

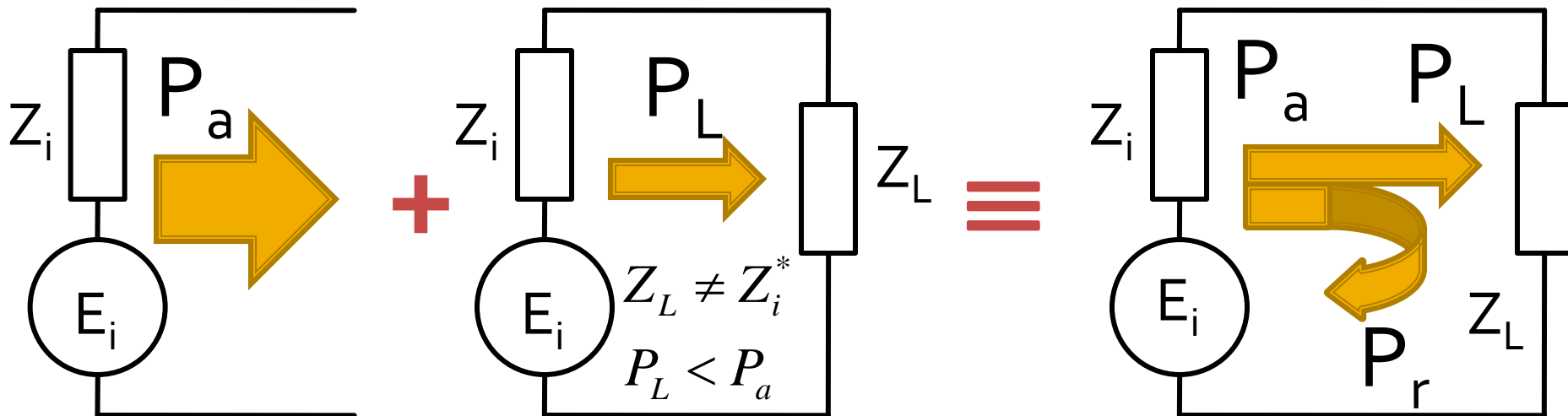
Laboratory 4 (w9-10)

2020/2021

Microwave Devices and Circuits

Short theory

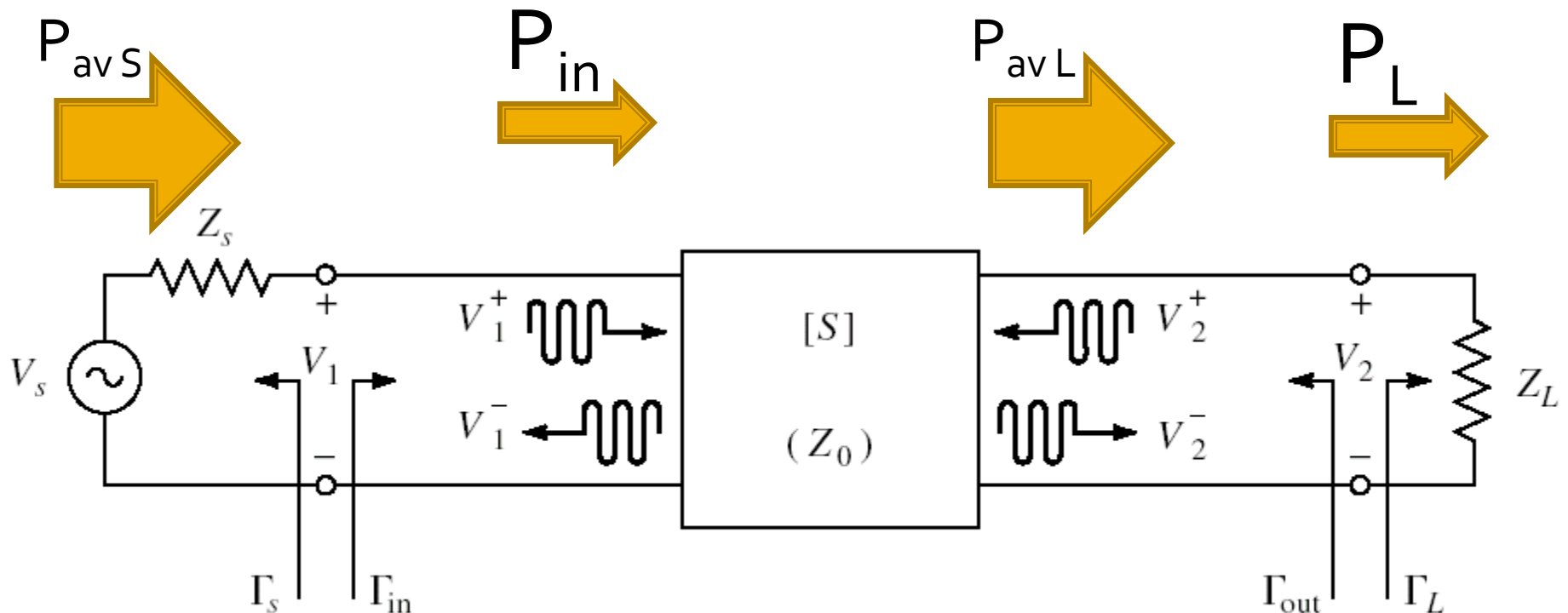
Reflection and power / Model



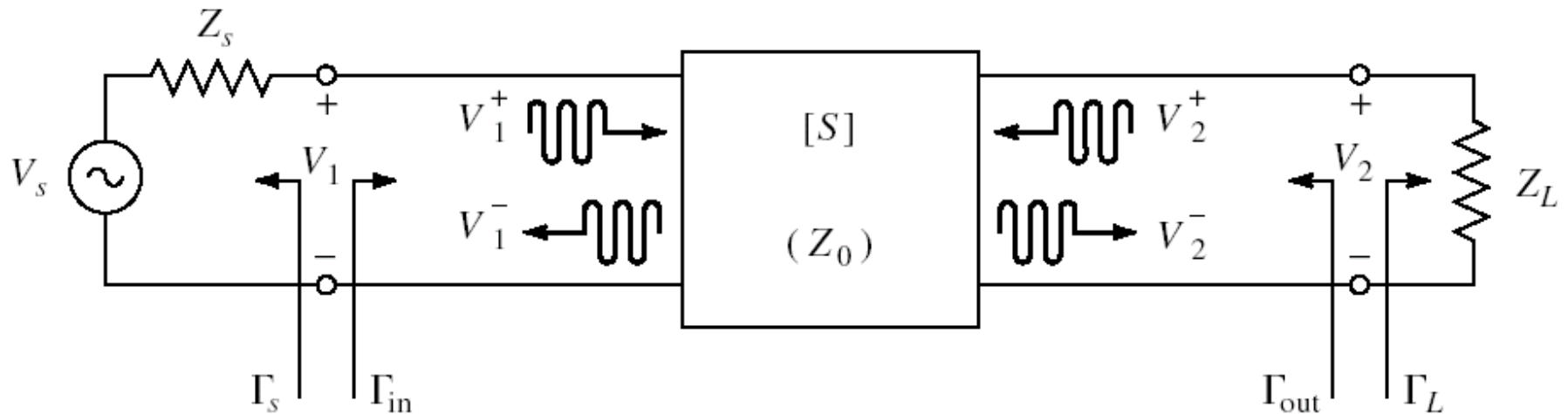
- The source has the ability to send to the load a certain maximum power (available power) P_a
- For a particular load the power sent to the load is less than the maximum (mismatch) $P_L < P_a$
- The phenomenon is **"as if"** (model) some of the power is reflected $P_r = P_a - P_L$
- The power is a **scalar**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

Power / Matching

- Two ports in which matching influences the power transfer

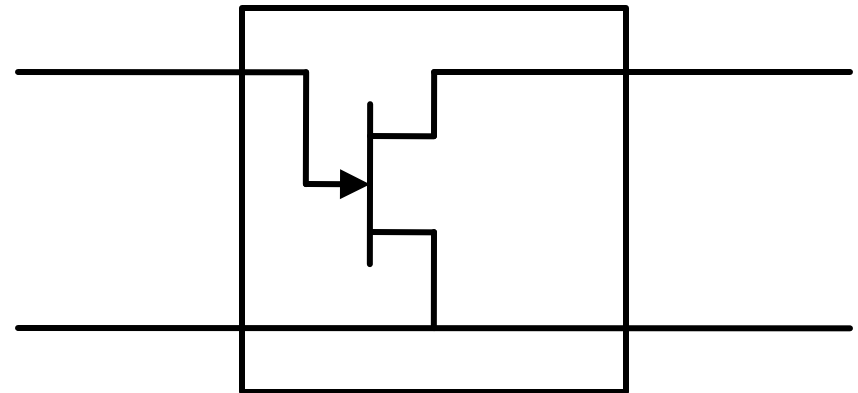
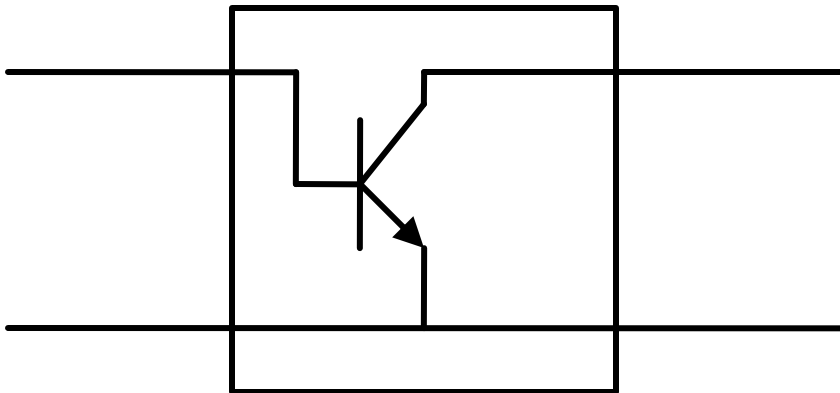
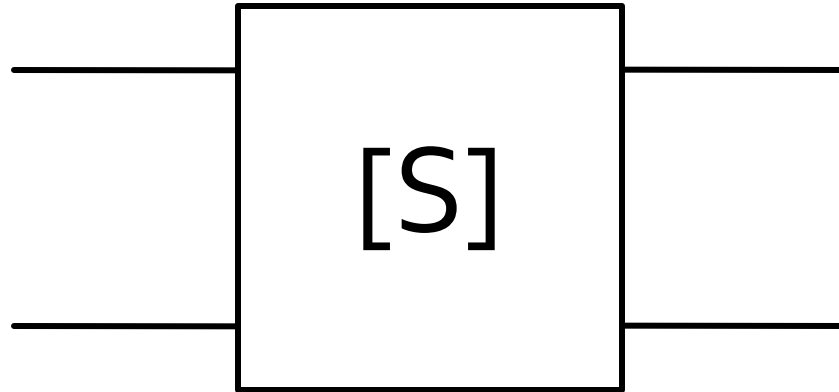


Amplifier as two-port

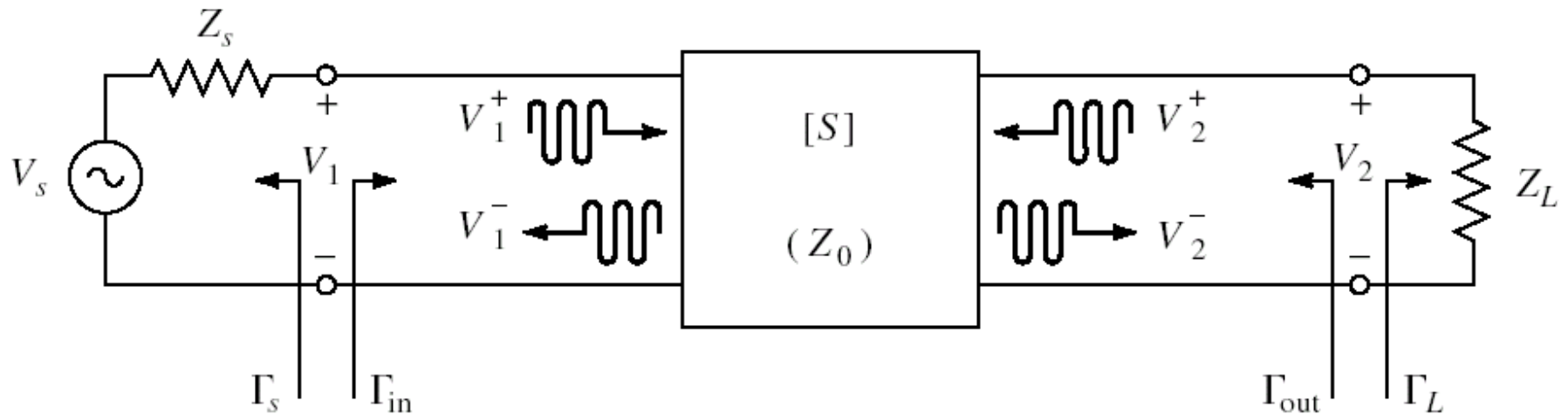


- Characterized with S parameters
- normalized at Z_0 (implicit 50Ω)
- Datasheets: S parameters for specific bias conditions

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

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

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

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

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

Output stability circle (CSOUT)

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

- 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)

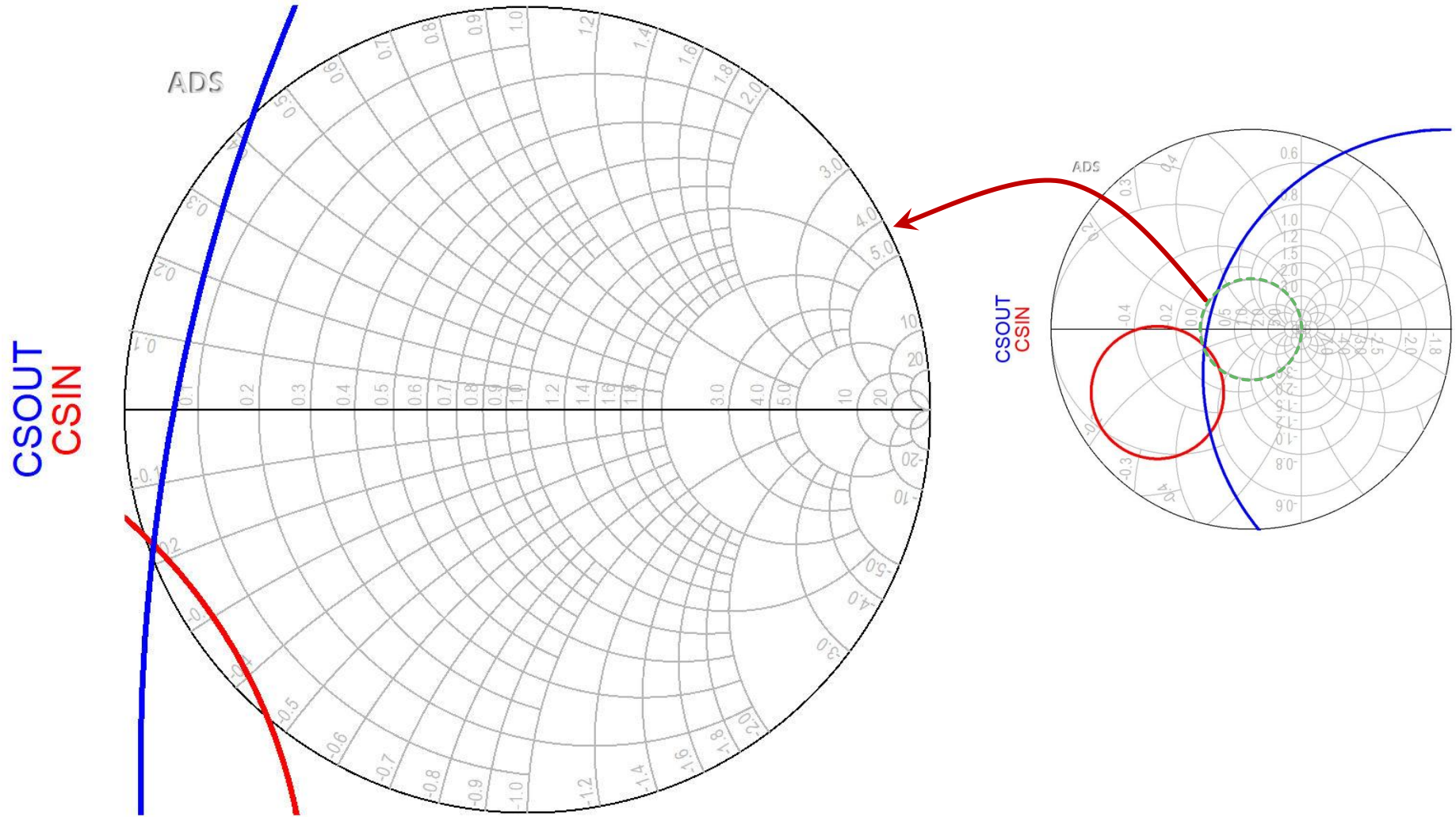
$$C_L = \frac{(S_{22} - \Delta \cdot S_{11}^*)^*}{|S_{22}|^2 - |\Delta|^2} \quad R_L = \frac{|S_{12} \cdot S_{21}|}{\left| |S_{22}|^2 - |\Delta|^2 \right|}$$

Input stability circle (CSIN)

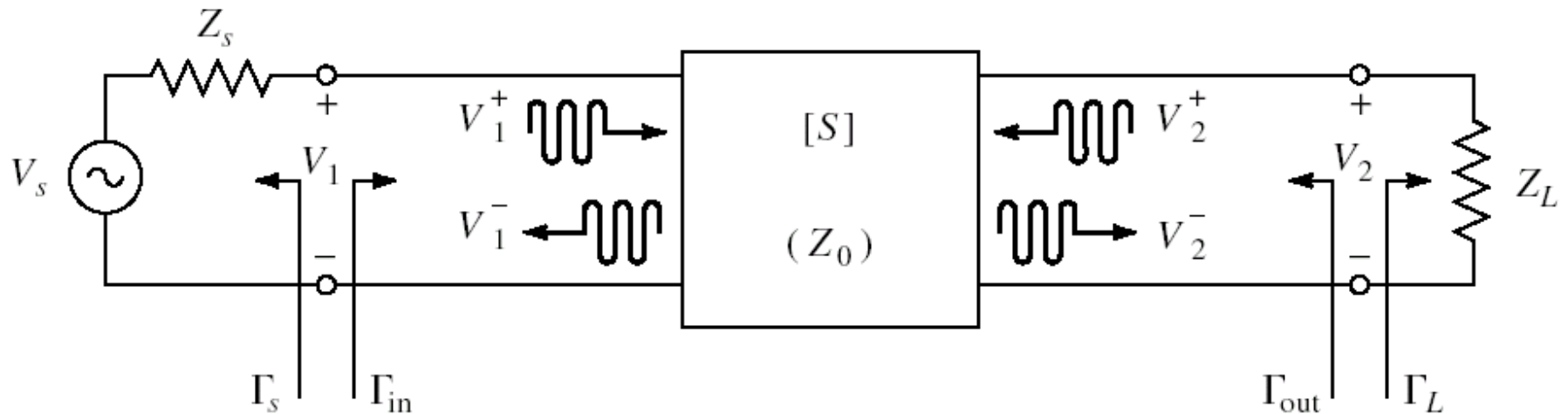
- Similarly
$$\left| \Gamma_{out} \right| = 1 \quad \left| S_{22} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_S}{1 - S_{11} \cdot \Gamma_S} \right| = 1$$
- We obtain the equation of a circle in the complex plane, which represents the locus of Γ_S for the **limit between stability and instability** ($|\Gamma_{out}| = 1$)
- This circle is the **input stability circle** (Γ_S)

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

ADS



Amplifier as two-port



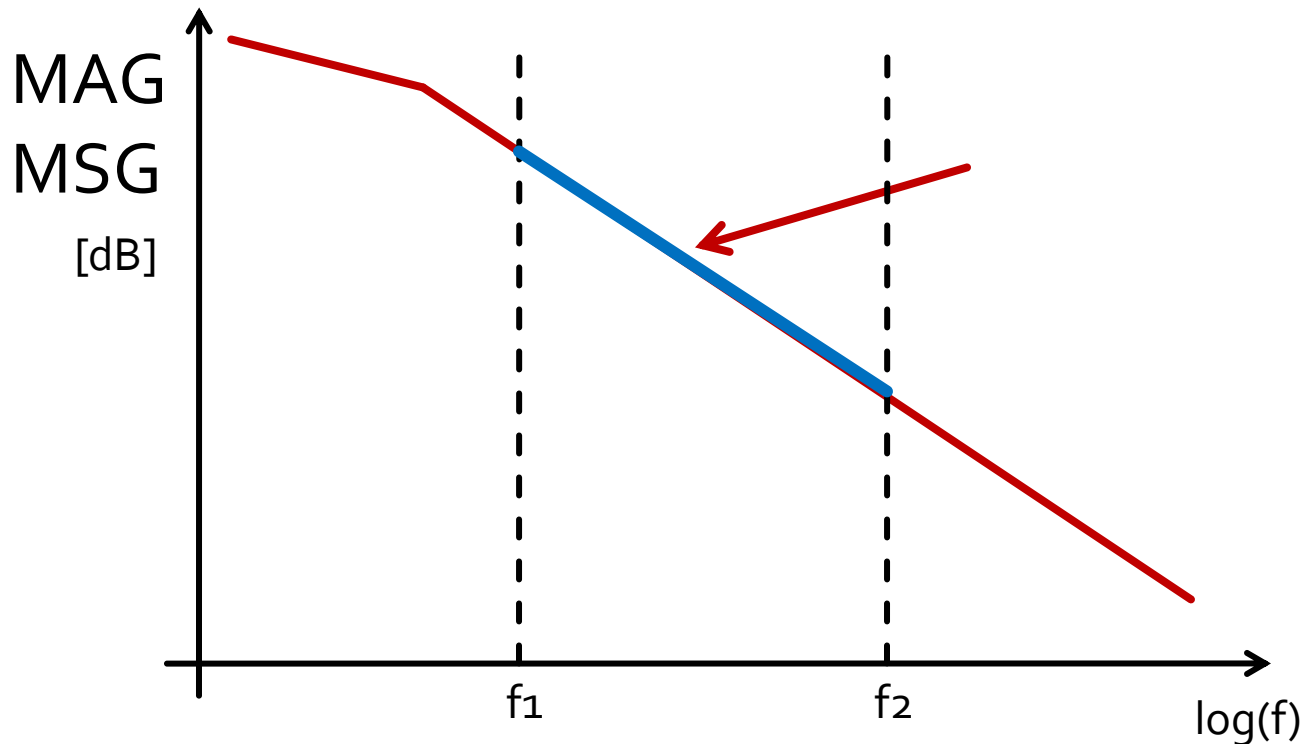
- For an amplifier two-port we are interested in:
 - stability
 - **power gain**
 - noise (sometimes – small signals)
 - linearity (sometimes – large signals)

