

Microwave Circuits and Devices

Laboratory no. 3

Low noise transistor amplifier

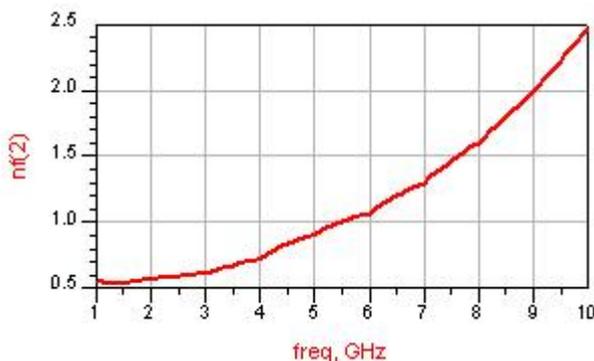
1. Choosing the right transistor

Depending on the design requirements (G [dB] and NF [dB] @ f [GHz]), the choice of a particular transistor is imposed by its ability to provide the gain and the noise factor at that frequency. In principle, it is recommended to start from the selection guide (one of the first pages in any written component catalog) as it lists some of the key values of those components. A first step is to select "Low Noise" transistors, as power transistors, general purpose or pulse operation transistors are not suitable for this design.

Low Noise pHEMTs (Typical Specifications @ 25°C Case Temperature)

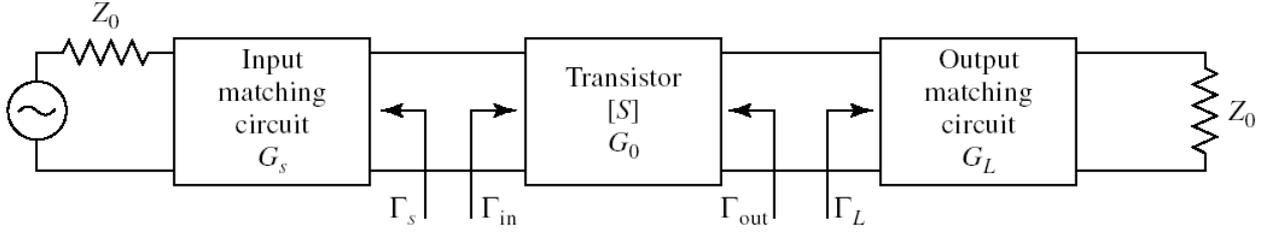
Part Number	Gate Width (μm)	Frequency Range (GHz)	Test Freq. (GHz)	V_{dd} (V)	I_{dd} (mA)	NF_0 (dB)	G_a (dB)	OIP3 (dBm)	$P_{1\text{dB}}$ (dBm)	Package
ATF-33143	1600	0.45 - 6	2	4	80	0.5	15.0	33.5	+22	SOT-343 (SC-70)
ATF-331M4	1600	0.45 - 6	2	4	60	0.6	15.0	31	+19	MiniPak ^[2]
ATF-34143	800	0.45 - 6	2	4	60	0.5	17.5	31.5	+20	SOT-343 (SC-70)
ATF-35143	400	0.45 - 6	2	2	15	0.4	18.0	21	+10	SOT-343 (SC-70)
ATF-38143	800	0.45 - 6	2	2	10	0.4	16.0	22	+12	SOT-343 (SC-70)
ATF-36077	200	1.5 - 18	12	1.5	10	0.5	12.0	—	+5	70 mil SM
ATF-36163	200	1.5 - 18	12	1.5	15	1.2	10.0	—	+5	SOT-363 (SC-70)

Above is an example of the selection guide for transistors from Agilent. Not all selection guides show the recommended "Frequency Range", but if it exists, the manufacturer's indication may be taken into account. Instead, the "Test Frequency", minimum noise factor (NF_0), and associated gain (G_a) (at that test frequency) are always present. We must remember that the parameters that interest us vary with the frequency, typically the gain expressed in dB decreases linearly with the frequency and the noise factor expressed in dB increases exponentially with the frequency (under normal use conditions – bellow is the typical variation for ATF 34143). Usually, an extrapolation from the test frequency should be made to estimate typical values at the desired operating frequency. Also note that signal performance strongly depends on the bias point, so it is recommended, after choosing the transistor, to look for the optimal bias point for the given application (noise/gain/frequency).



