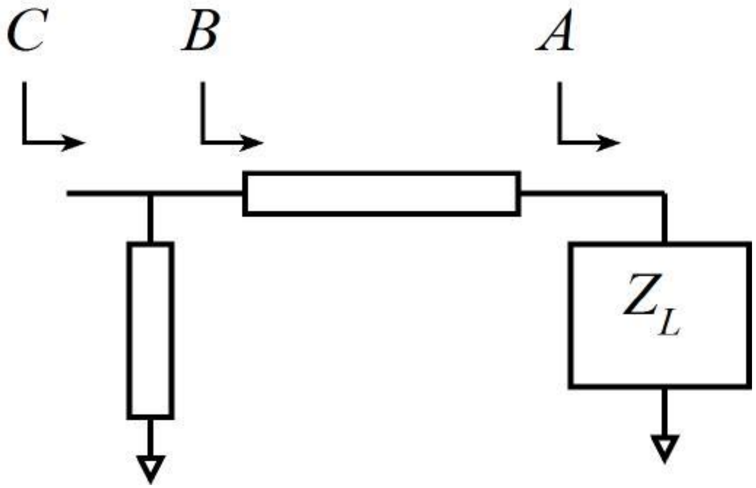


2nd Shunt-Stub Matching Network

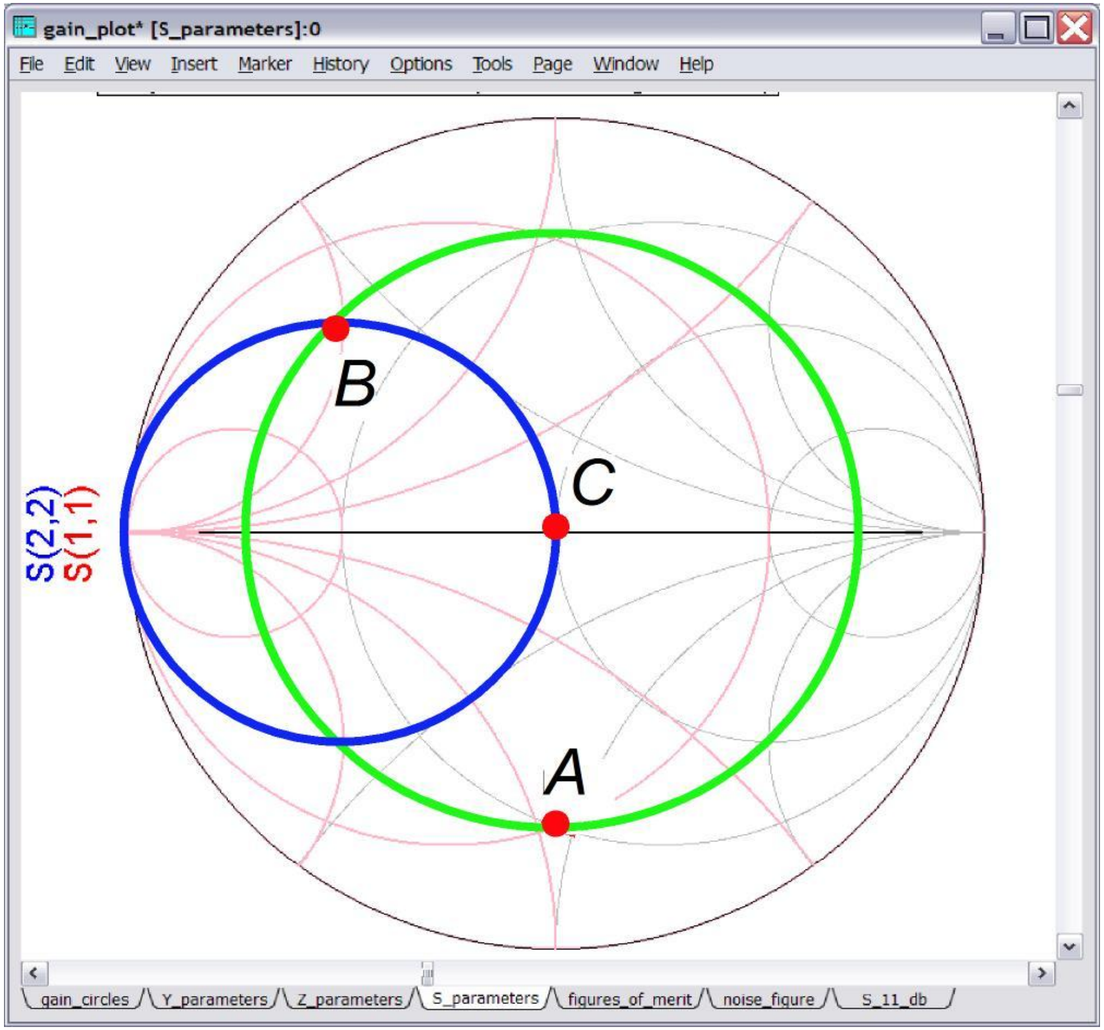
A shorter series line section TL_1 brings $Z_{matched}$ from A to B