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 ($L_3 + C_9$)
 - improve stability
 - improve VSWR
 - control performance at multiple frequencies
 - improve amplifier's bandwidth

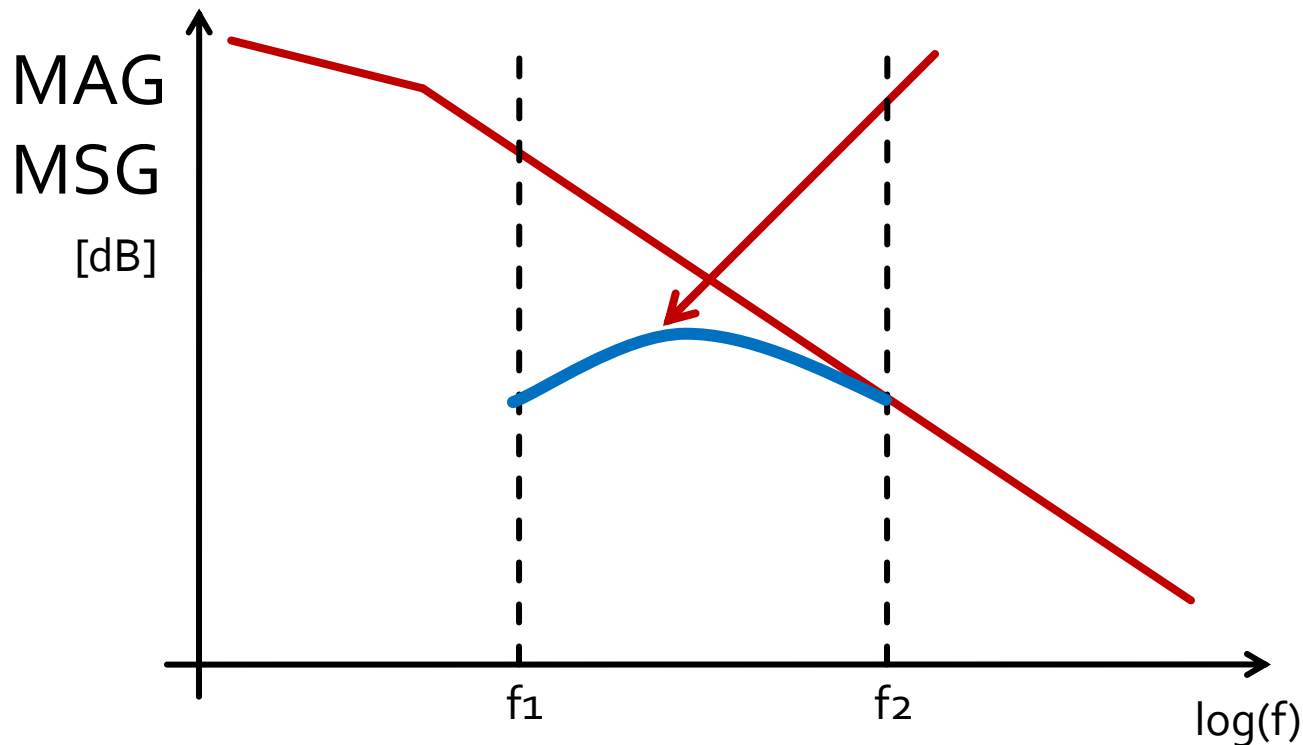
Wide bandwidth amplifier

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

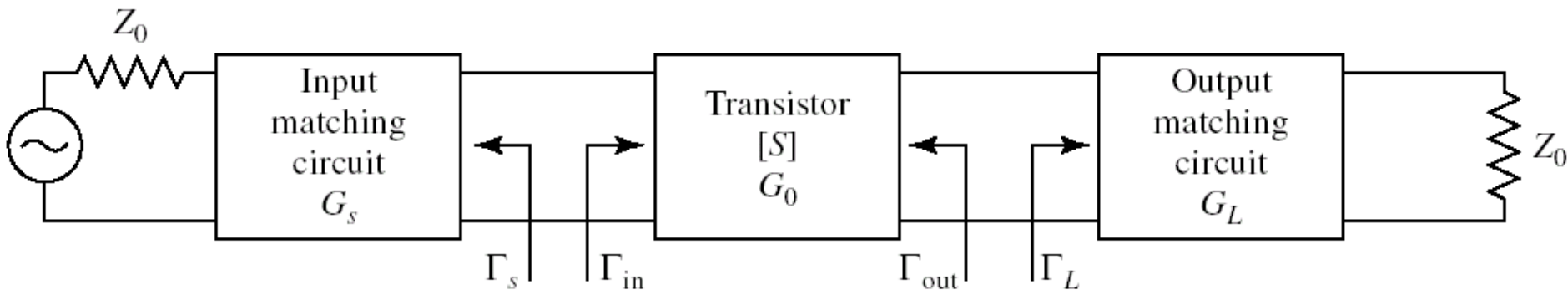


Wide bandwidth amplifier

- 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:

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

$$G_s = \frac{1 - |\Gamma_s|^2}{|1 - S_{11} \cdot \Gamma_s|^2}$$

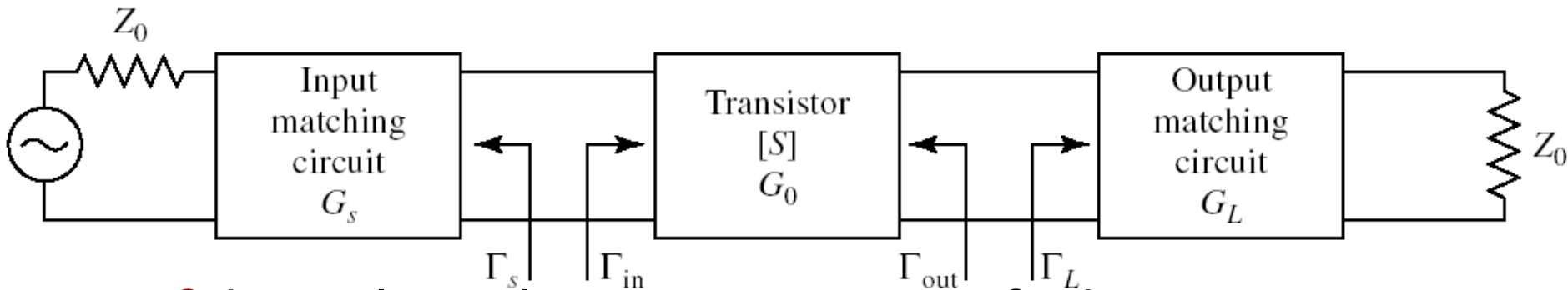
$$G_s = G_s(\Gamma_s)$$

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

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

$$G_L = G_L(\Gamma_L)$$

Design for Specified Gain

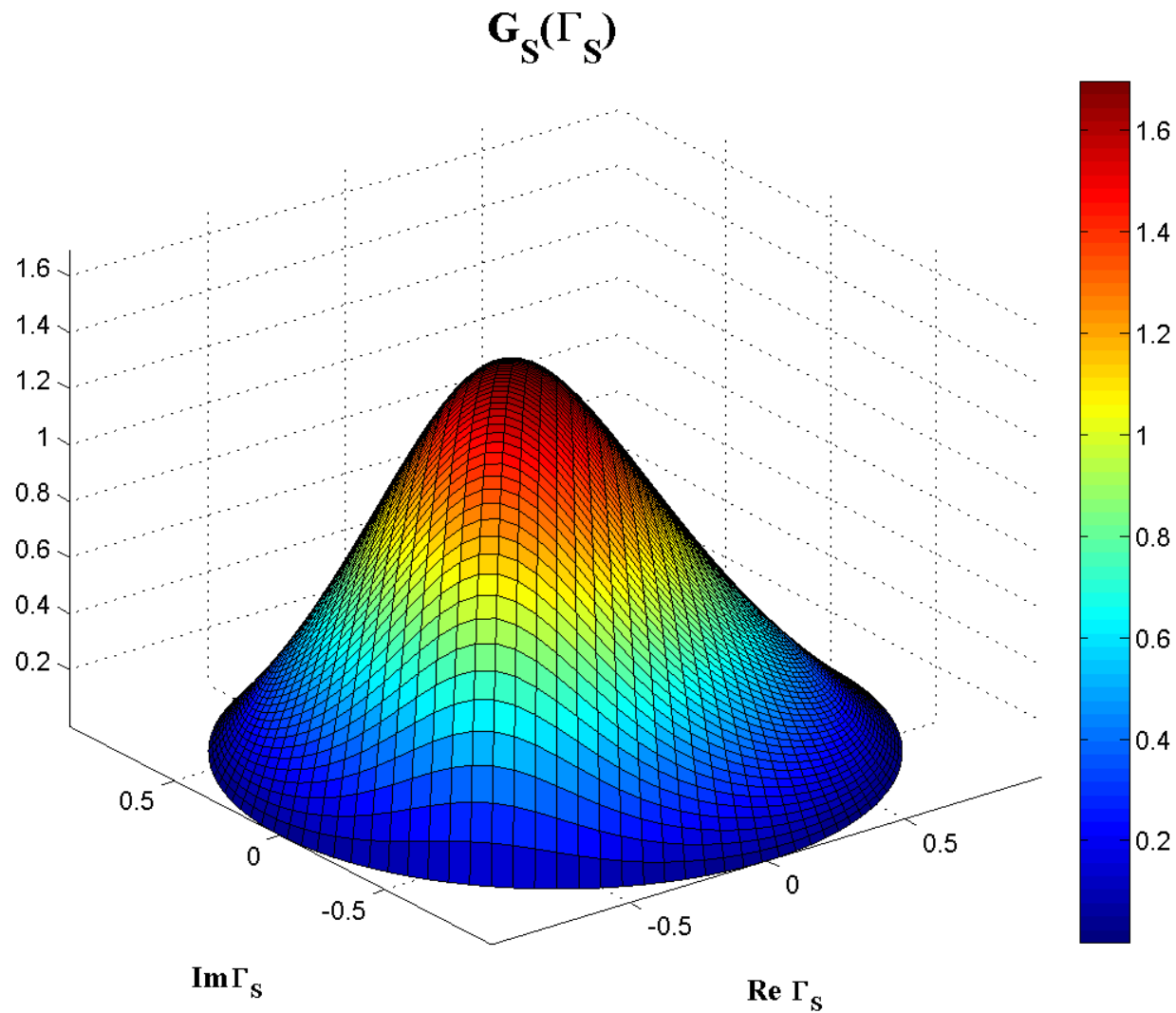


- If the unilateral assumption is justified :
 - power gain added by the input matching circuit **is not** influenced by the output matching circuit $G_s = G_s(\Gamma_s)$
 - power gain added by the output matching circuit **is not** influenced by the input matching circuit $G_L = G_L(\Gamma_L)$
- Output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

$$G_T = G_s \cdot G_0 \cdot G_L$$

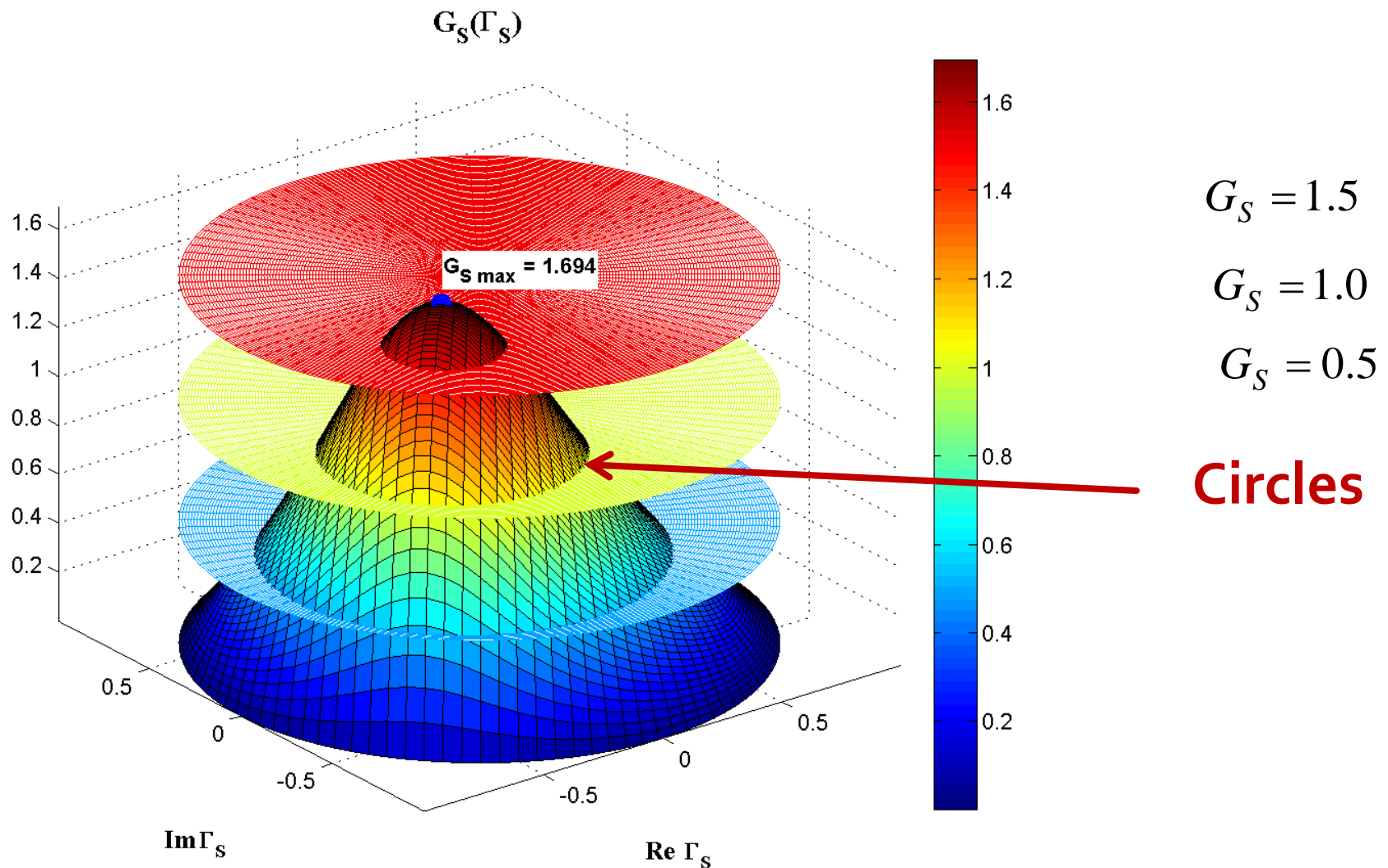
$$G_T[dB] = G_s[dB] + G_0[dB] + G_L[dB]$$

$$G_S(\Gamma_S)$$

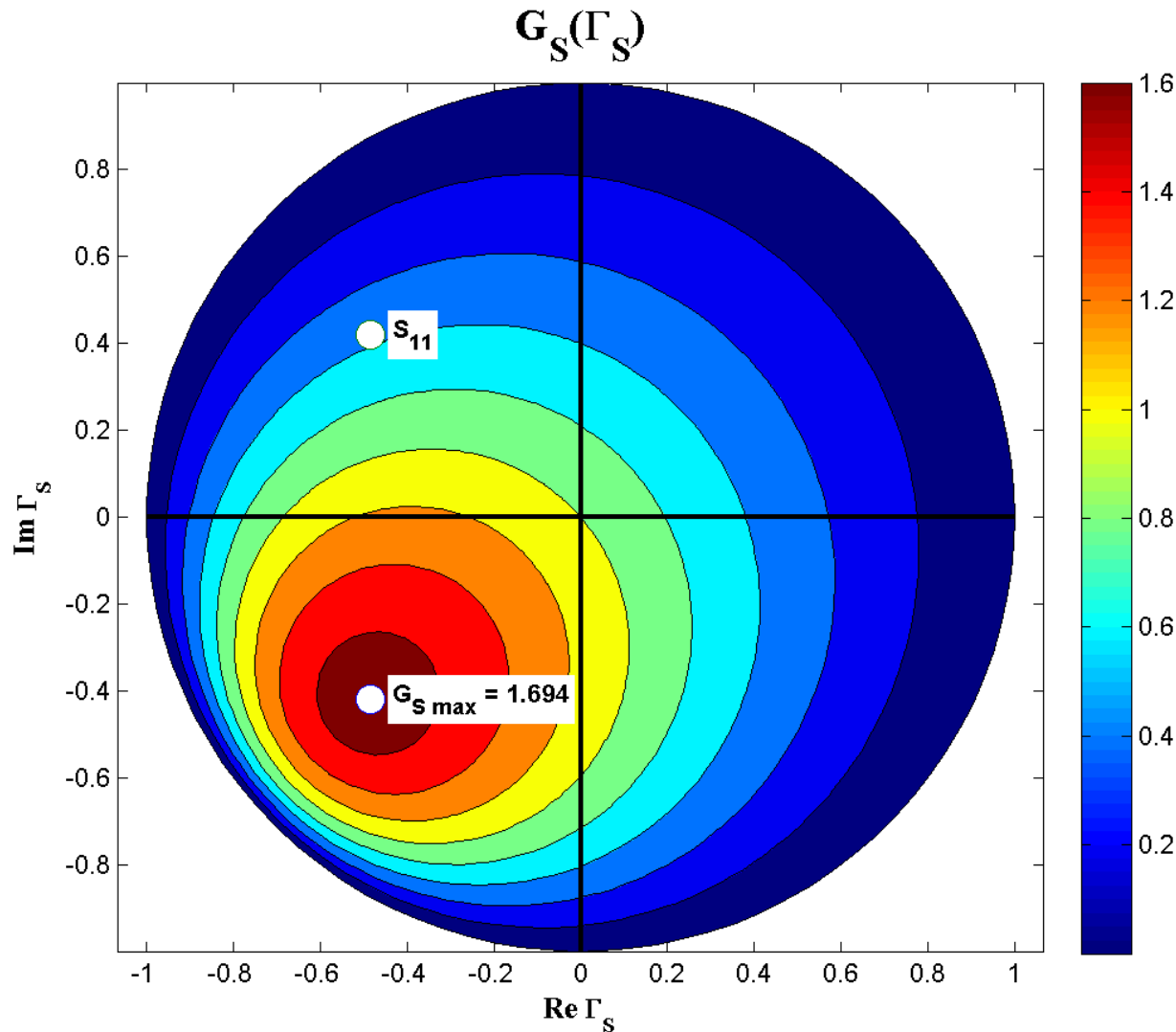


$$G_S = \frac{1 - |\Gamma_S|^2}{|1 - S_{11} \cdot \Gamma_S|^2}$$

$G_S(\Gamma_S)$, constant value contours



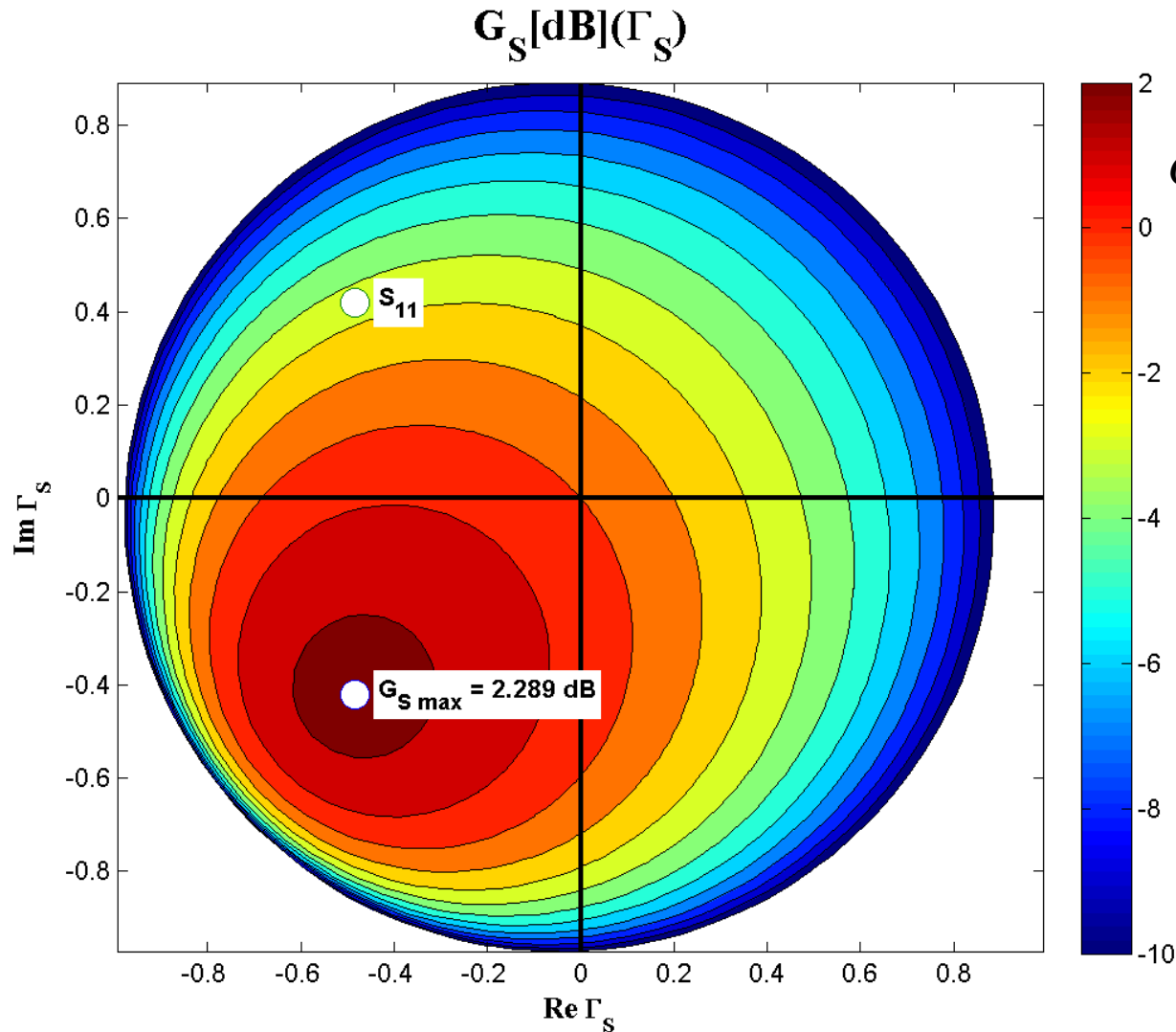
$G_S(\Gamma_S)$, constant value contours



