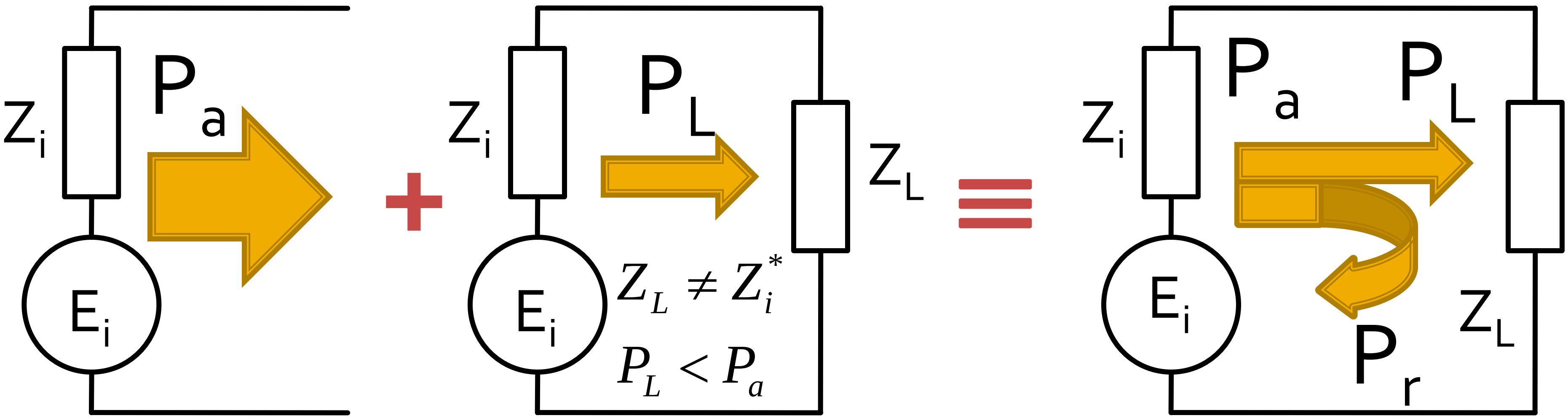
Laboratory 3 (w7-8)

2021/2022

Microwave Devices and Circuits

Short theory

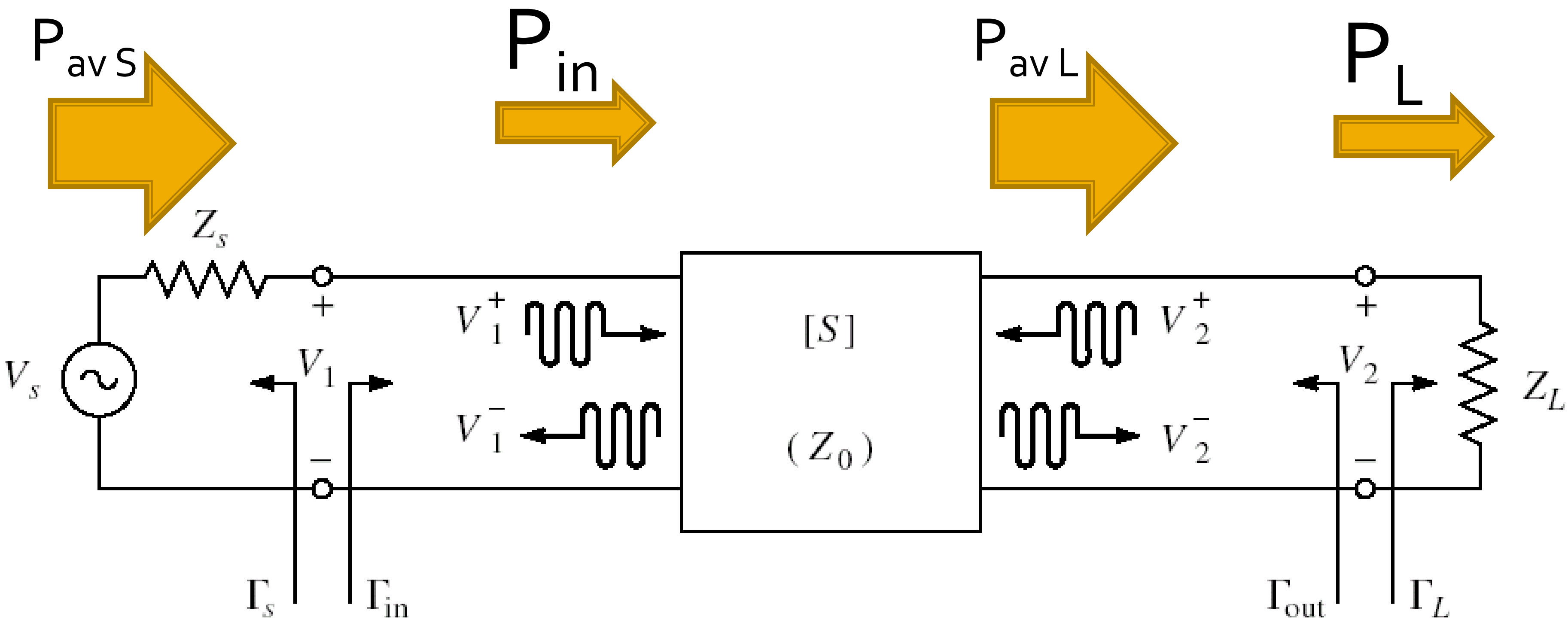
Reflection and power / Model



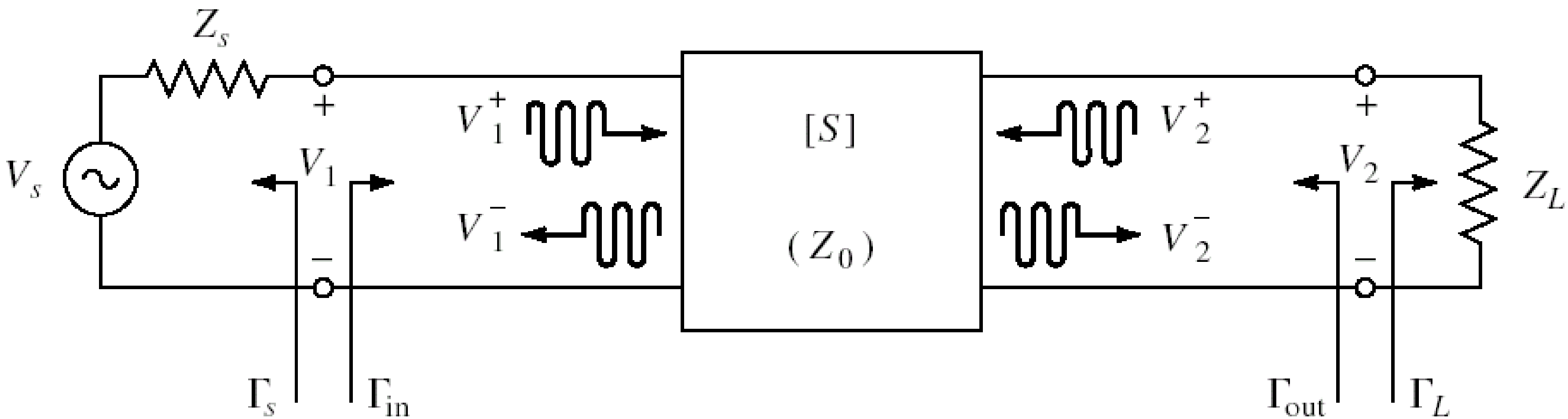
- The source has the ability to sent to the load a certain maximum power (available power) P_a
- For a particular load the power sent to the load is less than the maximum (mismatch) $P_L < P_a$
- The phenomenon is **"as if"** (model) some of the power is reflected $P_r = P_a - P_L$
- The power is a **scalar !**

Power / Matching

- Two ports in which matching influences the power transfer

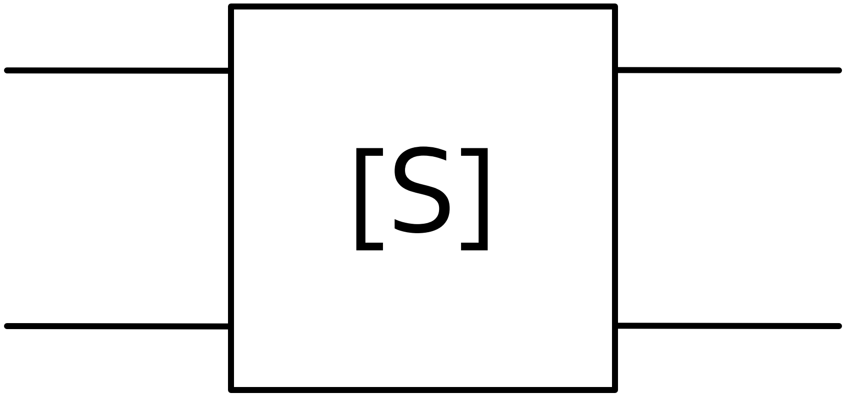


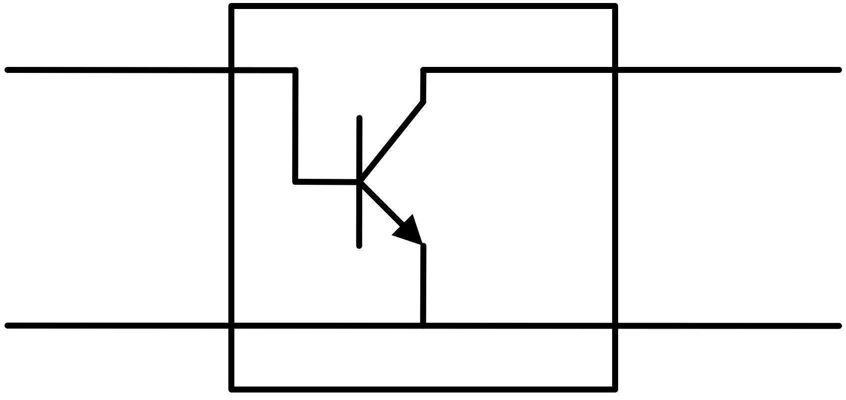
Amplifier as two-port

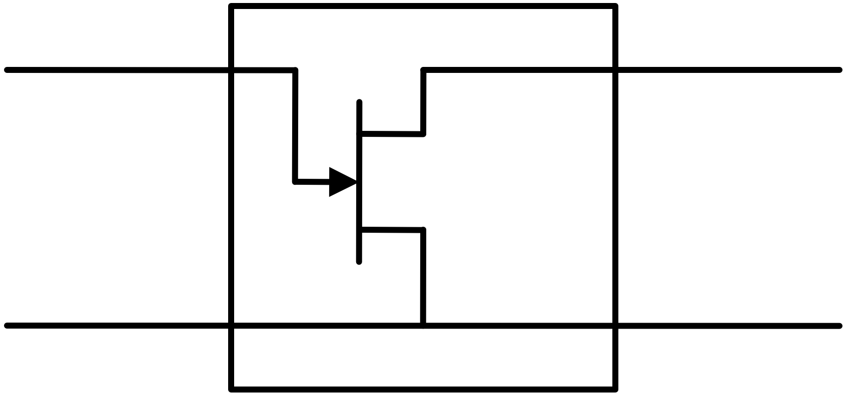


- Charaterized with S parameters
- normalized at Zo (implicit 50Ω)
- Datasheets: S parameters for specific bias conditions

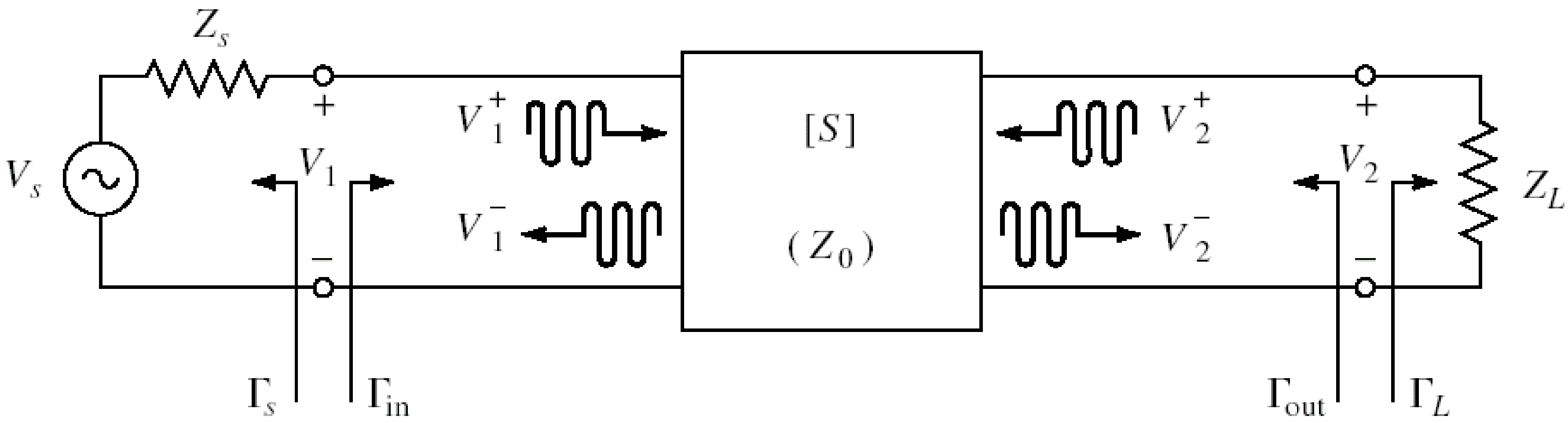
S parameters







Amplifier as two-port



- For an amplifier two-port we are interested in:
  - **stability**
  - power gain
  - noise (sometimes – small signals)
  - linearity (sometimes – large signals)

Stability

$$|\Gamma_{in}| < 1 \qquad \left| S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L} \right| < 1$$

- We can calculate conditions to be met by Γ_L to achieve stability

$$|\Gamma_{out}| < 1 \qquad \left| S_{22} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_S}{1 - S_{11} \cdot \Gamma_S} \right| < 1$$

- We can calculate conditions to be met by Γ_S to achieve stability

Output stability circle (CSOUT)

$$\left|\Gamma_L - \frac{\left(S_{22} - \Delta \cdot S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}\right| = \left|\frac{S_{12} \cdot S_{21}}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}\right| \qquad \left|\Gamma_L - C_L\right| = R_L$$

- We obtain the equation of a circle in the complex plane, which represents the locus of Γ_L for the **limit between stability and instability** ($|\Gamma_{in}| = 1$)
- This circle is the **output stability circle** (Γ_L)

$$C_L = \frac{\left(S_{22} - \Delta \cdot S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2} \qquad R_L = \frac{\left|S_{12} \cdot S_{21}\right|}{\left|\left|S_{22}\right|^2 - \left|\Delta\right|^2\right|}$$

Input stability circle (CSIN)

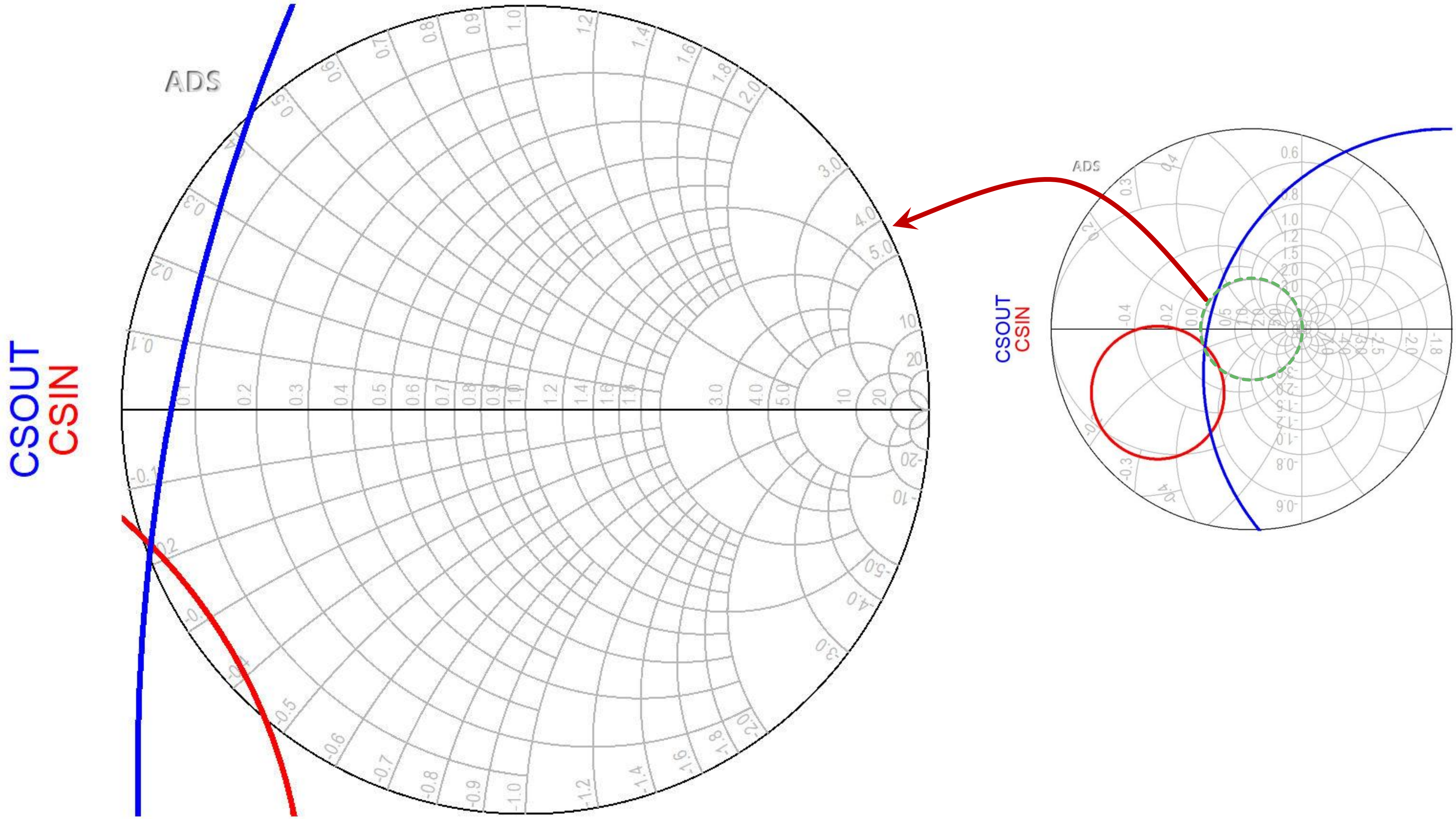
- Similarly

$$|\Gamma_{out}| = 1 \qquad \left| S_{22} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_S}{1 - S_{11} \cdot \Gamma_S} \right| = 1$$

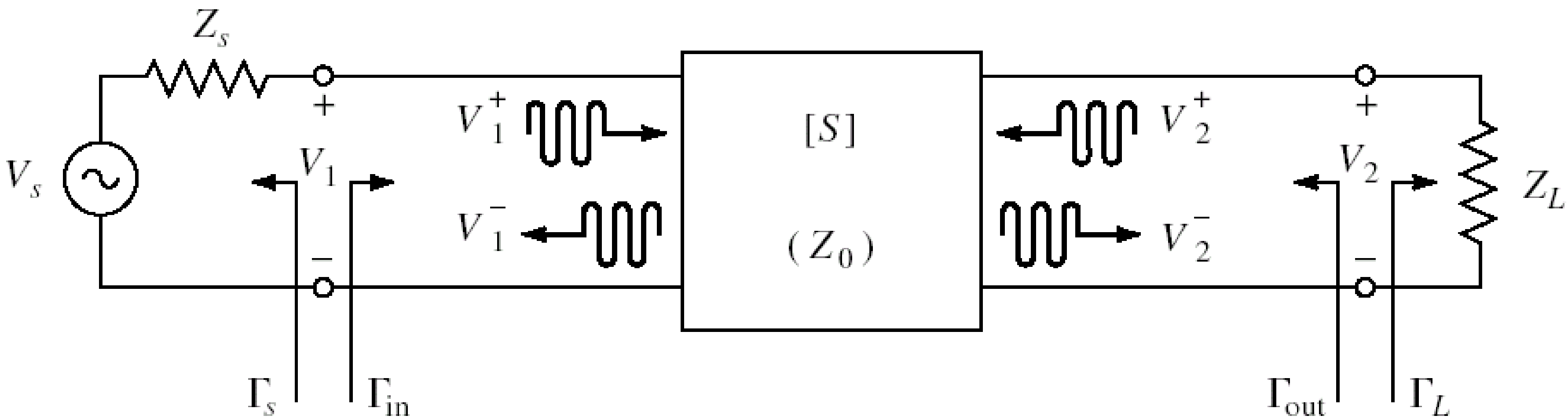
- We obtain the equation of a circle in the complex plane, which represents the locus of Γ_S for the **limit between stability and instability** ($|\Gamma_{out}| = 1$)
- This circle is the **input stability circle** (Γ_S)

$$C_S = \frac{\left(S_{11} - \Delta \cdot S_{22}^*\right)^*}{|S_{11}|^2 - |\Delta|^2} \qquad R_S = \frac{|S_{12} \cdot S_{21}|}{\left||S_{11}|^2 - |\Delta|^2\right|}$$