Note. The fulfillment of separate conditions does not necessarily mean that the application as a whole will be fully satisfied. For example, a low noise amplifier involves simultaneously fulfilling several conditions: gain / noise / stability / realizability of components needed for impedance matching. It might be necessary to return to the transistor selection phase if later the chosen component proves unsuitable.

2. Short introduction – two-port design for specified gain



The transistor is characterized by its scattering matrix (S parameters). By convention (unless otherwise specified) the S parameters are defined (and measured when entered in the datasheet) by direct connection of the transistor between a source with internal impedance $Z_S = Z_0 = 50\Omega$ and a load with $Z_L = Z_0 = 50\Omega$. It is not required and neither assumed that the transistor is matched or operating properly with this source and/or load.

Even if they are made with passive components, the input and output matching circuits can introduce a power gain higher than unity (positive in dB) by **better matching (in terms of power transmission) the transistor to the source and load**. We compute the transducer power gain of the amplifier (G_T):

$$G_S = \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_S \Gamma_{in}|^2} ; G_0 = |S_{21}|^2 ; G_L = \frac{1 - |\Gamma_L|^2}{|1 - S_{22} \Gamma_L|^2}$$

$$G_T = G_S G_0 G_L ; G_T = \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_S \Gamma_{in}|^2} \cdot |S_{21}|^2 \cdot \frac{1 - |\Gamma_L|^2}{|1 - S_{22} \Gamma_L|^2}$$

$$G_T [\text{dB}] = G_S [\text{dB}] + G_0 [\text{dB}] + G_L [\text{dB}]$$

This unilateral condition (nonreciprocal characteristic, $S_{12} \approx 0$) is approximately true for many transistor devices in which case the unilateral transducer power gain is:

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

$$G_{S_{\max}} = \frac{1}{1 - |S_{11}|^2} \text{ for } \Gamma_S = S_{11}^* \text{ (restrictive condition, a single point)}$$

$$G_{L_{\max}} = \frac{1}{1 - |S_{22}|^2} \text{ for } \Gamma_L = S_{22}^* \text{ (restrictive condition, a single point)}$$

$$G_{TU_{\max}} = \frac{1}{1 - |S_{11}|^2} \cdot |S_{21}|^2 \cdot \frac{1}{1 - |S_{22}|^2}$$

For any other value chosen for the supplemental gain from the input matching circuit $G_{S1} < G_{S_{\max}}$, there are numerous values of the reflection coefficient Γ_S (other than $\Gamma_S = S_{11}^*$) that provide that gain. In the polar diagram in which the complex reflection coefficient Γ_S is represented, the locus of these points is a circle:

constant gain circle of the input section (corresponding to $G_{S1} < G_{S_{max}}$). Any point **on** this circle results in a gain $G_S = G_{S1} < G_{S_{max}}$, any point **inside** this circle will yield a gain $G_S > G_{S1}$ (better, but $G_S \leq G_{S_{max}}$), any point **outside** this circle will yield a gain $G_S < G_{S1}$. We must remember that we represent the complex reflection coefficient Γ_S so a particular point on the Smith Chart will result from a particular design of the input matching circuit leading to that particular reflection coefficient at the input of the transistor when looking towards the source. Similarly, we treat the output matching circuit, the choice of a particular gain $G_{L1} < G_{L_{max}}$ from the output matching circuit leading to a **constant gain circle of the output section** (and placement of Γ_L in relation to this circle).