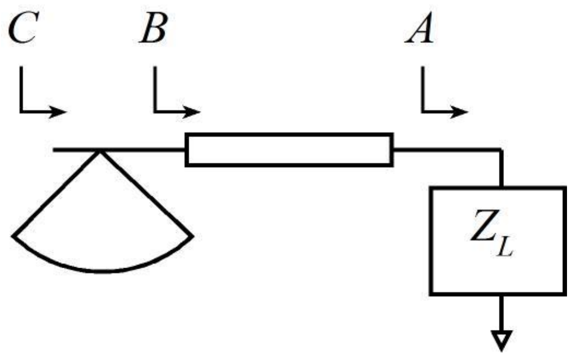
The shunt stub must now be inductive





3rd Shunt-Stub Matching Network





Series line brings load to $Y/Y_0 = 1 \pm jB$

Microstrip Radial Shunt stub adds $Y_{stub}/Y_0 = \mp jB$

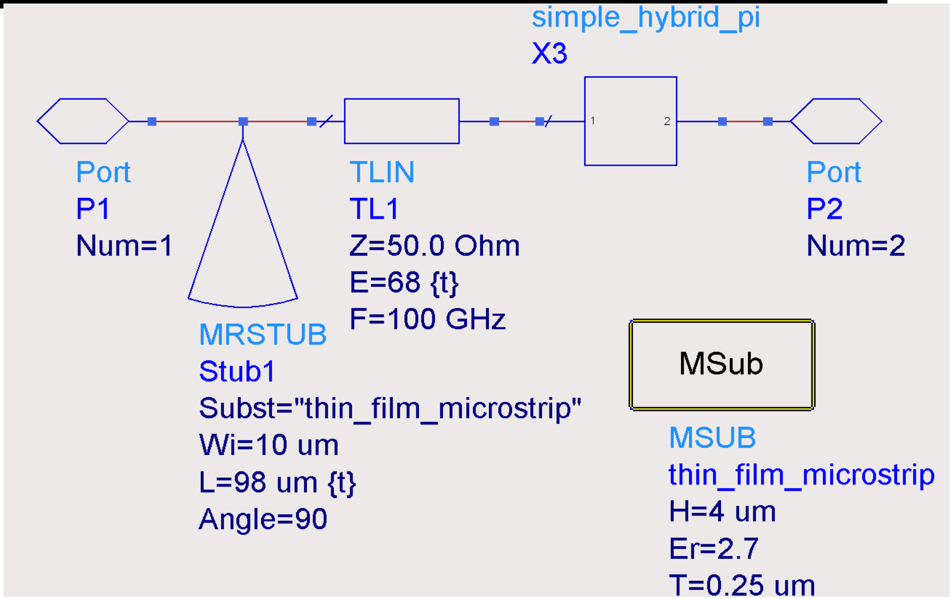
Combination brings load to $Y/Y_0 = 1 + j0$

Radial stub:

a wedge-shaped capacitor with distributed effects accurately modelled.

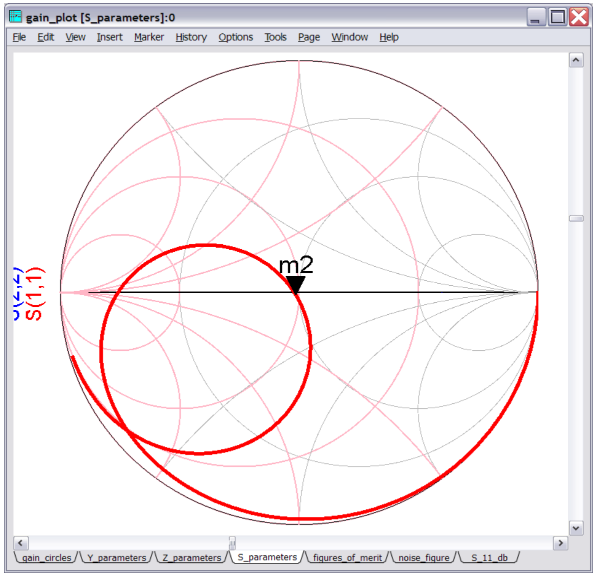
3rd Shunt-Stub Matching Network

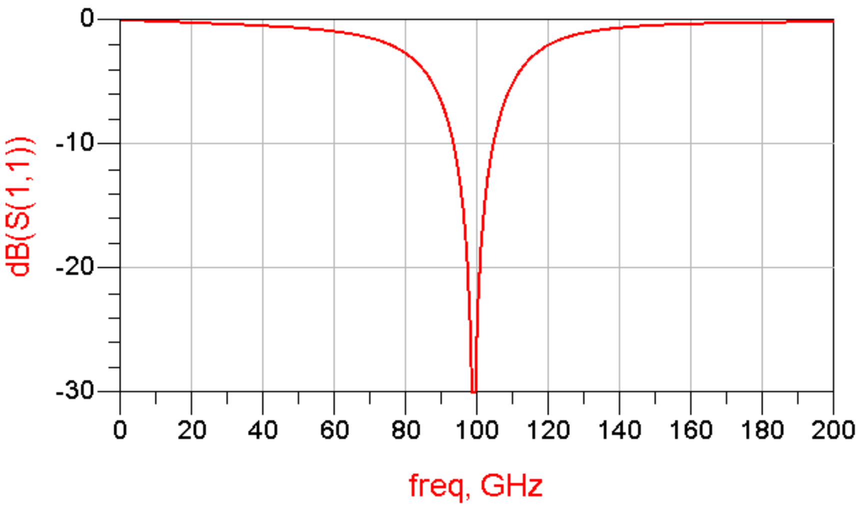
Final Values



Performance vs Frequency

(DC - 200 GHz frequency sweep, marker at 100 GHz)





Shunt-Stub Matching Networks...

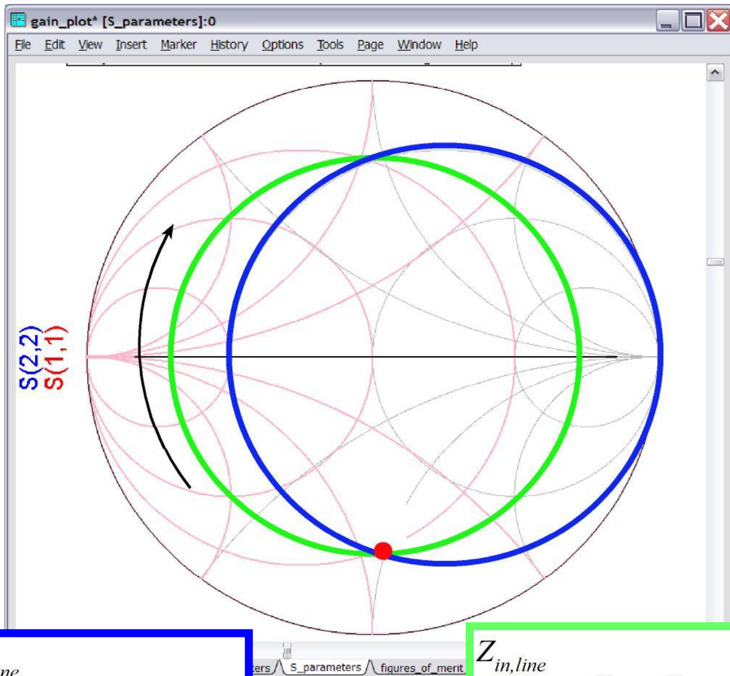
...with general line impedance

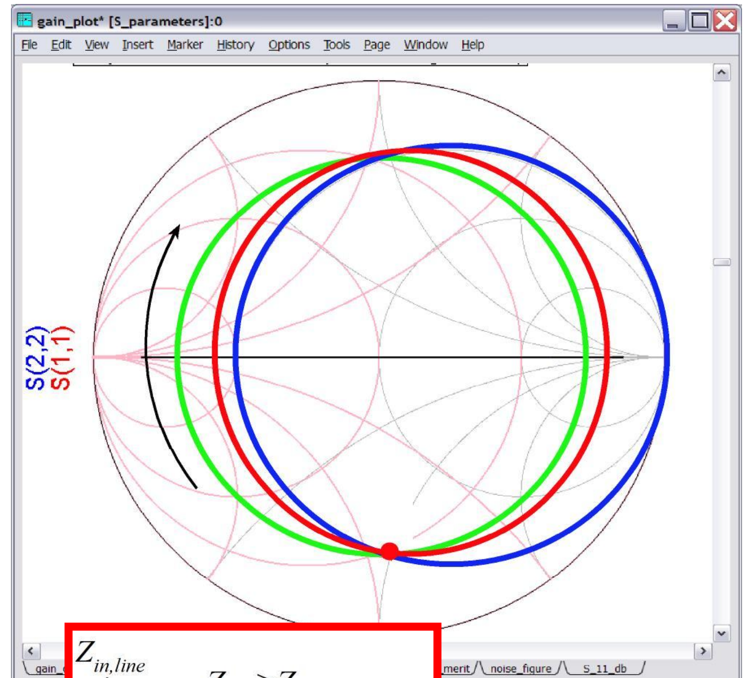
Trajectories for Adding a High-Zo Series Line