ADS



Amplifier as two-port



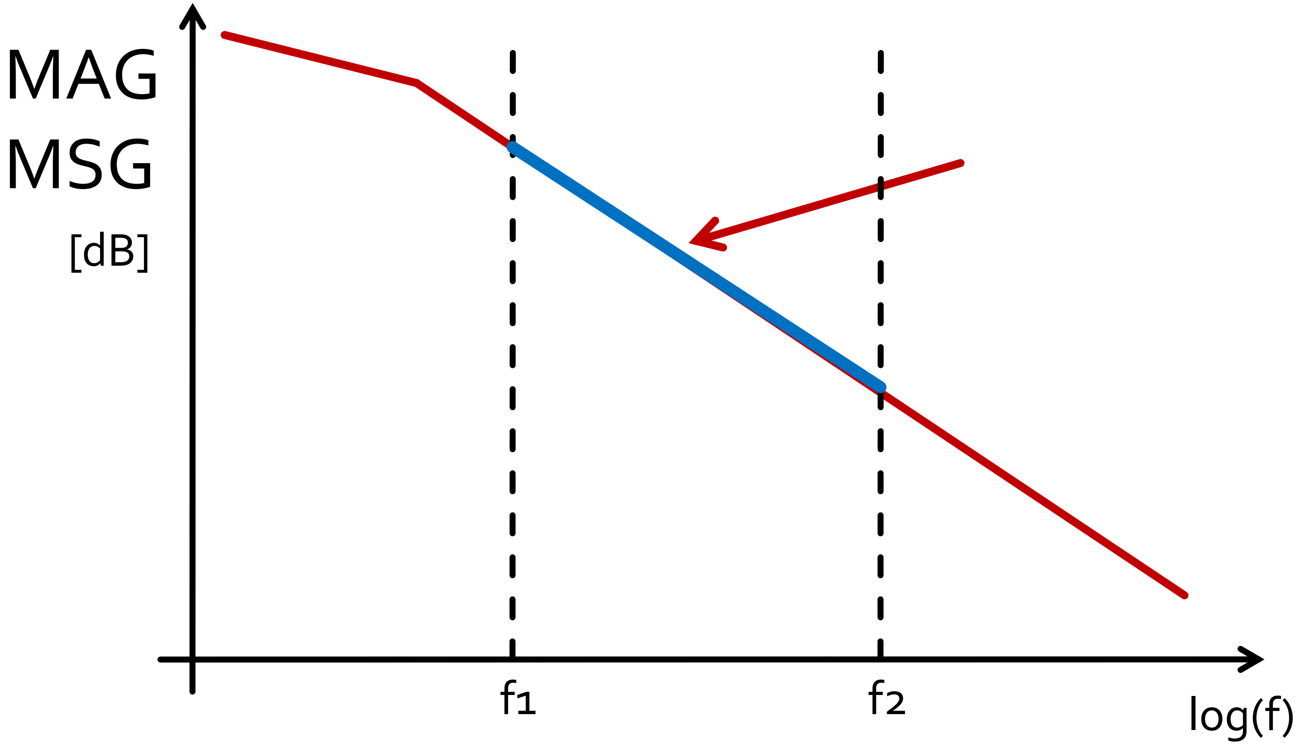
- For an amplifier two-port we are interested in:
  - stability
  - **power gain**
  - noise (sometimes – small signals)
  - linearity (sometimes – large signals)

Design for Specified Gain

- In many cases we need an approach other than "brute force" when we prefer to design for **less than the maximum obtainable gain**, in order to:
  - improve noise behavior (L3 + C9)
  - improve stability
  - improve VSWR
  - control performance at multiple frequencies
  - improve amplifier's bandwidth

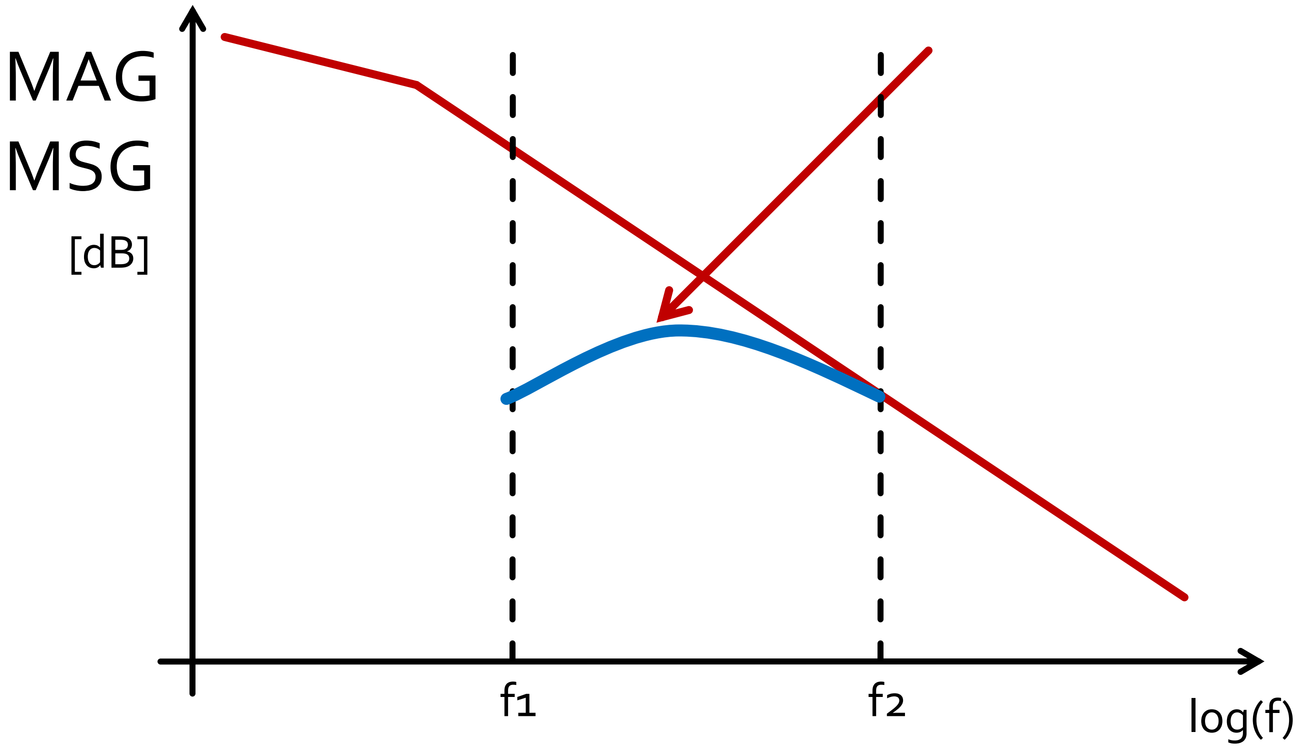
Wide bandwidth amplifier

- Design for maximum gain at two different frequencies creates an frequency unbalanced amplifier

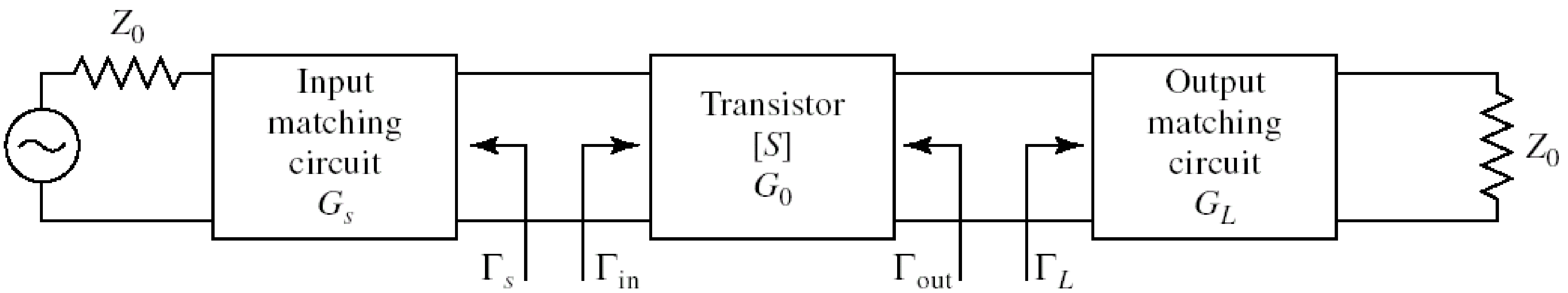


Wide bandwidth amplifier

- Design for maximum gain at highest frequency
- Controlled mismatch at lower frequency
  - eventually at more frequencies inside the bandwidth



Design for Specified Gain



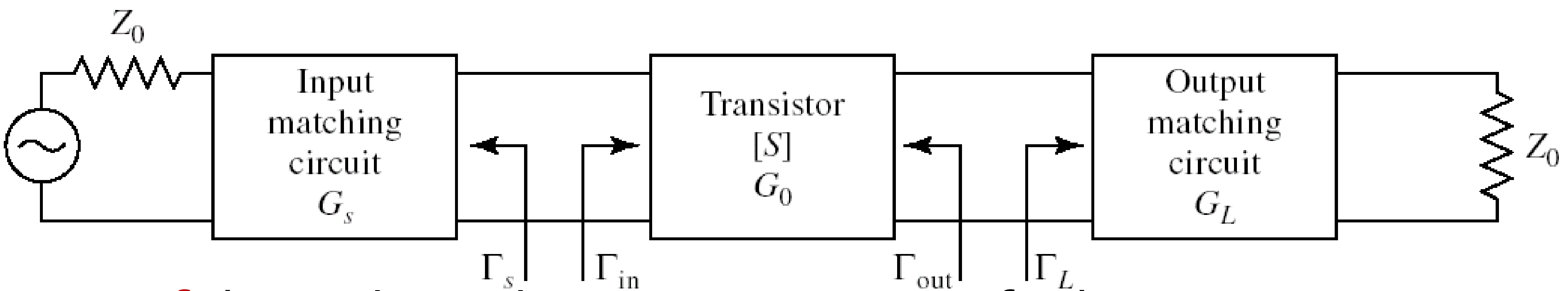
- In the unilateral assumption:

$$G_{TU} = \frac{1-|\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2}\cdot|S_{21}|^2\cdot\frac{1-|\Gamma_L|^2}{|1-S_{22}\cdot\Gamma_L|^2}$$

$$G_S = \frac{1-|\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2} \qquad G_0 = |S_{21}|^2 \qquad G_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\cdot\Gamma_L|^2}$$

$$\boxed{G_S = G_S(\Gamma_S)} \qquad \boxed{G_L = G_L(\Gamma_L)}$$

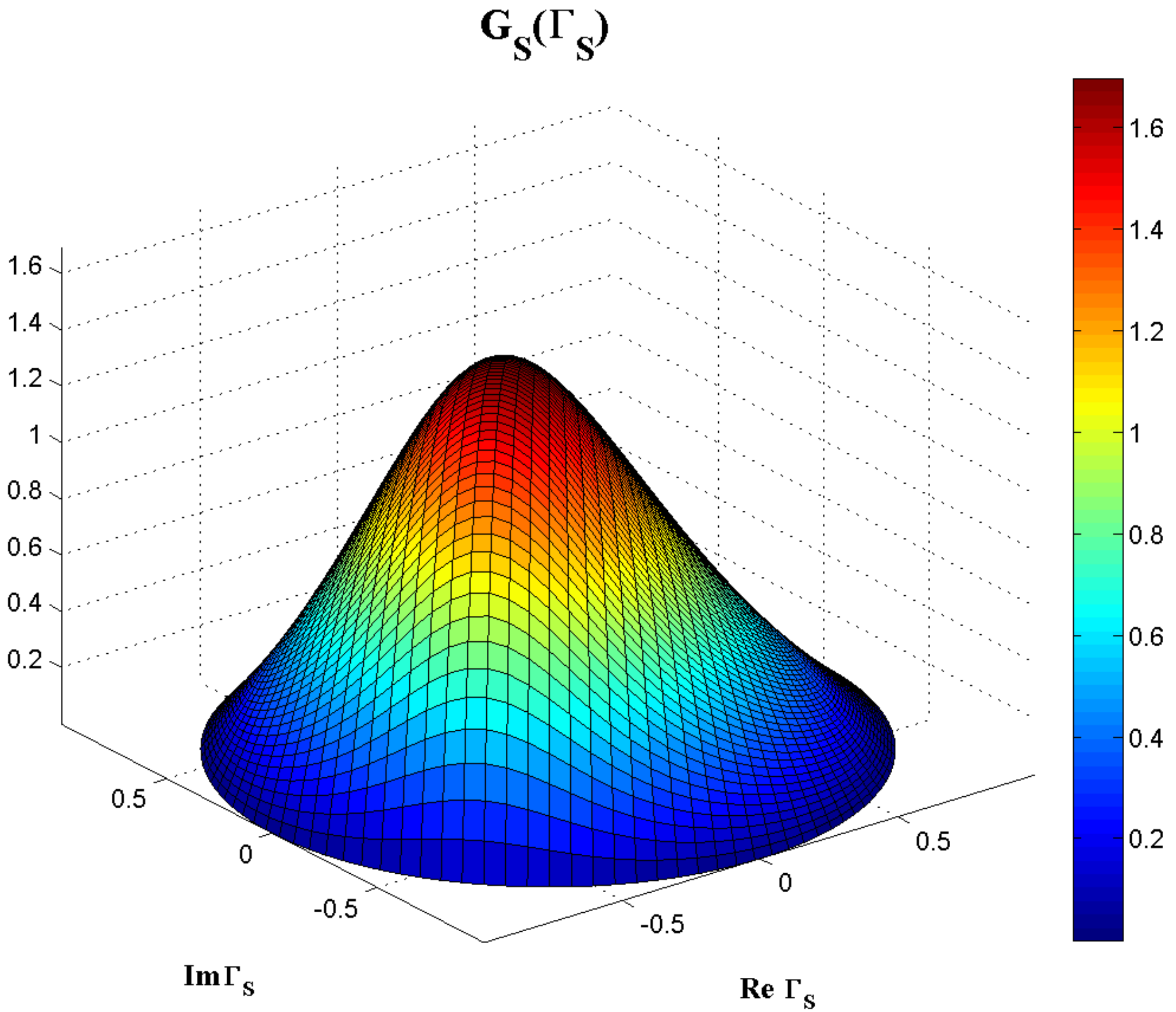
Design for Specified Gain



- **If** the unilateral assumption is justified :
  - power gain added by the input matching circuit **is not** influenced by the output matching circuit $G_S = G_S(\Gamma_S)$
  - power gain added by the output matching circuit **is not** influenced by the input matching circuit $G_L = G_L(\Gamma_L)$
- Output /Input match can be designed independently
  - We can impose different demands for input/output
  - Total gain is:

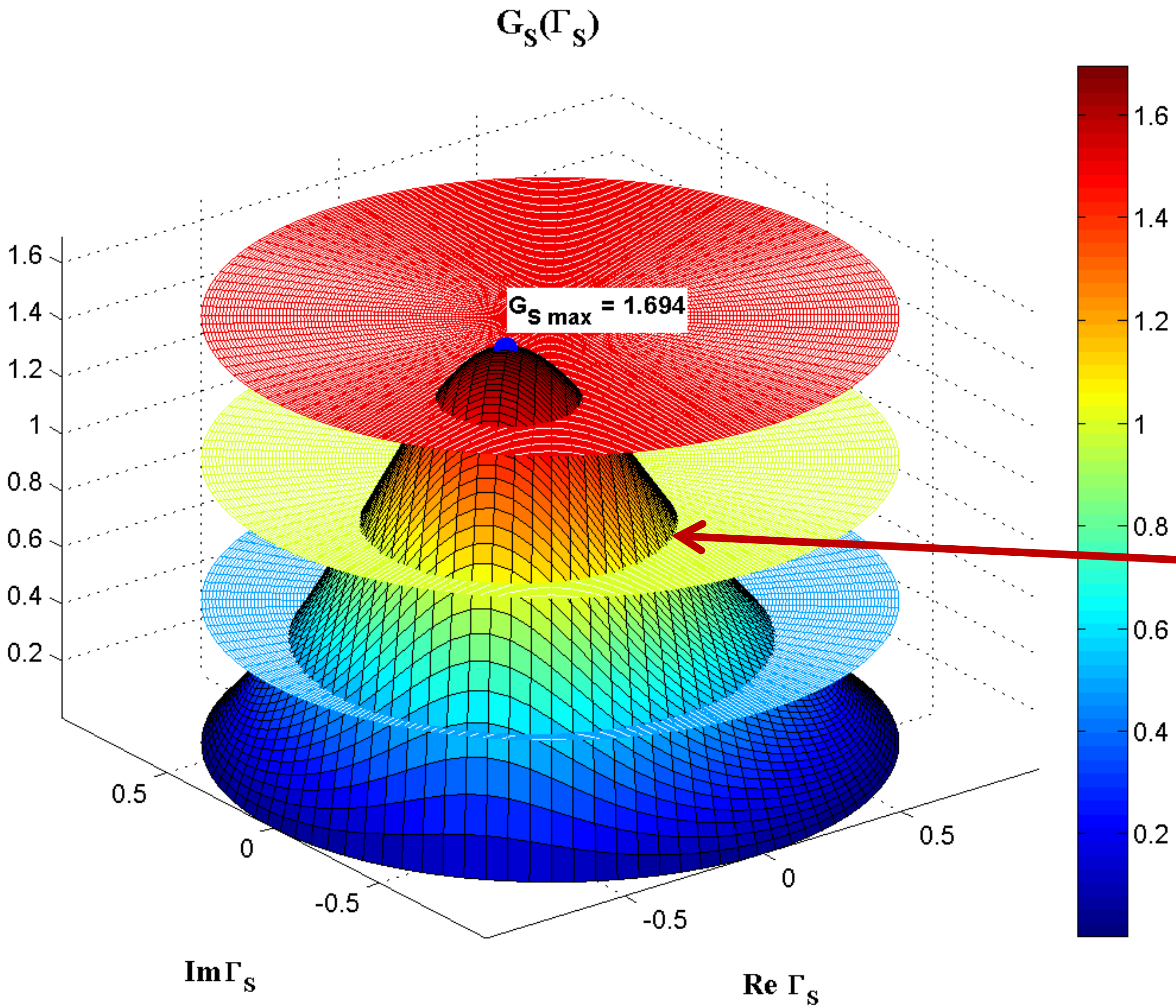
$$G_T = G_S \cdot G_0 \cdot G_L \qquad G_T[dB] = G_S[dB] + G_0[dB] + G_L[dB]$$

$G_S(\Gamma_S)$



$$G_S = \frac{1-|\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2}$$

$G_S(\Gamma_S)$, constant value contours



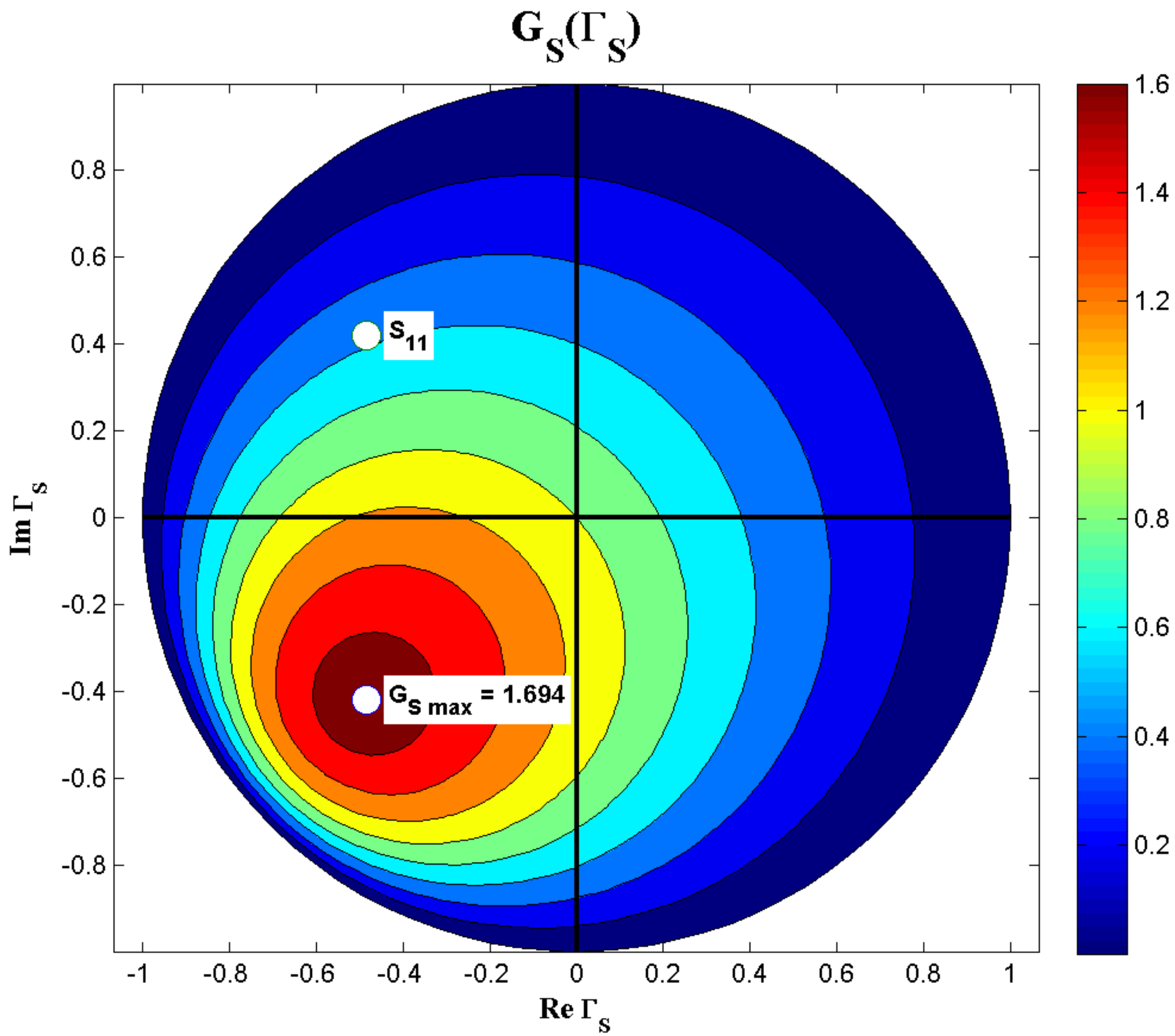
$G_S = 1.5$

$G_S = 1.0$

$G_S = 0.5$

Circles

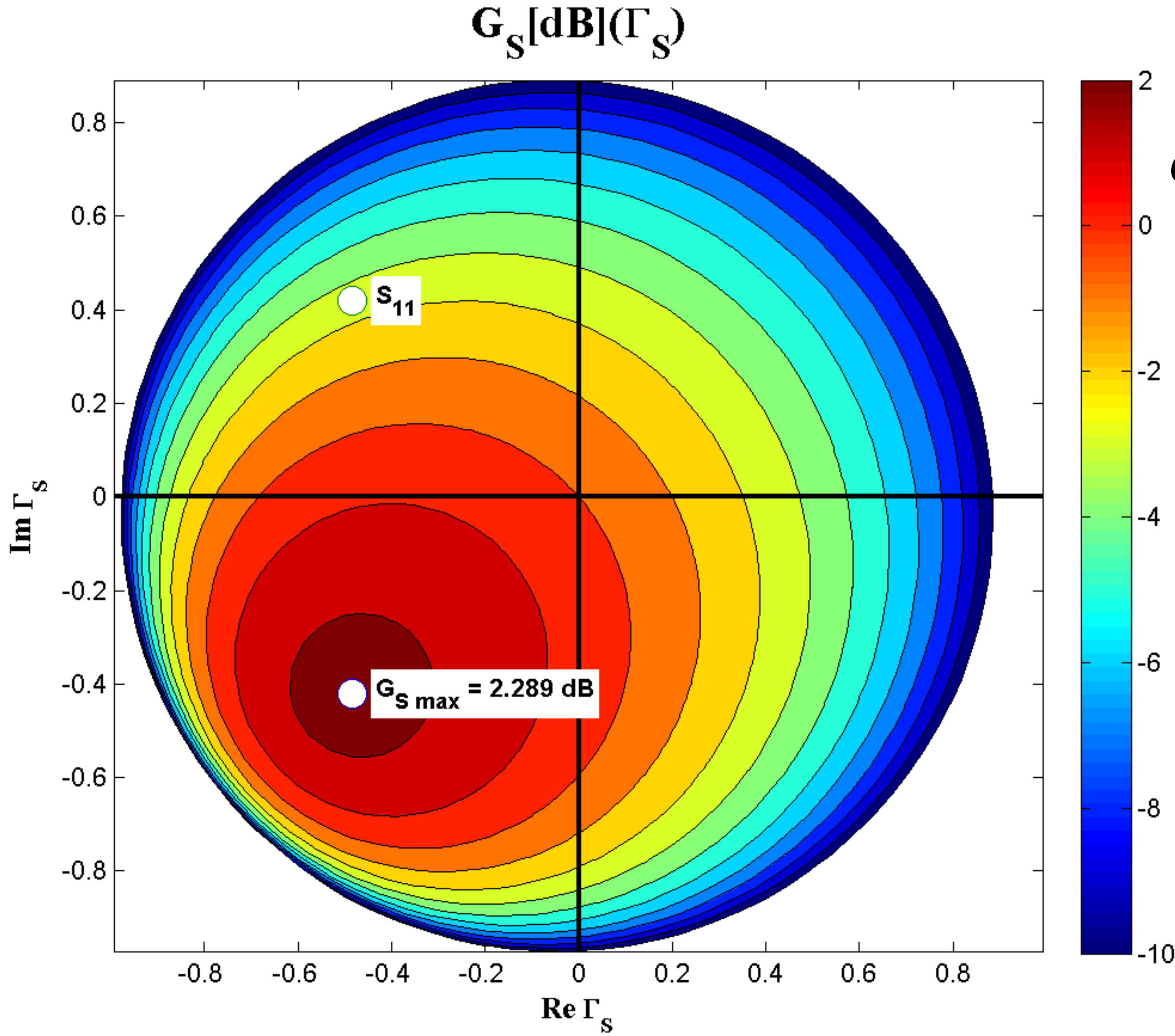
$G_S(\Gamma_S)$, constant value contours