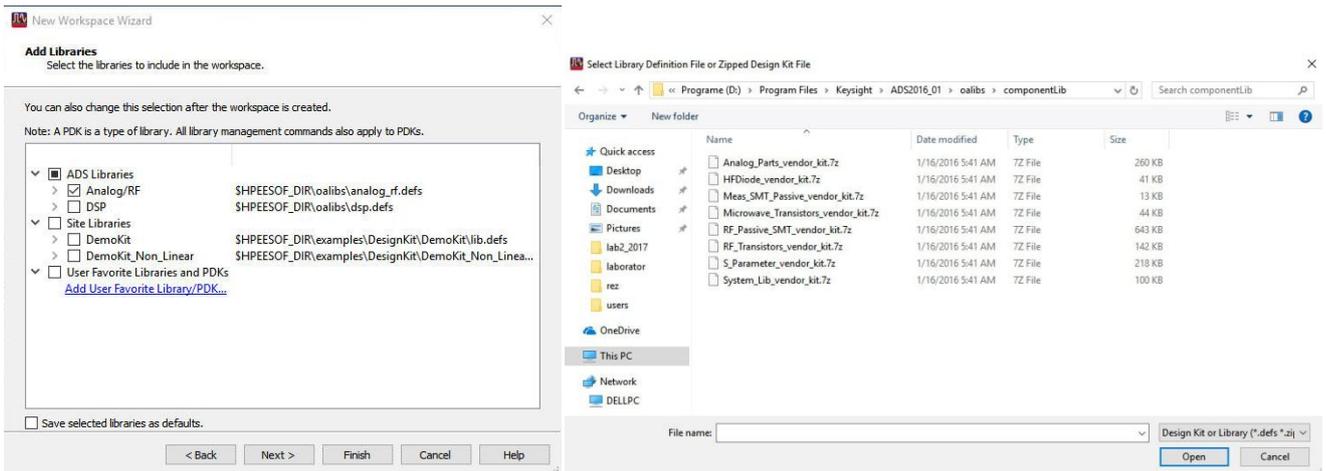
The analysis of the stability of the amplifier (see the theory in lecture 7) leads to the definition of the **input stability circle** (as the locus of Γ_S for the limit between stability and instability for the transistor) and the **output stability circle** (as the locus of Γ_L for the limit between stability and instability). These circles divide the complex plane into two regions, stable and unstable. The identification of the regions depends on the position of the Smith Chart center (origin of the complex plane) relative to the stability circles and the values of $|S_{11}|$ and $|S_{22}|$, but generally for most commercial transistors in the recommended frequency range, the largest area in the Smith Chart is the stable region (empirical rule, not always correct - most of the transistors are designed to work as an amplifier, so they are mostly stable).

As far as noise is concerned, there is a minimum value (NF_{min}) of the noise factor that can be obtained from the transistor for a certain value of the reflection coefficient $\Gamma_S = \Gamma_{opt}$ (restrictive condition, a single point). The **constant noise figure circle** represents the locus of Γ_S for which a noise factor $NF = NF_1 > NF_{min}$ is obtained, any point **inside** this circle will yield a noise factor $NF < NF_1$ (better, but with $NF \geq NF_{min}$), any point **outside** of the circle will yield a noise factor $NF > NF_1$. There are two major differences over the constant gain circles: the constant noise figure circle can be drawn only for the input of the transistor (Γ_S) and the constant noise figure circle depends on the noise parameters ($NF_{min}, \Gamma_{opt}, R_n$) specific to the low-noise transistors, additionally to the S parameters.

An important result is: the noise that characterizes the amplifier **will not depend on the output matching circuit** in any way, which allows you to focus on getting the smallest possible noise (down to NF_{min} if possible) when designing the input matching circuit, any gain problems generated by this process (low gain, imbalanced amplifier) being corrected by the appropriate design of the output matching circuit.