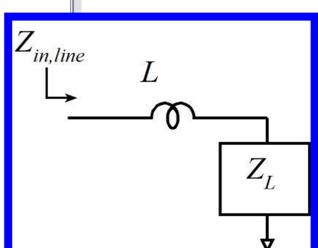
Adding Series inductance

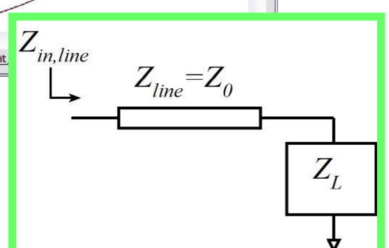
Adding series line $Z_{line} = Z_0$

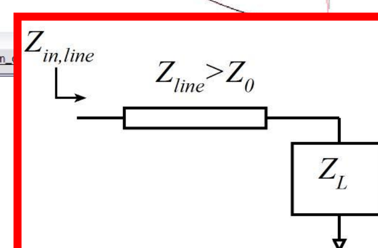
Adding series line $Z_{line} > Z_0$





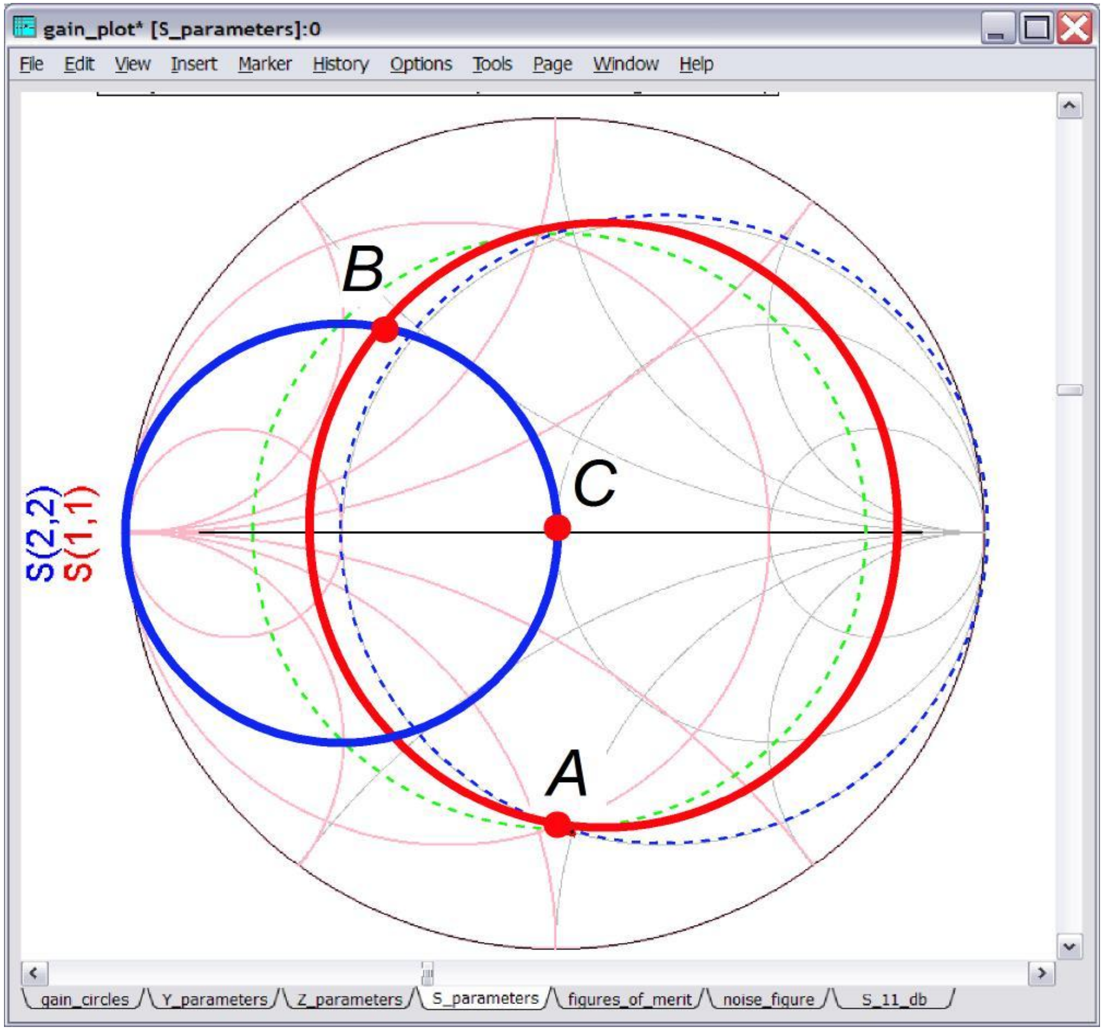


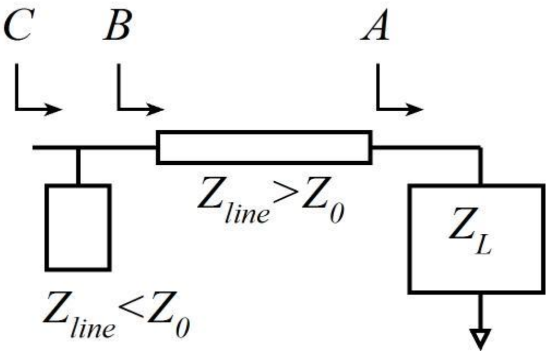




Behavior is intermediate between series inductance & series line of impedance Z_0