$$G_S = \frac{1-\left|\Gamma_S\right|^2}{\left|1-S_{11}\cdot\Gamma_S\right|^2}$$

$$G_{S\max} = G_S\Big|_{\Gamma_S = S_{11}^*}$$

G_S[dB](Γ_S), constant value contours



$$G_S[dB] = 10 \cdot \log\left(\frac{1-|\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2}\right)$$

$$G_{S\,max} = G_S\big|_{\Gamma_S = S_{11}^*}$$

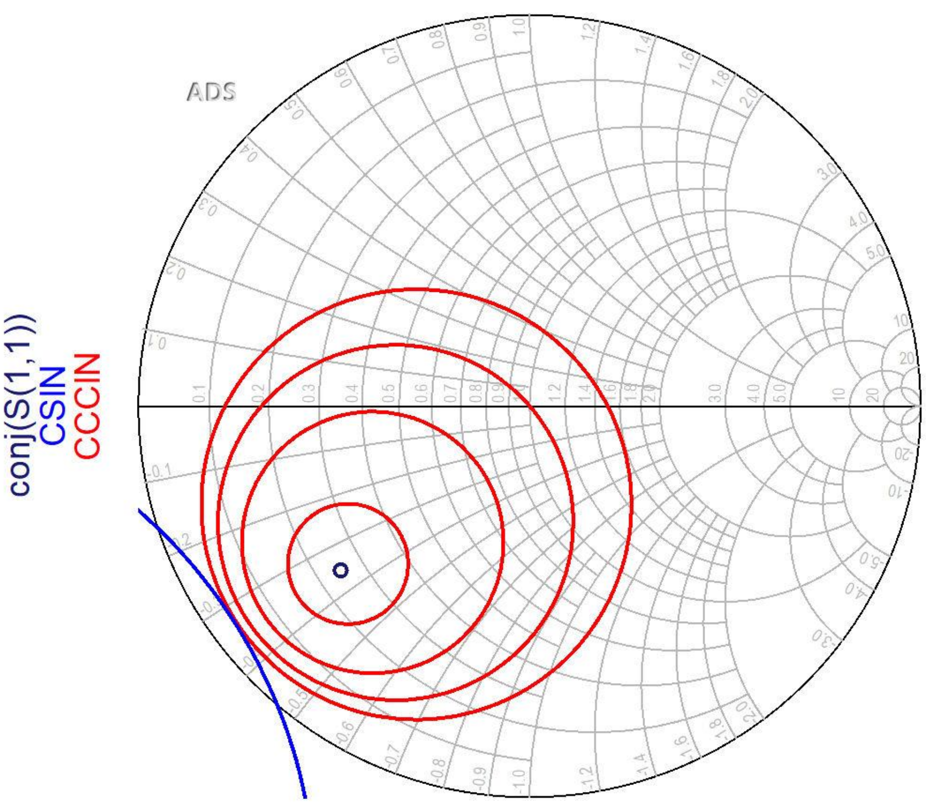
Input section constant gain circles

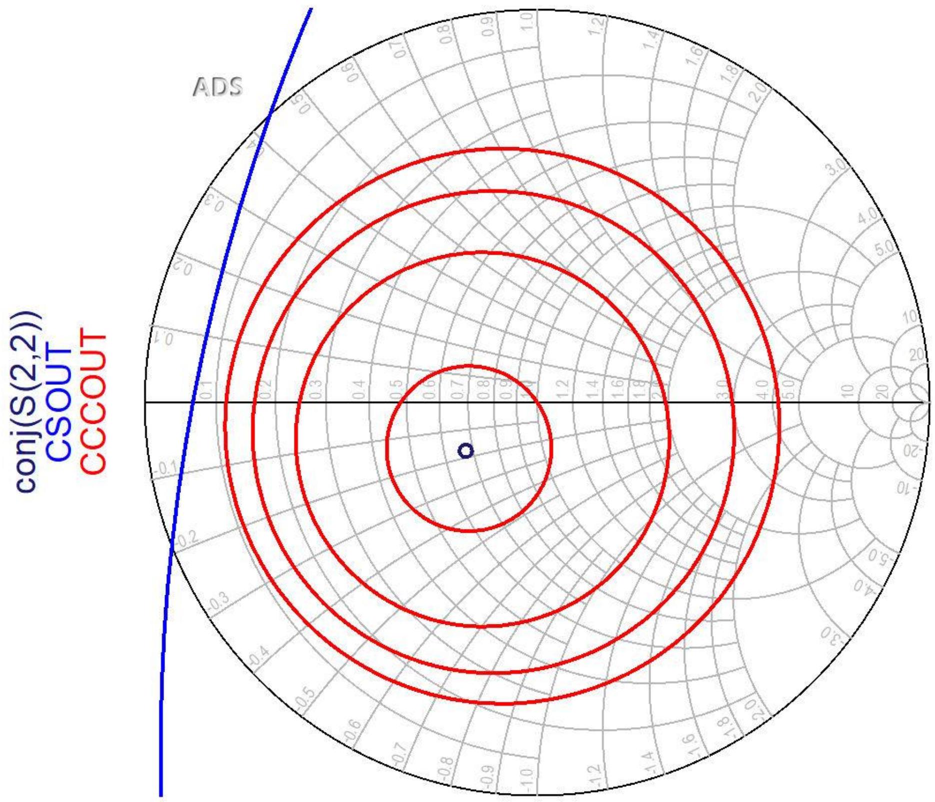
$$\left|\Gamma_S - \frac{g_S \cdot S_{11}^*}{1-(1-g_S)\cdot|S_{11}|^2}\right| = \frac{\sqrt{1-g_S}\cdot\left(1-|S_{11}|^2\right)}{1-(1-g_S)\cdot|S_{11}|^2} \qquad |\Gamma_S - C_S| = R_S$$

$$C_S = \frac{g_S \cdot S_{11}^*}{1-(1-g_S)\cdot|S_{11}|^2} \qquad R_S = \frac{\sqrt{1-g_S}\cdot\left(1-|S_{11}|^2\right)}{1-(1-g_S)\cdot|S_{11}|^2}$$

- Equation of a circle in the complex plane where Γ_S is plotted
- **Interpretation**: Any reflection coefficient Γ_S which plotted in the complex plane lies **on** the circle drawn for $g_{circle} = G_{circle}/G_{Smax}$ will lead to a gain $G_S = G_{circle}$
  - Any reflection coefficient Γ_S plotted **outside** this circle will lead to a gain $G_S < G_{circle}$
  - Any reflection coefficient Γ_S plotted **inside** this circle will lead to a gain $G_S > G_{circle}$
- Similar discussion for output port (Γ_L) **CCCIN/CCCOUT**

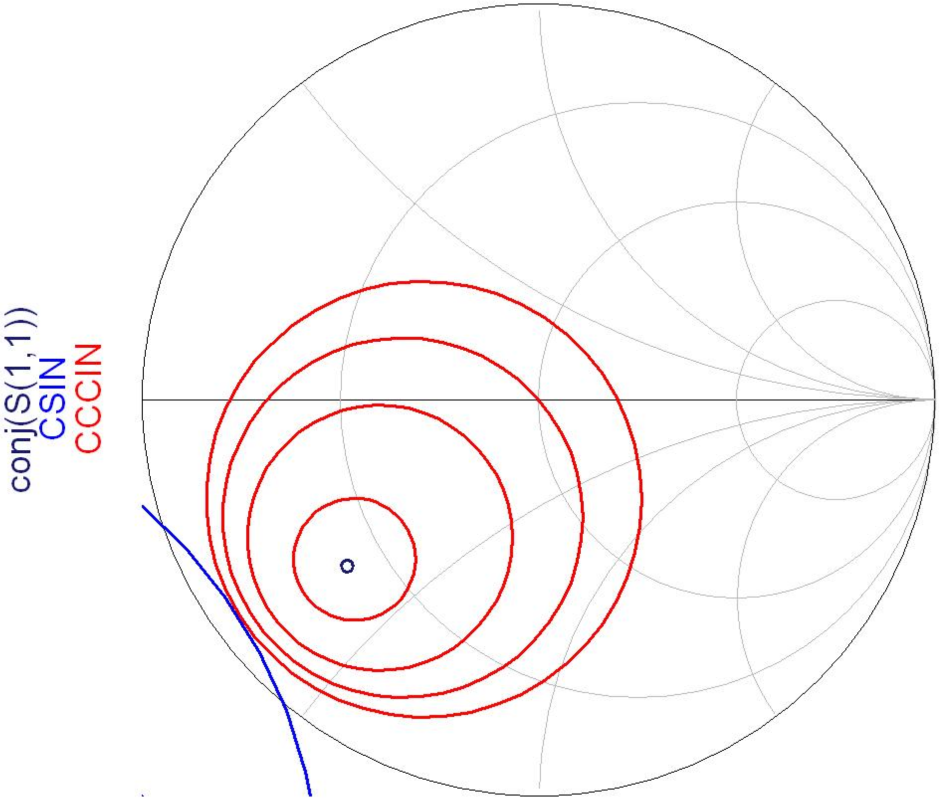
CCCIN, CCCOUT

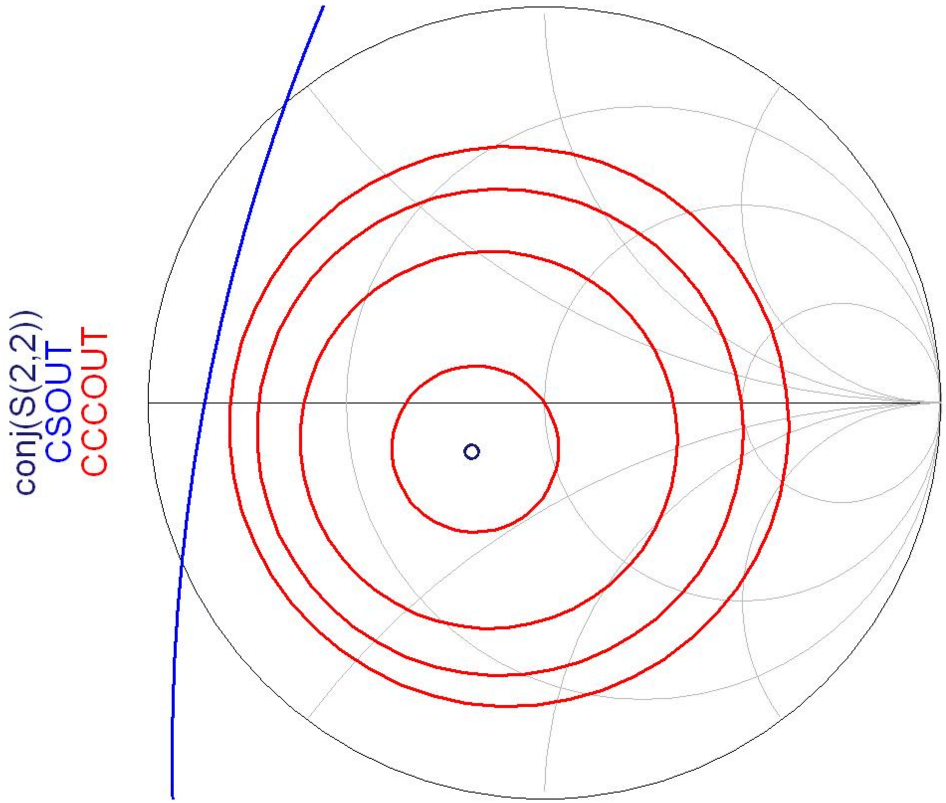




- Circles are plotted for requested values (**in dB!**)
- It is usefull to compute G_{Smax} and G_{Lmax} before
  - in order to request relevant circles

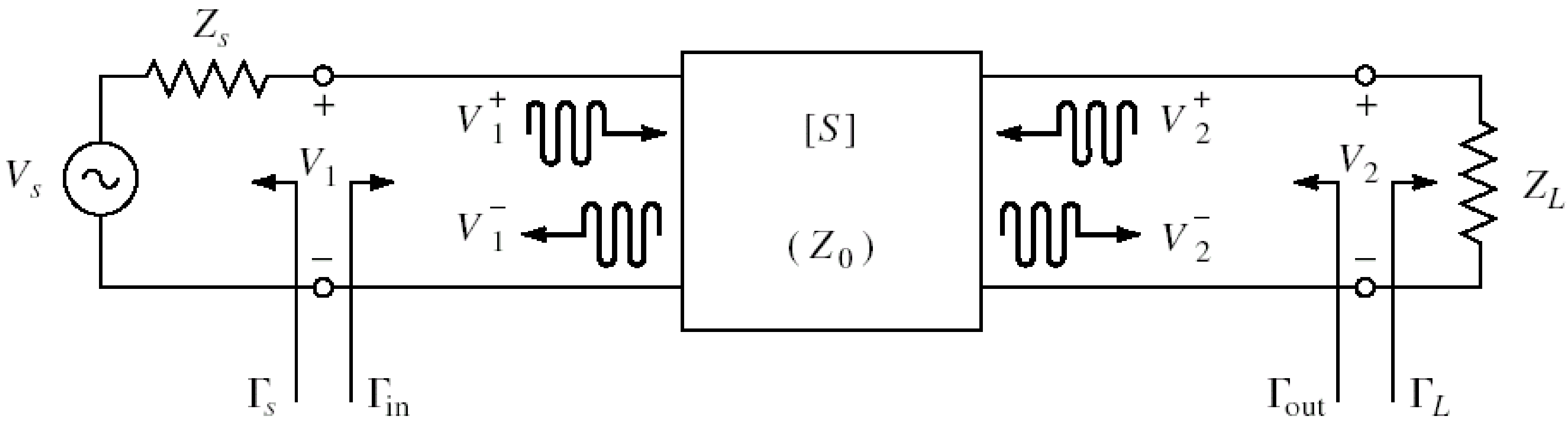
CCCIN, CCCOUT





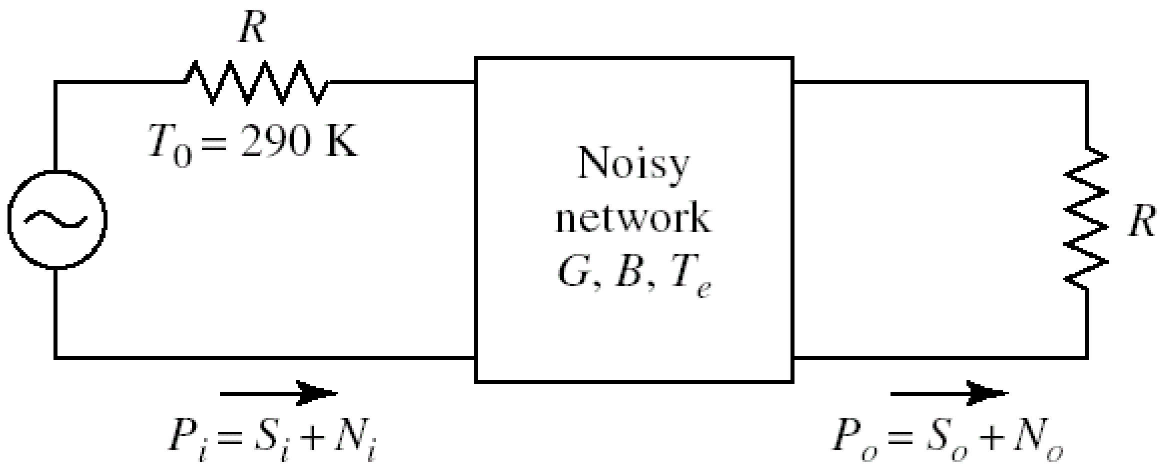
- Cercurile se reprezinta pentru valorile cerute in dB
- Este utila calcularea G_{Smax} si G_{Lmax} anterior

Amplifier as two-port



- For an amplifier two-port we are interested in:
  - stability
  - power gain
  - **noise** (sometimes – small signals)
  - linearity (sometimes – large signals)