3. ADS models for devices

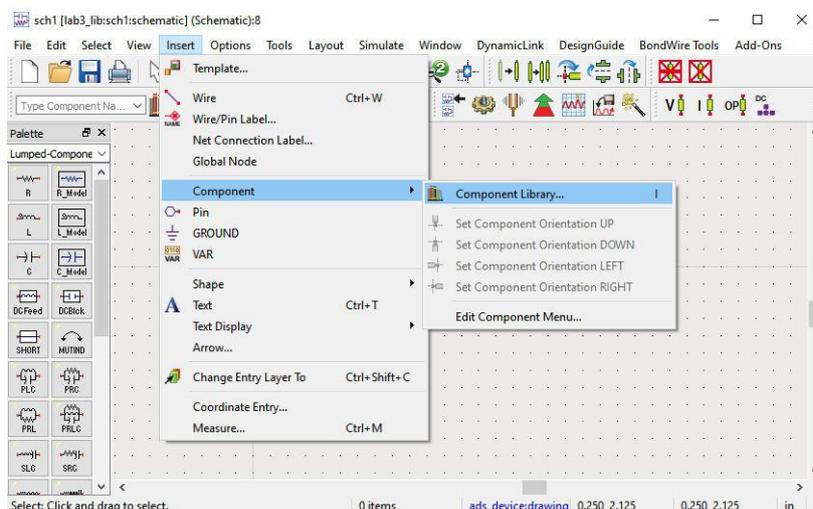
The signal behavior of microwave components is characterized by the scattering matrix (S parameters). A transistor has three terminals but it is treated from all points of view as a two-port (one of the terminals, the emitter or the source, is common between the input and the output port). To enter these parameters in the simulation, for some devices you can use the default libraries of each software product.



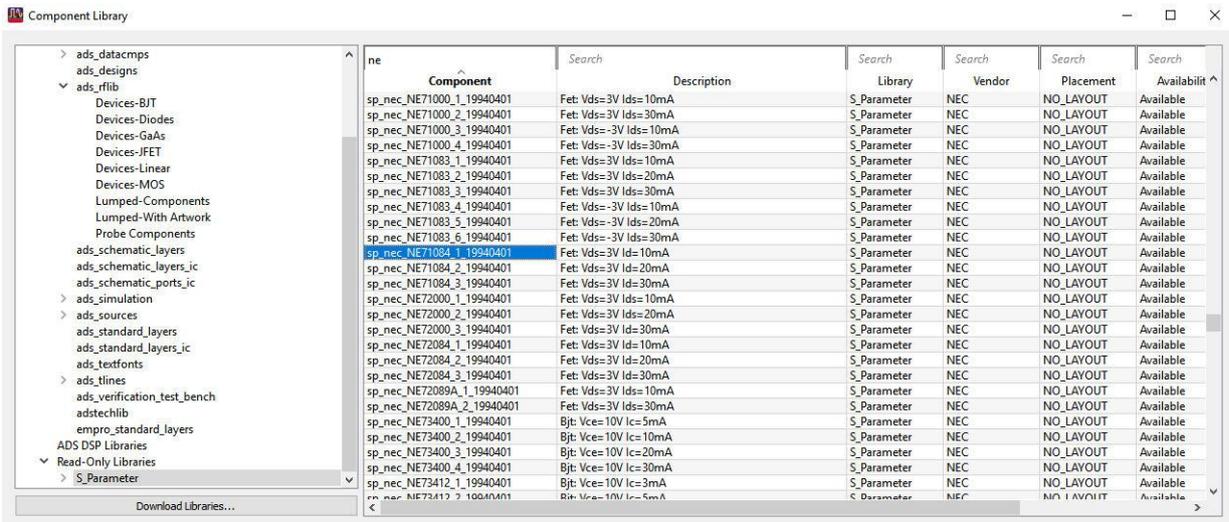
In ADS 2016, **if** the S parameters libraries have never been used (for example after a fresh install), in order to access them in a workspace it is necessary to add the libraries while in the "Create a new workspace"  command, in the library addition window (press Next twice). If the "Add Libraries" window looks like above (in the "User Favorite Libraries and PDKs" section the "S_parameter_vendor_kit" library **is not** listed), click the "Add User Favorite Library / PDK" link and indicate the "oalibs\componentLib" subdirectory from the directory in which ADS was installed and choose the file "S_parameter_vendor_kit.7z". Then target the decompression to a directory where you want the files to be unzipped (in the lab create the D:\ DCMR\S2P directory). If this operation has already been performed at least once, in the "User Favorite Libraries and PDKs" section the "S_parameter_vendor_kit" checkbox will be present and you will select it.