Matching Network with High-Zo Series & Low-Zo Shunt Lines



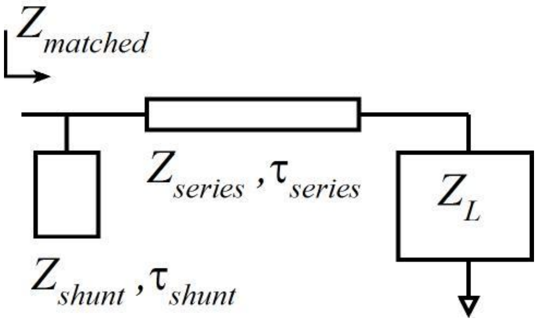


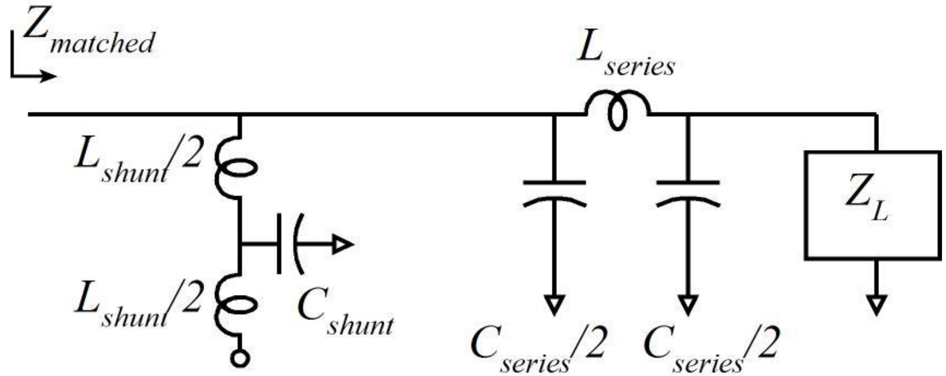
Series line brings load to $Y/Y_0 = 1 \pm jB$

Shunt stub adds $Y_{stub}/Y_0 = \mp jB$

Series line is mostly inductive, shunt line is mostly capacitive.

Lumped vs. Distributed Matching Networks





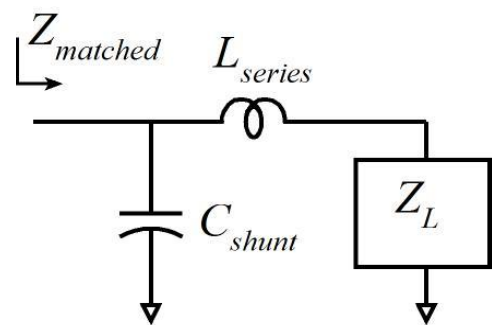
$$L_{shunt} = \tau_{shunt} Z_{shunt} \quad C_{shunt} = \frac{\tau_{shunt}}{Z_{shunt}} \qquad L_{series} = \tau_{series} Z_{series} \quad C_{series} = \frac{\tau_{series}}{Z_{series}}$$

If we force $Z_{series} \to \infty$ and $Z_{shunt} \to 0$,

while holding L_{series} & C_{shunt} constant,

then $C_{series} = L_{series} / Z_{series}^2 \to 0$

and $L_{shunt} = C_{shunt} Z_{shunt}^2 \to 0$



L-C matching network is limiting case of high-Z/low-Z network.

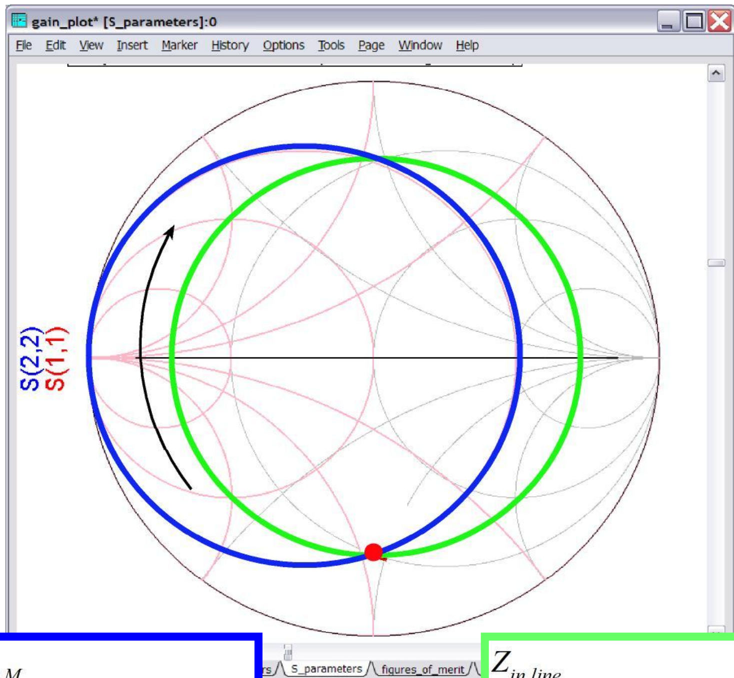
Distributed matching networks can be approximated by LC networks

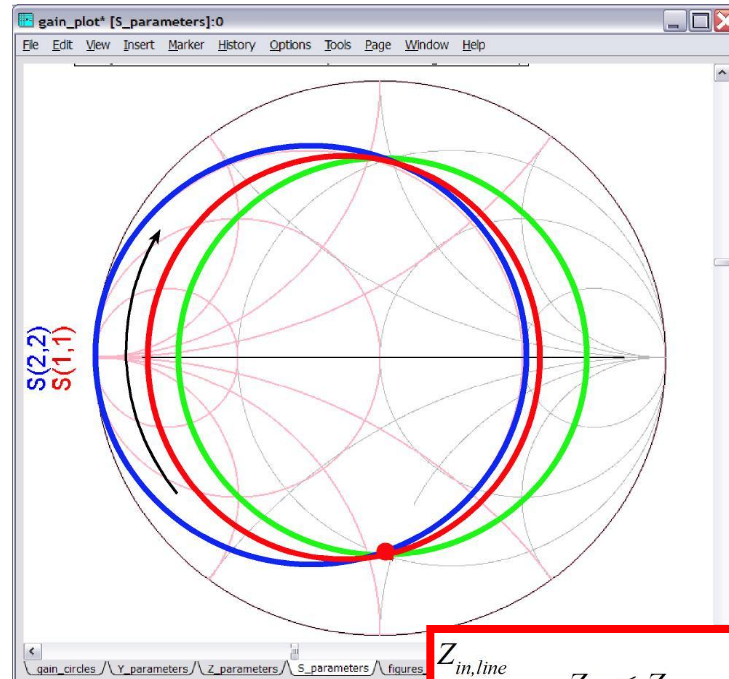
Trajectories for Adding a Low-Zo Series Line