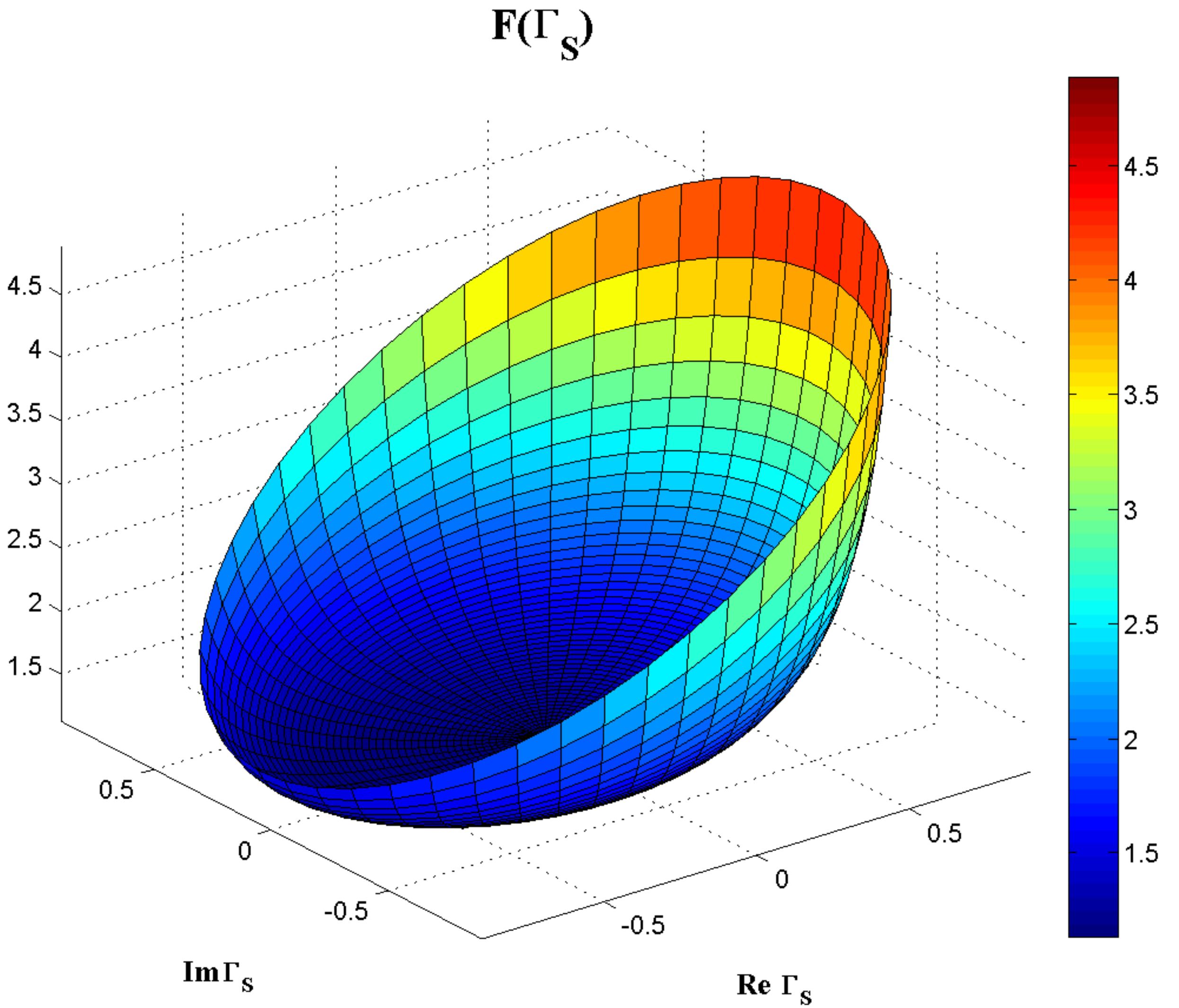
Noise Figure F



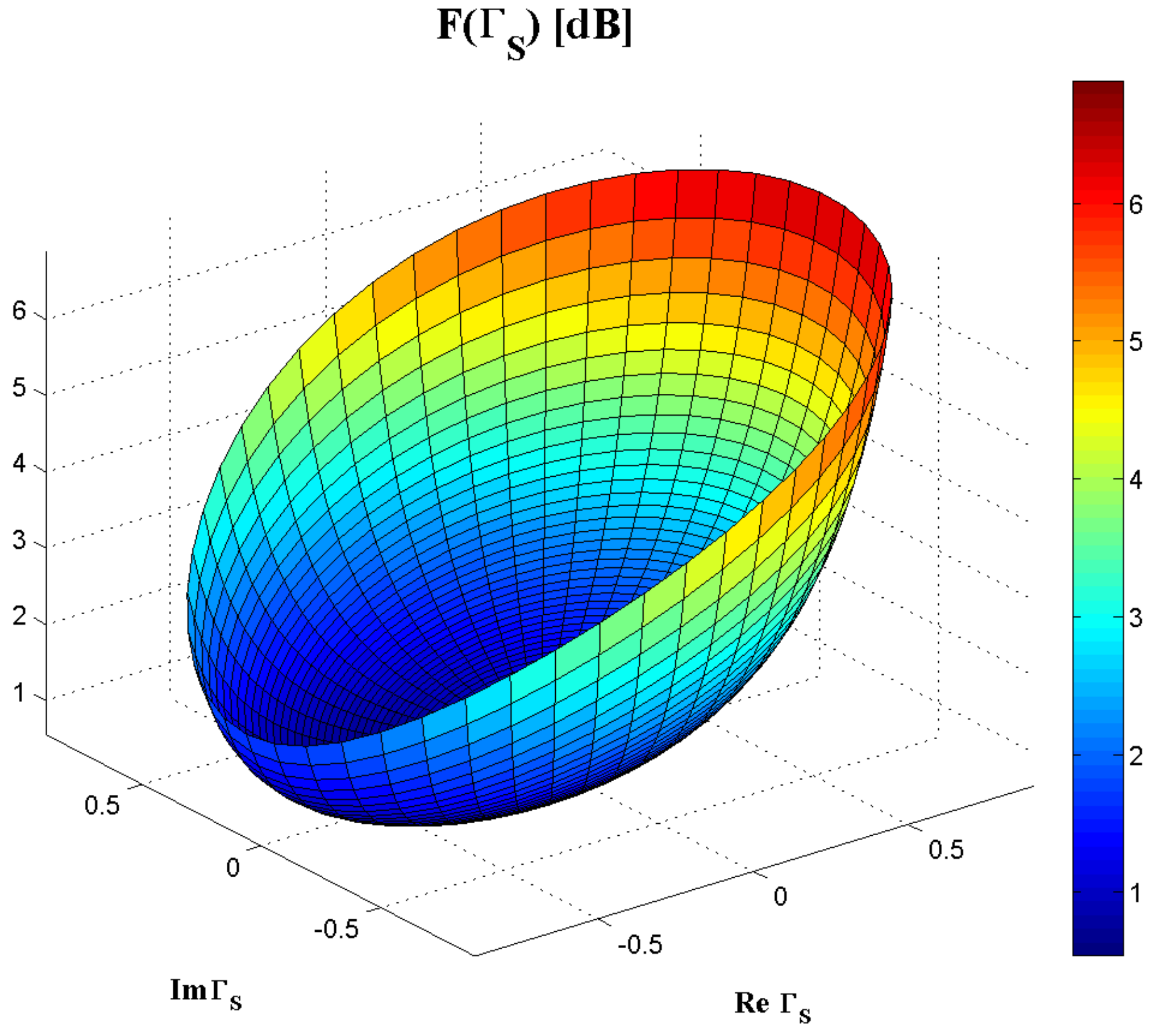
- The noise figure F, is a measure of the reduction in signal-to-noise ratio between the input and output of a device

$$F = \left. \frac{S_i / N_i}{S_o / N_o} \right|_{T_0 = 290K}$$

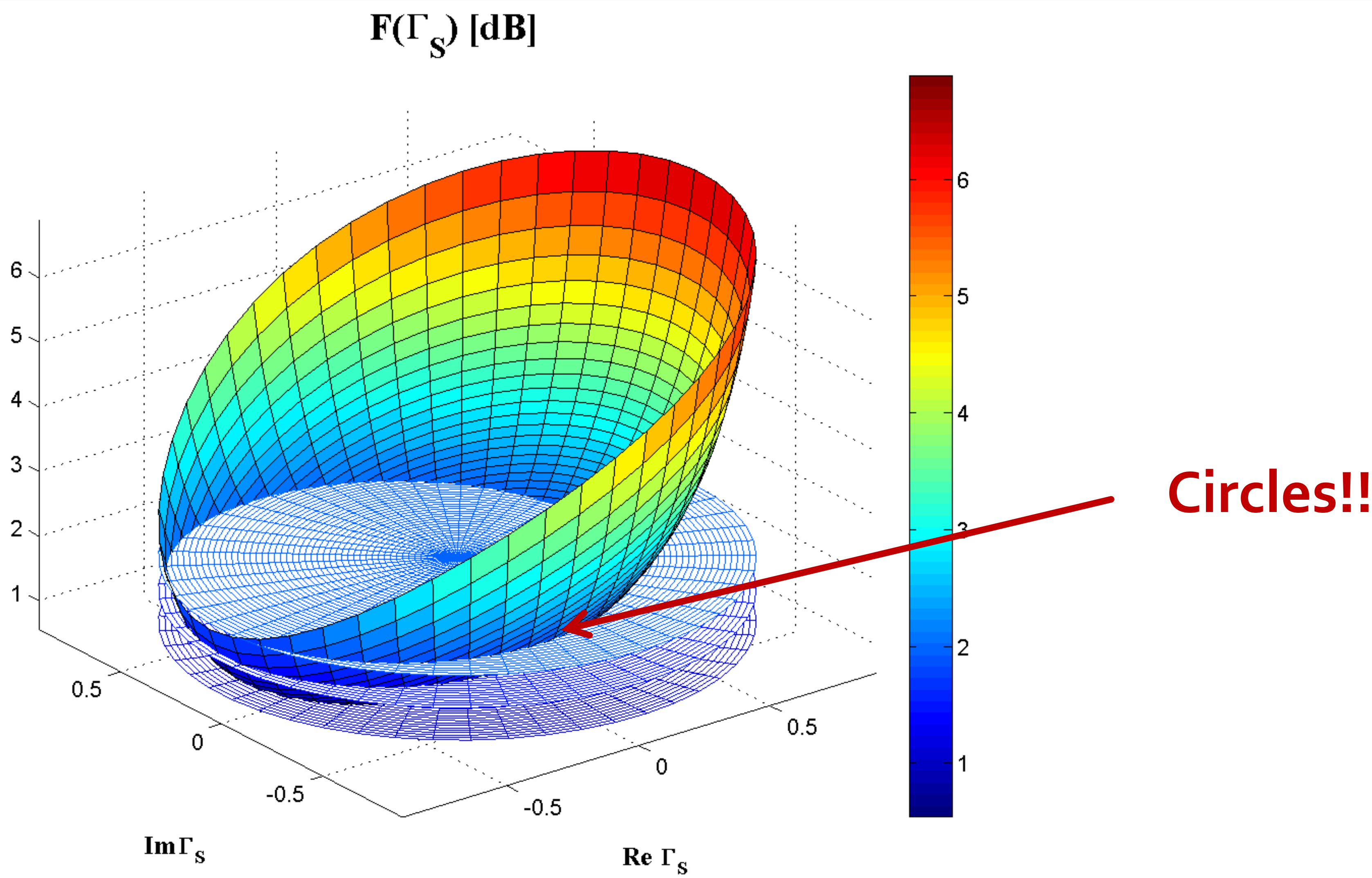
$F(\Gamma_S)$



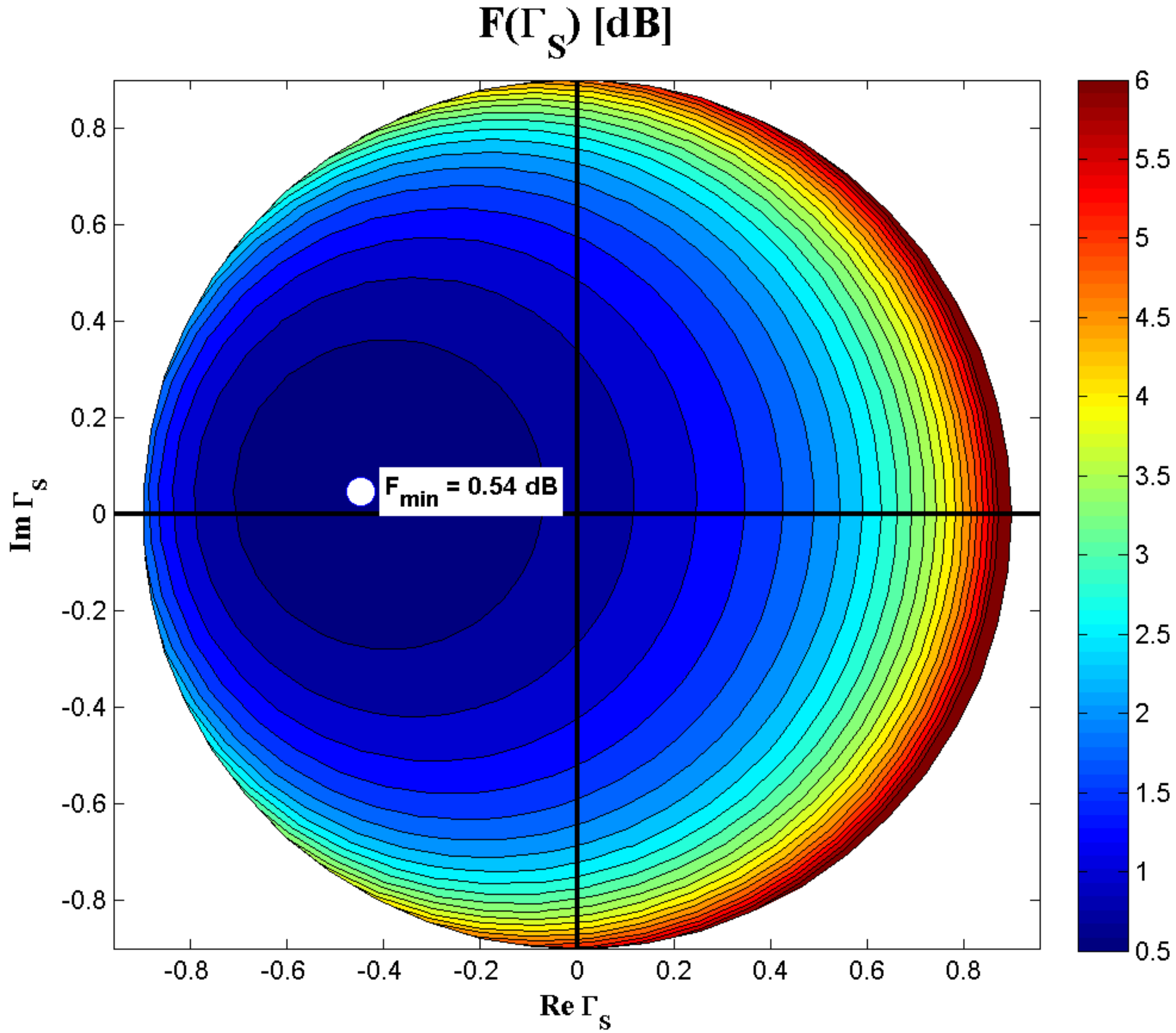
F[dB](Γ_S)



F[dB](Γ_S), constant value contours

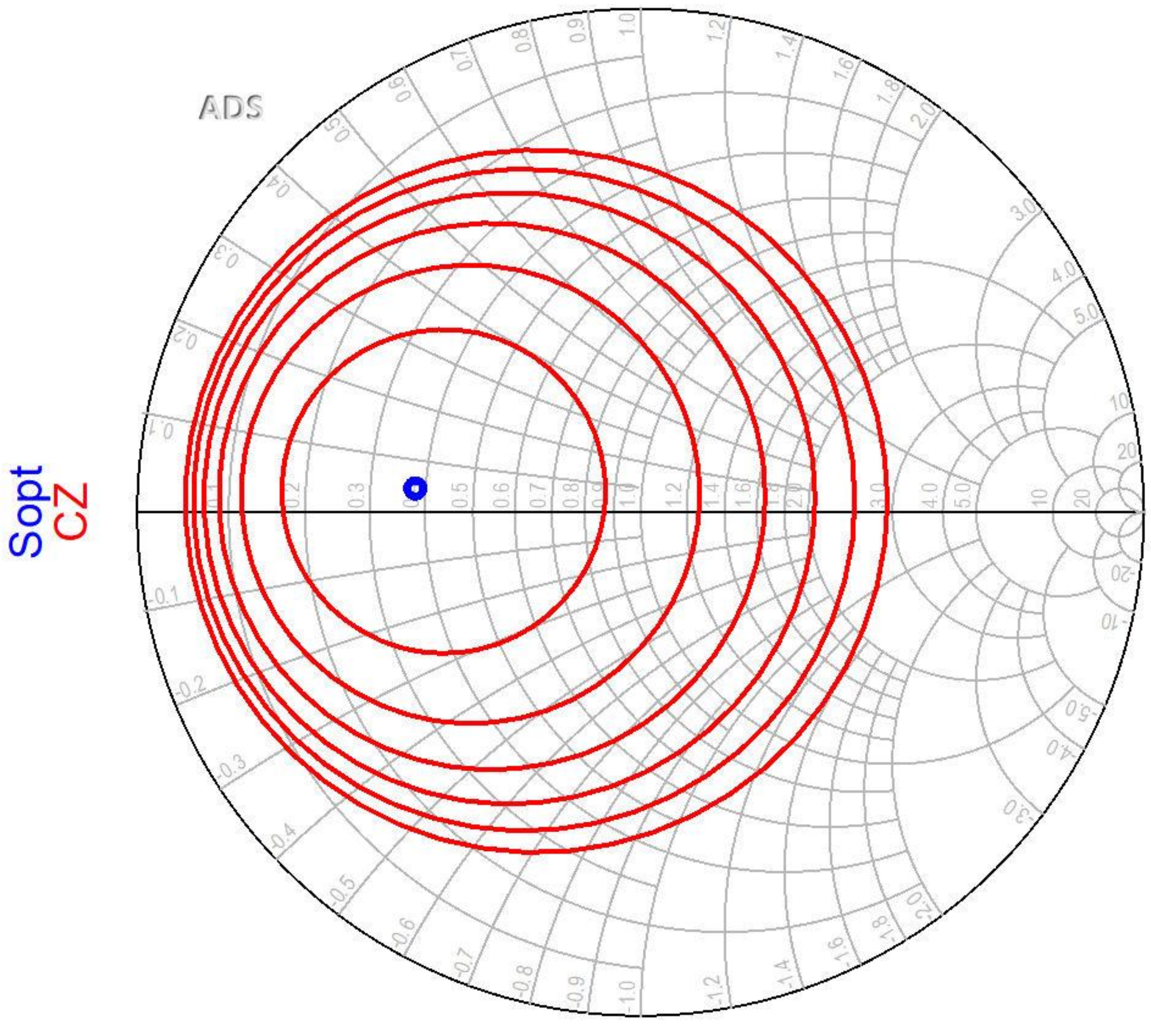


$G_S[dB](\Gamma_S)$, constant value contours



$\Gamma opt = 0.45 \angle 174°$

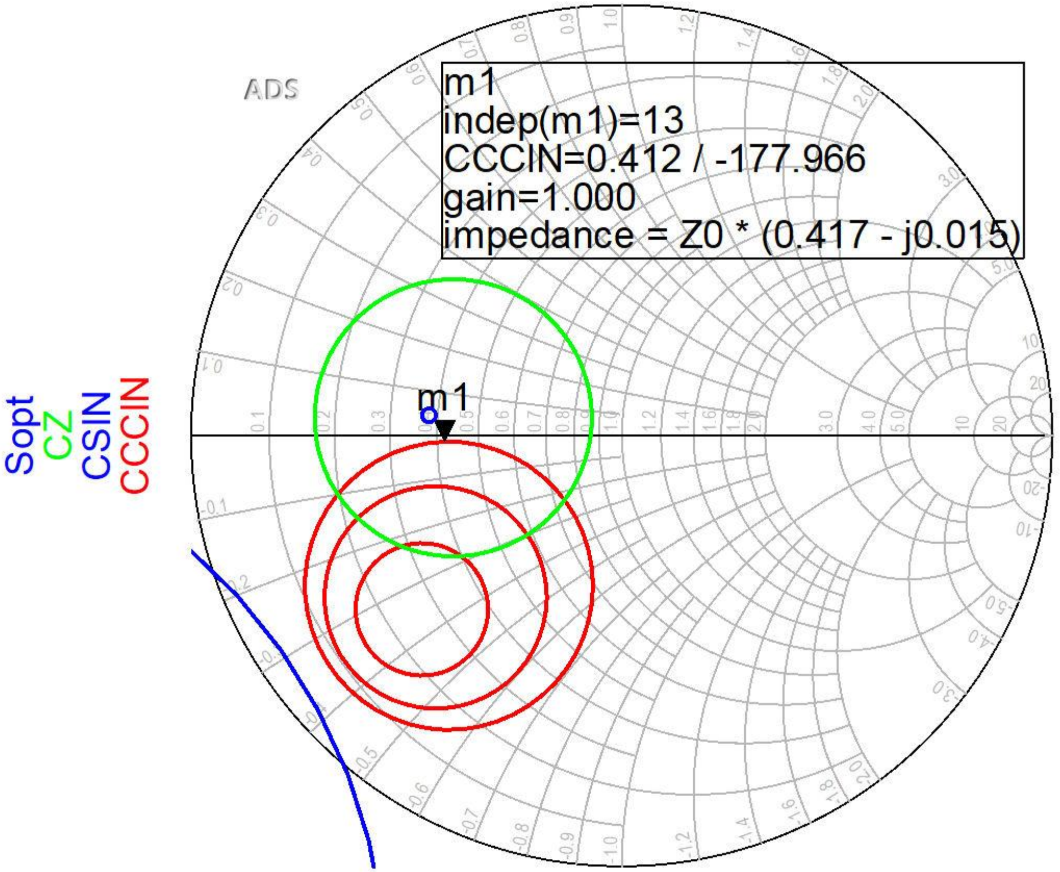
CZ – Noise Circle (input port only!)