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

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

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



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

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

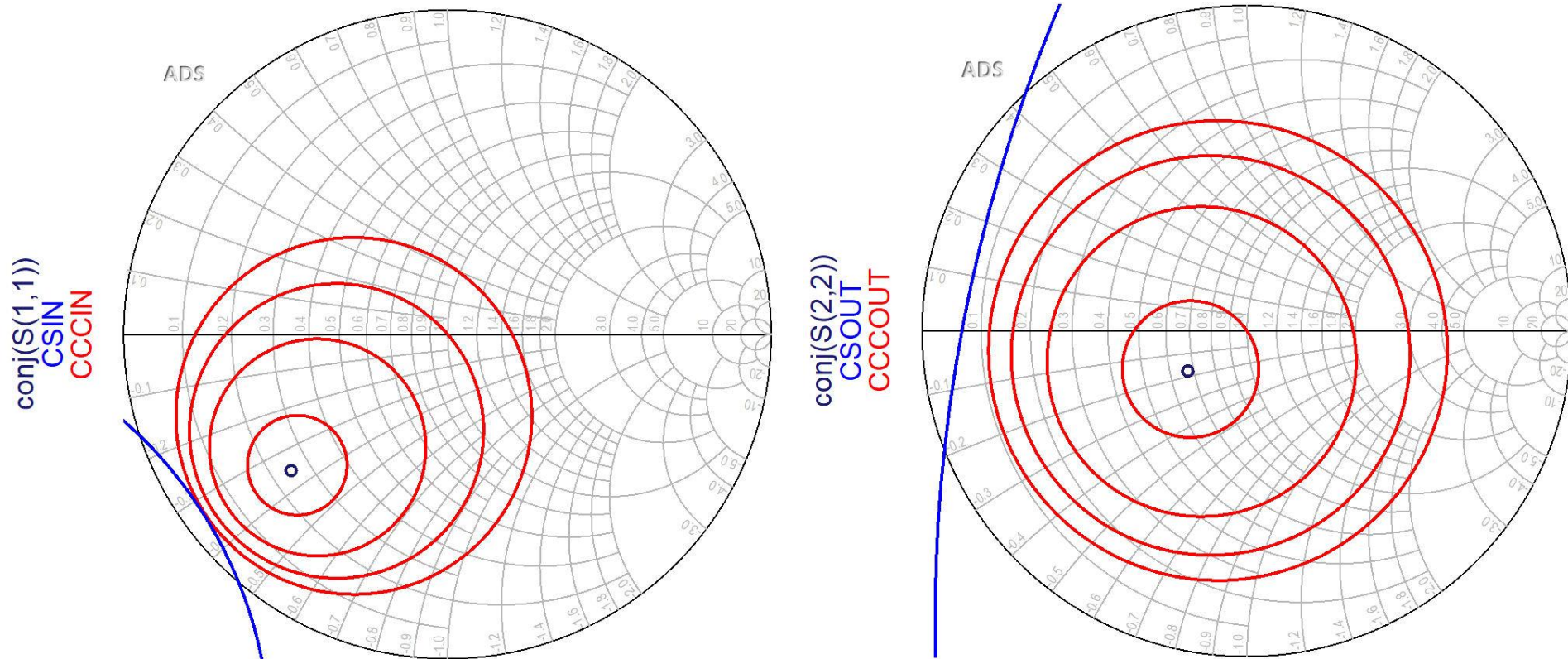
Input section constant gain circles

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

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

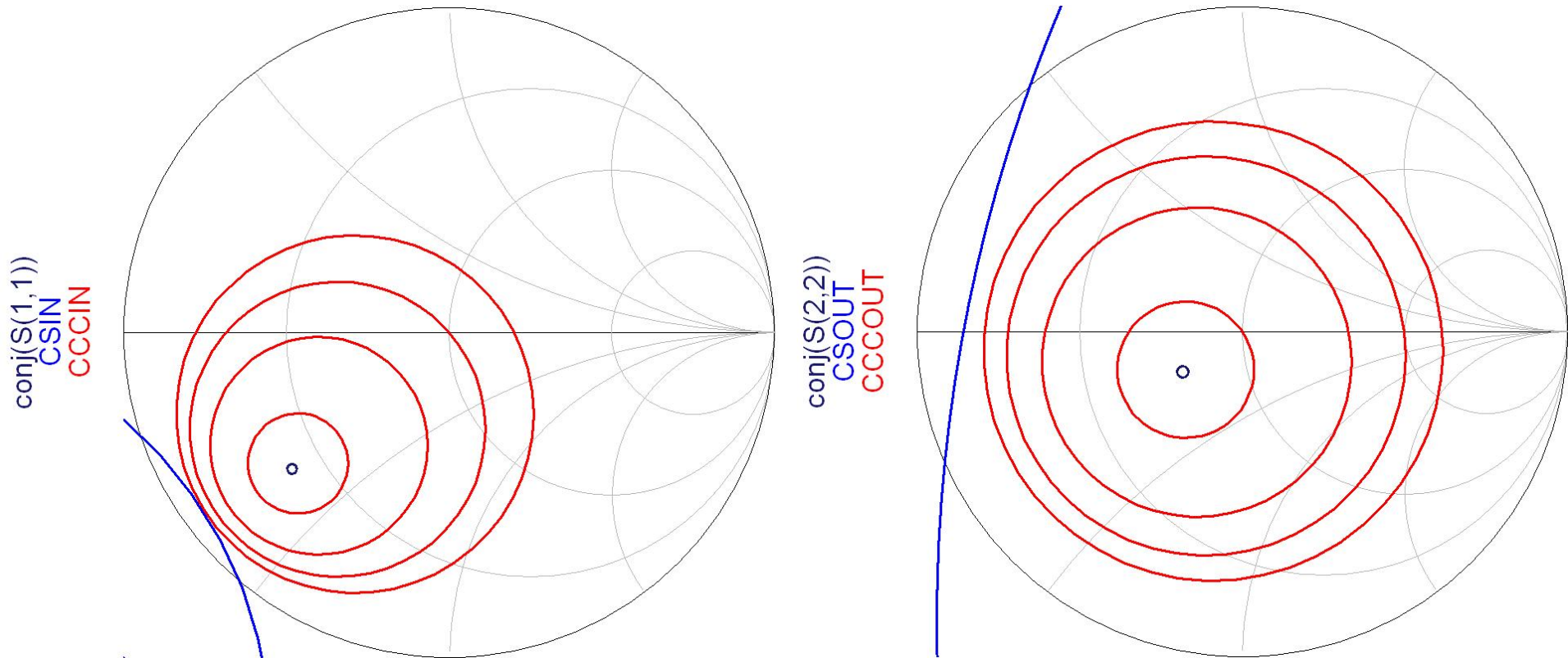
- Equation of a circle in the complex plane where Γ_S is plotted
- **Interpretation:** Any reflection coefficient Γ_S which plotted in the complex plane lies **on** the circle drawn for $g_{\text{circle}} = G_{\text{circle}}/G_{\text{Smax}}$ will lead to a gain $G_S = G_{\text{circle}}$
 - Any reflection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

CCIN, CCOUT



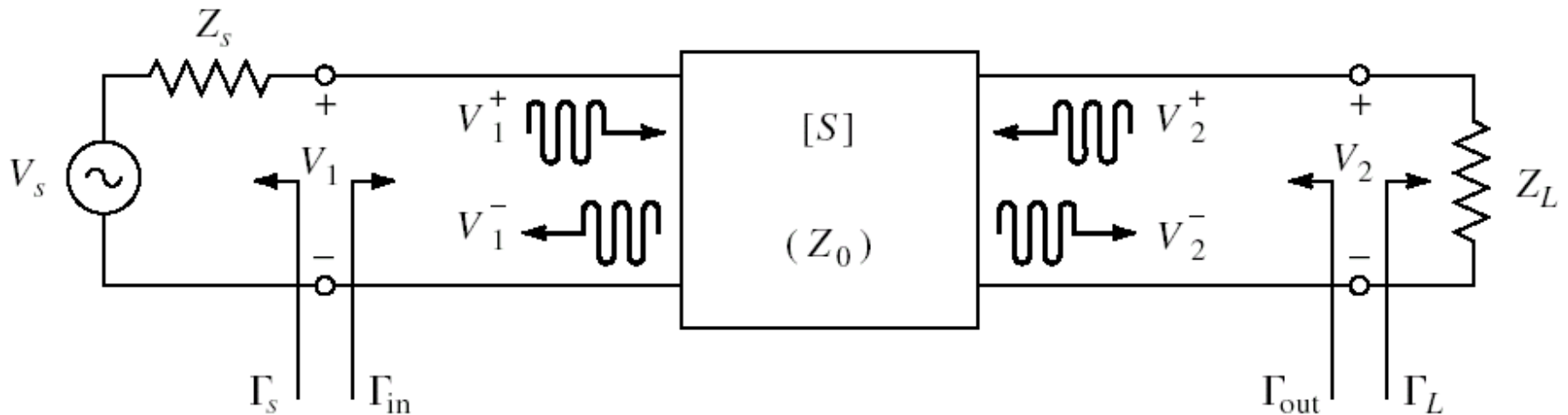
- Circles are plotted for requested values (**in dB!**)
- It is useful to compute $G_{S_{\max}}$ and $G_{L_{\max}}$ before
 - in order to request relevant circles

CCGIN, CCCOUT



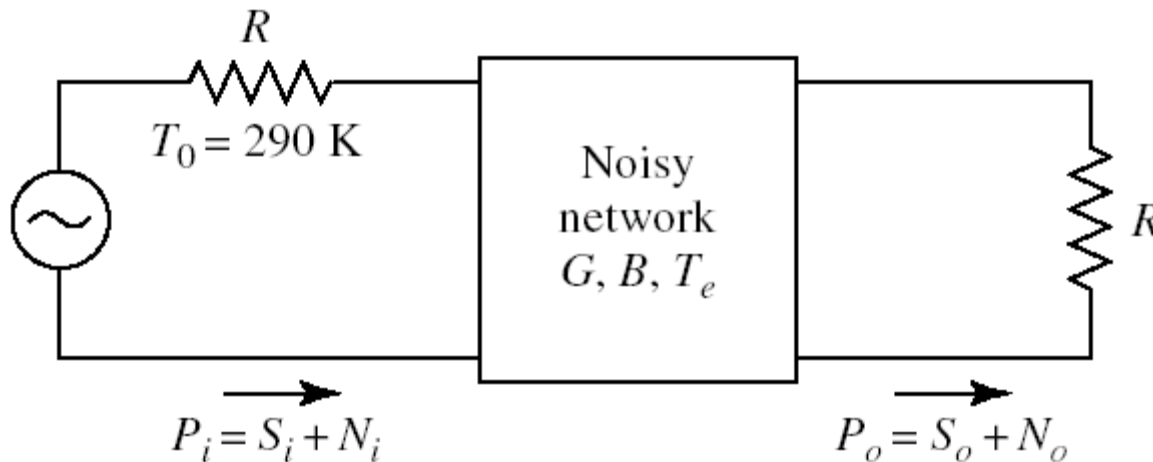
- Cercurile se reprezinta pentru valorile cerute in dB
- Este utila calcularea $G_{S_{\max}}$ si $G_{L_{\max}}$ anterior

Amplifier as two-port



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

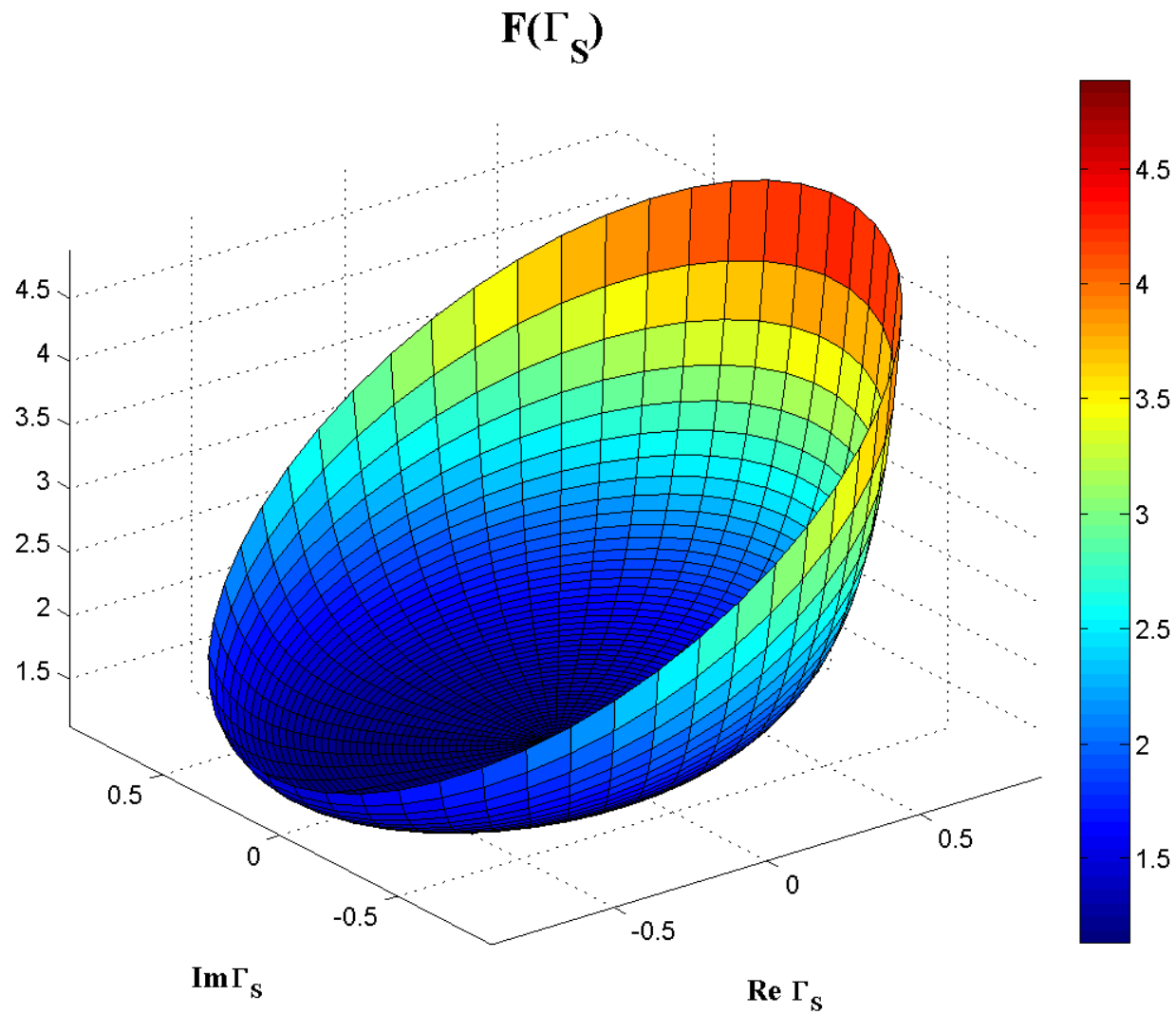
Noise Figure F



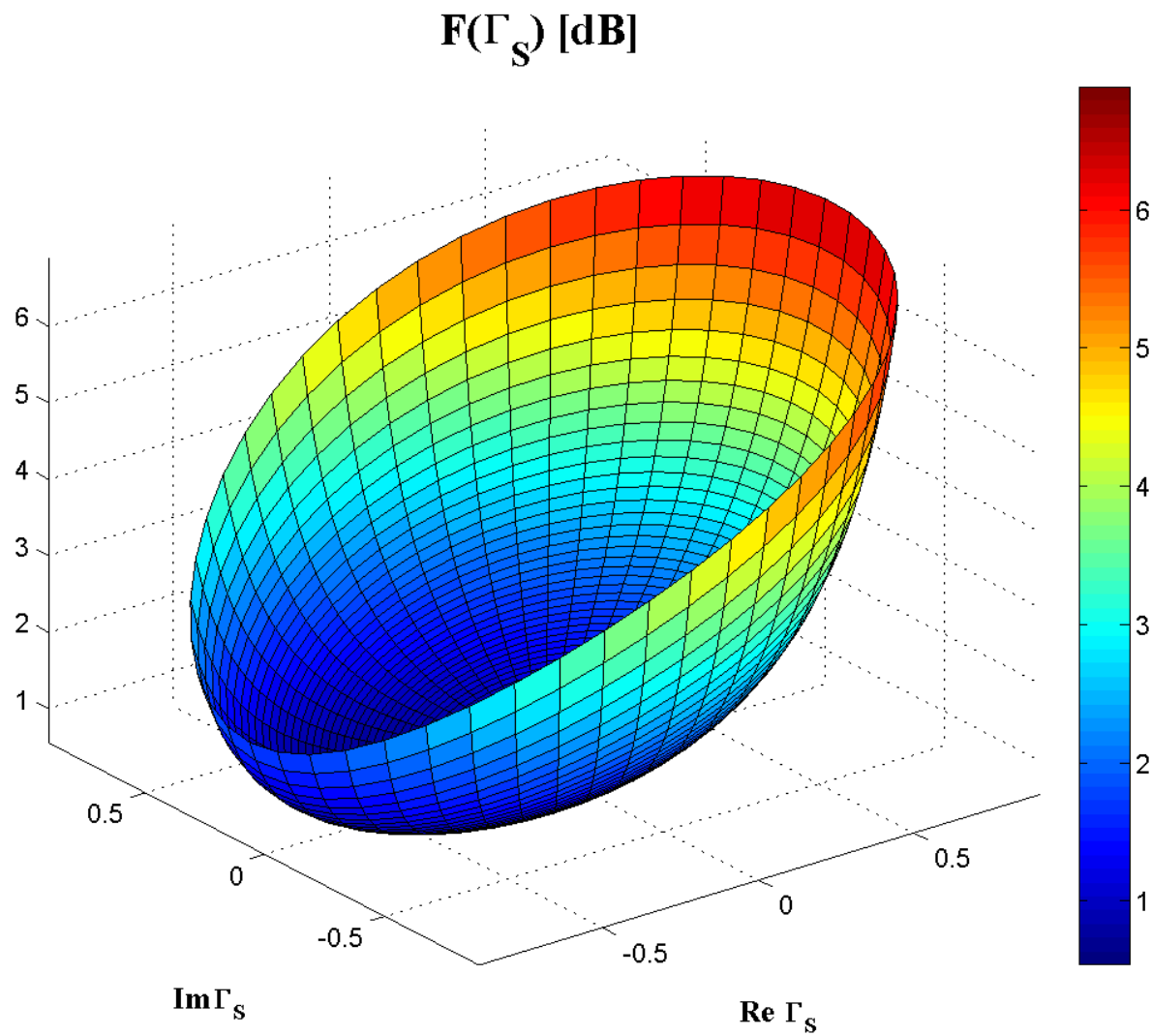
- The noise figure F , is a measure of the reduction in signal-to-noise ratio between the input and output of a device