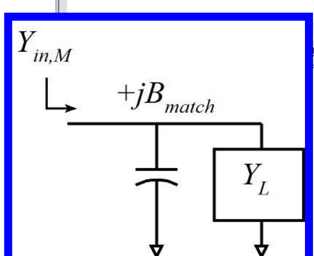
Adding shunt capacitance

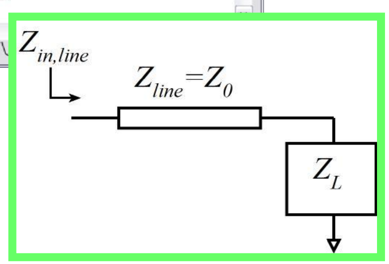
Adding series line $Z_{line} = Z_0$

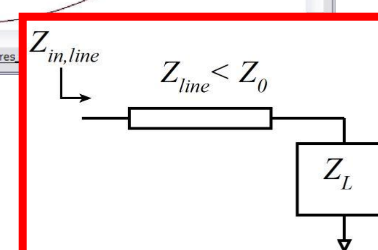
Adding series line $Z_{line} < Z_0$





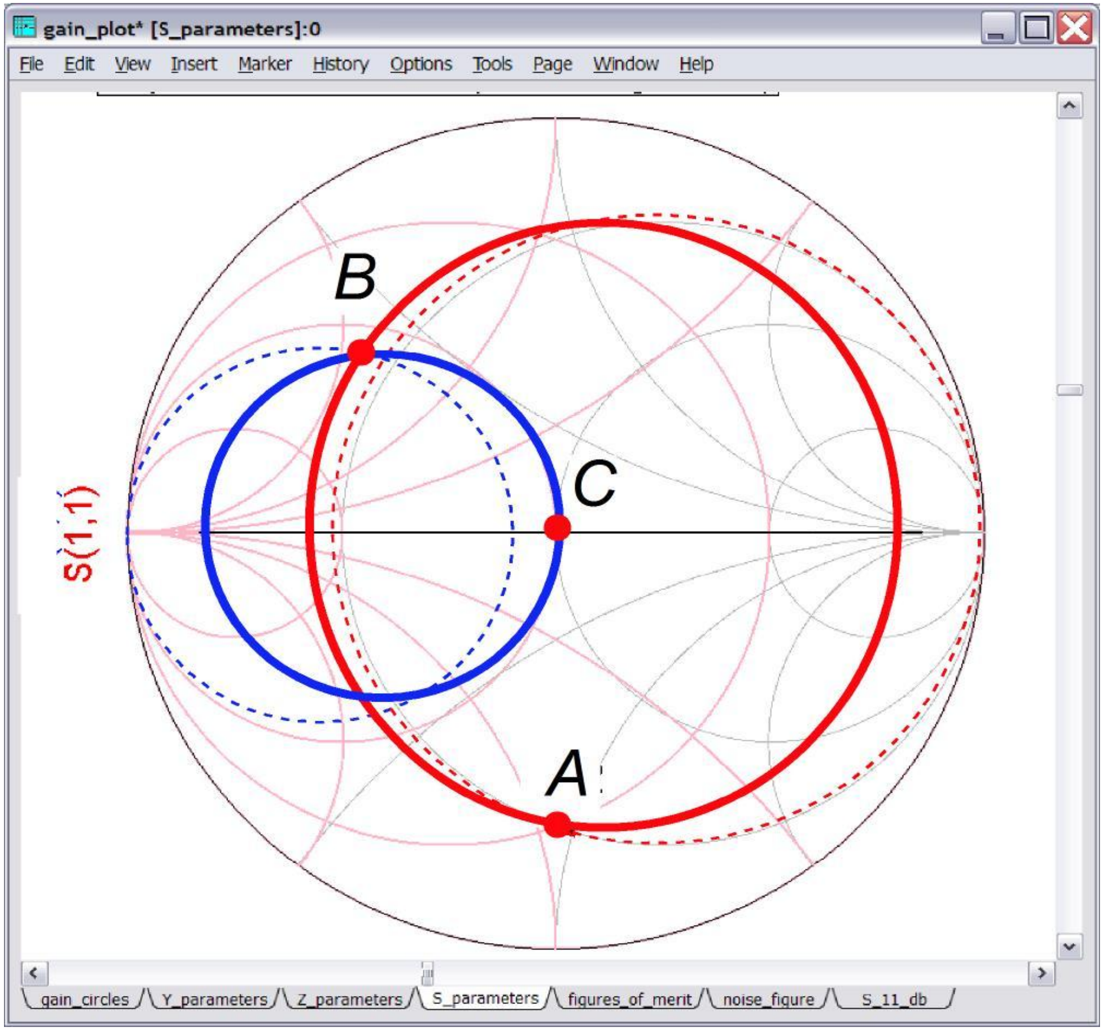


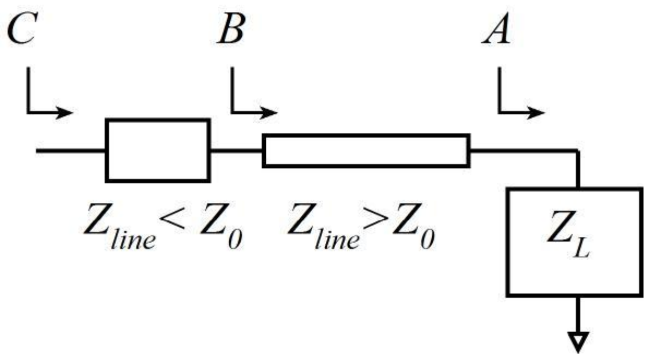




Behavior is intermediate between shunt capacitance & series line of impedance Z_0

Matching Network with High-Zo Series & Low-Zo Series Lines



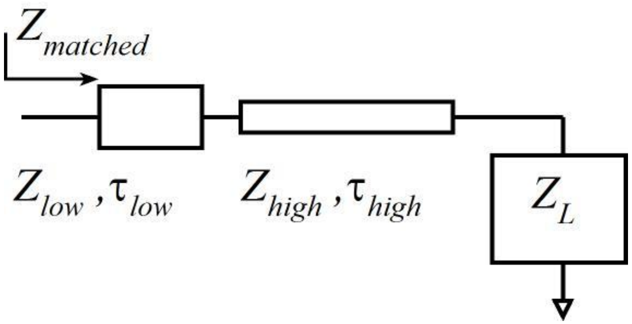


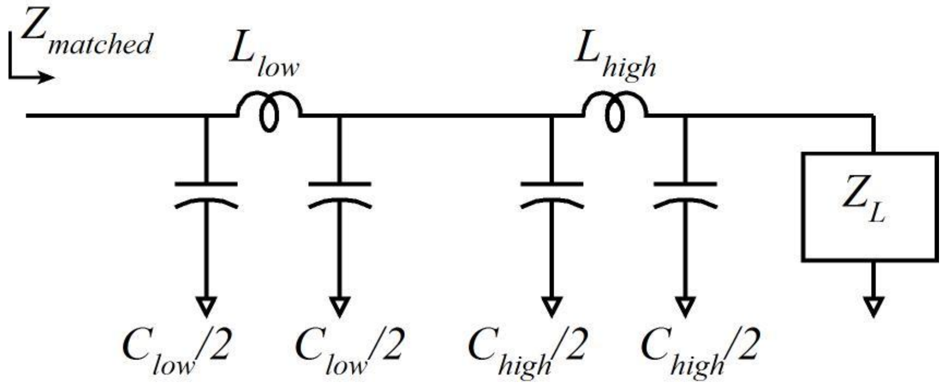
Series line is mostly inductive.