Example, LNA @ 5 GHz

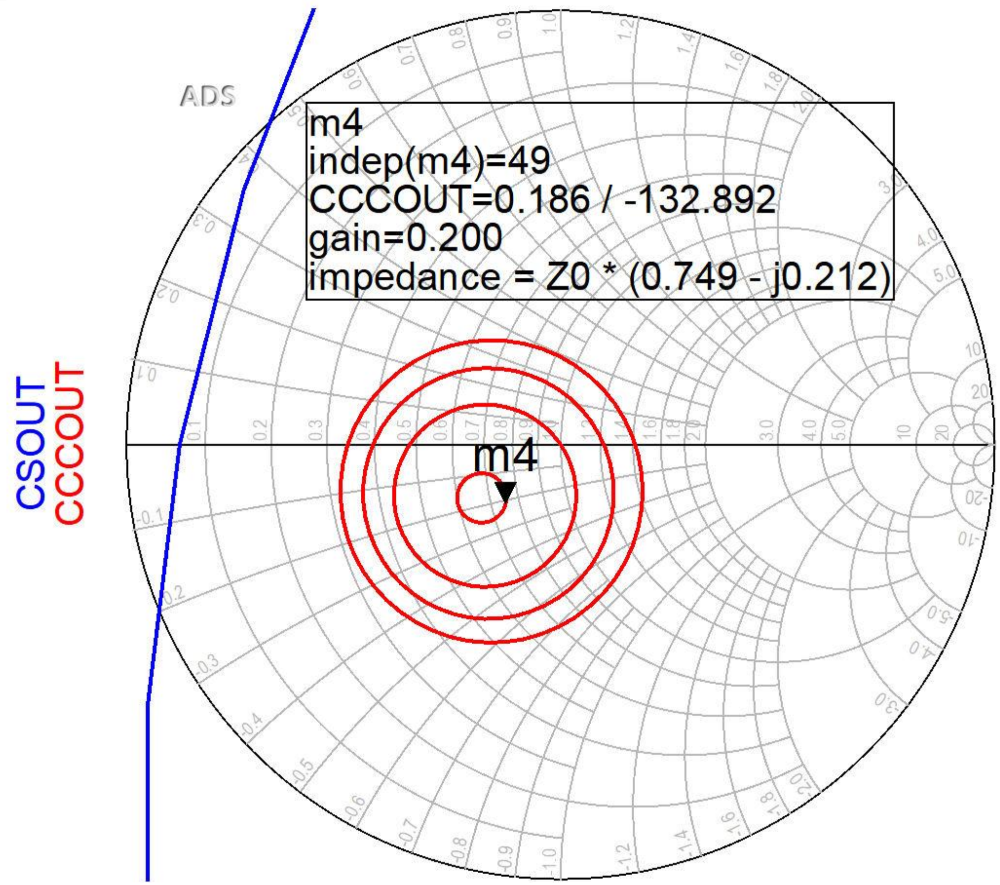
- Low Noise Amplifier
- At the input port we must compromise between
  - noise (~~input~~ constant noise circle **CZ**)
  - power gain (input constant gain circle **CCCIN**)
  - stability (input stability circle **CSIN**)
- At the output port noise **does not intervene** (no influence). The compromise is between:
  - power (output constant gain circle **CCCOUT**)
  - stability (output stability circle **CSOUT**)

Input matching circuit



- If we can afford a 1.2dB decrease of the input gain for better NF,Q (Gs = 1 dB), position m1 above is better
- We obtain better (smaller) NF

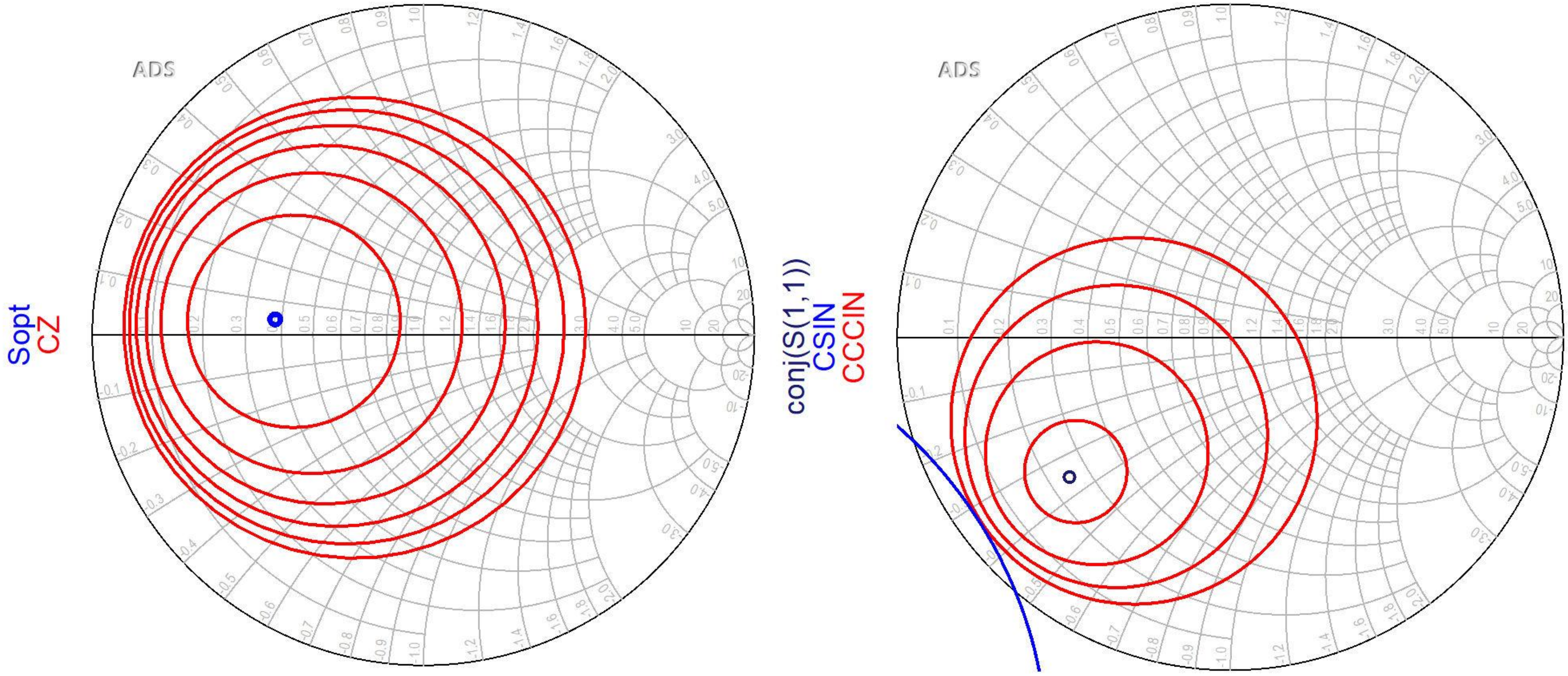
Output matching circuit



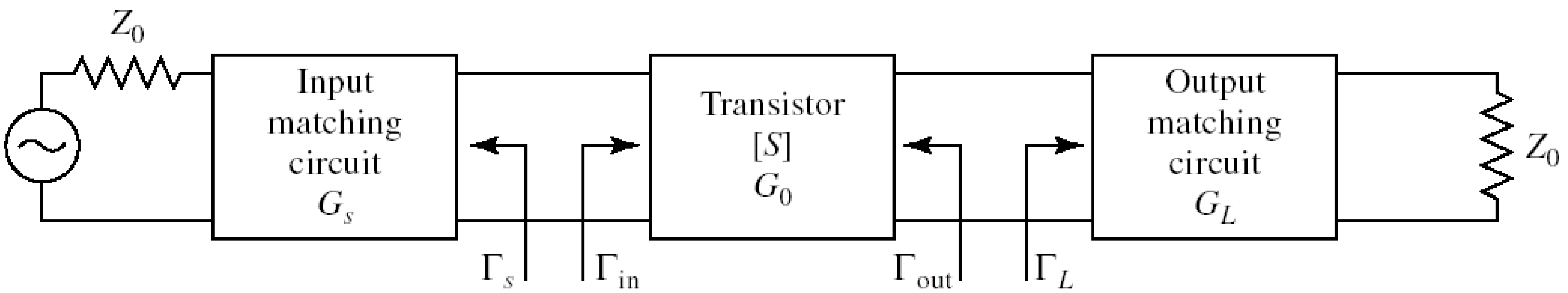
- output constant gain circles CCCOUT: -0.4dB, -0.2dB, 0dB, +0.2dB
- The lack of noise restrictions allows optimization for better gain (close to maximum – position m4)

LNA – Low Noise Amplifier

- Usually a transistor suitable for implementing an LNA at a certain frequency will have input gain circles and noise circles in the same area for Γ_S



Design for Specified Gain



- In the unilateral assumption:

$$G_{TU} = \frac{1-|\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2}\cdot|S_{21}|^2\cdot\frac{1-|\Gamma_L|^2}{|1-S_{22}\cdot\Gamma_L|^2}$$

$$G_S = \frac{1-|\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2}$$

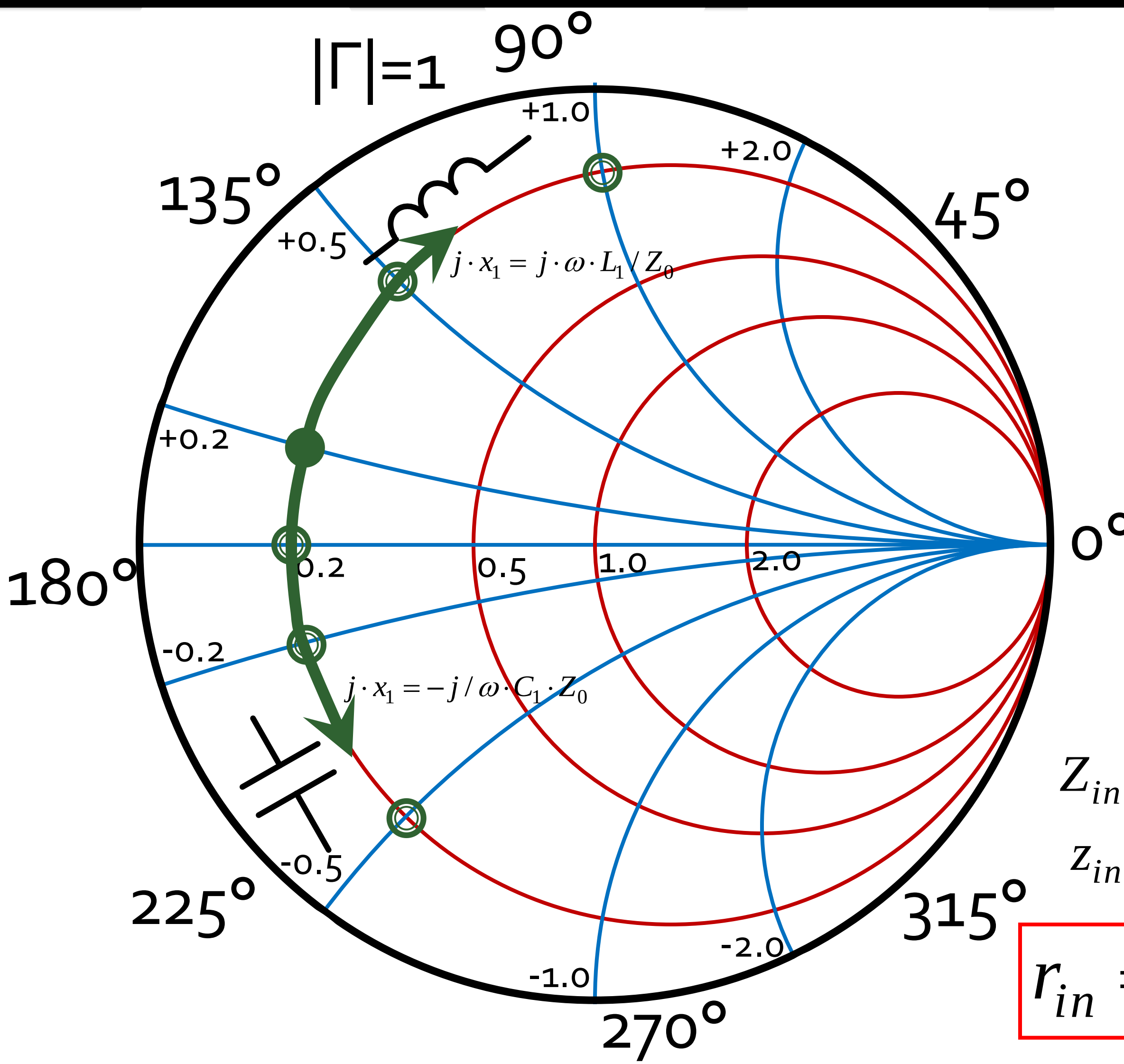
$$G_S = G_S(\Gamma_S)$$

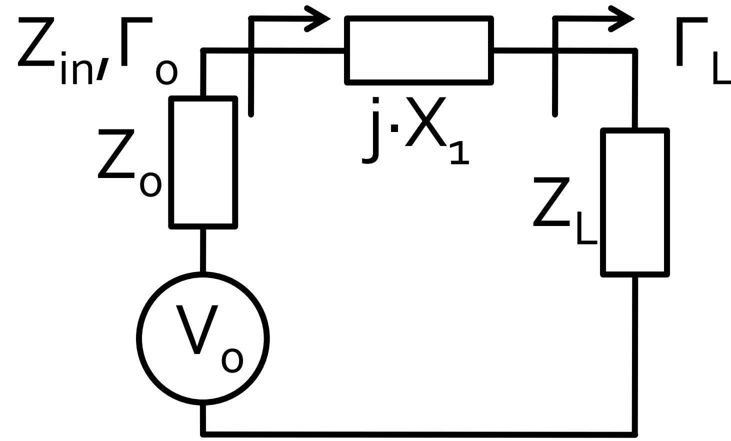
$$G_0 = |S_{21}|^2$$

$$G_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\cdot\Gamma_L|^2}$$

$$G_L = G_L(\Gamma_L)$$

The Smith Chart, series reactance





$Z_0 = 50\Omega$

$Z_L = R_L + j \cdot X_L = 10\Omega + j \cdot 10$

$z_L = r_L + j \cdot x_L = 0.2 + j \cdot 0.2$

$\Gamma_L = 0.678 \angle 156.5°$

$Z_{in} = Z_L + j \cdot X_1 = R_L + j \cdot (X_L + X_1$

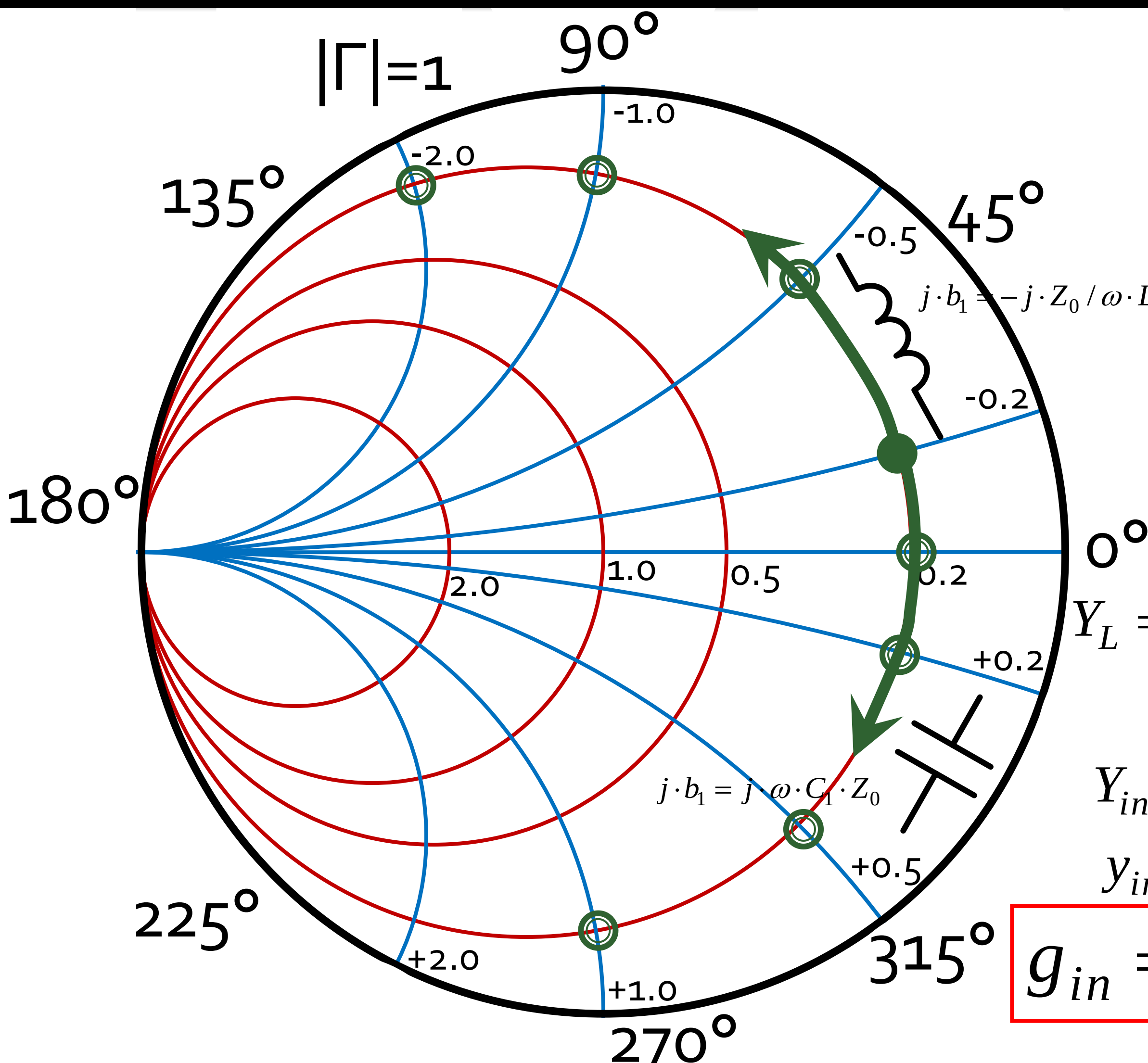
$z_{in} = r_L + j \cdot (x_L + x_1)$

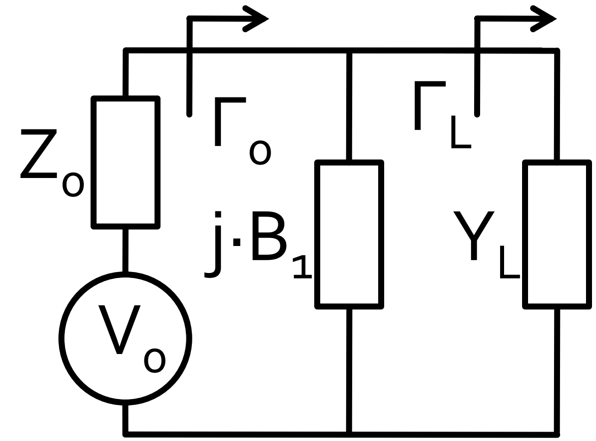
$r_{in} = r_L$

$j \cdot x_1 = j \cdot \omega \cdot L_1 / Z_0 > 0$

$j \cdot x_1 = -j / \omega \cdot C_1 \cdot Z_0 < 0$

The Smith Chart, shunt susceptance





$Z_0 = 50\Omega, Y_0 = 0.02\,S$

$\Gamma_L = 0.678\angle 23.5°$

$Y_L = G_L + j\cdot B_L = 0.004\,S + j\cdot 0.004$

$y_L = g_L + j\cdot b_L = 0.2 - j\cdot 0.2$

$Y_{in} = Y_L + j\cdot B_1 = G_L + j\cdot\left(B_L + B_1\right)$

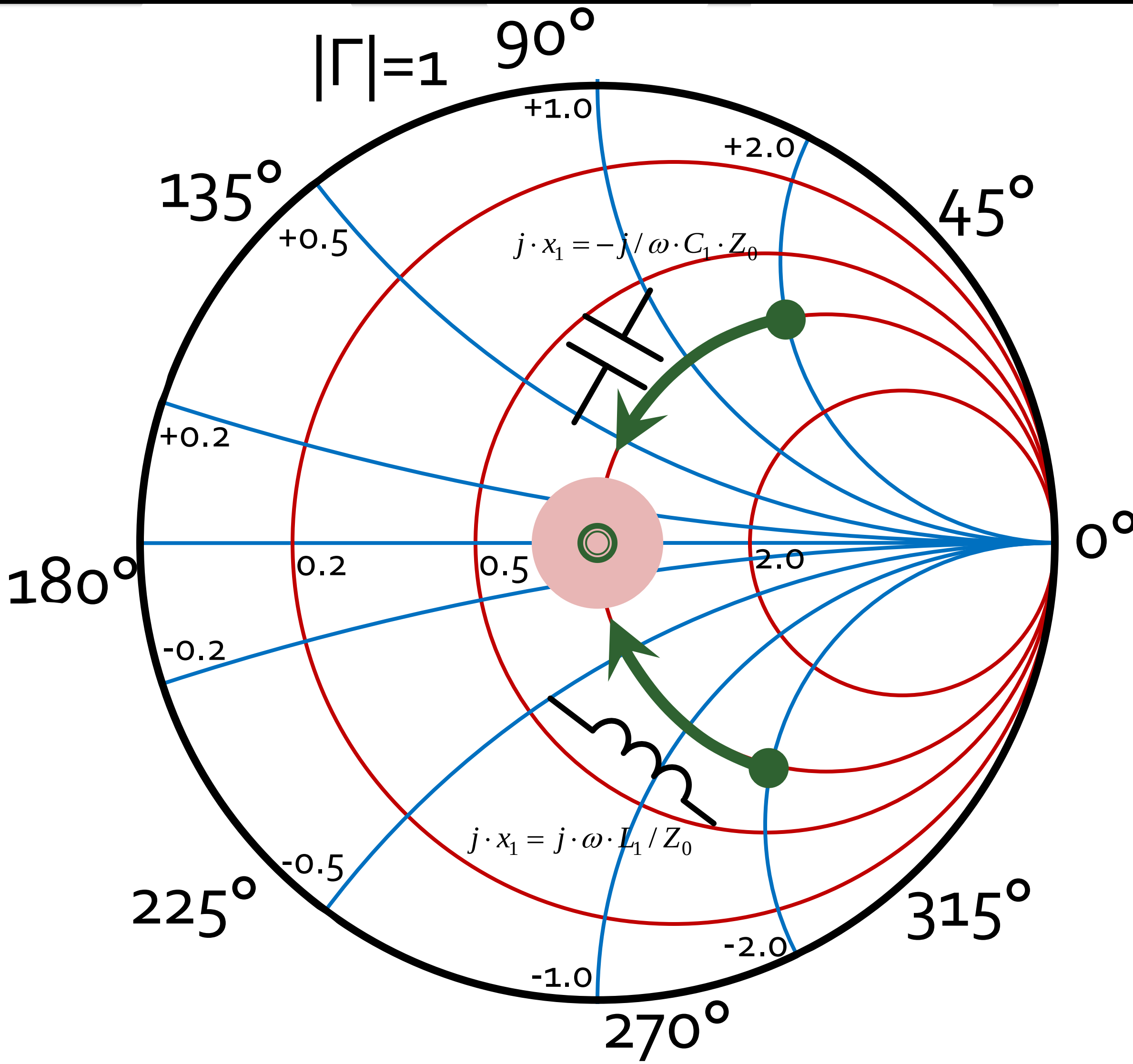
$y_{in} = g_L + j\cdot\left(b_L + b_1\right)$