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

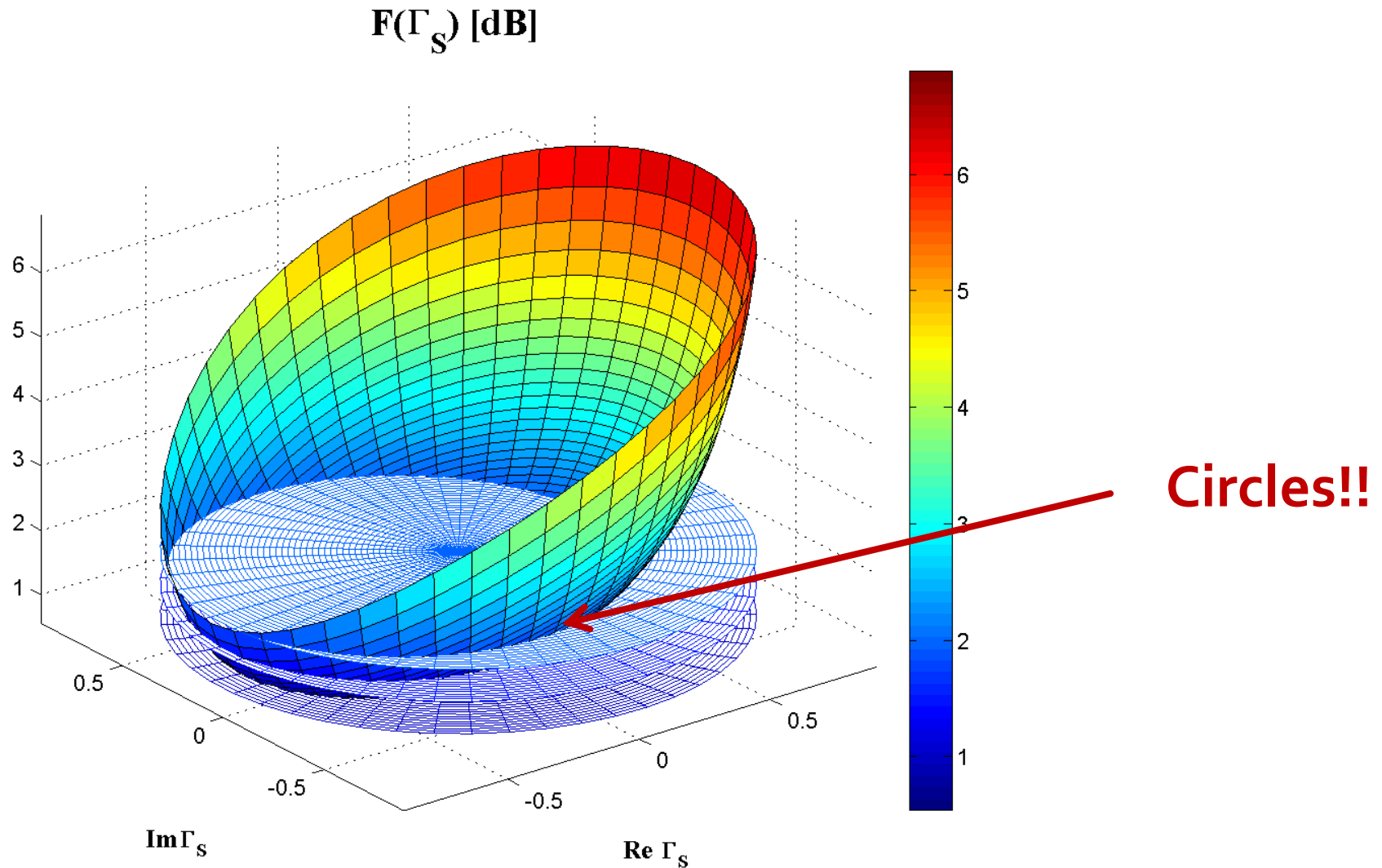
$F(\Gamma_s)$



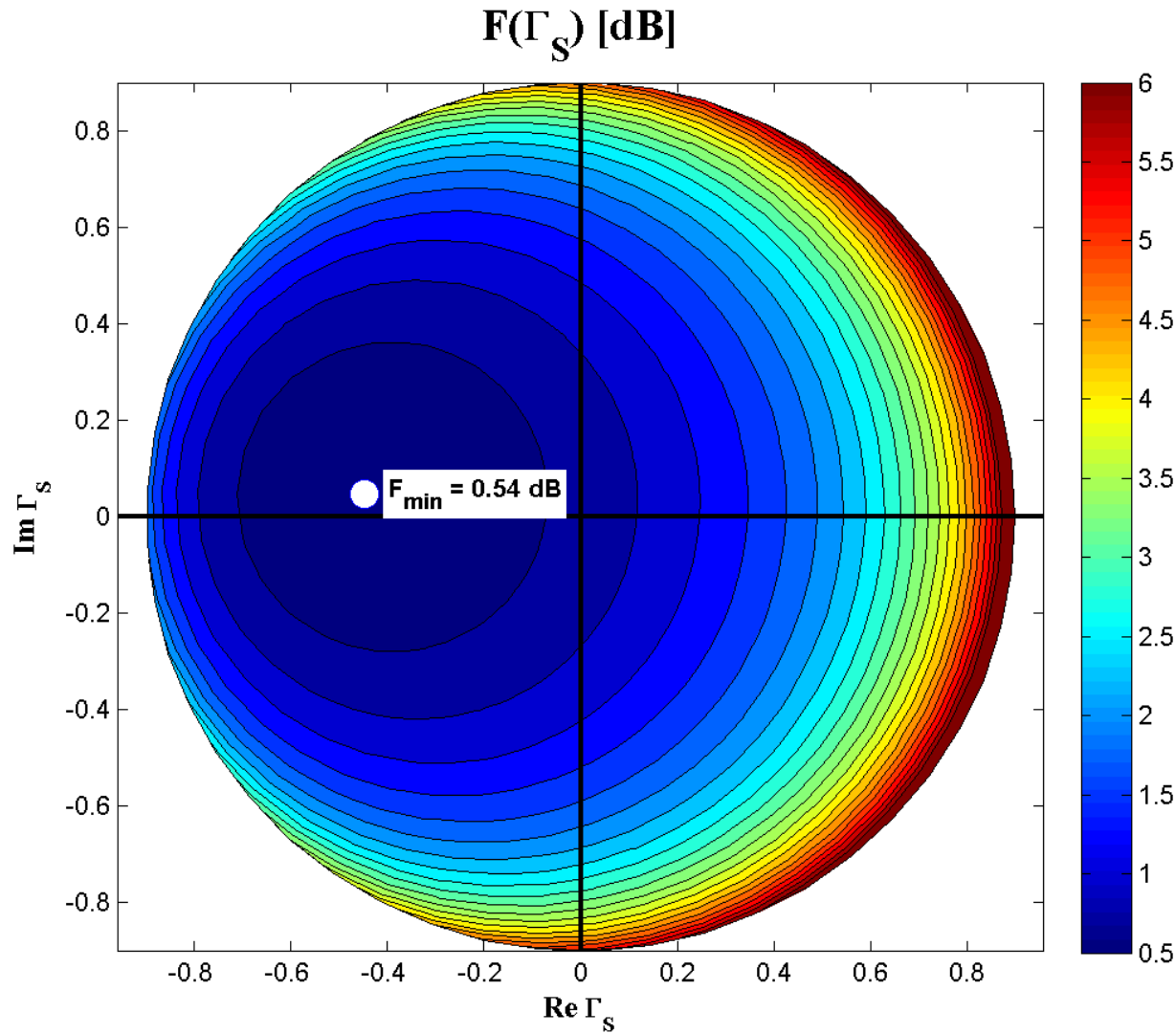
$F[\text{dB}](\Gamma_s)$



$F[\text{dB}](\Gamma_s)$, constant value contours

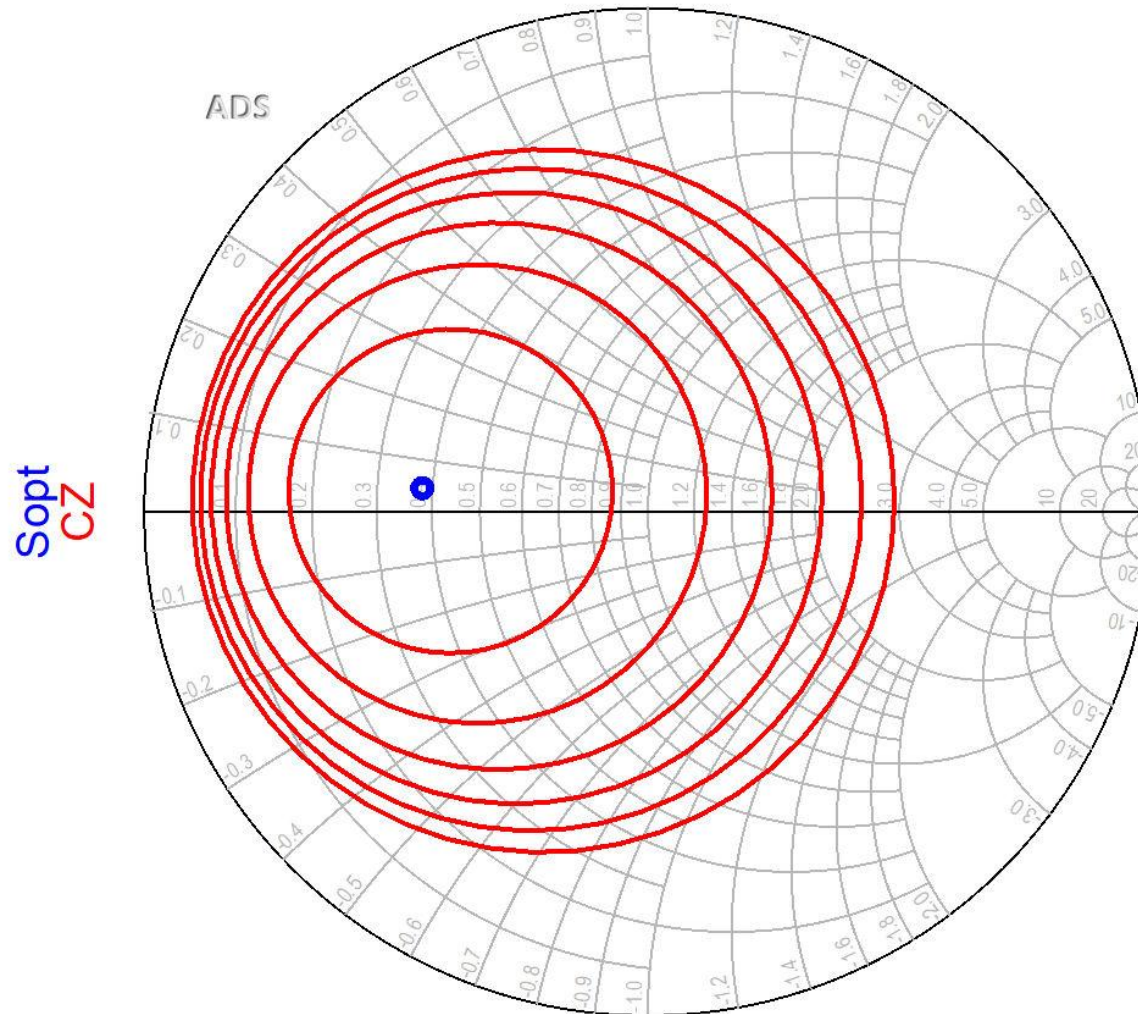


$G_s[\text{dB}](\Gamma_s)$, constant value contours



$$\Gamma_{\text{opt}} = 0.45 \angle 174^\circ$$

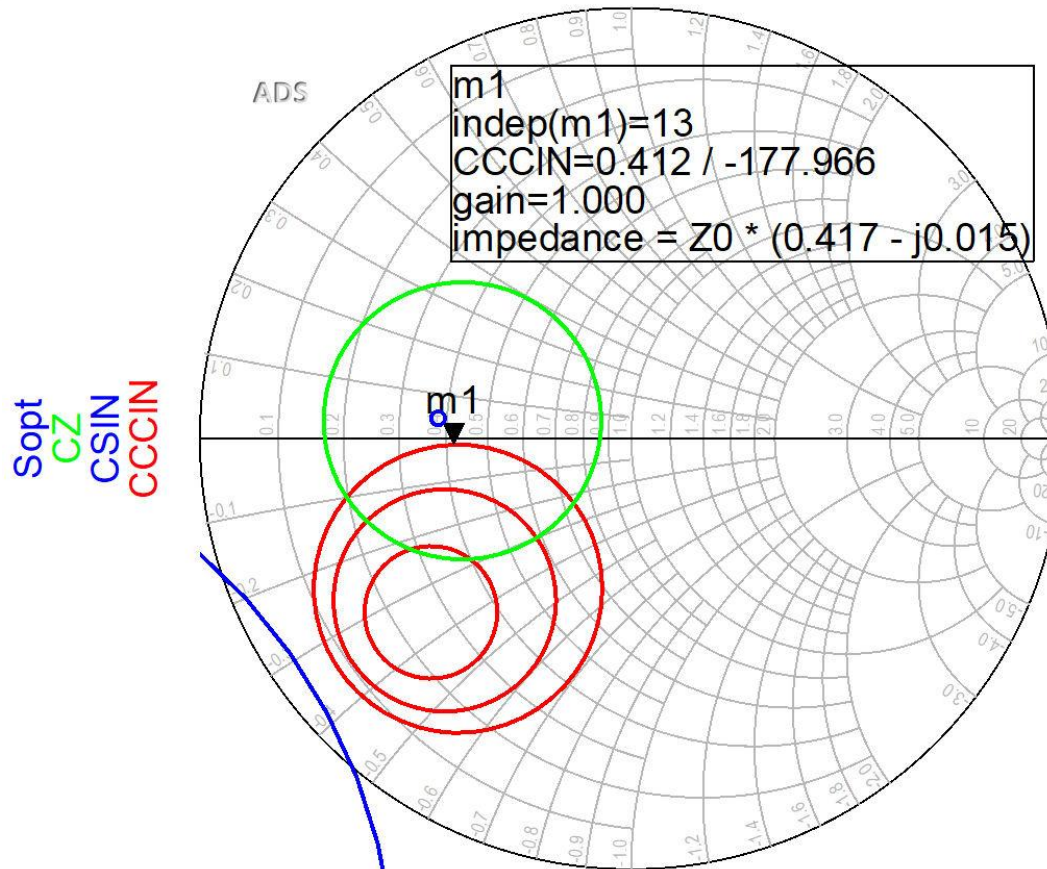
CZ – Noise Circle (input port only!)



Example, LNA @ 5 GHz

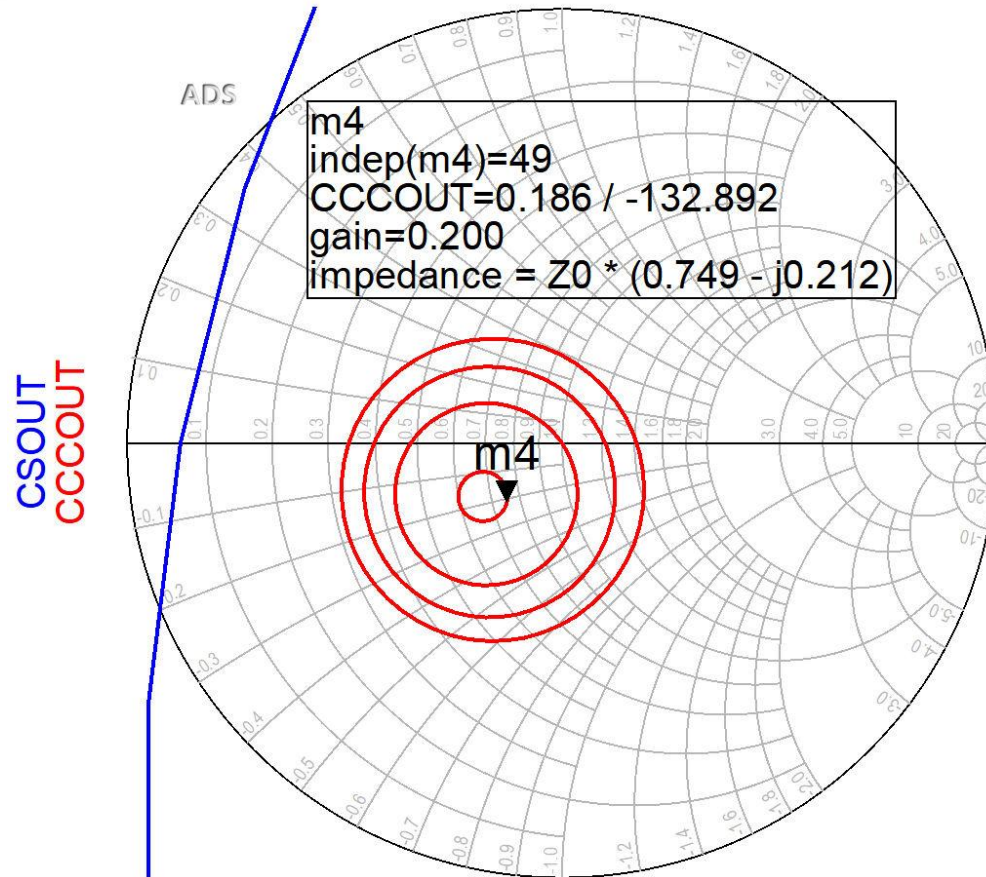
- Low Noise Amplifier
- At the input port we must compromise between
 - noise (~~input~~ constant noise circle **CZ**)
 - power gain (input constant gain circle **CCCIN**)
 - stability (input stability circle **CSIN**)
- At the output port noise **does not intervene** (no influence). The compromise is 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 ($G_s = 1$ dB), position m1 above is better
- We obtain better (smaller) NF

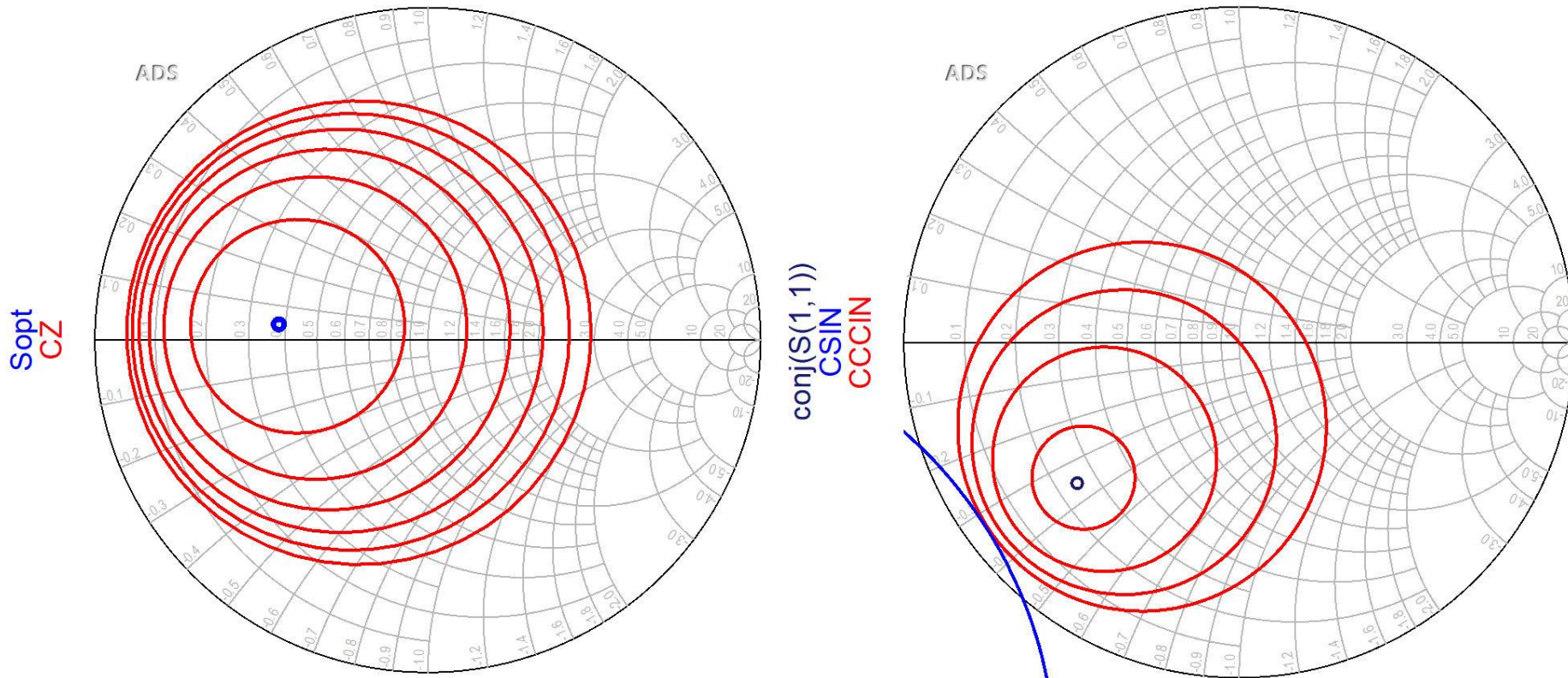
Output matching circuit



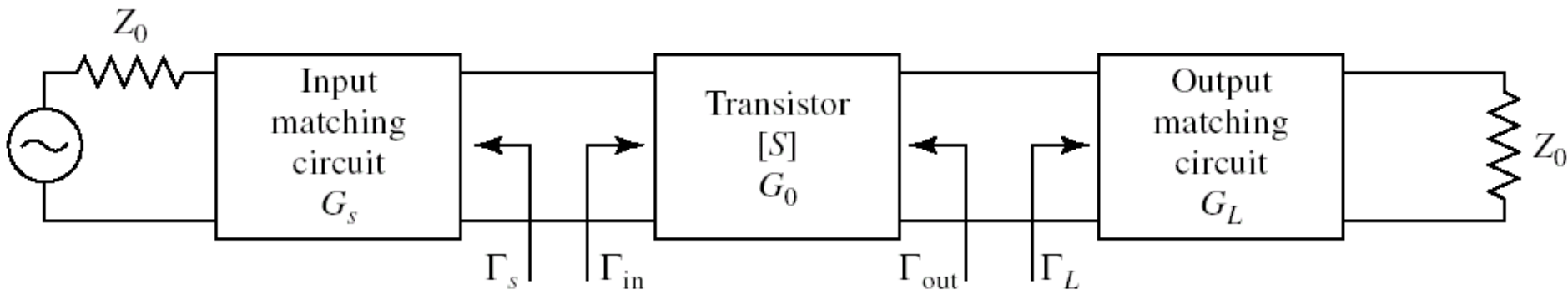
- output constant gain circles CCCOUT: -0.4dB, -0.2dB, 0dB, +0.2dB
- The lack of noise restrictions allows optimization for better gain (close to maximum – position m4)