Shunt line is mostly capacitive

Dotted lines show lumped (L,C) trajectory

Lumped vs. Distributed Matching Networks





$$L_{high} = \tau_{high} Z_{high} \qquad C_{high} = \frac{\tau_{high}}{Z_{high}}$$

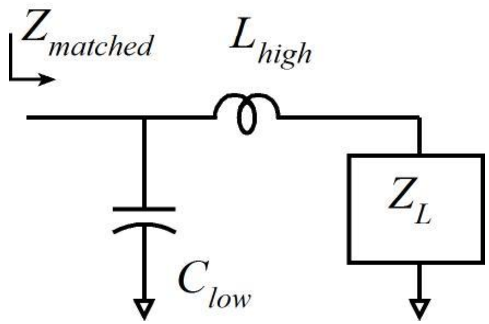
$$L_{low} = \tau_{low} Z_{low} \qquad C_{low} = \frac{\tau_{low}}{Z_{low}}$$

If we force $Z_{high} \to \infty$ and $Z_{low} \to 0$,

while holding L_{high} & C_{low} constant,

then $C_{high} = L_{high} / Z_{high}^2 \to 0$

and $L_{low} = C_{low} Z_{low}^2 \to 0$

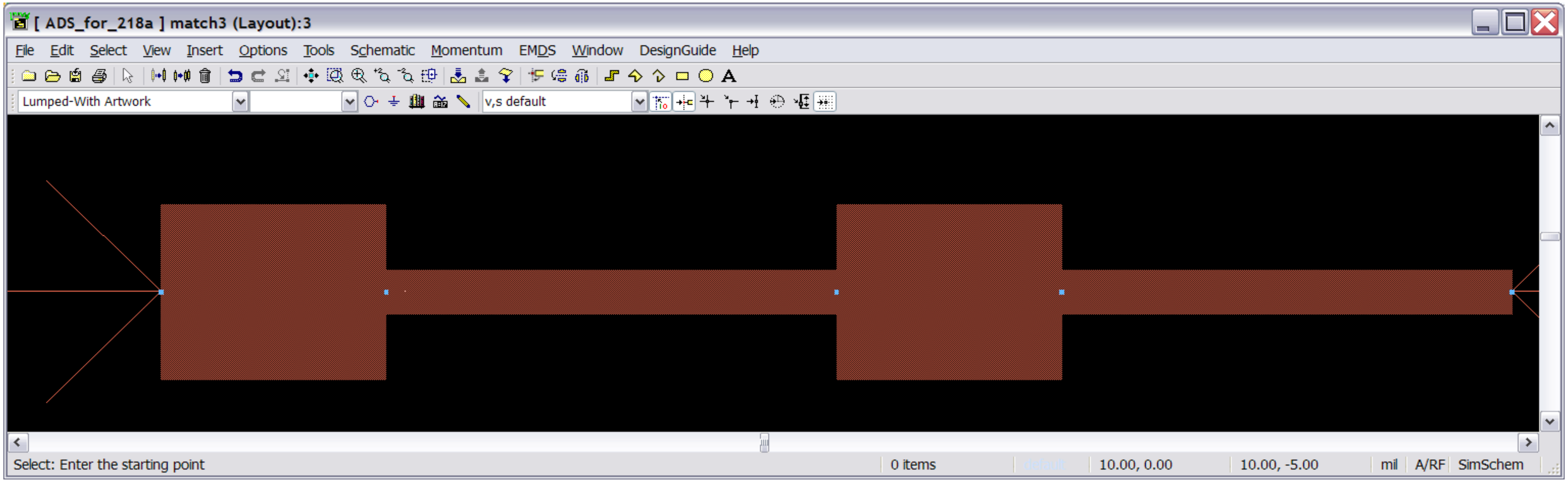


L - C matching network is limiting case of high - Z/low - Z network.

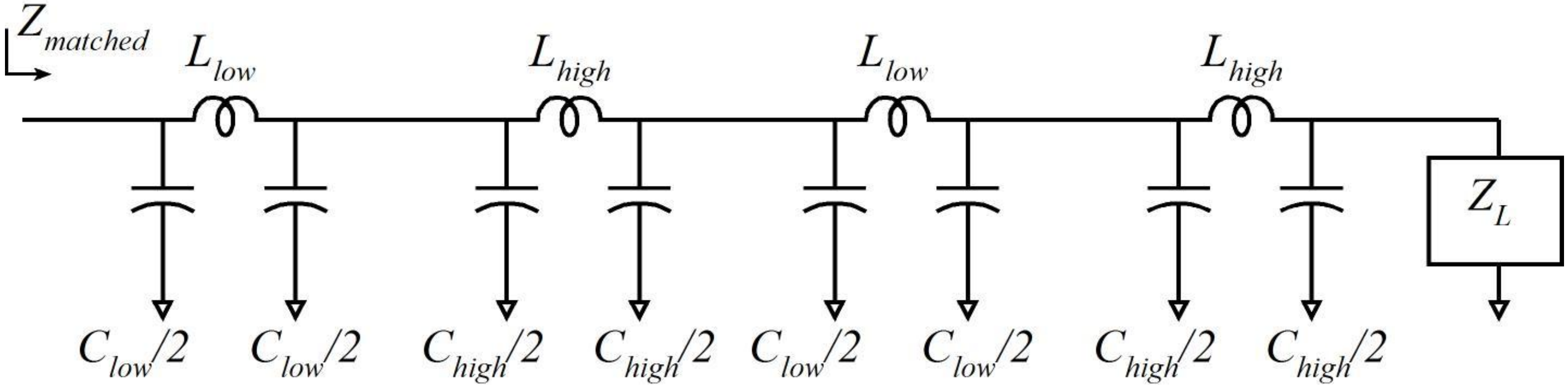
Distributed matching networks can be approximated by LC networks