In ADS 2016, access to the libraries enabled as mentioned above is done by choosing from the menu **Insert > Component > Component Library**, which shows the libraries manager window (as in the following figures). For this lab's assignment, linear libraries that do not contain layout data are used, you will find them in the bottom of the window **Read-Only Libraries > S_Parameter**. The components are grouped by the manufacturer, but you can search for a specific code. It should be noted that each device appears multiple times in the list, corresponding to the various DC bias conditions.

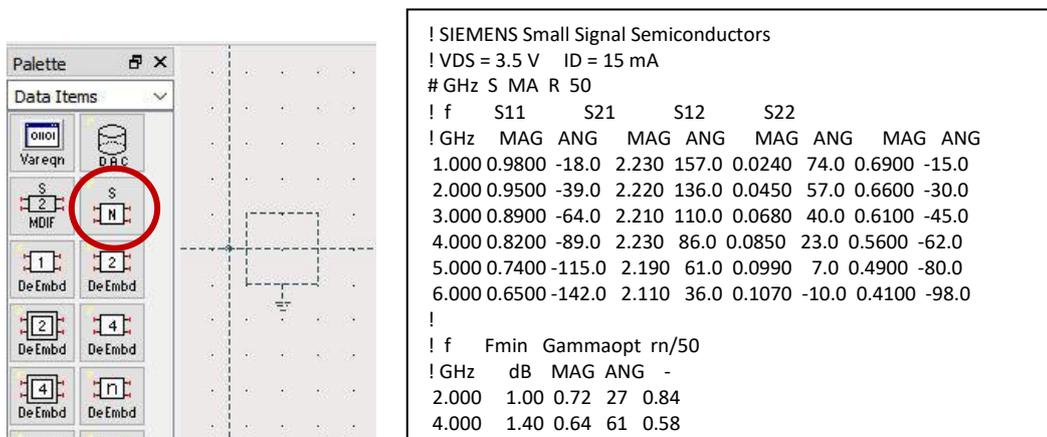
Note: It is usually worth performance wise to investigate the various possible polarizations after choosing a specific device and to choose the optimal bias for your specific application.