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:

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

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

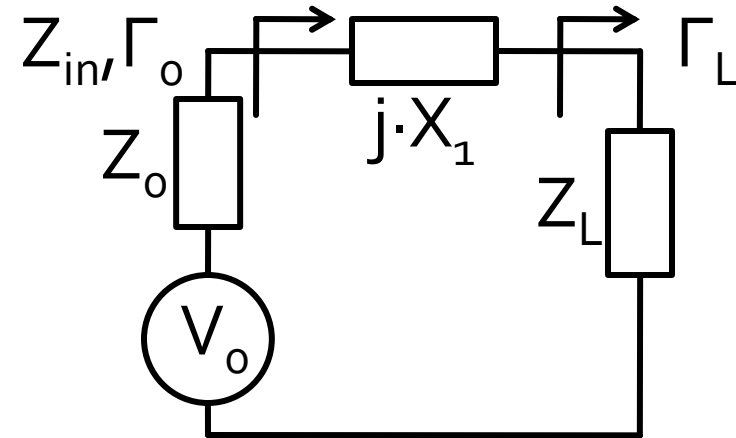
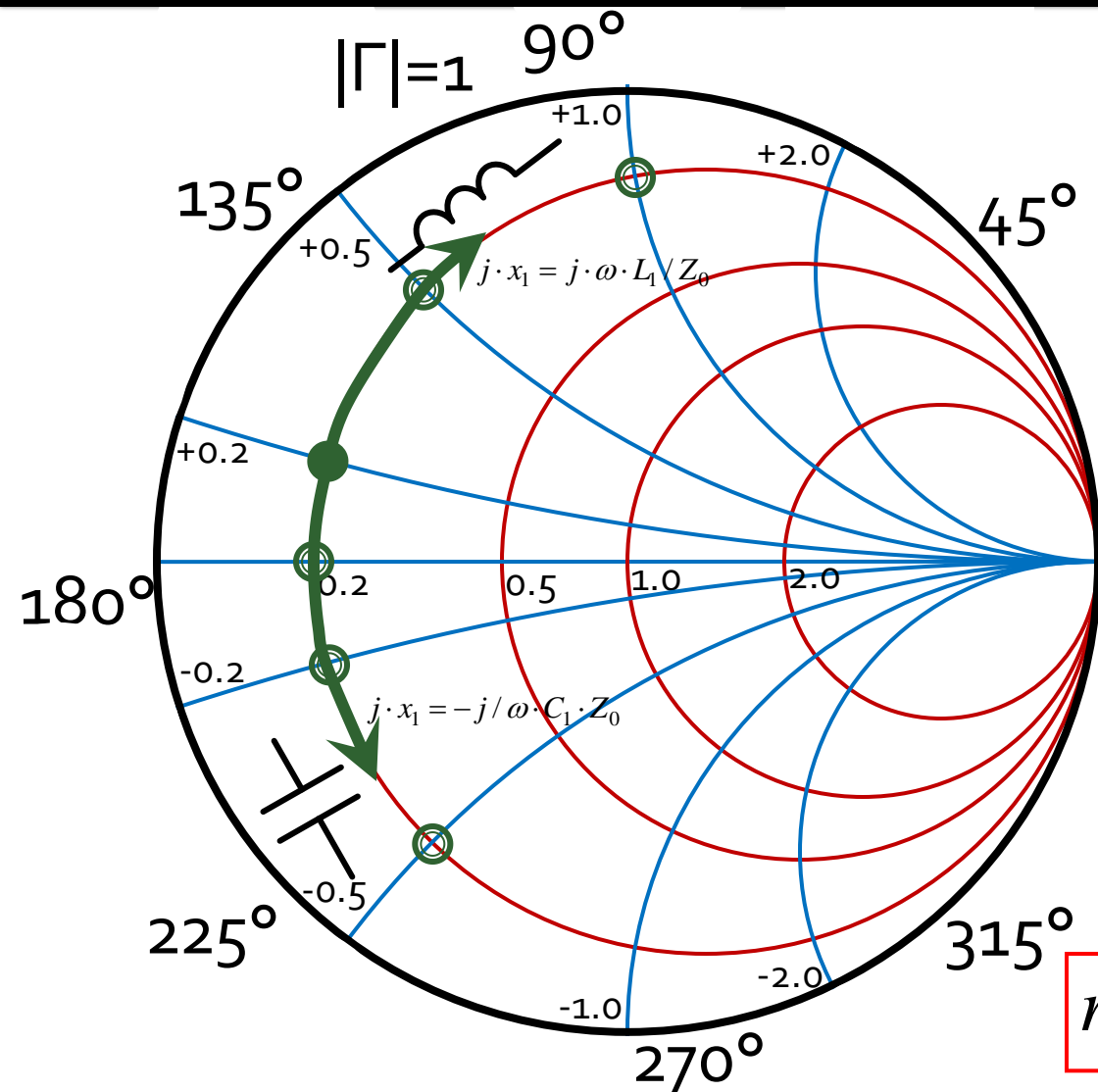
$$G_S = G_S(\Gamma_s)$$

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

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

$$G_L = G_L(\Gamma_L)$$

The Smith Chart, series reactance



$$Z_0 = 50\Omega$$

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

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

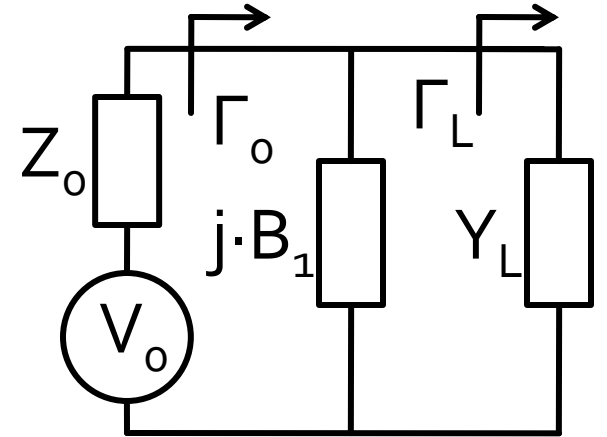
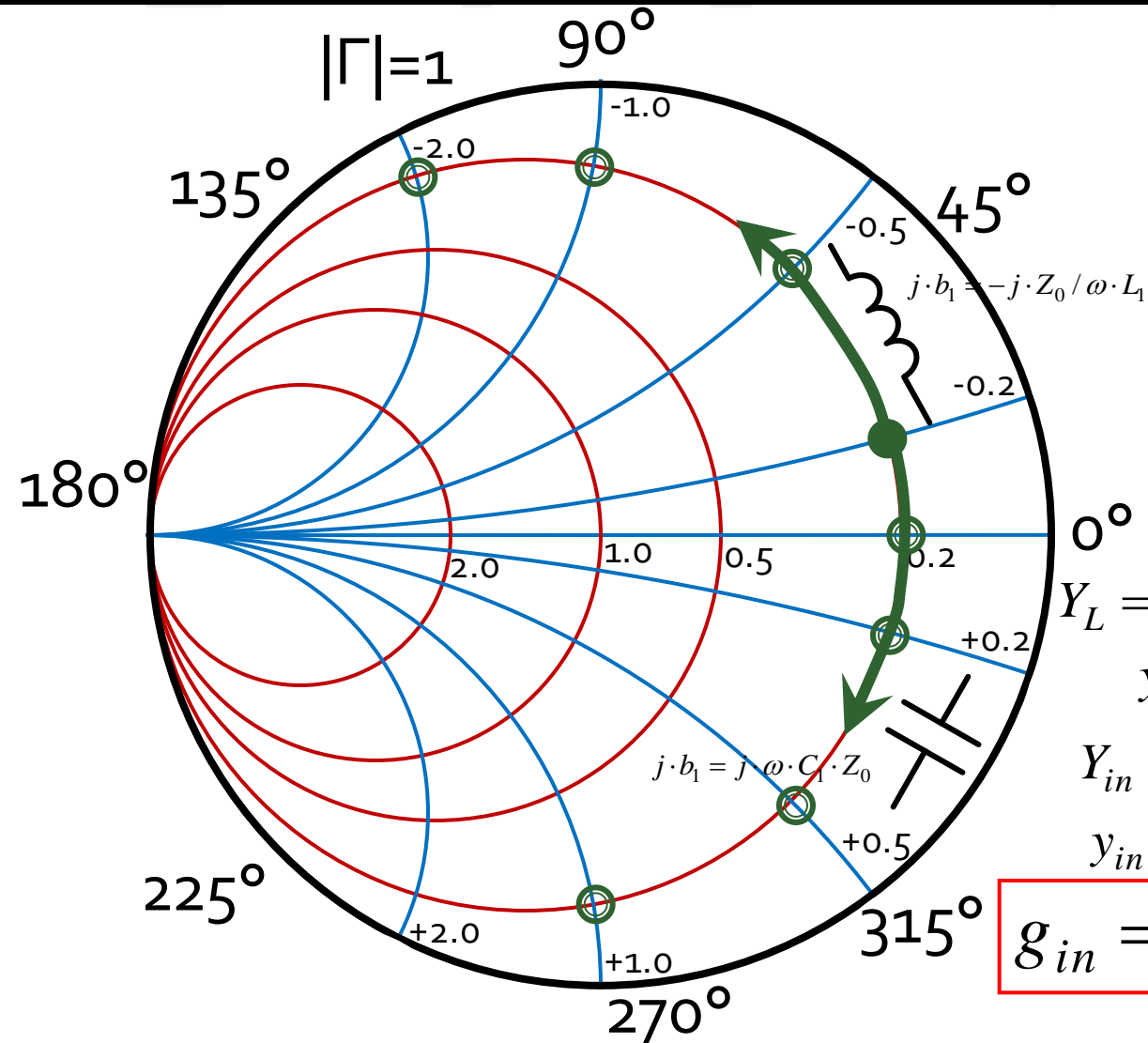
$$\Gamma_L = 0.678 \angle 156.5^\circ$$

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

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

$$r_{in} = r_L \quad \begin{aligned} j \cdot x_1 &= j \cdot \omega \cdot L_1 / Z_0 > 0 \\ j \cdot x_1 &= -j / \omega \cdot C_1 \cdot Z_0 < 0 \end{aligned}$$

The Smith Chart, shunt susceptance



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

$$\Gamma_L = 0.678 \angle 23.5^\circ$$

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

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

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

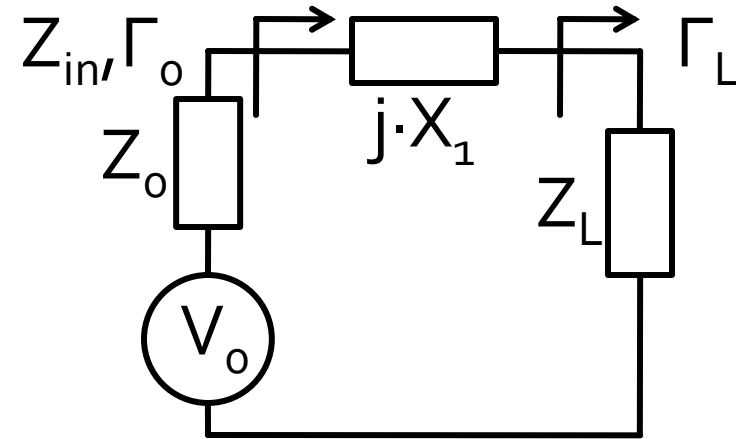
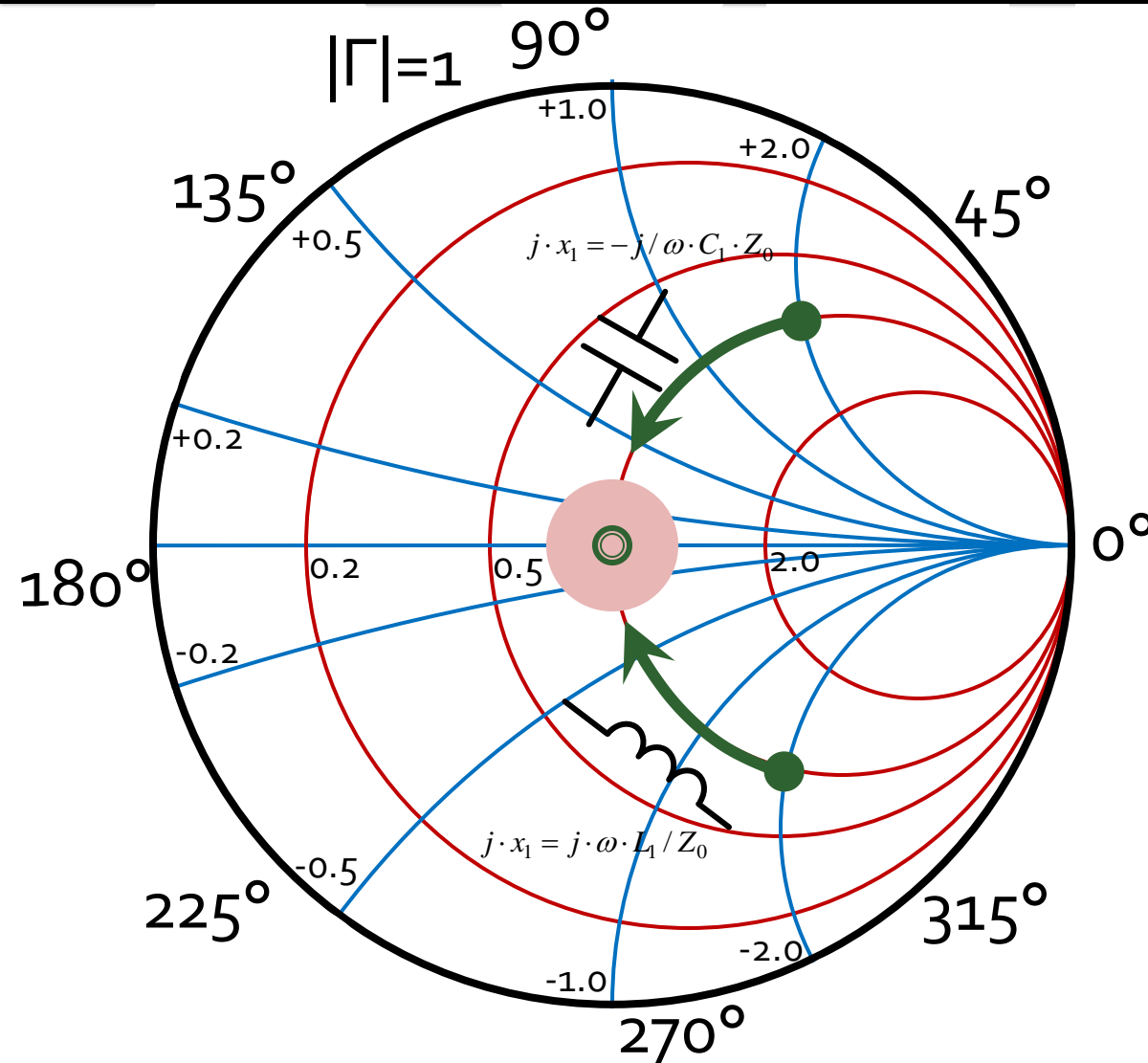
$$y_{in} = g_L + j \cdot (b_L + b_1)$$

$$g_{in} = g_L$$

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

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

Matching, series reactance



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

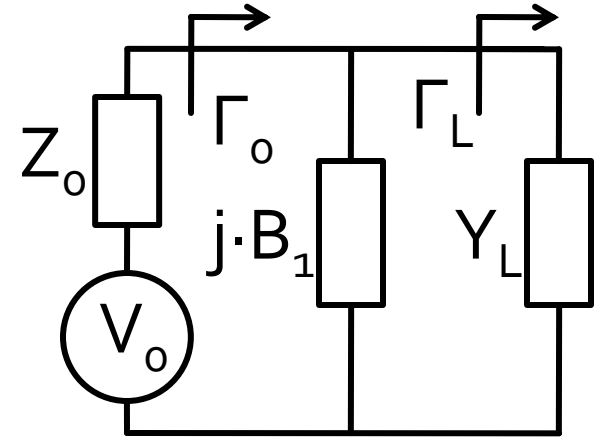
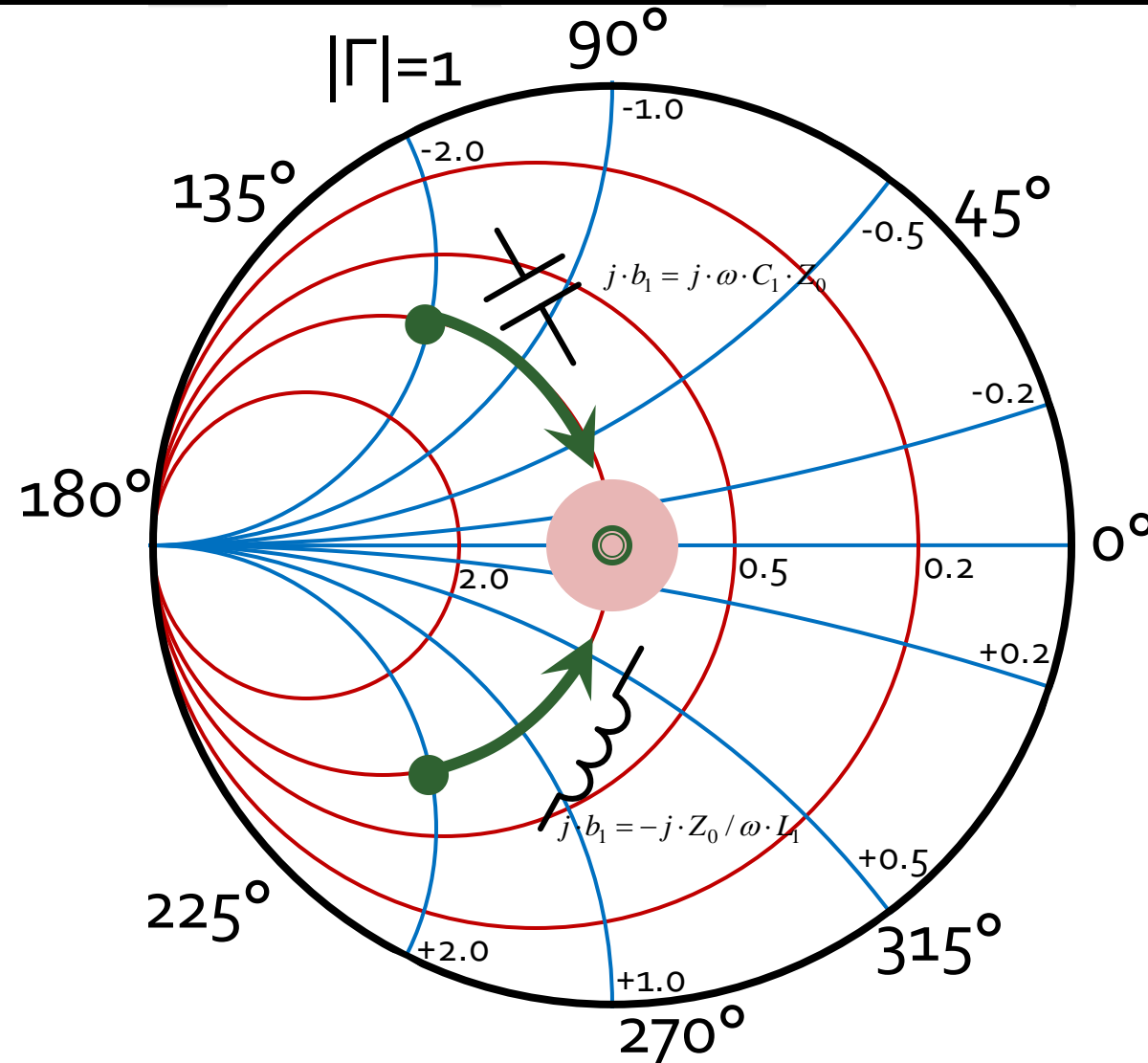
$$Z_{in} = r_L + j \cdot (x_L + x_1)$$