Lumped vs. Distributed Matching Networks

Given this mask layout…

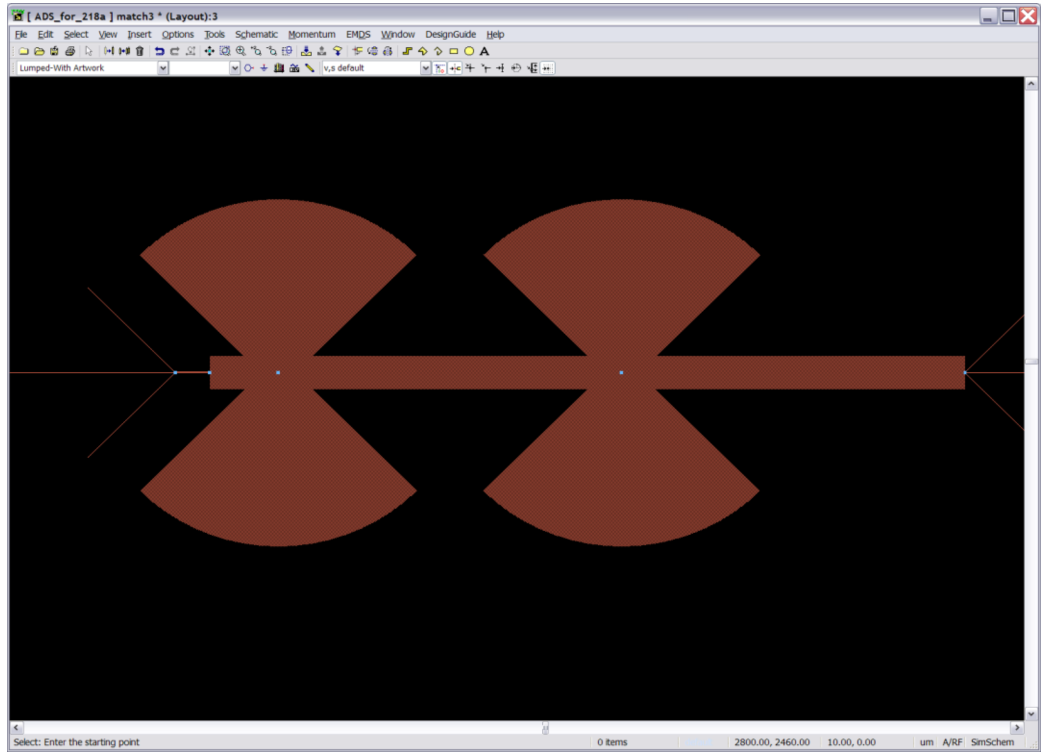


…your eyes should see this.

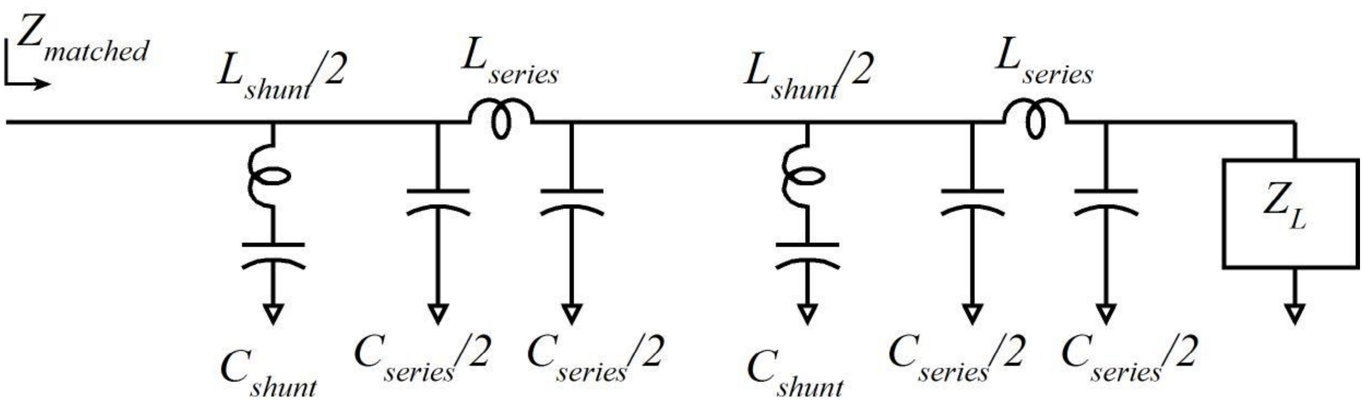


Lumped vs. Distributed Matching Networks

Given this mask layout…

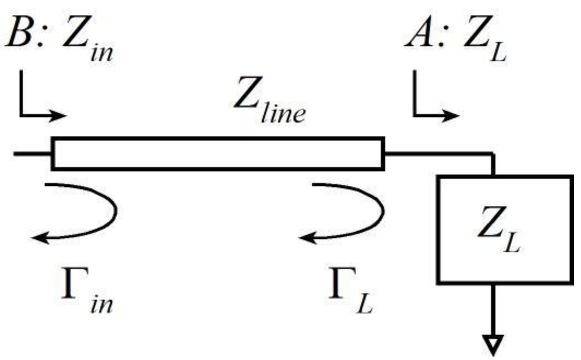


…your eyes should see this.



Quarter-wave and related Matching Networks...

Quarter-wave Impedance Tranformer



$$\text{At load}: \frac{Z_L}{Z_{line}} = \frac{1+\tilde{\Gamma}_L}{1-\tilde{\Gamma}_L}$$

$$\text{At input}: \frac{Z_{in}}{Z_{line}} = \frac{1+\tilde{\Gamma}_{in}}{1-\tilde{\Gamma}_{in}}$$

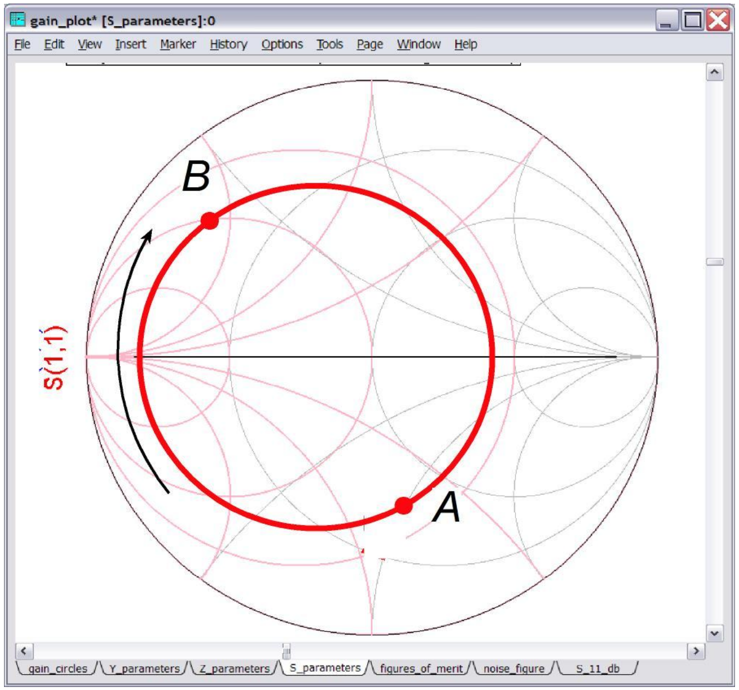
But:

$$\tilde{\Gamma}_{in} = \tilde{\Gamma}_L e^{-j4\pi l/\lambda} = -\tilde{\Gamma}_L \text{ if } l = \lambda/4$$