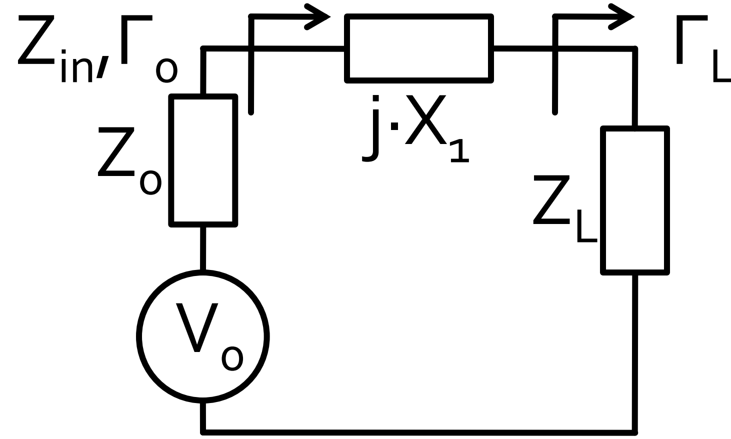
$g_{in} = g_L$

$j\cdot b_1 = j\cdot\omega\cdot C_1\cdot Z_0 > 0$

$j\cdot b_1 = -j\cdot Z_0 / \omega\cdot L_1 < 0$

Matching, series reactance





$$z_L = r_L + j\cdot x_L$$

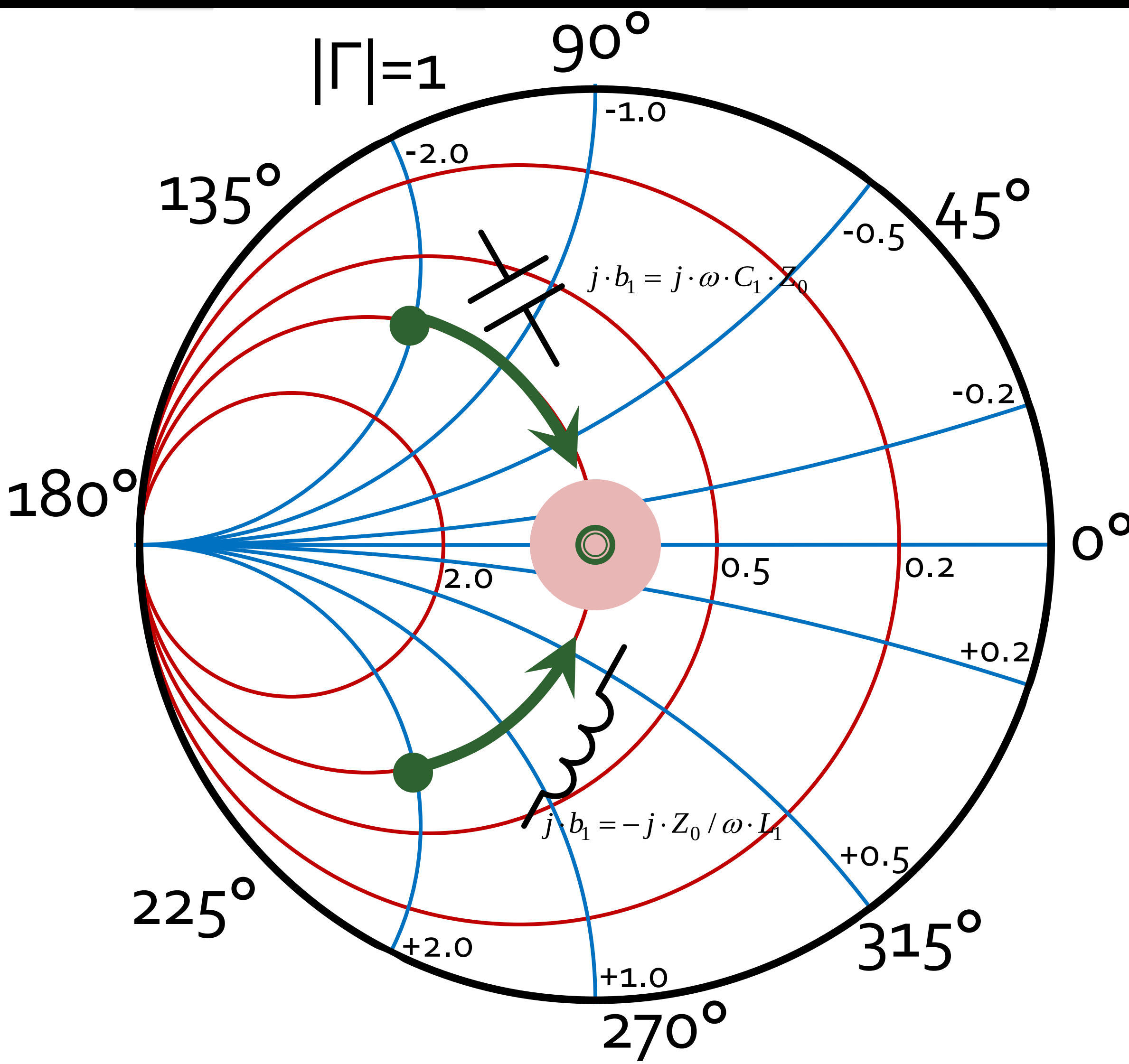
$$z_{in} = r_L + j\cdot(x_L + x_1)$$

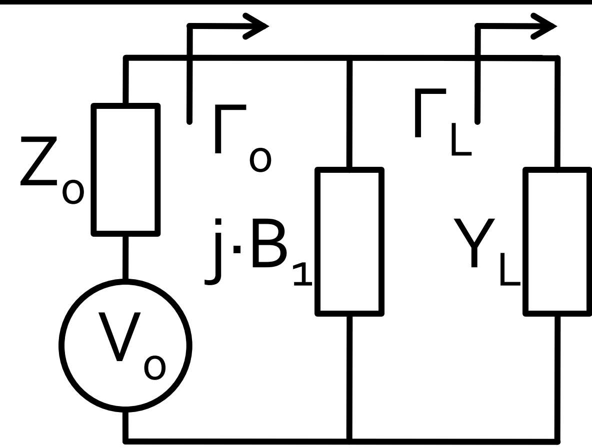
$$r_{in} = r_L$$

- Match can be obtained **if and only if** $r_L = 1$
- we compensate the reactive part of the load

$$j\cdot x_1 = -j\cdot x_L$$

Matching, shunt susceptance





$$y_L = g_L + j \cdot b_L$$

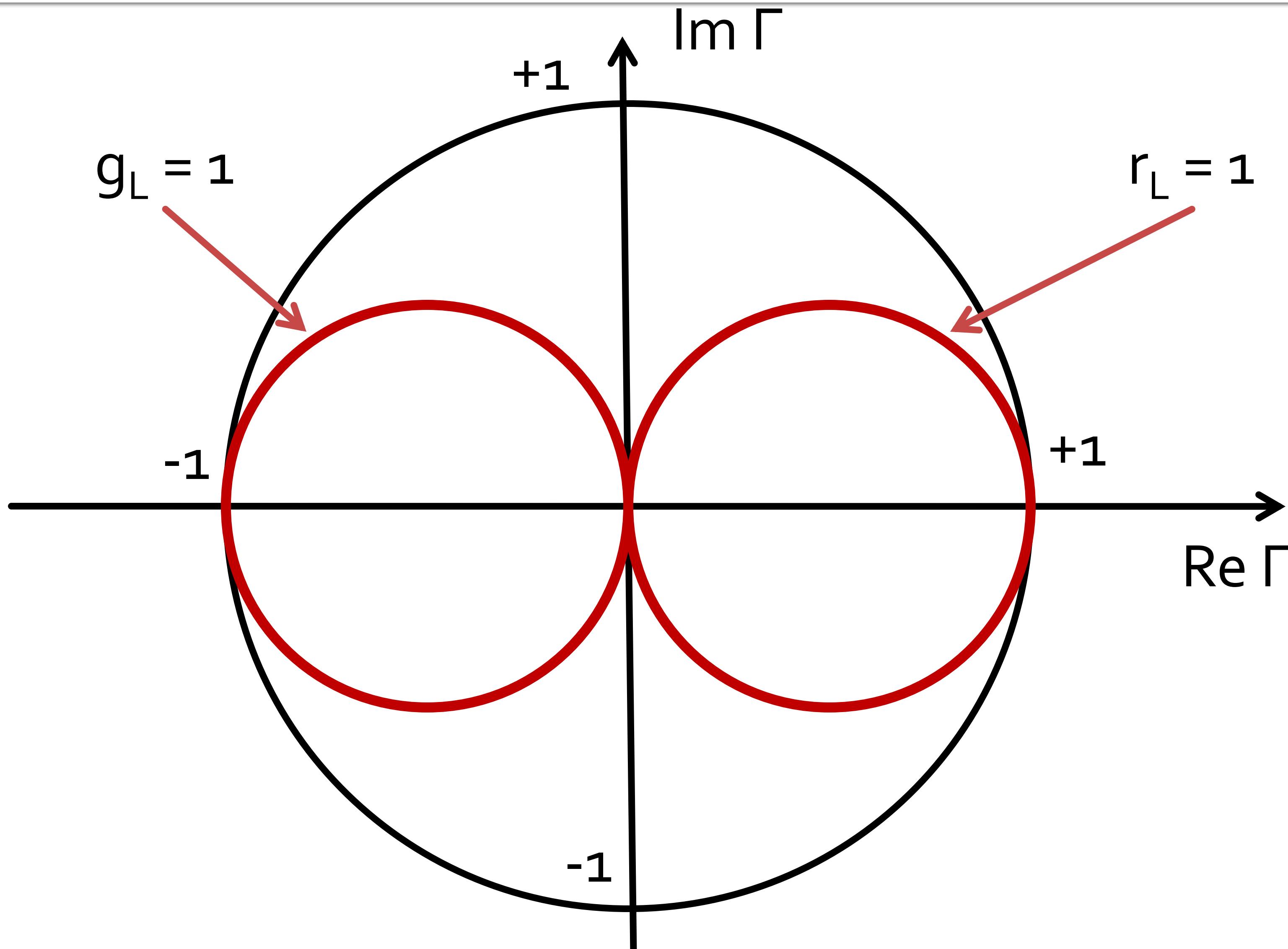
$$y_{in} = g_L + j \cdot (b_L + b_1)$$

$$g_{in} = g_L$$

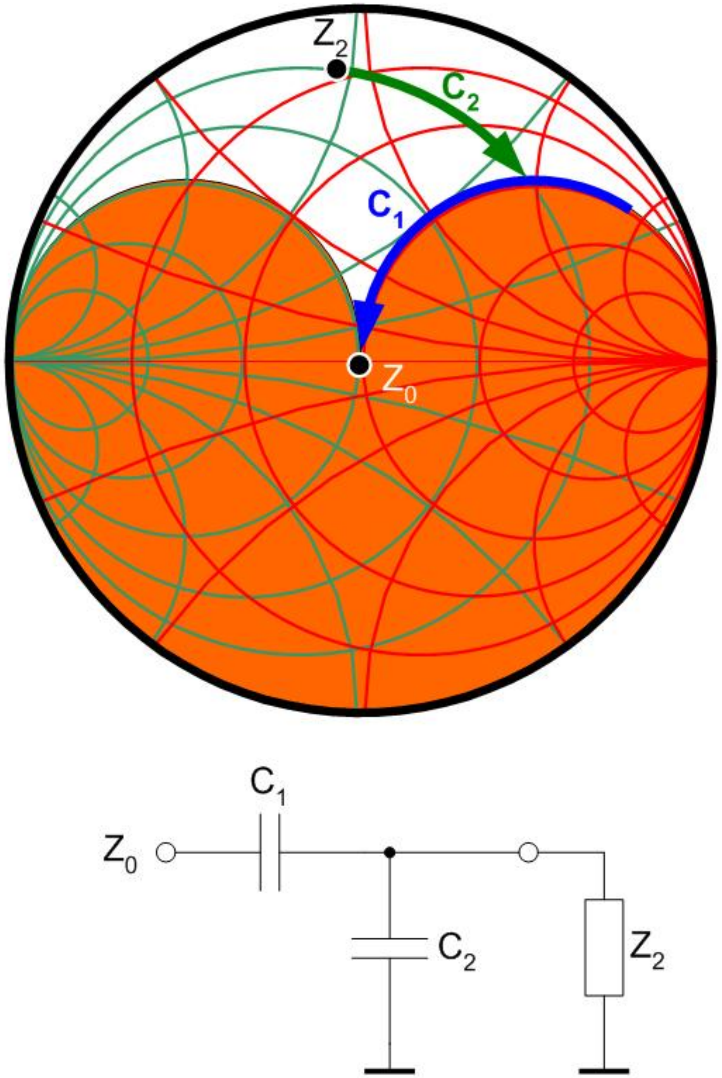
- Match can be obtained **if and only if** $g_L = 1$
- we compensate the reactive part of the load