$$r_{in} = r_L$$

- 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



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

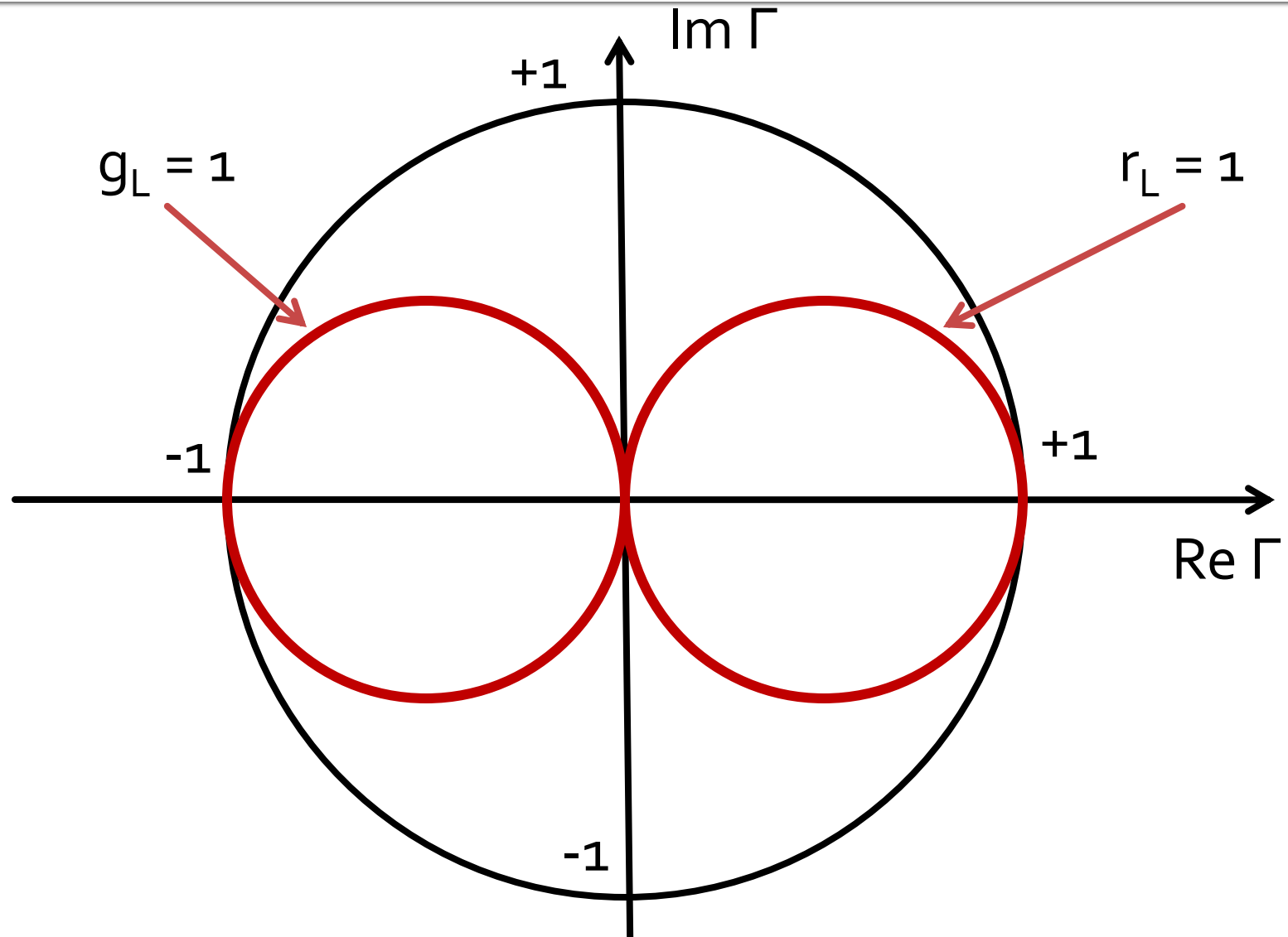
$$y_{in} = g_L + j \cdot (b_L + b_1)$$

$$g_{in} = g_L$$

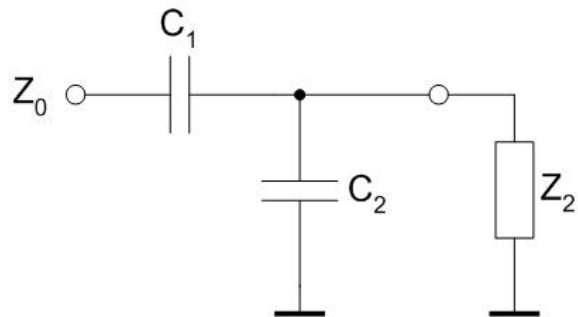
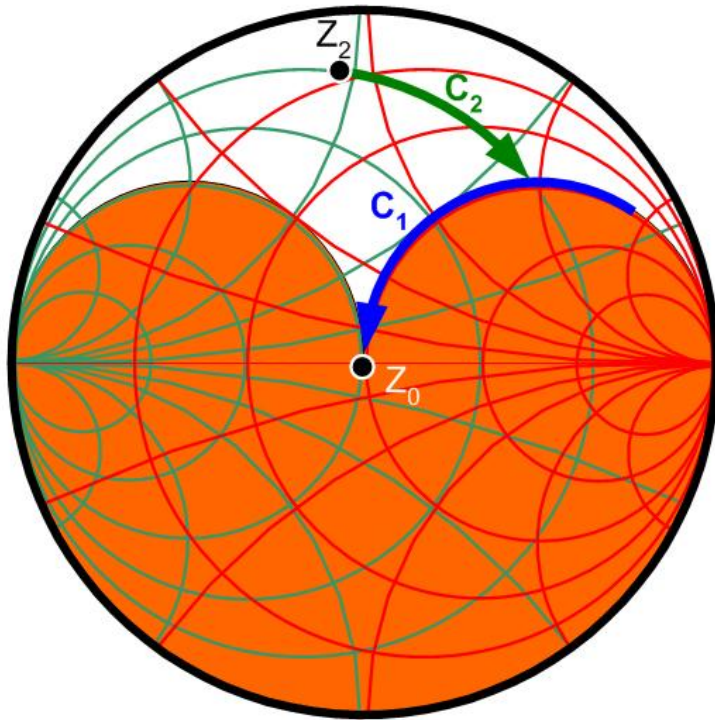
- Match can be obtained **if and only if** $g_L = 1$
- we compensate the reactive part of the load

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

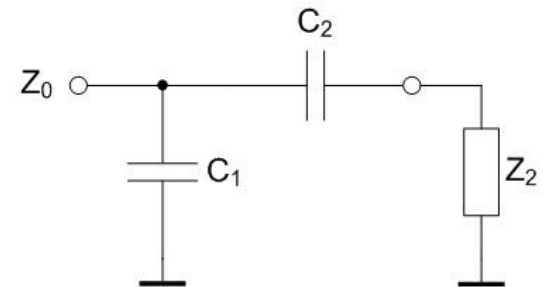
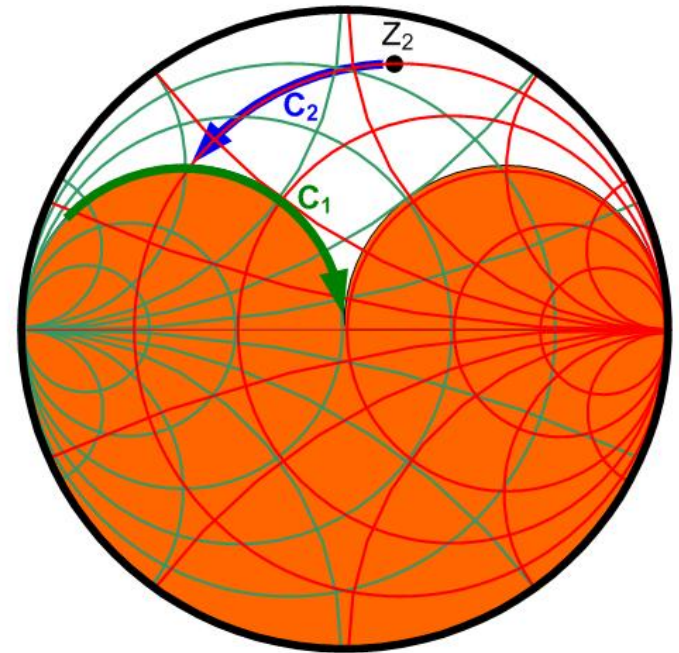
Smith chart, $r=1$ and $g=1$



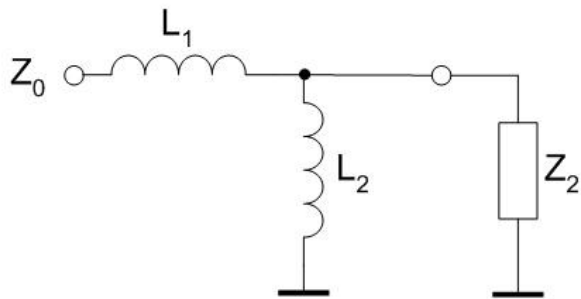
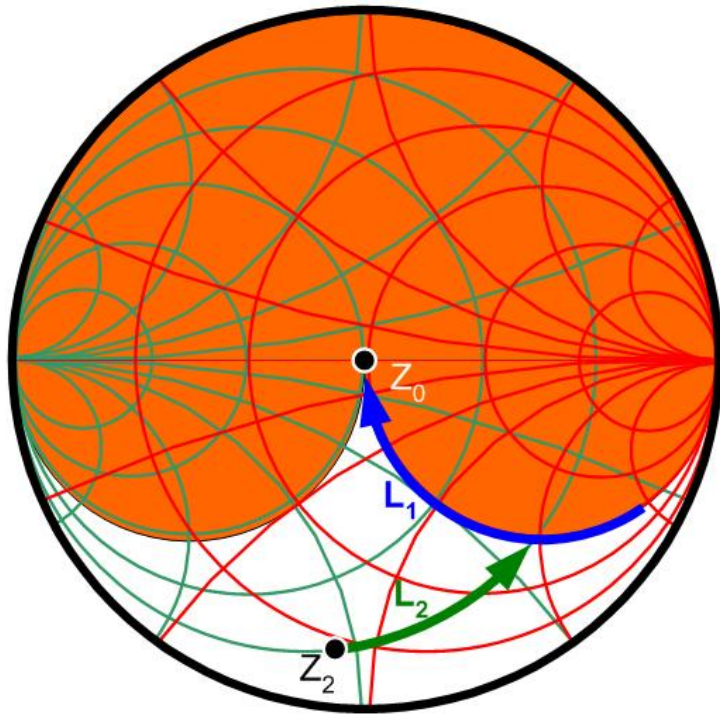
series C, shunt C / shunt C, series C



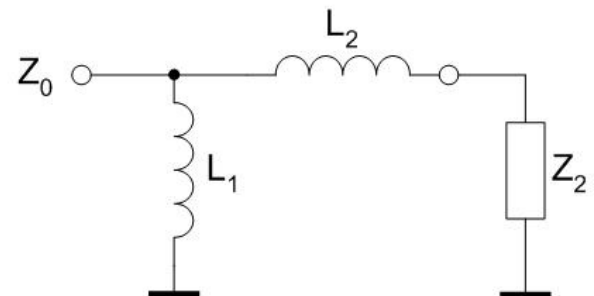
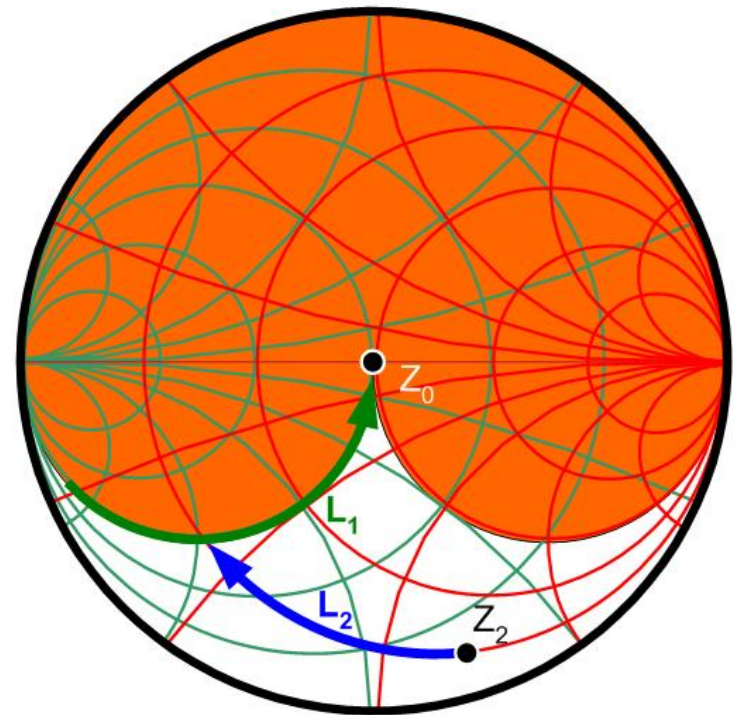
Forbidden area for
current network



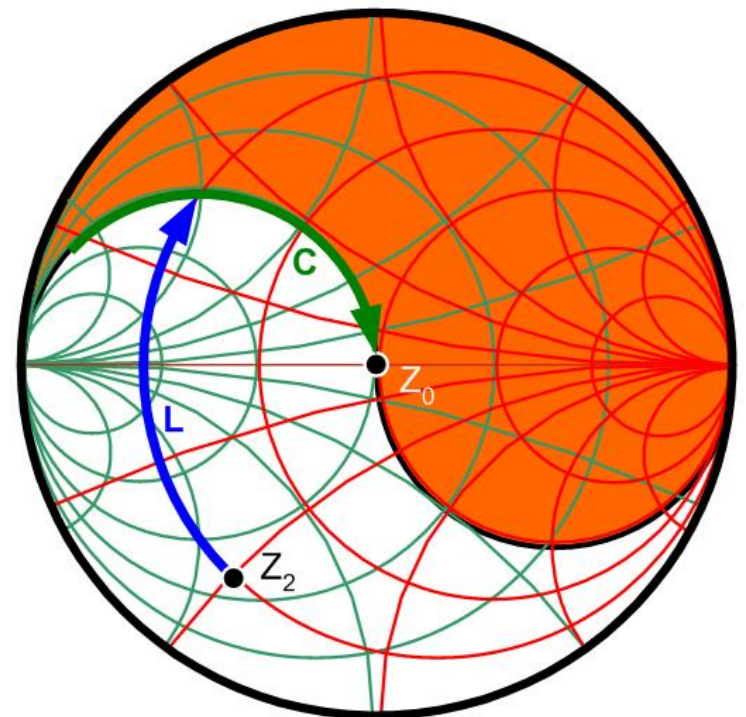
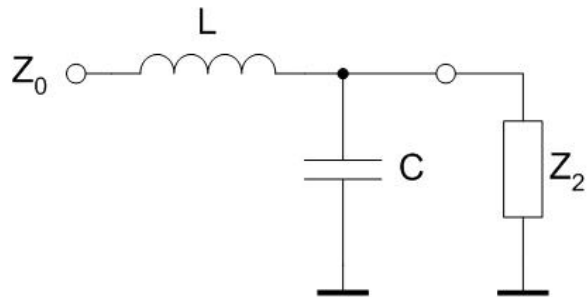
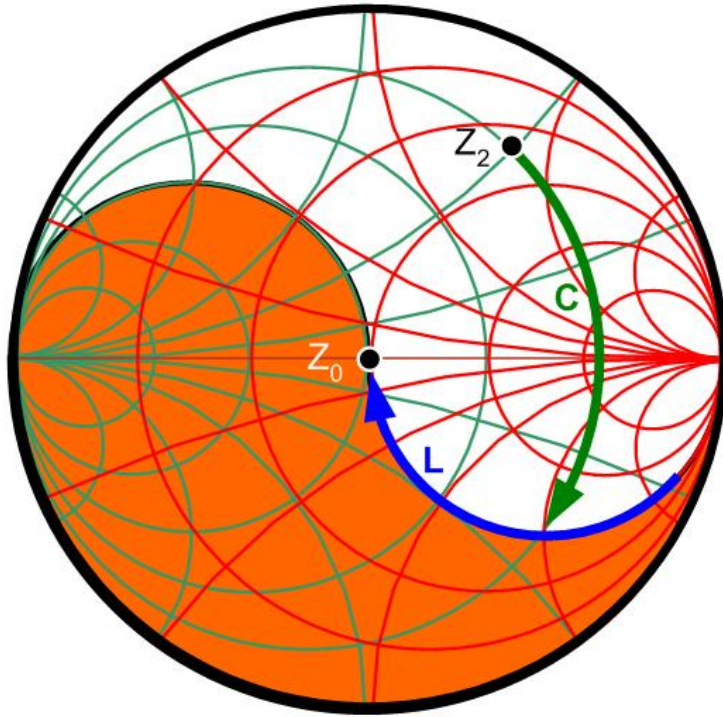
series L, shunt L / shunt L, series L




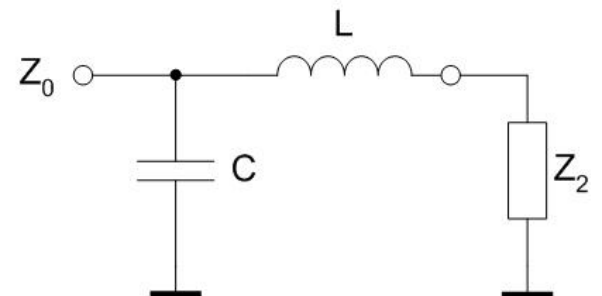
Forbidden area for
current network



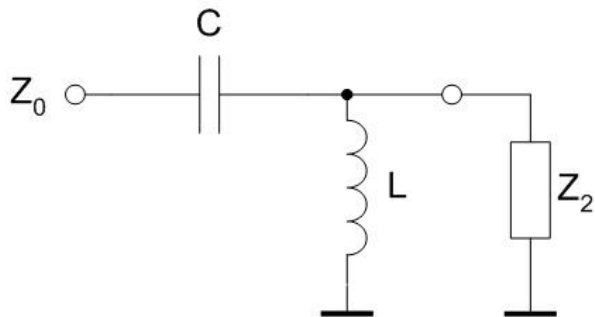
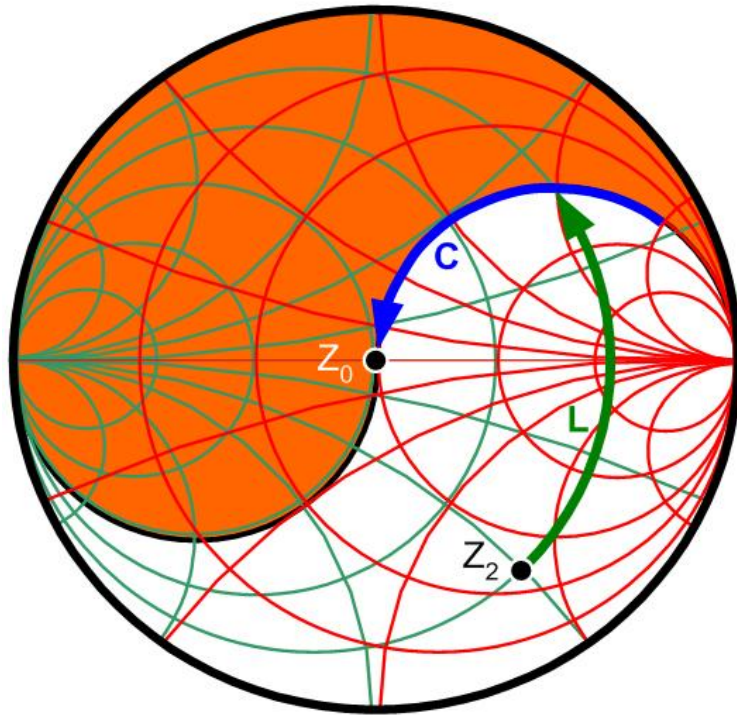
series L, shunt C / shunt C, series L