So:

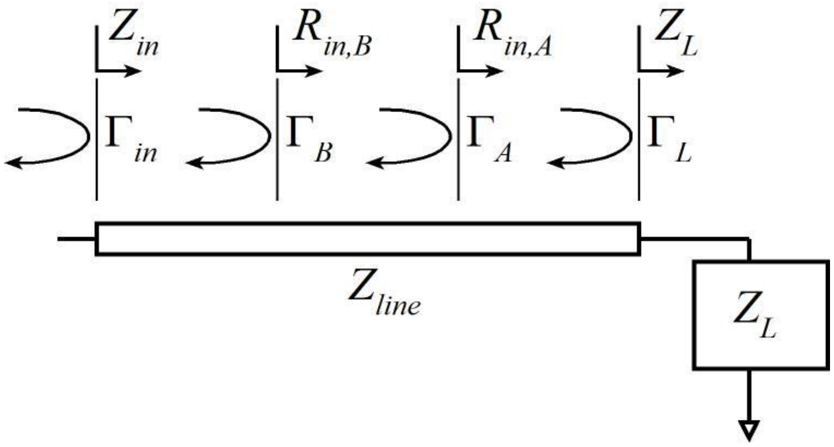
$$\frac{Z_{in}}{Z_{line}} = \left(\frac{Z_L}{Z_{line}}\right)^{-1} \text{ if } l = \lambda/4$$

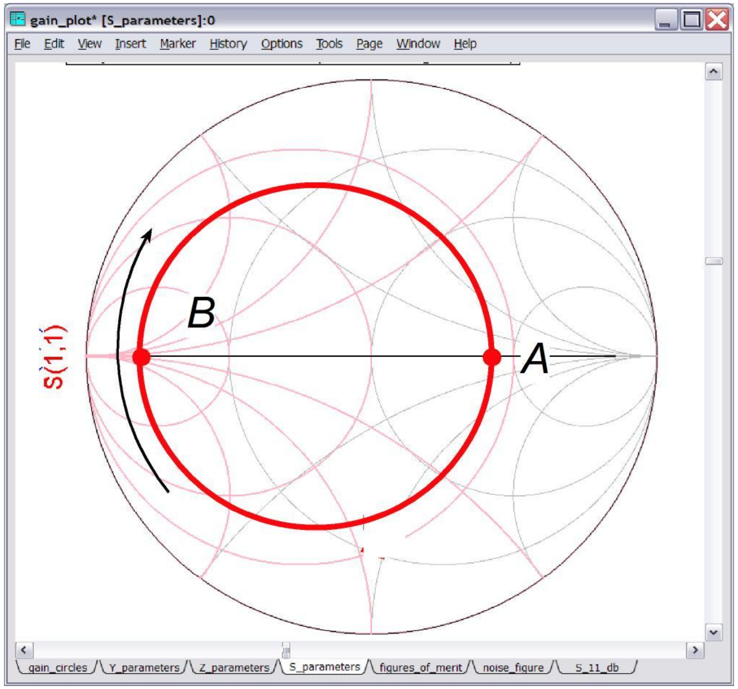
$$Z_{in} Z_L = Z_{line}^2 \text{ if } l = \lambda/4$$



$\tilde{\Gamma}_L$ and $\tilde{\Gamma}_{in}$ are relfection coeffiecients using Z_{line} as the impedance standard, not Z_0

Insight: Series Lines

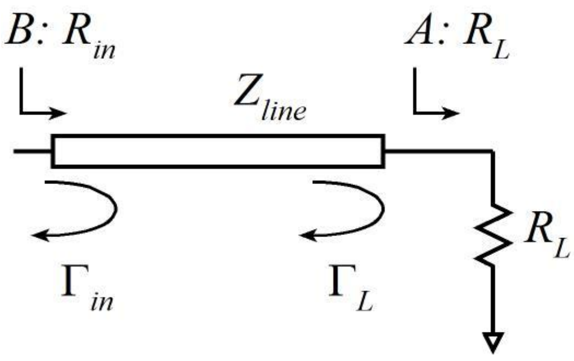


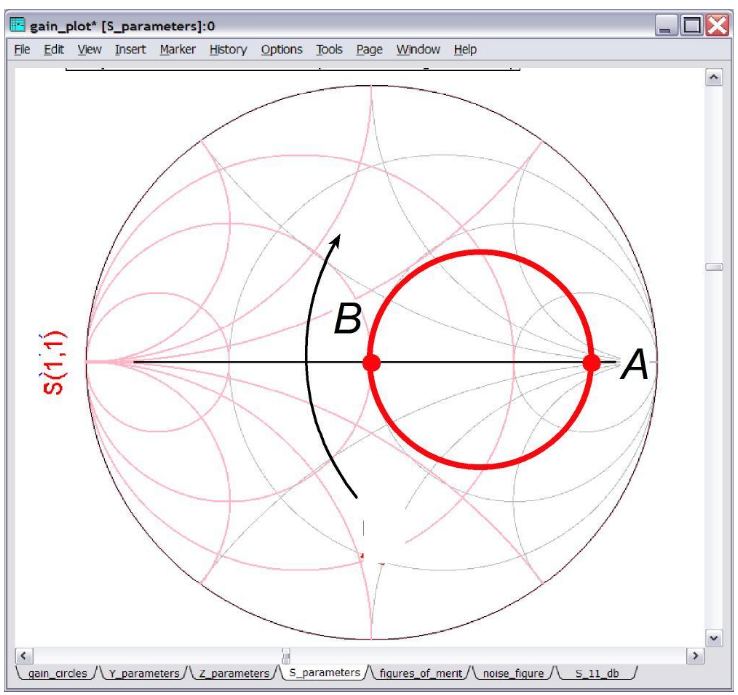


Regardless of the starting point (Z_L), and ending point (Z_{in}), the impedance trajectory contains the points (A, B), with resistive input impedance such that

$$R_{in,A} \cdot R_{in,B} = Z_{line}^2$$

Quarter-wave Impedance Tranformer: Resistive Loads





$$R_{in}R_L = Z_{line}^2$$

Pick line impedance to match Z_{in} to Z_0 :

$$Z_{line} = \sqrt{R_L Z_0}$$

Quarter-wave Impedance Tranformer: General Loads

For a general load impedance $Z_L = 1/Y_L = R_L + jX_L$
where $Y_L = G_L \pm jB_L$, one can add a shunt
susceptance $\mp jB_L$, bringing the load impedance
to $Z'_L = R'_L = 1/G_L$

Then one adds a quarter-wavelength line of impedance

$$Z_{line} = \sqrt{R_L Z_0}$$

to match the input impedance to Z_0.