$$j \cdot b_1 = -j \cdot b_L$$

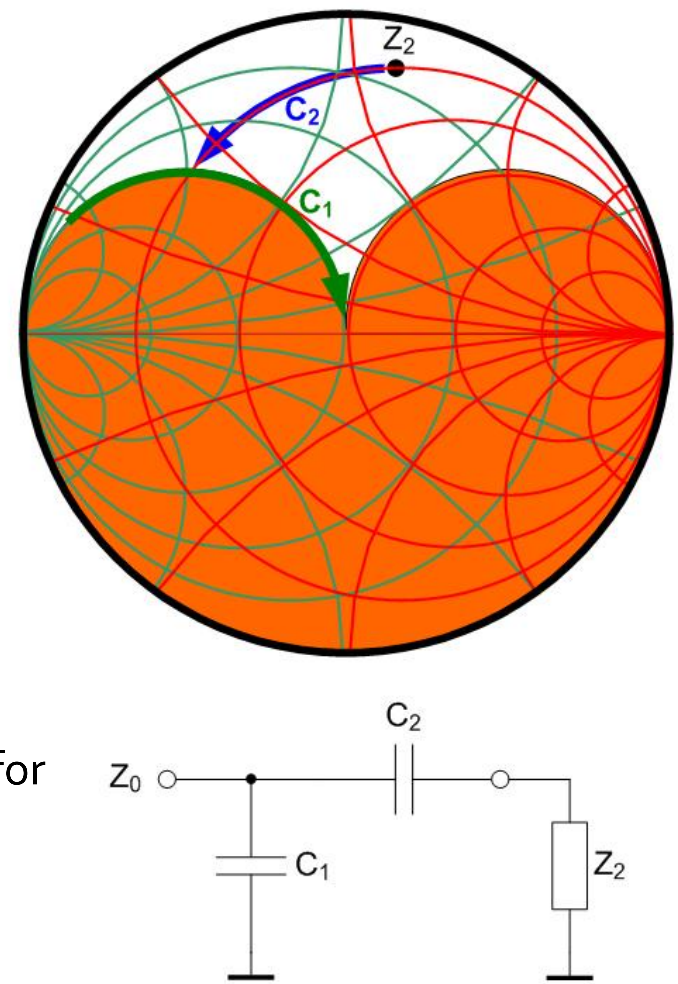
Smith chart, r=1 and g=1



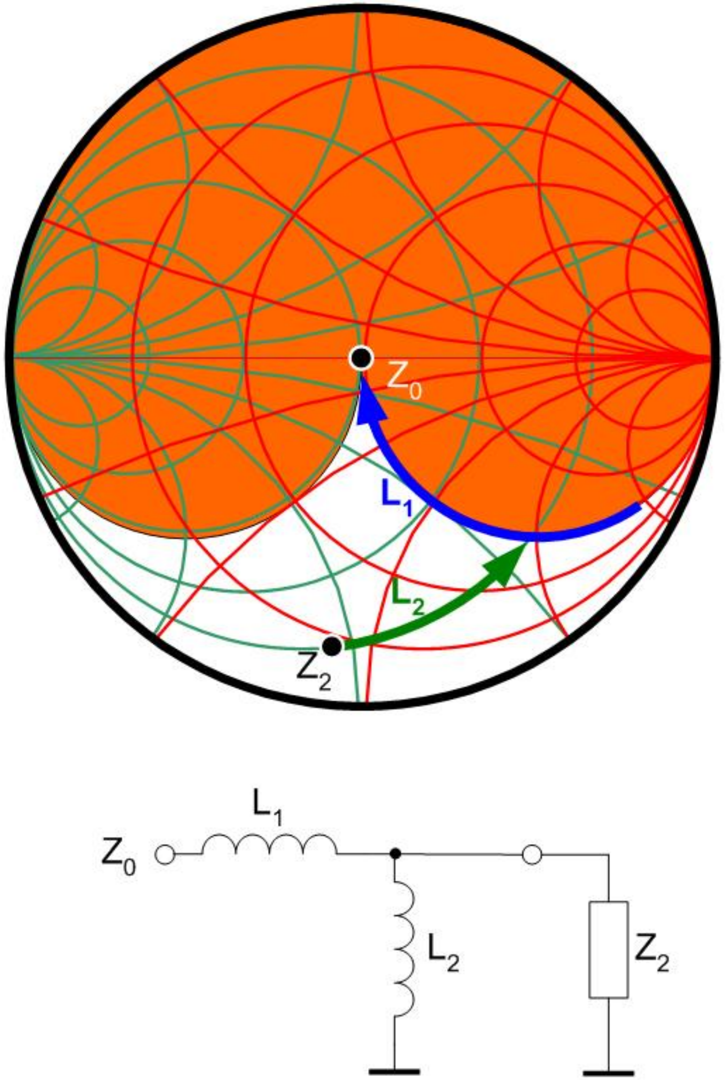
series C, shunt C / shunt C, series C



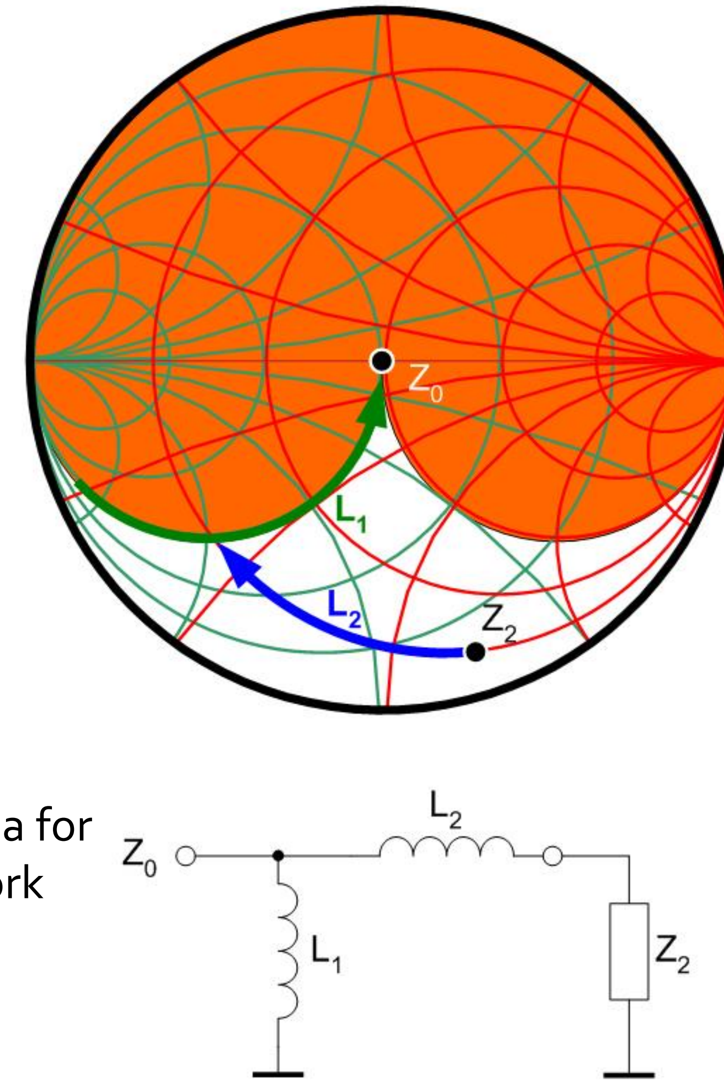
Forbidden area for current network



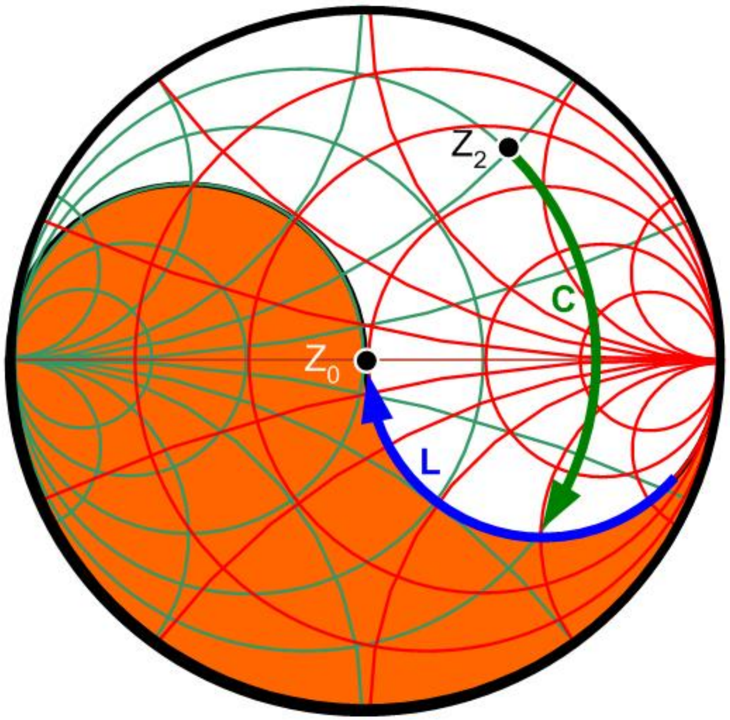
series L, shunt L / shunt L, series L

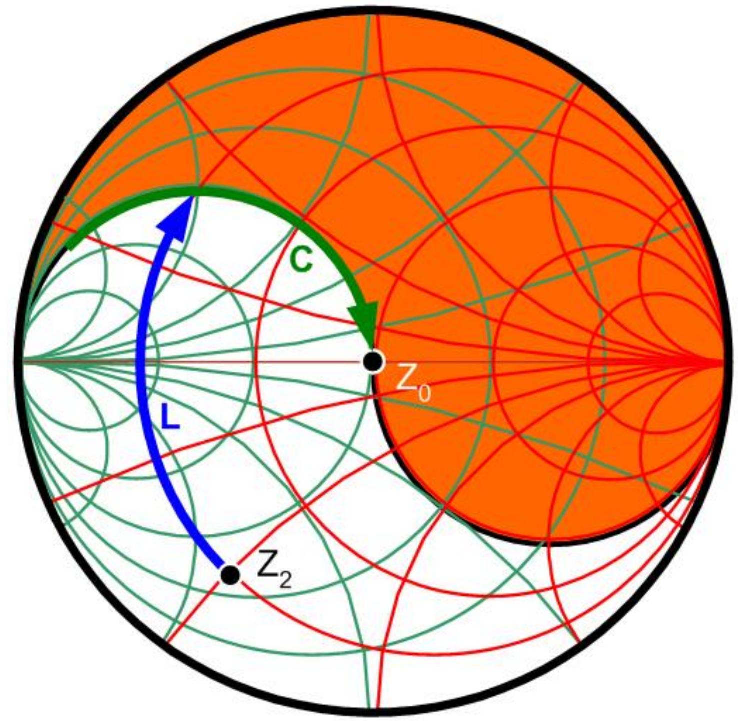


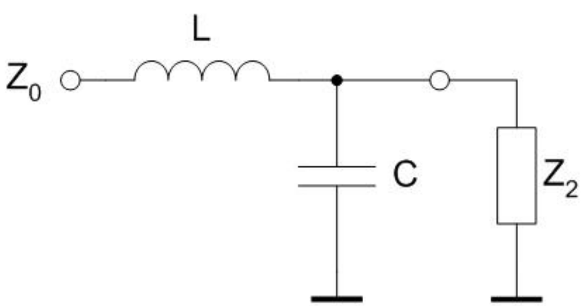
Forbidden area for current network



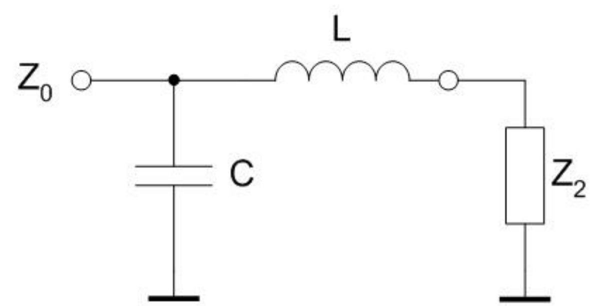
series L, shunt C / shunt C, series L



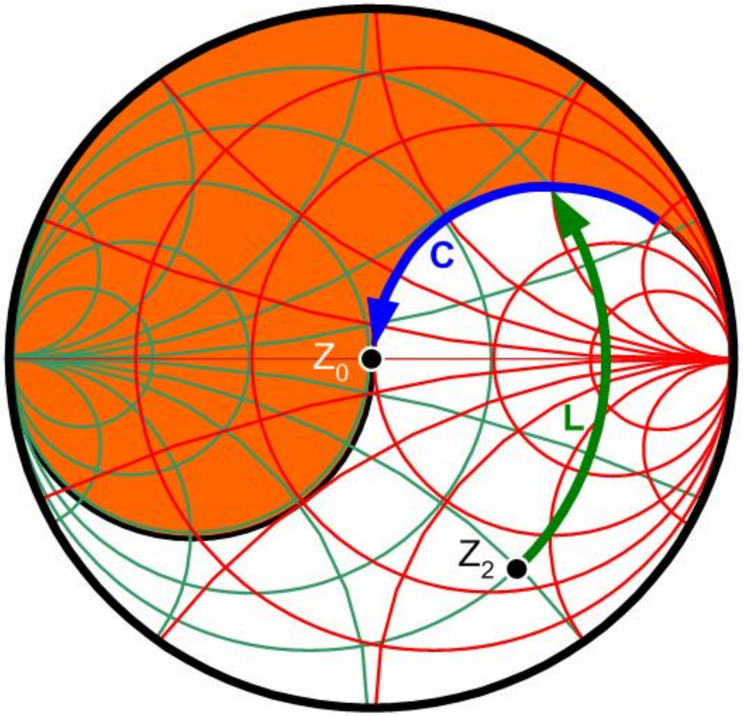


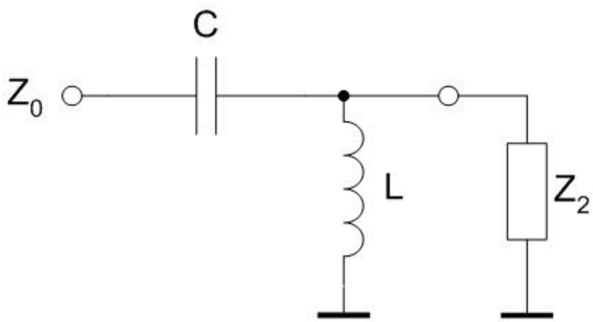


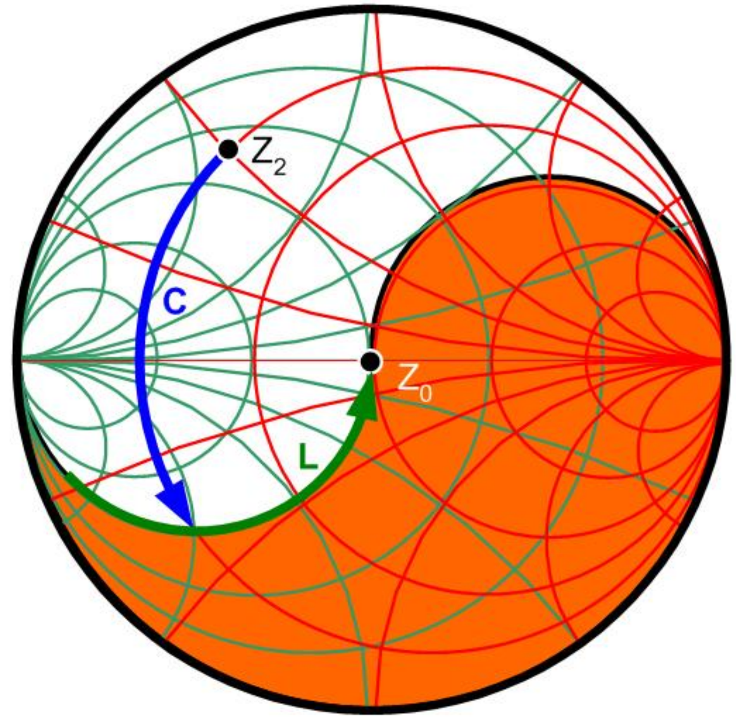
Forbidden area for current network

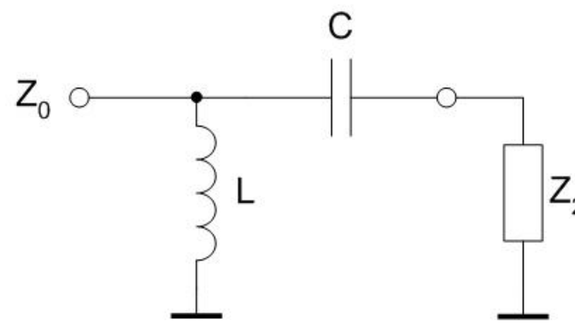


series C, shunt L / shunt L, series C



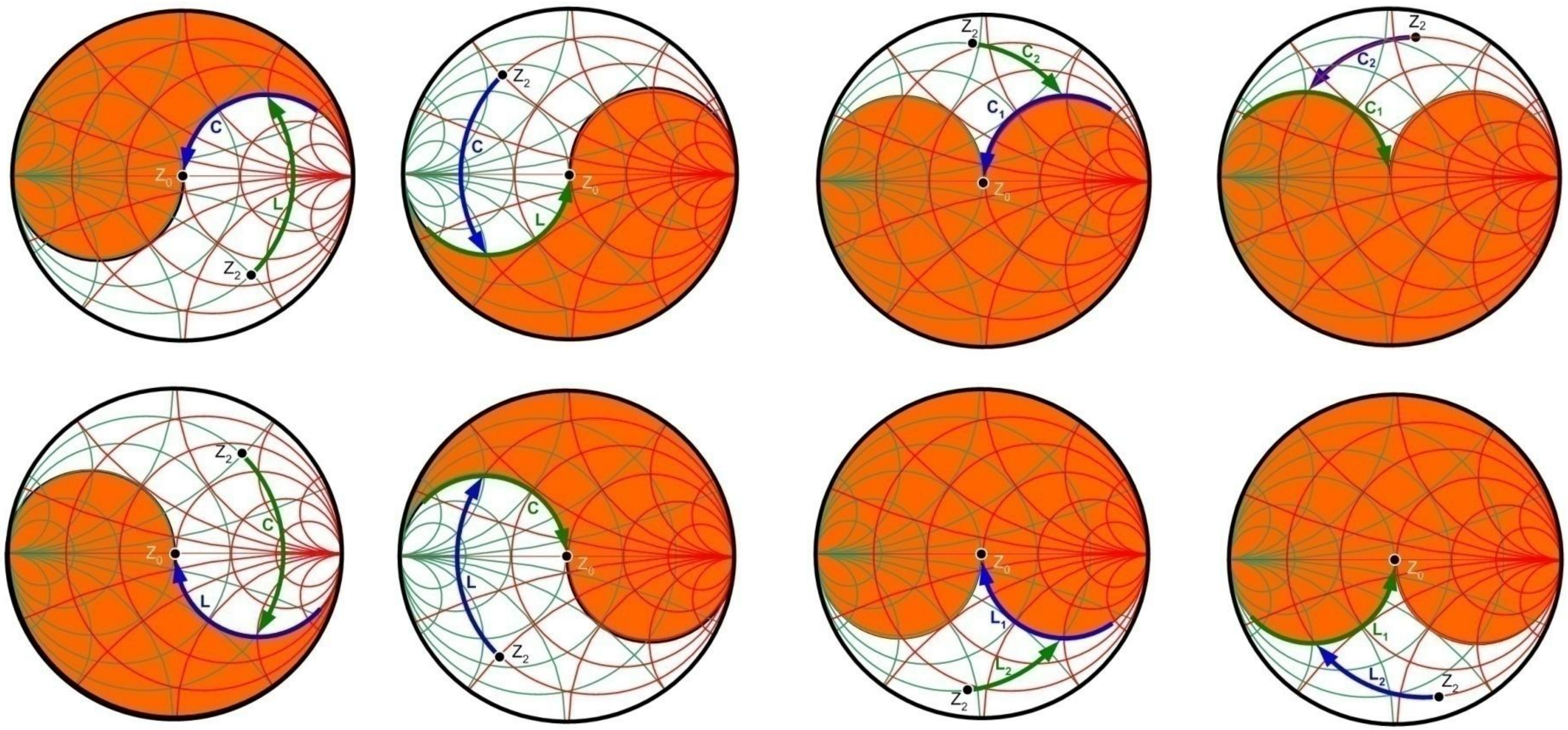


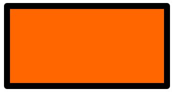




Forbidden area for current network

Matching with 2 reactive elements (L Networks)





Forbidden area for current network

Matching with 2 reactive elements (L Networks)

- For any Γ_L there are at least 2 possible L networks to achieve match (L+C)
- For some starting areas on the Smith Chart there are 4 possibilities (+2 C+C/L+L networks)
- We choose the network that requires components with existent/practically realizable values
- By adding the resistive elements, we can supplement the number of networks but with **loss of signal power (not recommended)**

Practical Procedure

Step 0

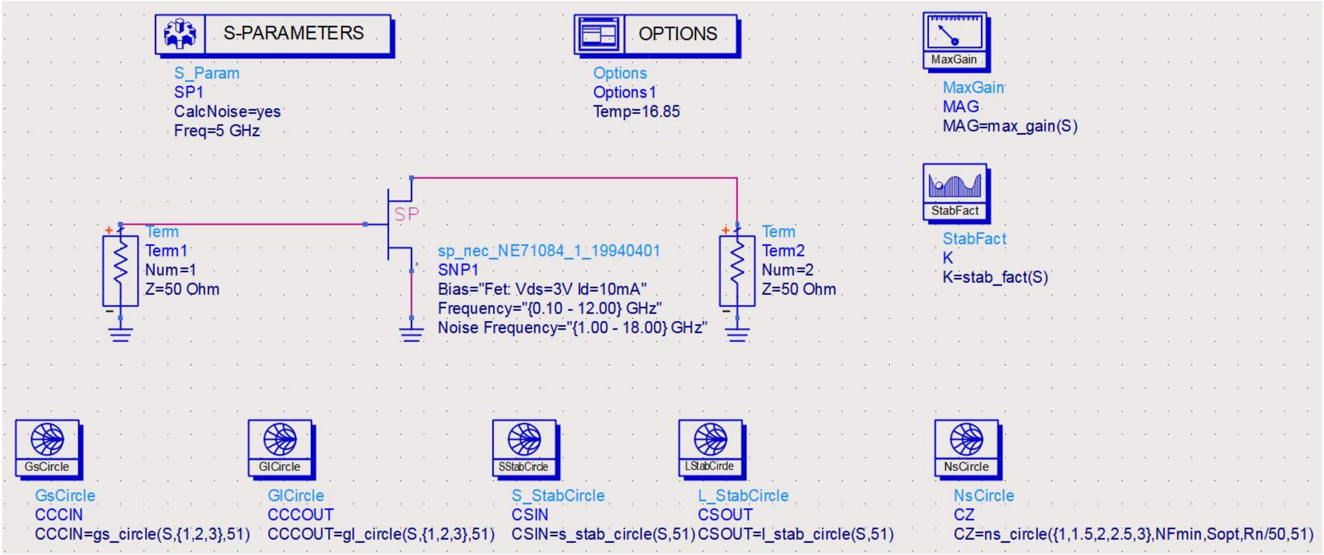
- Write by hand on a sheet of paper 100 times:
- **I solemnly promise to read the text AND NOT to jump from picture to picture**
- ☺

Step 1

- Laboratory 3-4 will take 2 sessions to complete:
  - lab 3: In the first session you will work with the design data in the example in the lab manual in order to create the **4 (correct) schematics** in a single ADS project
  - lab 4: starting from the 4 (**verified**) schematics to design your amplifier (individual data)
- **Caution!** the 4 schematics must be saved in the "networks" folder inside the "..._prj" folder (ADS project) in order to belong to that particular project (and have simulation enabled)

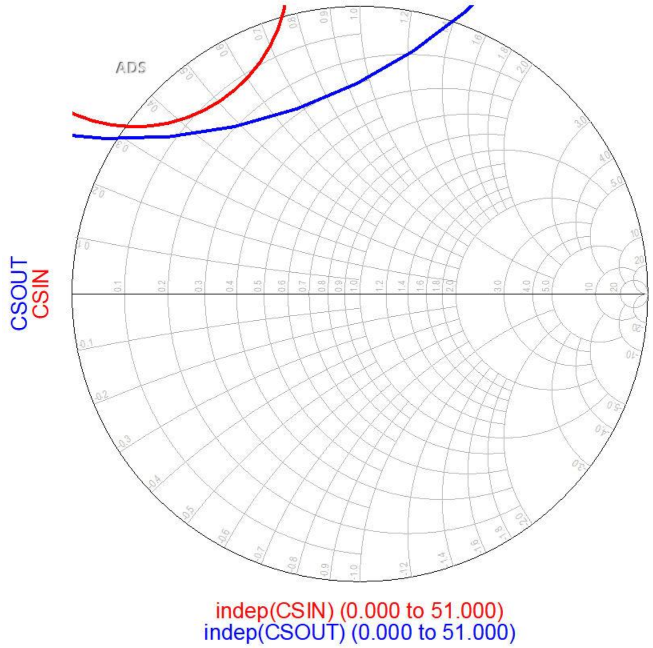
Schematic 1

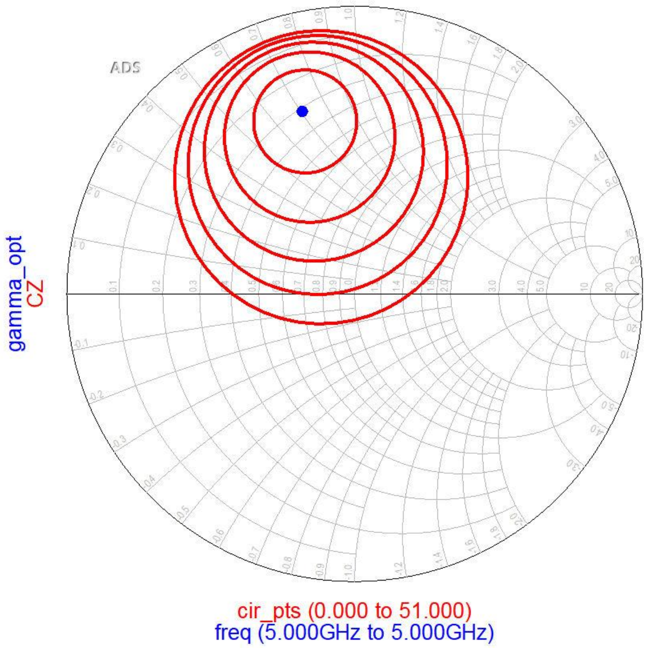
- allows investigation of the transistor at chosen design frequency



Schematic 1

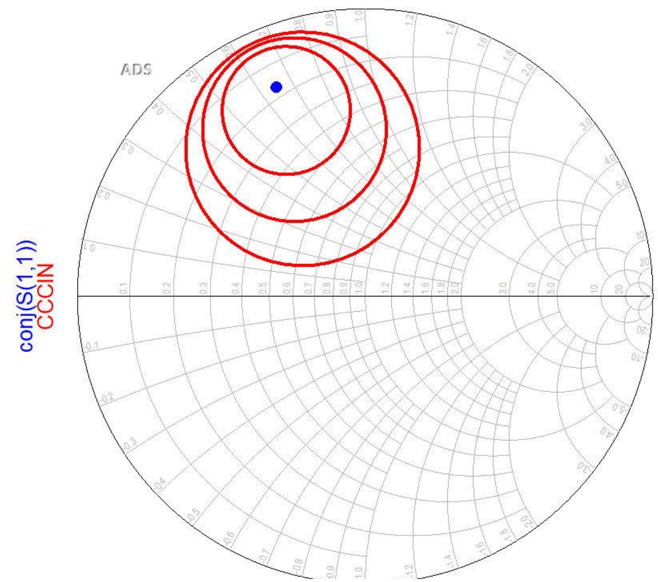
- **multiple circles (families)** are plotted and some required values are computed

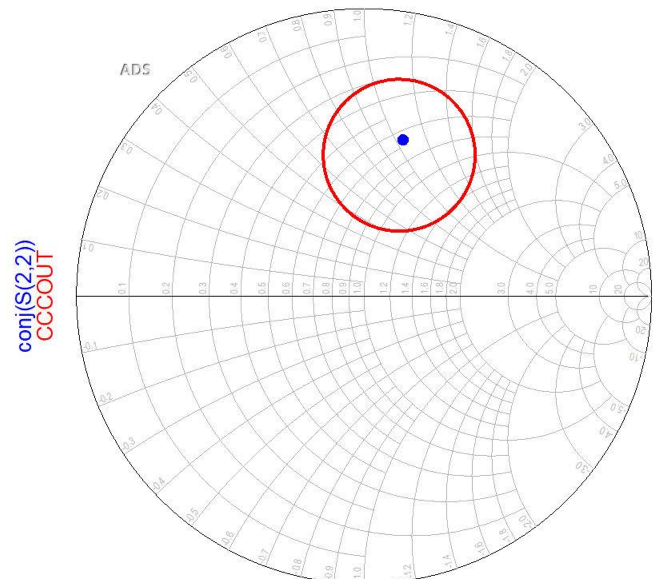




Schematic 1

- **multiple circles (families)** are plotted and some required values are computed





Eqn gamma_opt=Sopt

Eqn G0=10*log(mag(S(2,1))**2)

Eqn GSmax=10*log(1/(1-mag(S(1,1))**2))

Eqn GLmax=10*log(1/(1-mag(S(2,2))**2))

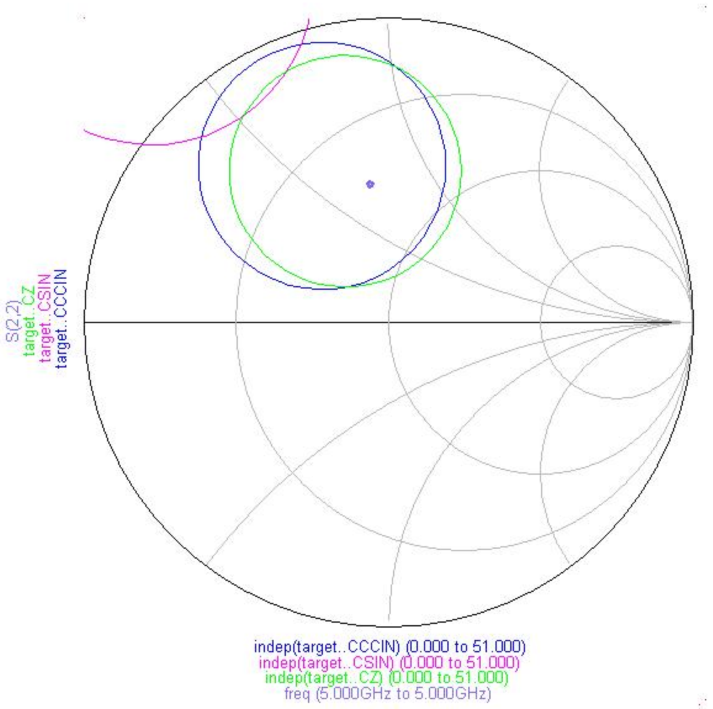
freq	K	MAG	NFmin	Sopt	Rn	G0	GLmax	GSmax
5.000 GHz	0.533	15.296	0.700	0.660 / 106....	19.500	8.974	1.634	4.249

Schematic 2

- Largely similar with schematic 1
- Analyzing results in **schematic 1** we choose **a single circle** adequate as target:
  - stability
  - power gain
  - noise (input)
- Plotting these circles is not required
  - they will be effectively used in **schematic 3**

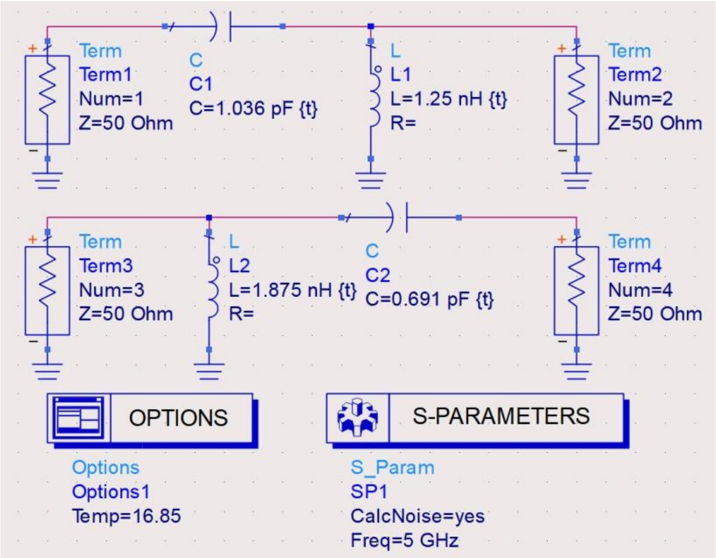
Schematic 2

- Even if the circles are not plotted, they must be **computed** (by simulation of schematic 2)