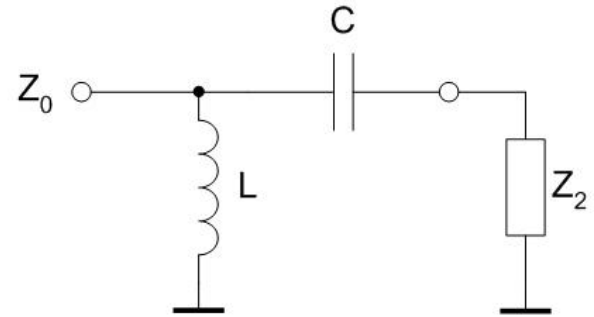
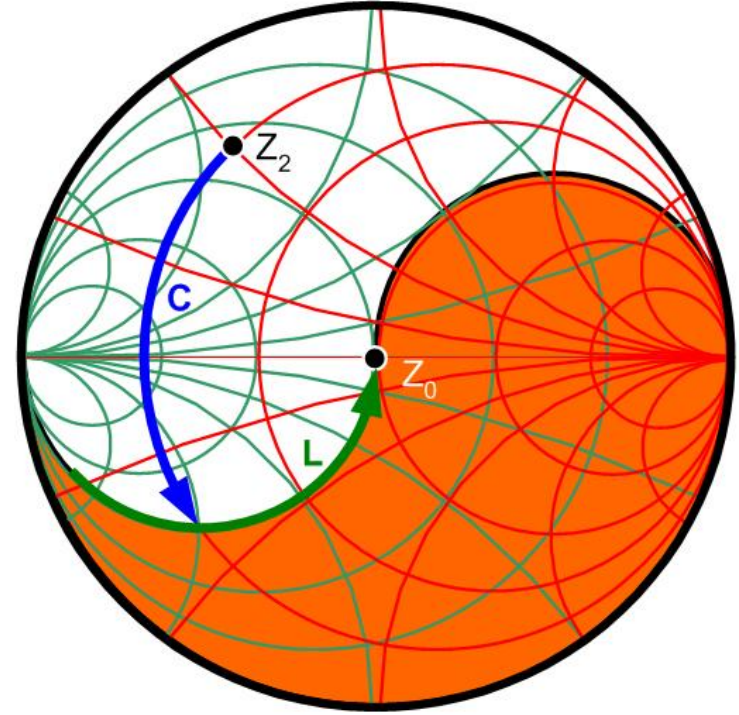
 Forbidden area for current network



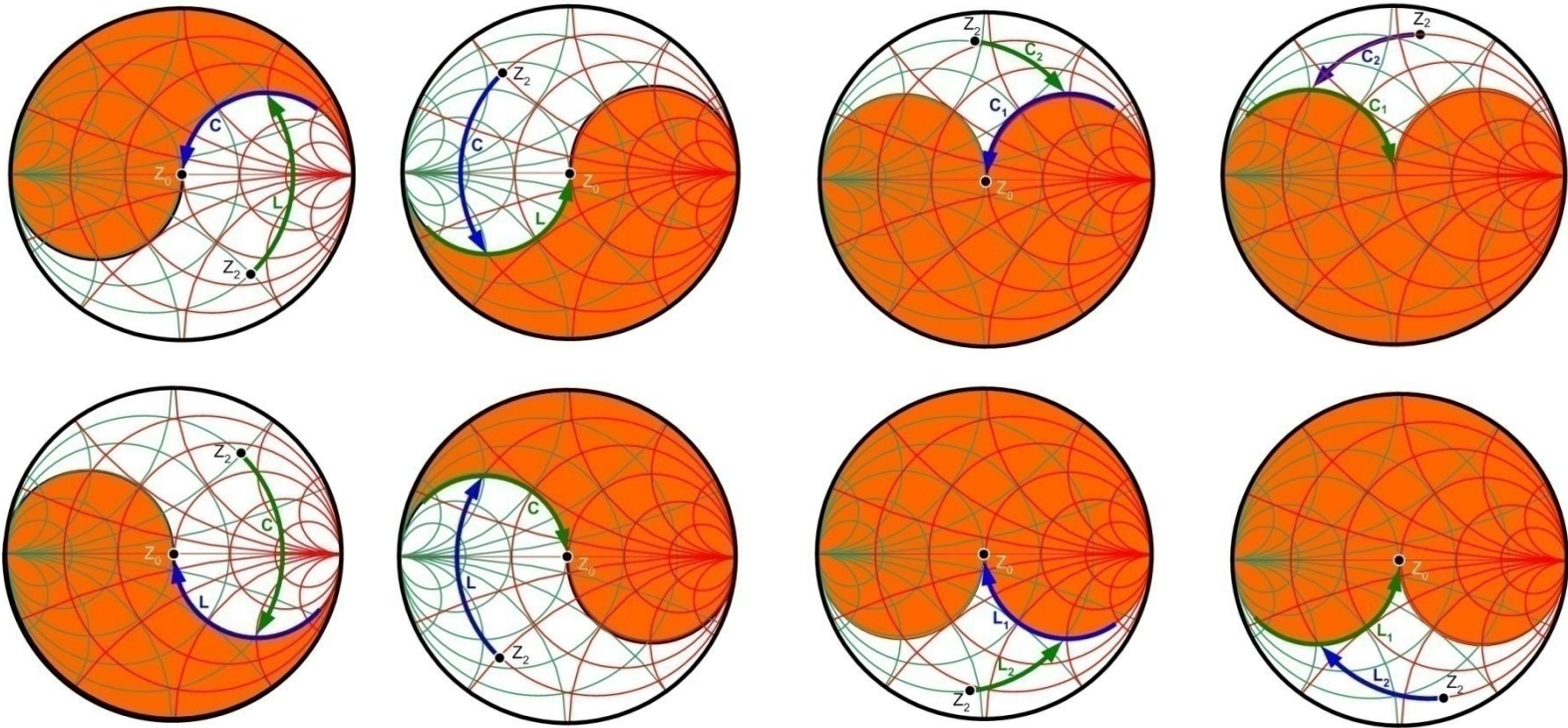
series C, shunt L / shunt L, series C



 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

- 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)

Step 0

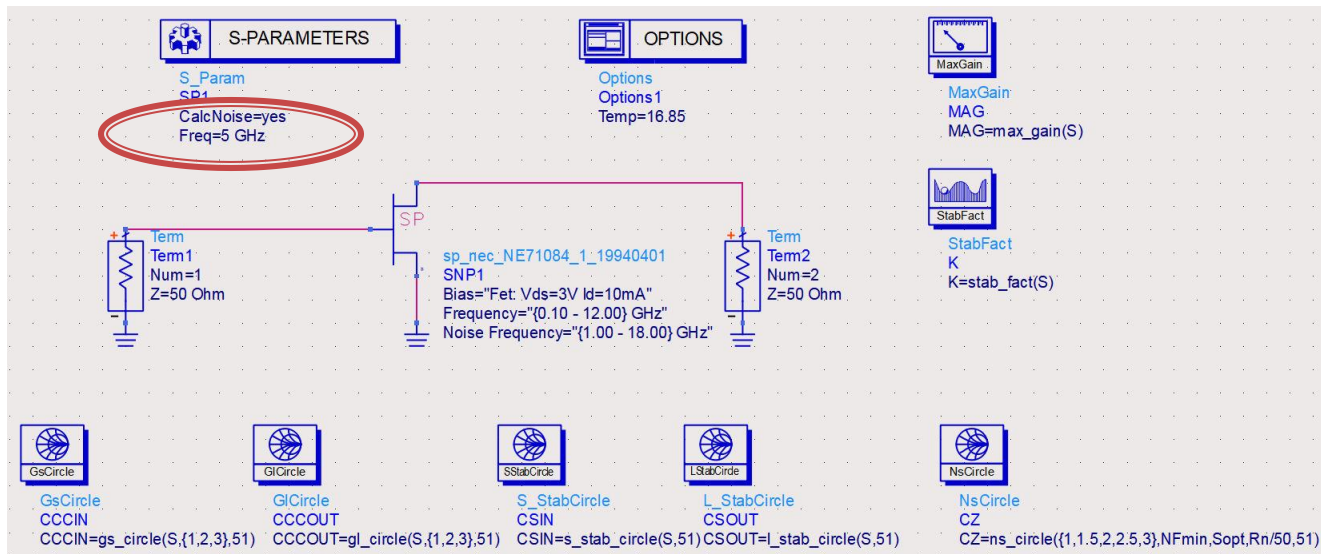
- Write by hand on a sheet of paper 100 times:
- I solemnly promise to read the text
AND NOT to jump from picture to
picture
- 😊

Step 1

- Get from the online exam interface from the rf-opto server your individual data
 - design frequency – **fo** [GHz]
 - noise factor – **NF** [dB] (upper limit for the design, if you obtain a lower value it's better, the lowest possible value is highly desirable)
 - power gain – **G** [dB] (lower limit for the design, if you obtain a higher value it's better, acceptable)

Step 2

- change the simulation frequency in **schematic 1** to **fo** and simulate it again



Step 3

- check some values in the table (some obtained from controllers, some from **equations!**)

$$\text{Eqn } \gamma_{\text{opt}} = S_{\text{opt}}$$

$$\text{Eqn } G_0 = 10 \cdot \log(\text{mag}(S(2,1))^2)$$

$$\text{Eqn } G_{\text{Smax}} = 10 \cdot \log(1/(1 - \text{mag}(S(1,1))^2))$$

$$\text{Eqn } G_{\text{Lmax}} = 10 \cdot \log(1/(1 - \text{mag}(S(2,2))^2))$$

freq	K	MAG	NFmin	Sopt	Rn	G0	GLmax	GSmax
5.000 GHz	0.533	15.293	0.700	0.160 / 106....	19.500	8.974	1.634	4.249

- verify that the transistor can meet the design requirements (otherwise you must choose another transistor)
 - $\text{NFmin} < \text{NF}$
 - $\text{MAG} > \text{G}$

Step 4

- check some values in the table (some obtained from **equations!**)

$$\text{Eqn } \gamma_{\text{opt}} = S_{\text{opt}}$$

$$\text{Eqn } G_0 = 10 \cdot \log(\text{mag}(S(2,1))^2)$$

$$\text{Eqn } G_{S\text{max}} = 10 \cdot \log(1/(1 - \text{mag}(S(1,1))^2))$$

$$\text{Eqn } G_{L\text{max}} = 10 \cdot \log(1/(1 - \text{mag}(S(2,2))^2))$$

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

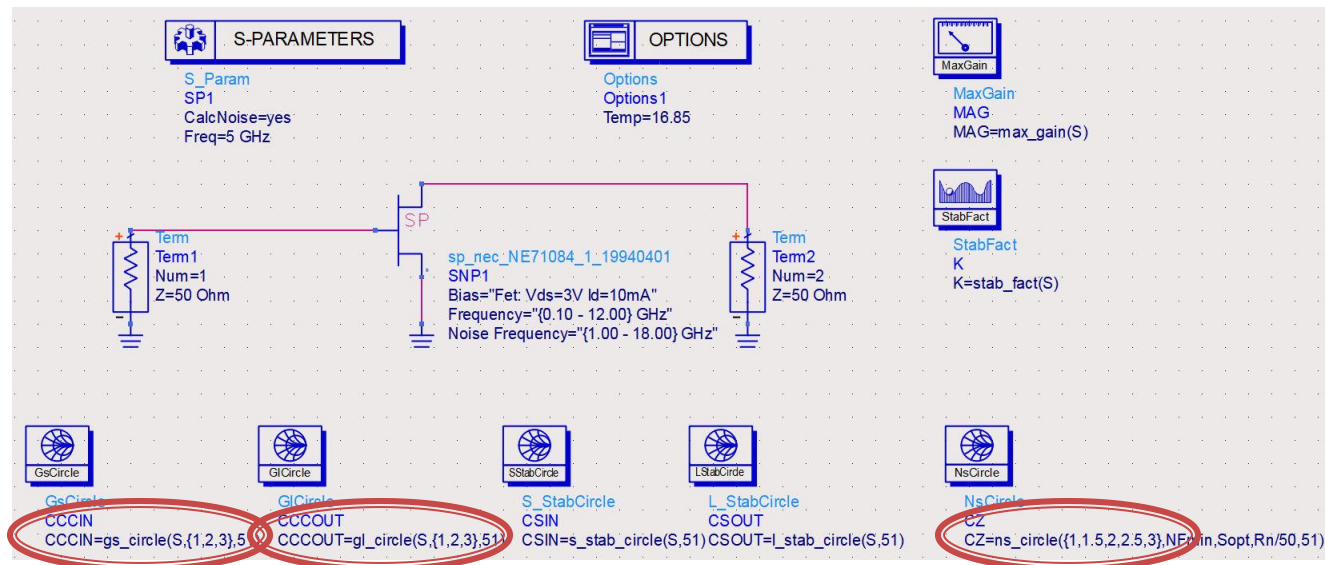
- To meet the gain requirement **choose** the supplemental values needed (supplemental to fixed value G_o)

$$G_{\text{design}}[dB] = G_{S_design}[dB] + G_0[dB] + G_{L_design}[dB]$$

$$G_{\text{design}}[dB] > G \quad G_{S_design}[dB] < GS \text{ max} \quad G_{L_design}[dB] < GL \text{ max}$$

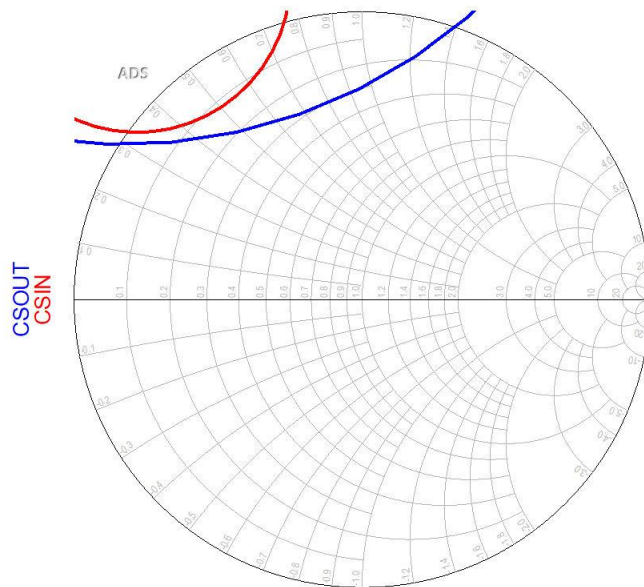
Step 5

- in schematic 1 change the values for the circles (instead of {1,2,3} choose some values close to GS_design, GL_design, NF_design) – all numerical values **must** be in **dB**

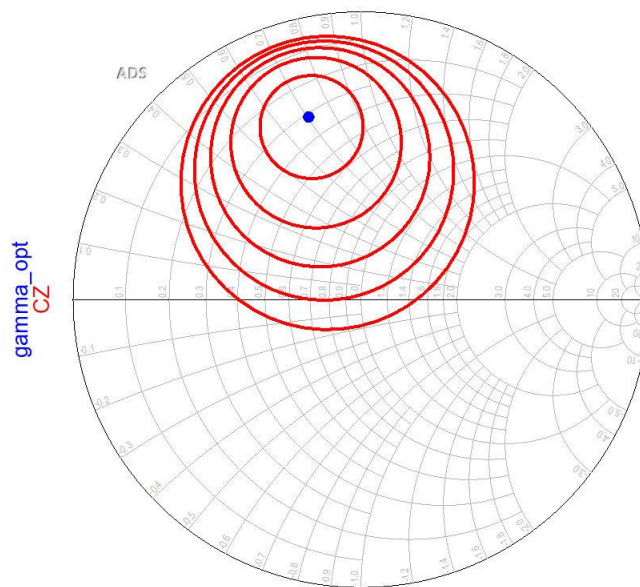


Step 6

- simulate, plot **groups of circles** and verify they are in the right position



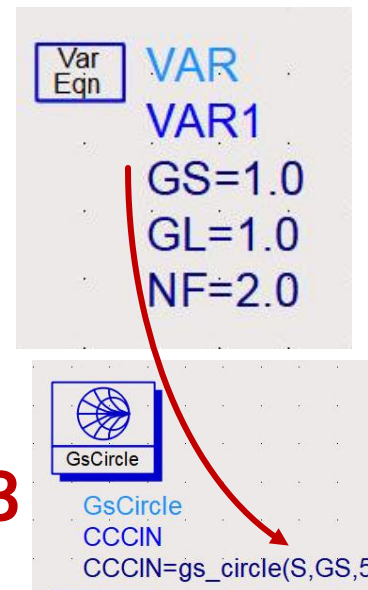
indep(CSIN) (0.000 to 51.000)
indep(CSOUT) (0.000 to 51.000)



cir_pts (0.000 to 51.000)
freq (5.000GHz to 5.000GHz)

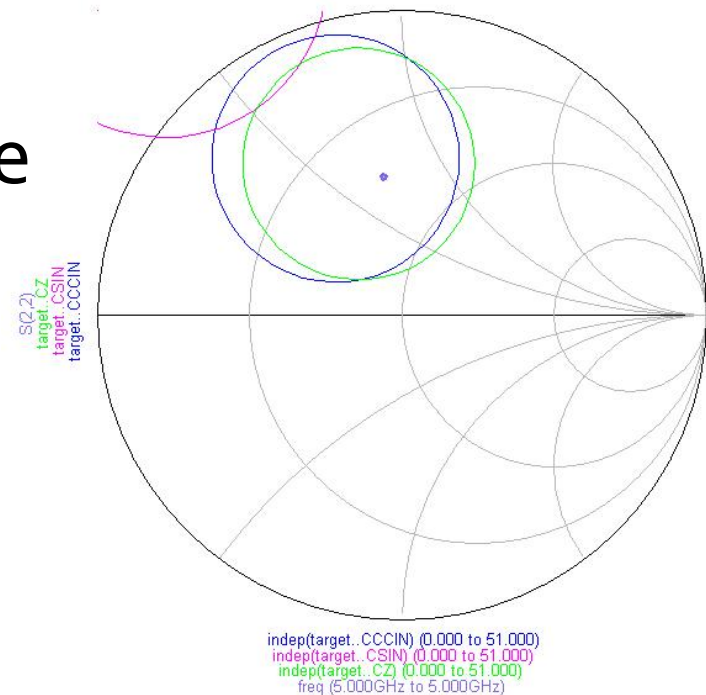
Step 7

- change the simulation frequency in **schematic 2** to **fo**
- analyze results in **schematic 1** and choose **a single circle** as target for the design (in **VAR**):
 - stability (input/output)
 - gain (input GS_design/output GL_design)
 - noise (input NF_design)
- plotting these circles is not required
 - they will be effectively used in **schematic 3**



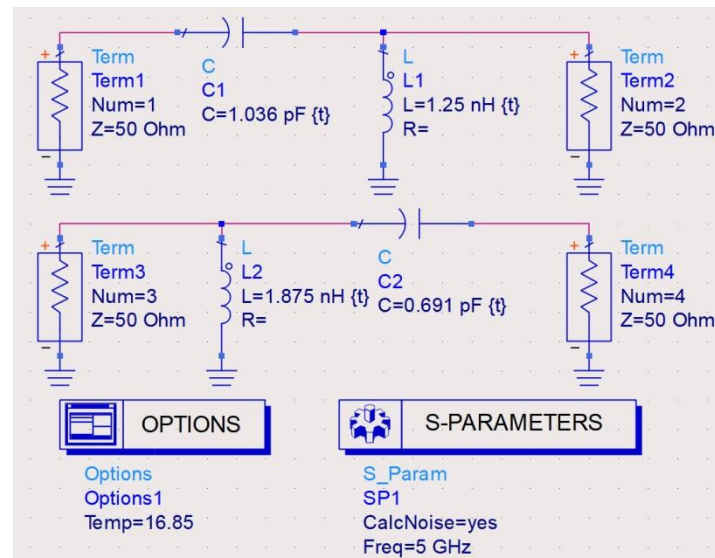
Step 7

- even if the circles are not plotted, they are **computed** (for the transistor)
 - 3 input plane (stability/gain/noise)
 - 2 output (stability/gain)
- It is recommended to provide a margin for the design:
 - $G_{\text{design}} > \mathbf{G + \Delta G}$
 - $NF_{\text{design}} < \mathbf{NF - \Delta NF}$
- simulate **schematic 2** again



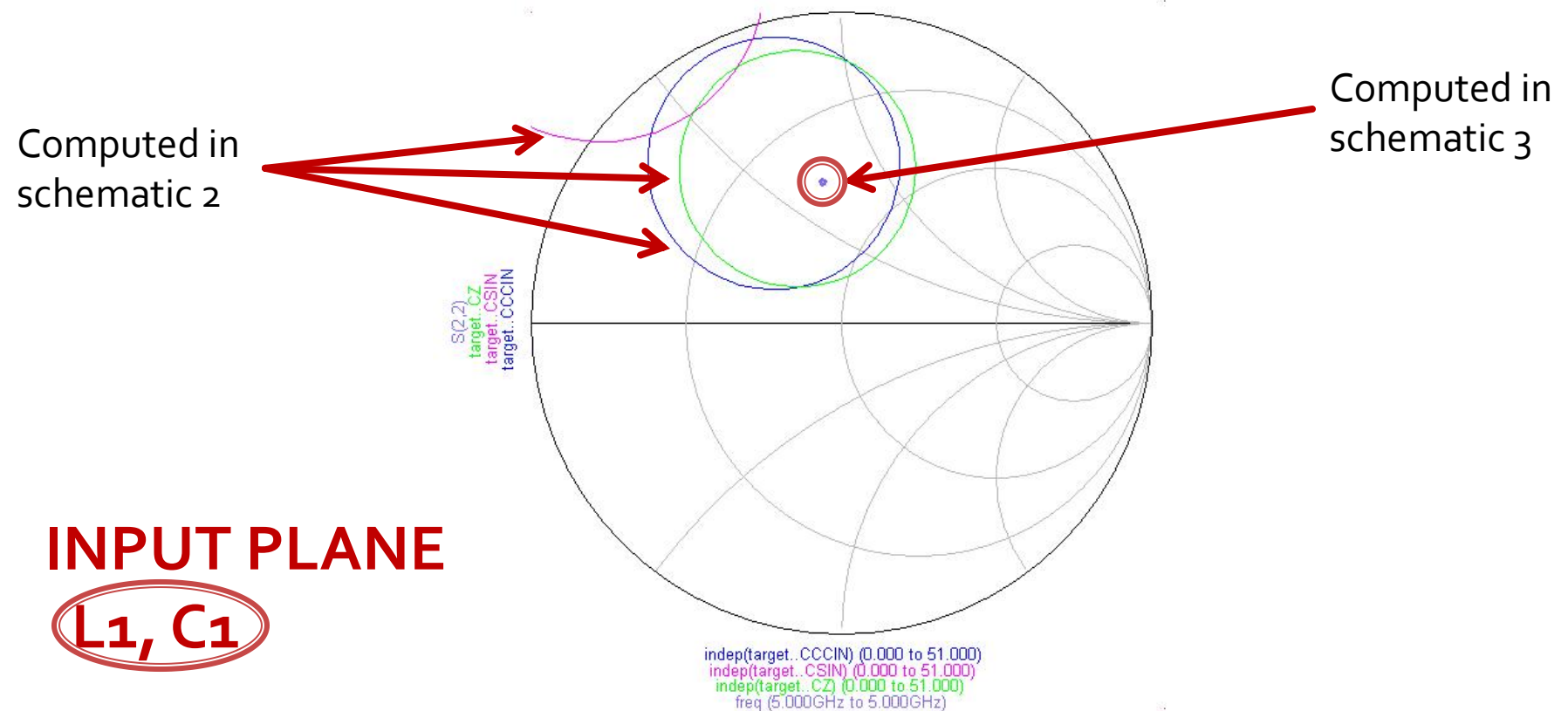
Step 8

- change the simulation frequency in **schematic 3** – **fo** and simulate it again
- plot and use the circles computed in **schematic 2** as target while tuning