Usage of ADS libraries



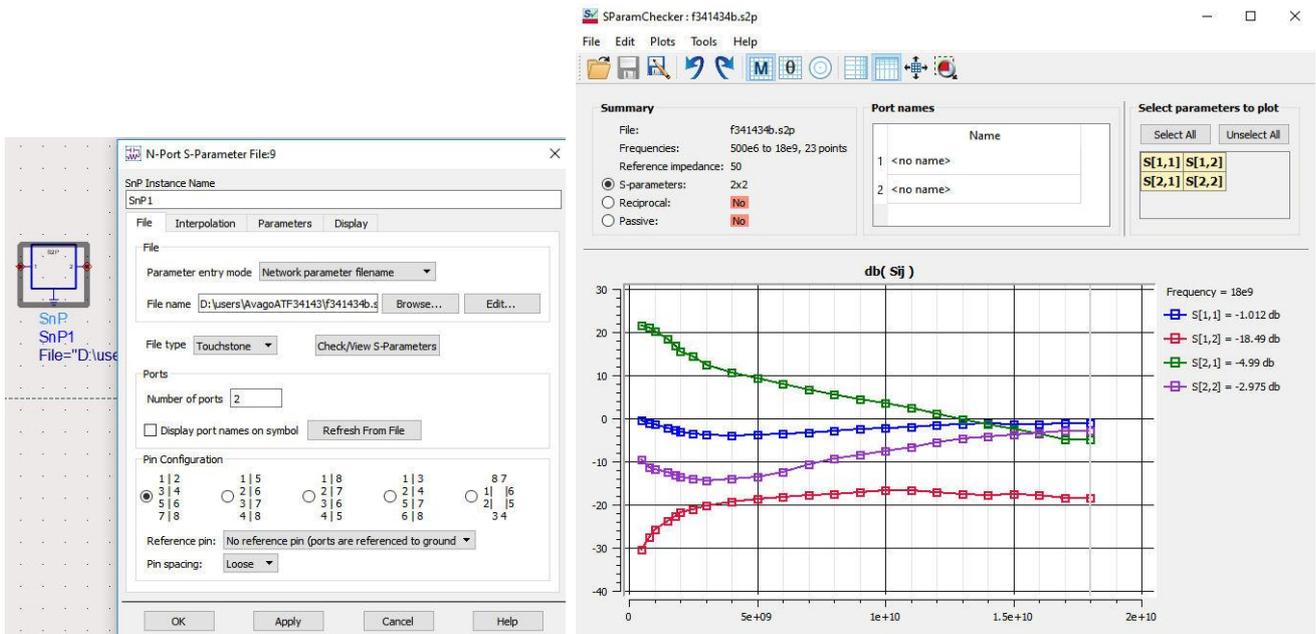
It is not required to limit to software's default libraries. What you really need for a device is the list of S and noise parameters at different frequencies. The values can be obtained from a traditional **datasheet** or can be obtained as ready to use **files** from the manufacturer's **website**. The standard format is called Touchstone and consists of clear text listings of the complex values in the form of a module/argument. The format is not difficult to interpret or modify/create if you cannot find the **s2p file**. The typical extension for transistors is "*.s2p" (2 represents the number of ports, a diode will have "*.s1p" files for example). Inserting such a model into ADS is made from the "Data Items" palette, where you choose the multiport component (as in the following figure) which allows inserting an external file in various formats, but the data you usually can find is in Touchstone format.



Usage of external s2p files

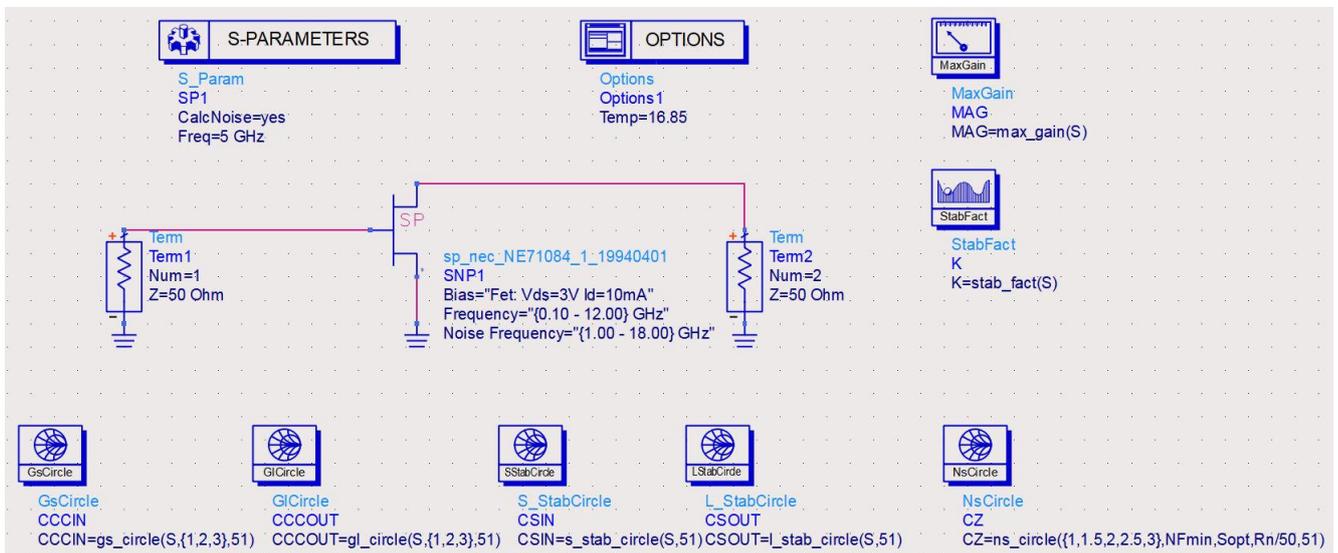
Double click the multiport icon to activate its properties window. The number of ports (2 for the transistor) can be set which causes the symbol to change in the schematic to reflect the number of ports you selected. The Check/View S-Parameters button launches the SParamChecker tool that allows you to quickly inspect the S parameters in the s2p file you previously loaded into the multiport (Browse button).