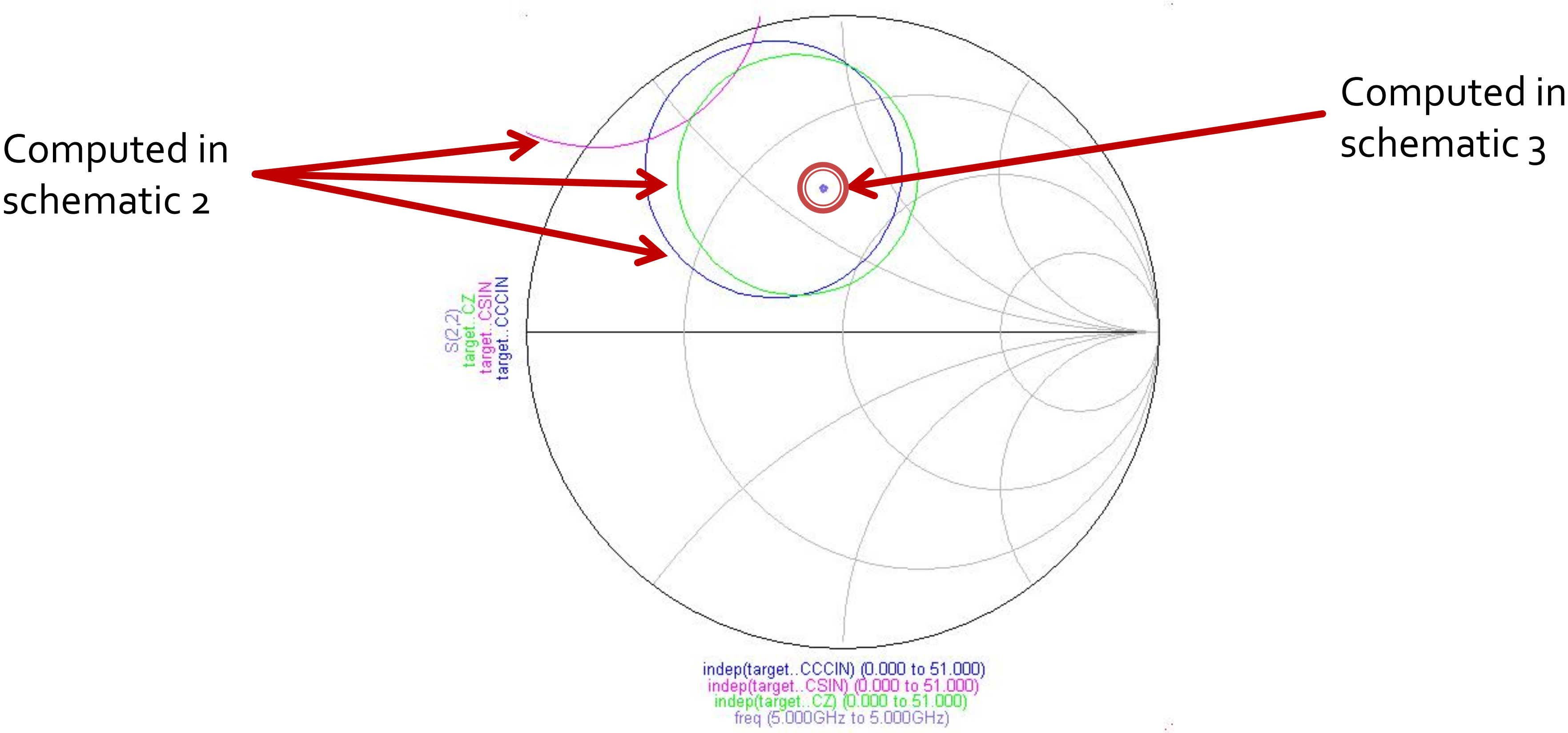
Schematic 3

- Uses circles computed in **schematic 2** as target
- **Tune** the components in the two L networks to reach the desired points



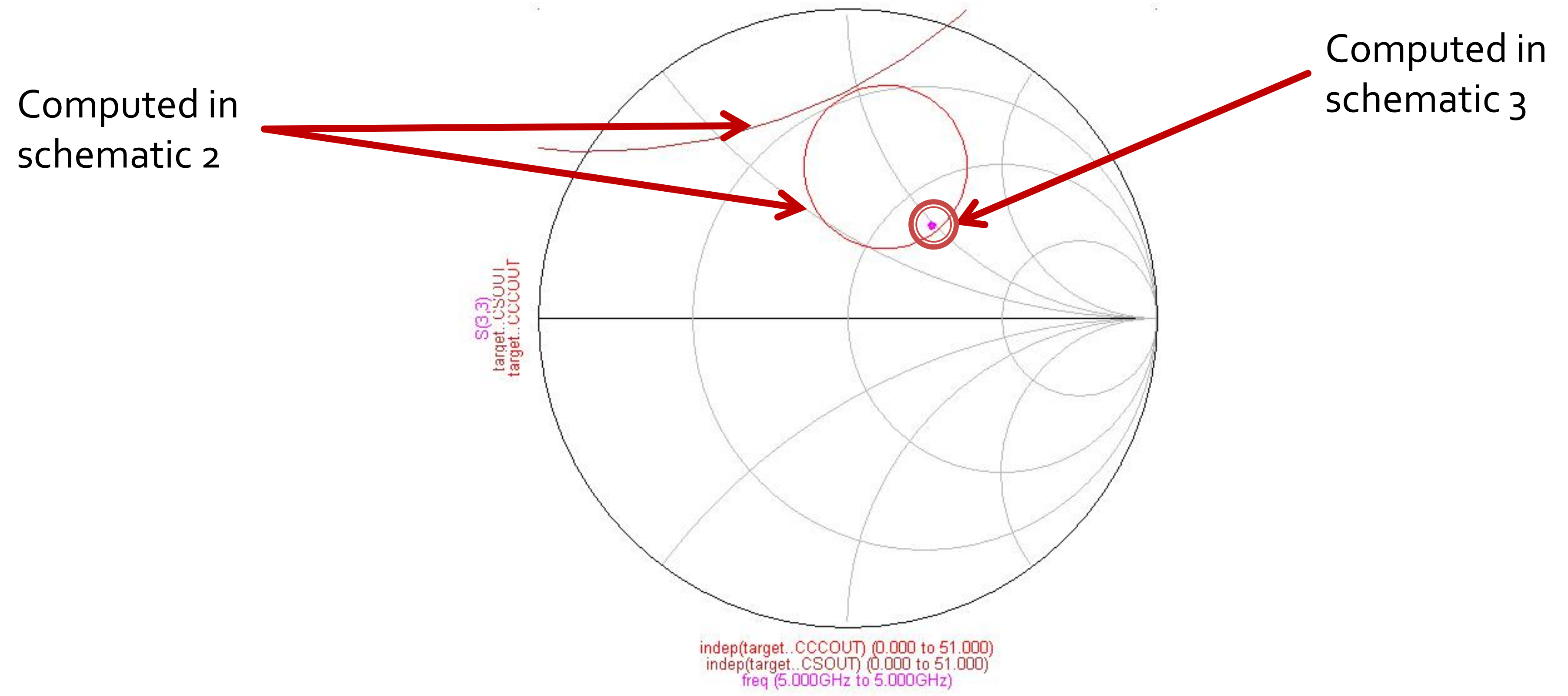
Schematic 3

- Tune the components in the two L networks to reach the desired points



Schematic 3

- Tune the components in the two L networks to reach the desired points

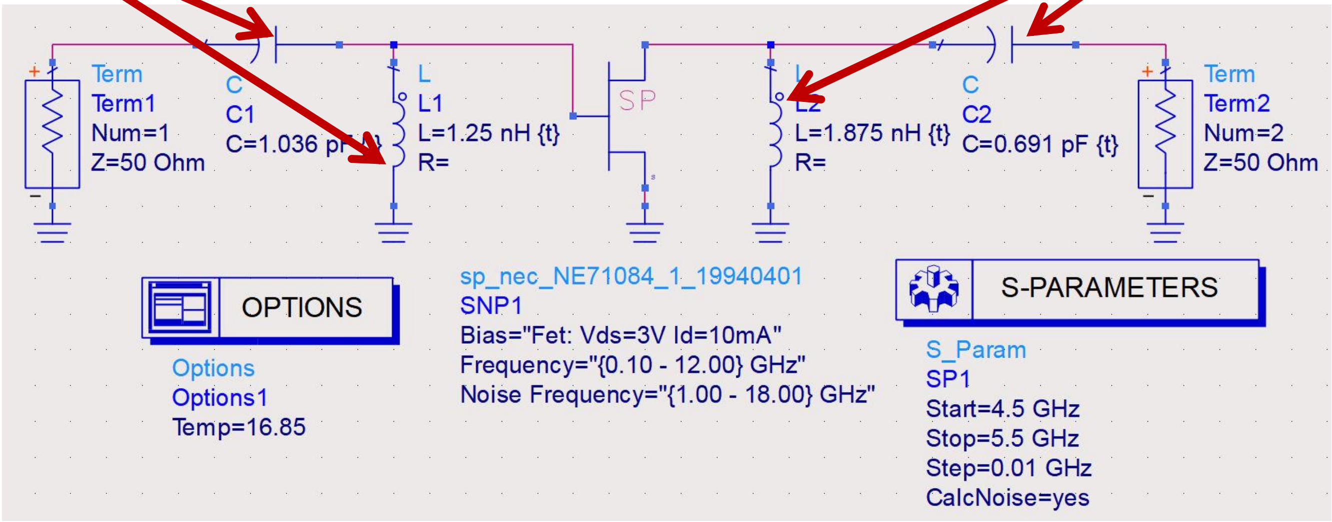


Schematic 4

- Insert the components obtained by tuning in **schematic 3** as input/output matching networks for the transistor

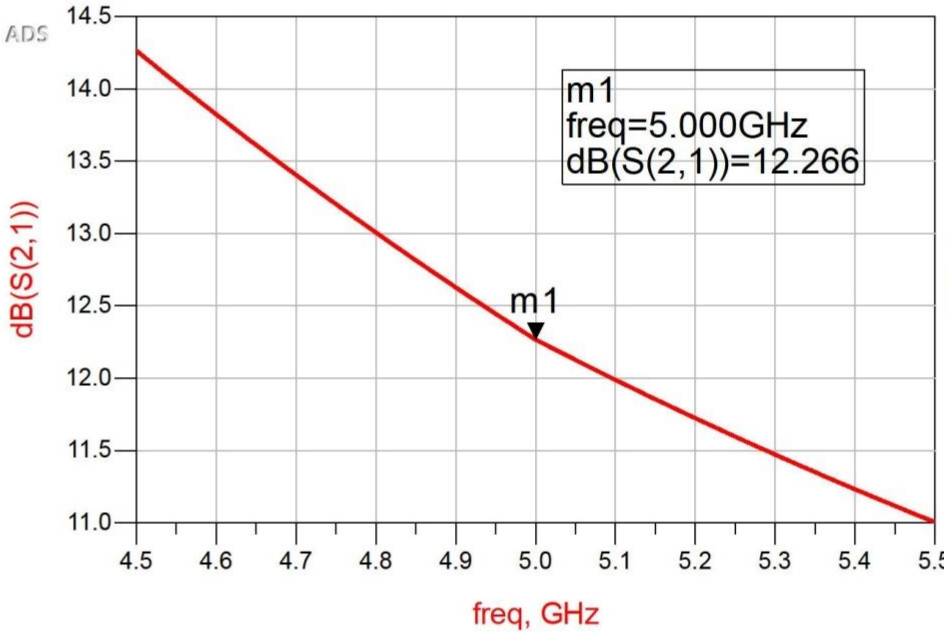
Obtained in schematic 3

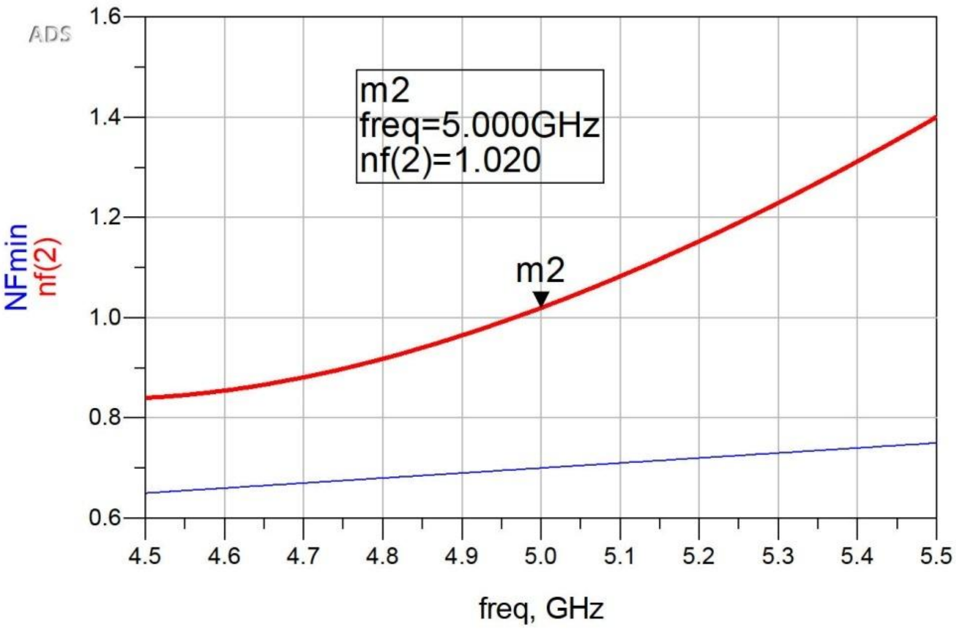
Obtained in schematic 3



Schematic 4

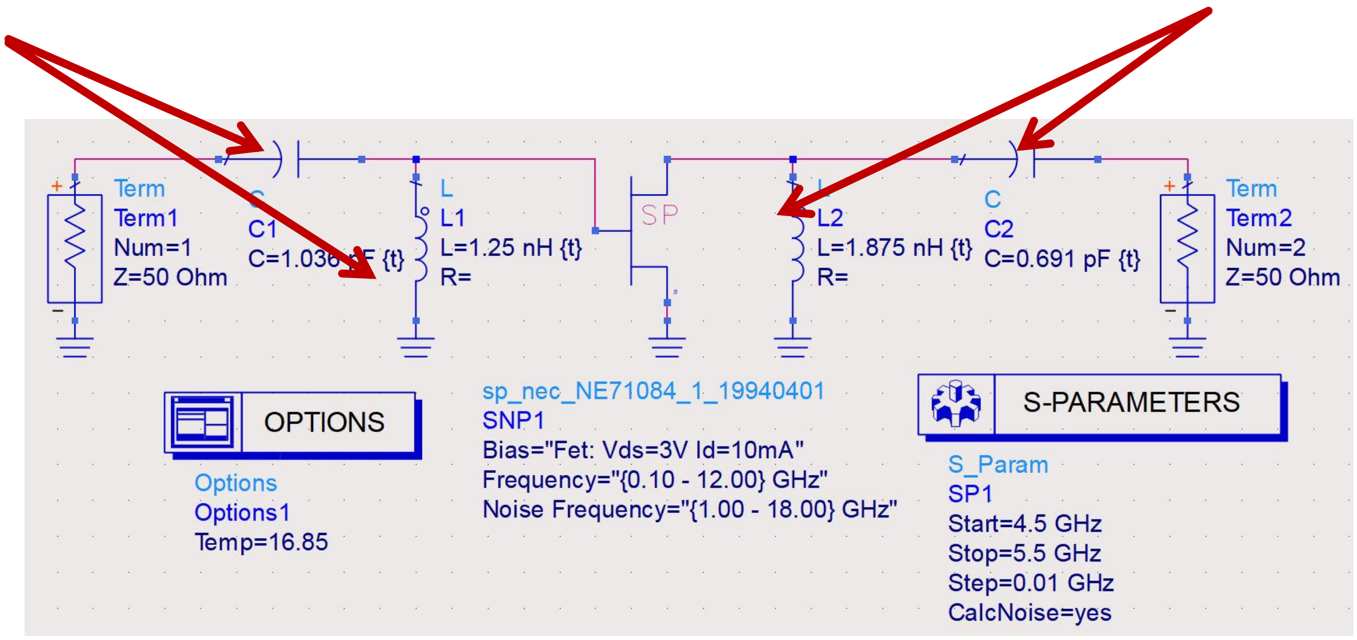
- Initial results, probably good but not perfect





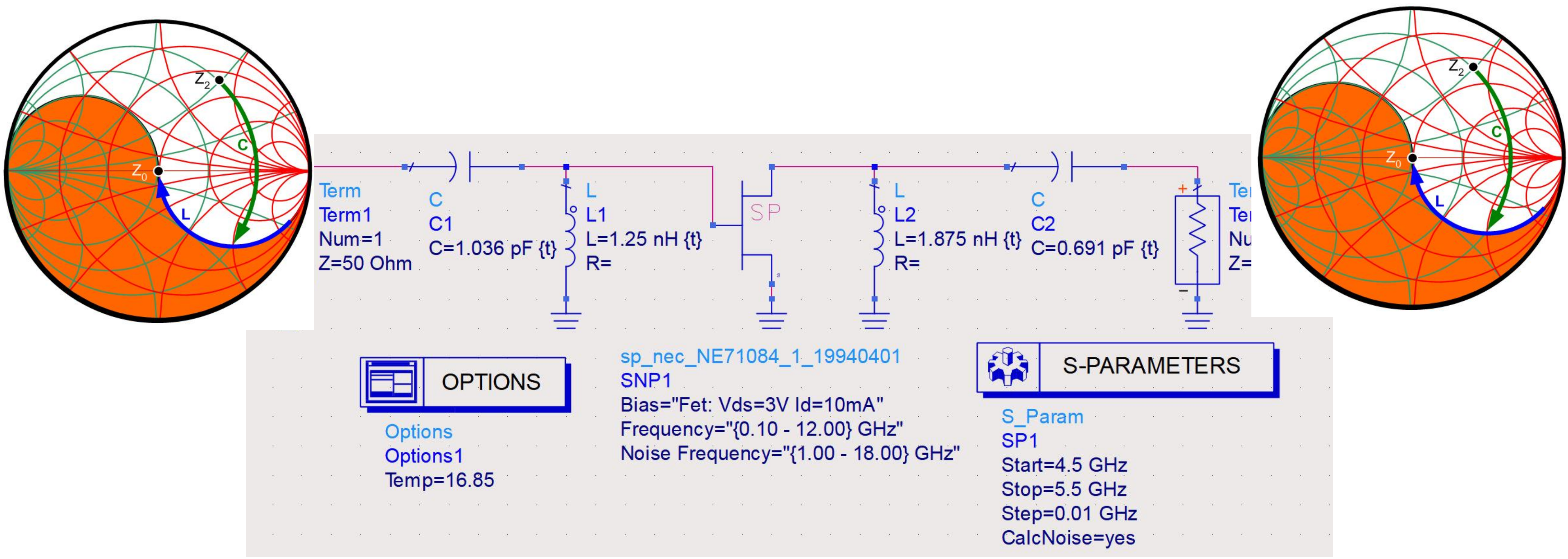
Schematic 4

- **Tune** the components in the input/output matching networks for better results



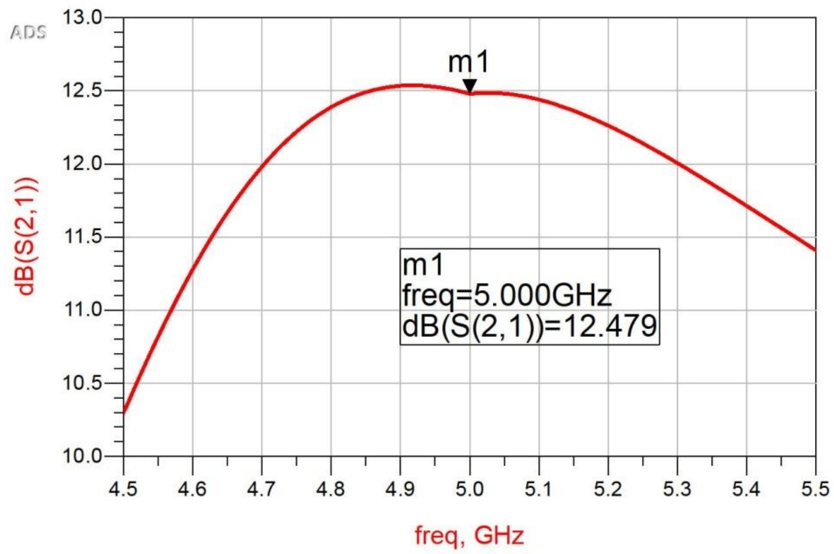
Schematic 4

- Tuning directly in schematic 4 (without passing through the other 3 schematics) has **zero** chances of success



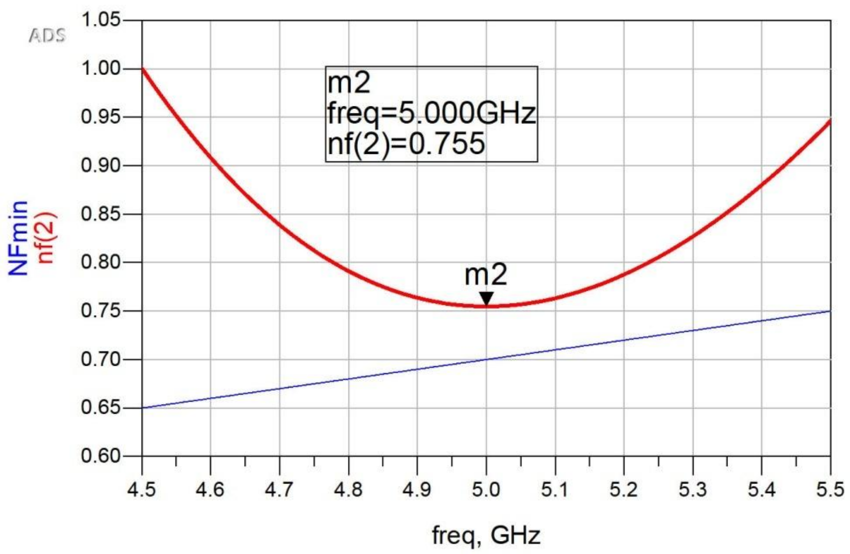
Schematic 4

- We obtain (after tuning) the final values and check the fulfillment of the design data:
  - Power gain



Schematic 4

- We obtain (after tuning) the final values and check the fulfillment of the design data:
  - Noise factor



Contact

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