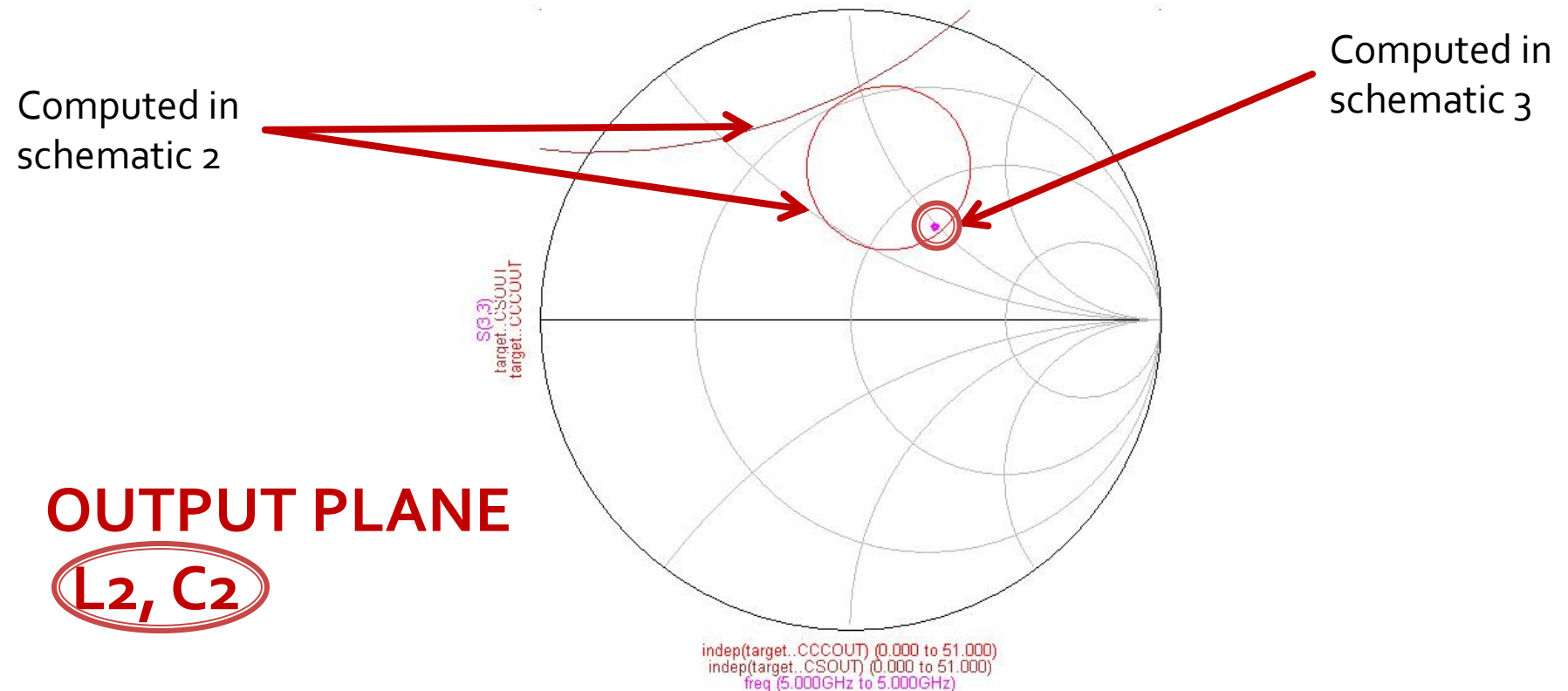
Step 9

- **tune** the components in the two L networks to reach the desired points



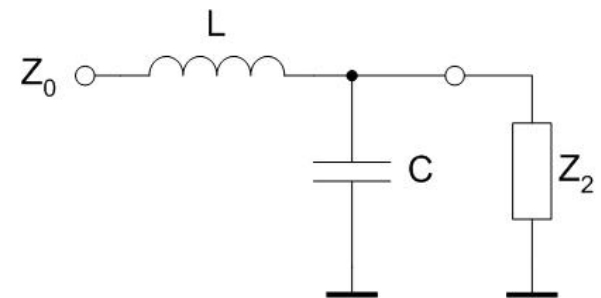
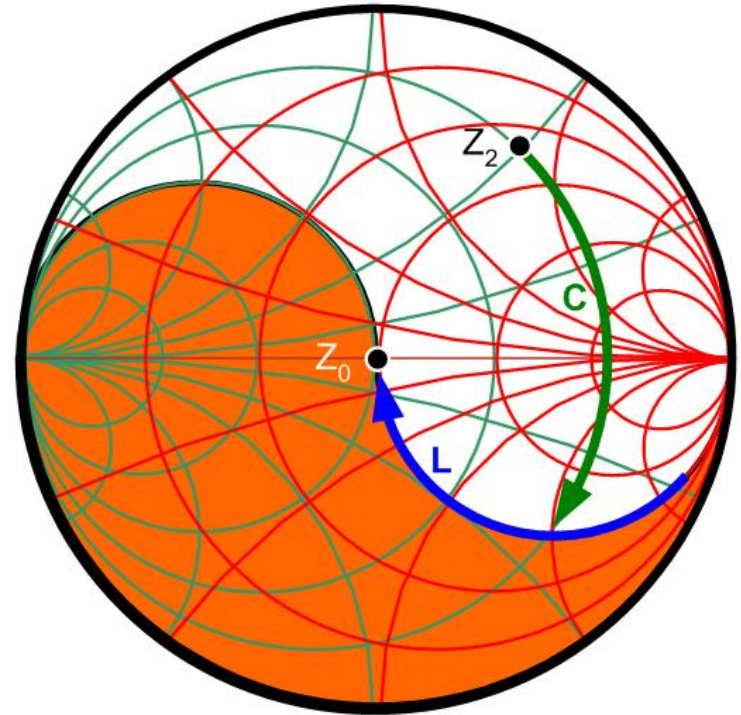
Step 10

- **tune** the components in the two L networks to reach the desired points



Step 11

- if you cannot reach the appropriate position (by relation to the circles) then most likely the desired position lies in the forbidden area for that particular L network
 - **change** to another L network (LC/CL, series/shunt etc)

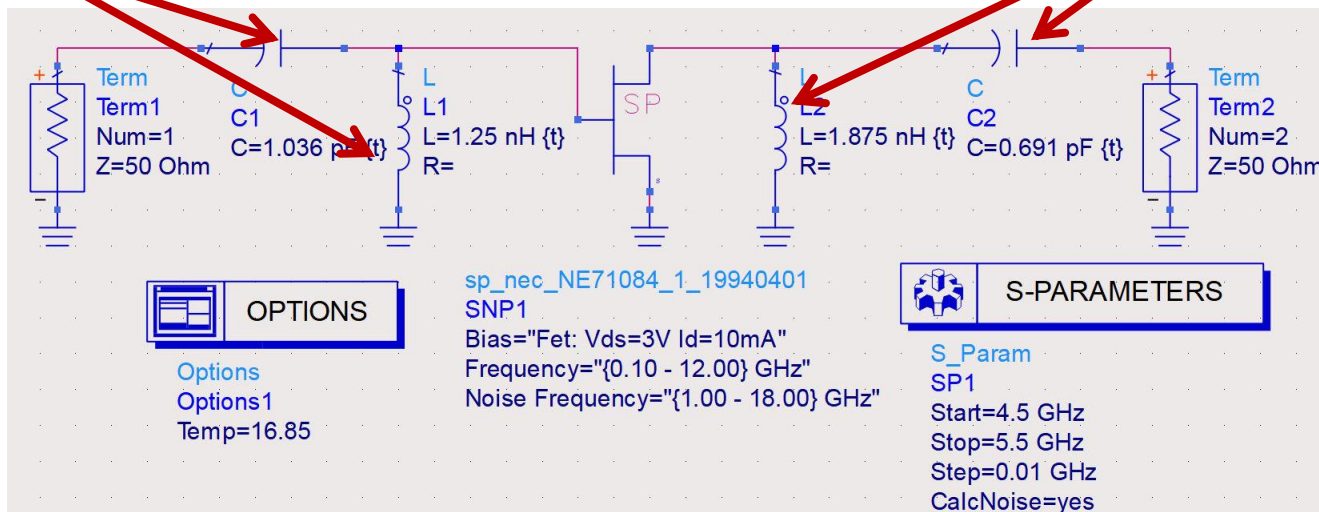


Step 12

- insert the components obtained by tuning in **schematic 3** as input/output matching networks for the transistor in **schematic 4** (values and network shape!)
- change the simulation frequencies in **schematic 4** – around **fo** (**fo** in the **center** of the simulation range) and simulate it again

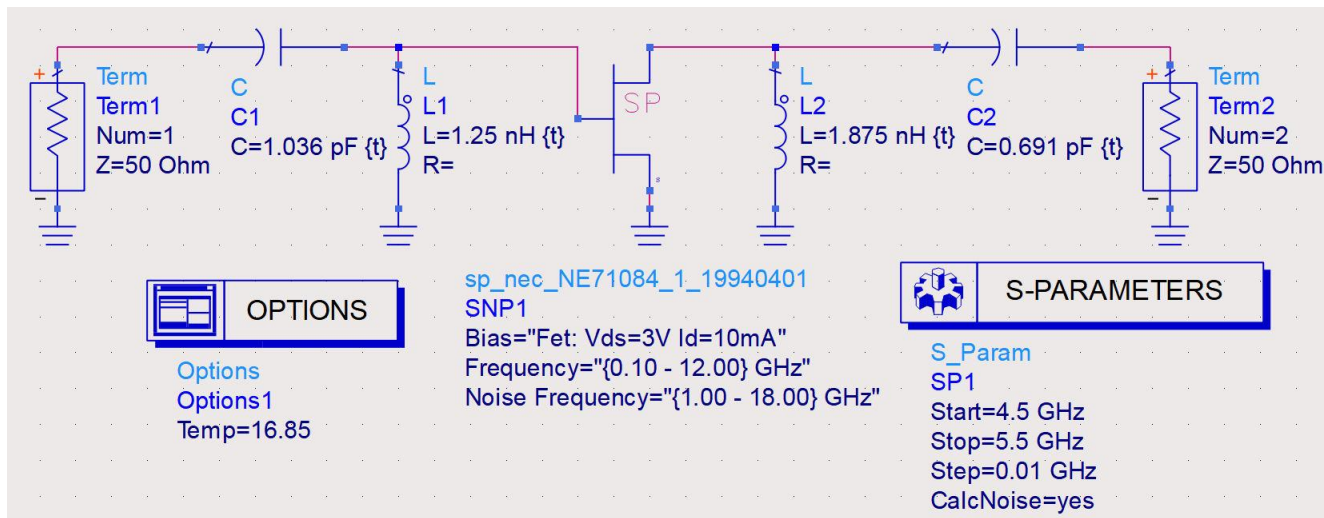
Obtained in
schematic 3

Obtained in
schematic 3



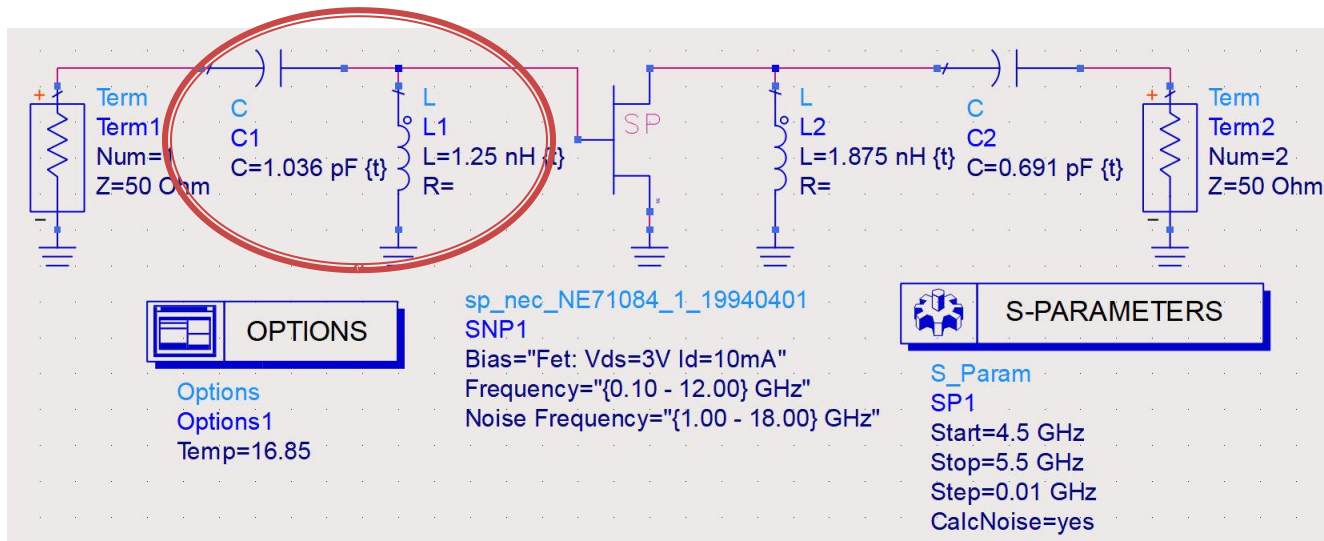
Step 13

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



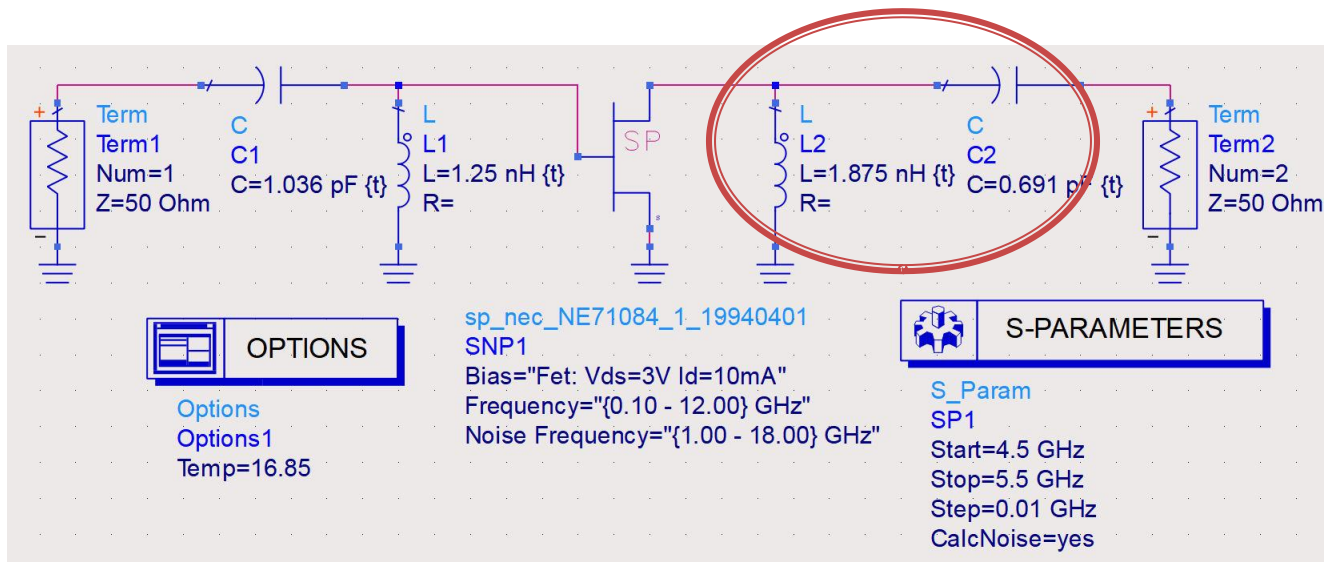
Final tune

- input components influence **both noise and gain**
 - they are first to tune, only these 2 while other components remain constant, checking the fulfillment of **noise** design target while sacrificing (accept worsening of) the **gain** (up to a point)



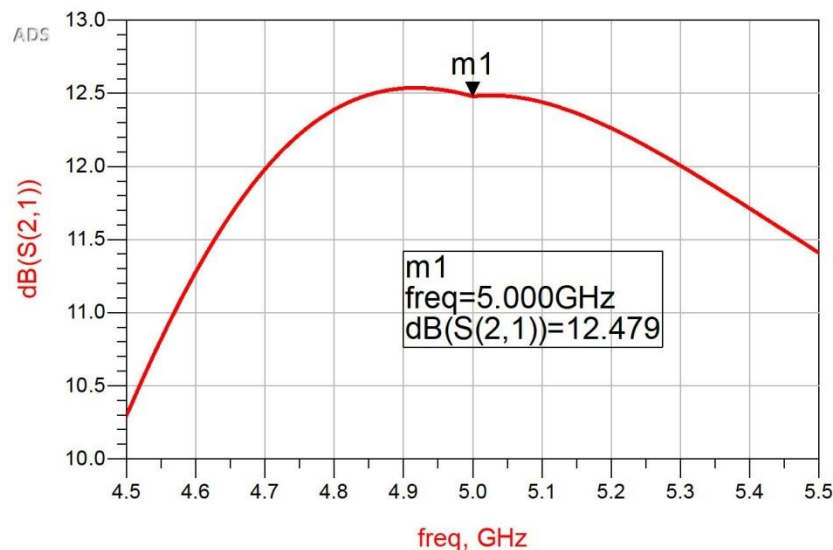
Final tune

- output components influence **only gain**
 - they are tuned next, only these 2 while other components remain constant, checking the fulfillment of **gain** design target, compensating its worsening during previous noise optimization



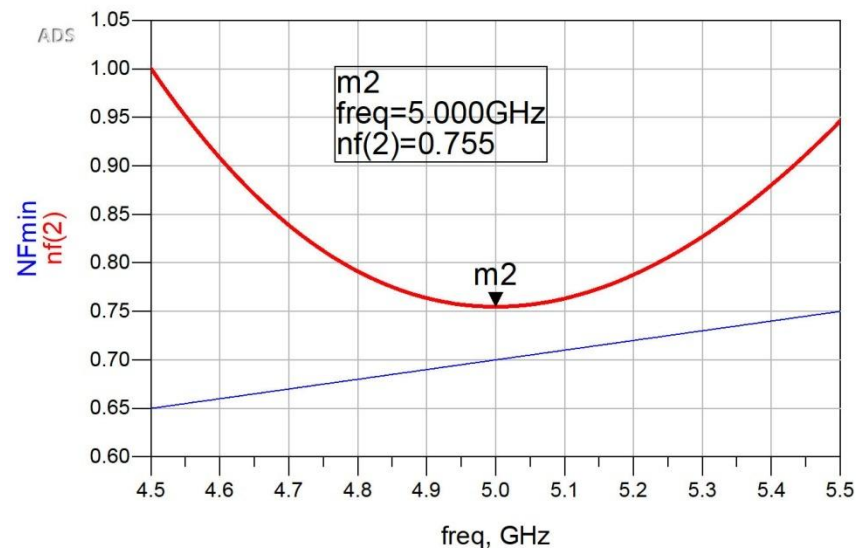
Final design

- We obtain (after tuning) the final values and check the fulfillment of the design goal:
 - Power gain – higher than the design goal, with a margin (0.5, 1, 2 dB), but we don't sacrifice the noise performance in order to increase it further
 - Band Pass behavior, around **fo**, is desirable (at least one of the L networks must be a HPF network)



Final design

- We obtain (after tuning) the final values and check the fulfillment of the design data:
 - Noise factor – lower than the design goal, as low as possible, the lower the better



rf-opto

- Online exam, Laboratory 4
- You must upload to the server 4 files:
 - project zap file (**required**)
 - final schematic (sch₄) – after final tune (image file: jpg/png, get it using “print screen”)
 - result: gain – after final tune (image file: jpg/png, get it using “print screen”)
 - result: noise – after final tune (image file: jpg/png, get it using “print screen”)

Contact

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