Note: For this lab's assignment it is recommended to check the presence of the noise parameters in the s2p file at the end (as in the previous figure). Not all bias conditions of a low noise transistor are characterized by good noise performance, and some possible polarizations will not have the noise data as their typical usage is in the final stages of a multi-stage amplifier where noise is less important (see Friis' formula).



4. Schematic 1 – Checking transistor's capabilities

It is recommended that you start with a simple schematic to quickly calculate important parameters for the selected transistor. Other than the transistor introduced by one of the above methods, all other components are from the "Simulation-S_param" palette. The transistor is connected directly between a 50Ω impedance source and a 50Ω impedance load, which corresponds to the reference configuration (in which the S parameters of the associated model were measured).



The example that follows suppose that we need to design an amplifier with a power gain of 11dB ($G > 11dB!$) and a noise factor of 2dB ($NF < 2dB!$) at 5GHz ($f = 5GHz!$) with the NE71084 transistor manufactured by NEC (CEL), biased at $V_{ds} = 3V$ and $I_d = 10mA$.

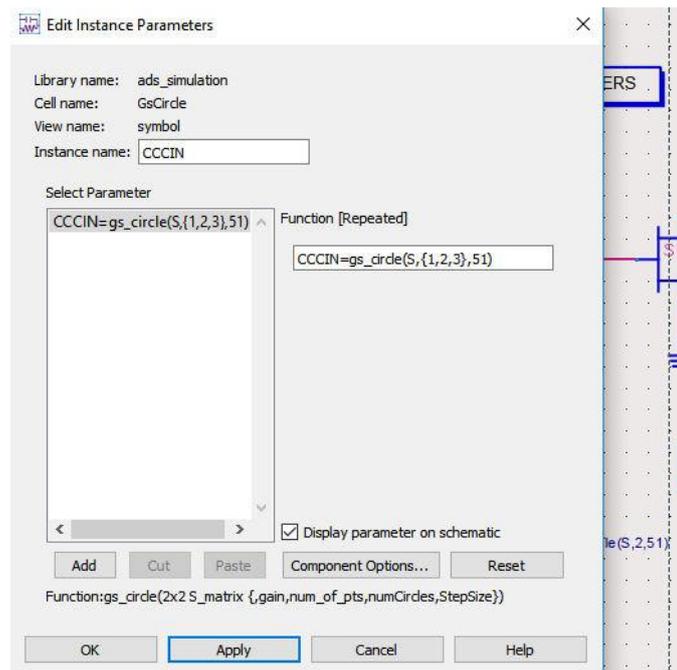
From the same "Simulation-S_param" palette we insert into the schematic the components for:

- Input/output constant gain circles (GsCircle, GIcircle)
- Input/output stability circles (S_StabCircle, L_StabCircle)
- Constant noise figure circle (NsCircle)

- MAG - Maximum Available Gain: (MaxGain)
- K – stability factor (StabFact)

You need to change the following parameters::

- For the SP1 simulation controller (S-Parameters) you must specify that you will compute the noise in the schematic (Noise > Calculate Noise)
- For the SP1 simulation controller (S-Parameters) you must specify that the simulation is a single frequency one – 5GHz (Frequency > Sweep type > Single point) – too many circles on the same chart make it unreadable
- For the Options component specify that the simulation temperature is 16.85°C (273.15+16.85 = 290K - the standard temperature for noise computation)
- Optional: For all components, the names of the variables which will store the simulation results can be changed to make them more intelligible. Take care to change the name of the variables created by underlying formulas and not the instance name: **CSIN** = s_stab_circle (S, 51) - Circle of **S**tability at the **I**Nput (you can change the instance name too if you wish but is not that important)
- Specify (where applicable) which circles you want to be calculated and plotted. Example: **CCOUT**=gl_circle(S,{1,2,3},51) will calculate the constant gain circles for the S-matrix of the whole schematic (so for the transistor in this case) for 3 output match gain G_L values: 1dB, 2dB, 3dB and plot each of the three circles using 51 points



Some parameters that are useful in design should be defined as additional variables. This can be done on the schematic (Measurement Equation) or **after the simulation has finished successfully**, in the Data display window that opens (see figure below). Thus you can enter equations using the button  and then entering the previously mentioned formulas for $G_0, G_{S_{max}}, G_{L_{max}}$. Eventually, some standard variable names (Sopt, Rn, NFmin - taken from the transistor datasheet) can be renamed to use suggestive names.

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

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

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

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

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

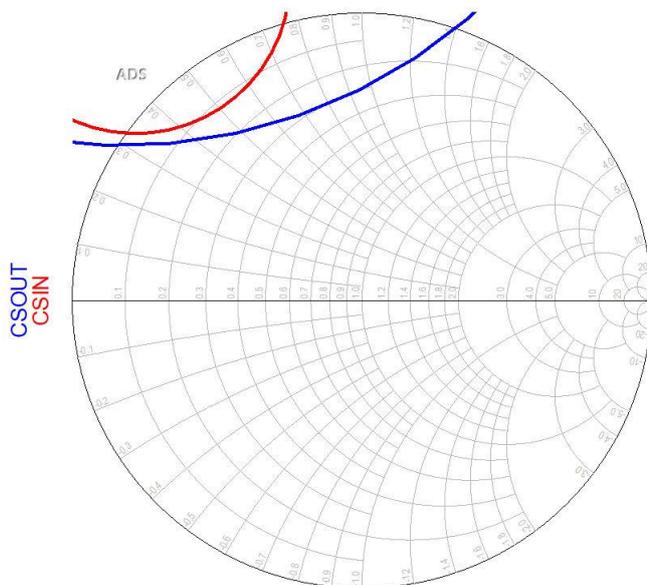
The simulation is made at a single frequency thus the values are better represented as a list (button 1234
5678). You should display the stability condition ($K < 1$, thus the transistor is conditionally stable), the noise parameters of the transistor $NF_{min}, \Gamma_{opt}, R_n$ (especially to verify their presence in the s2p file or library model) and the above computed power gains (Datasets and Equations > Equations).

We can estimate now the error we can expect because we consider the transistor to be unilateral. The above equations compute the gains in unilateral transistor approximation.

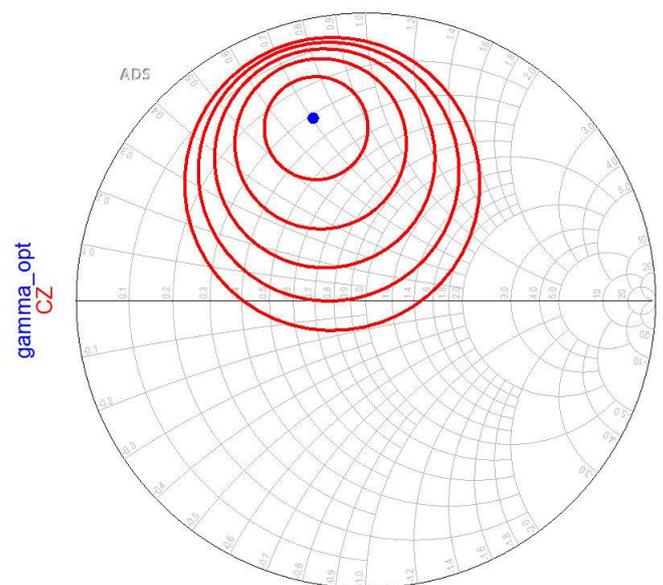
$$G_{TU}[\text{dB}] = G_S[\text{dB}] + G_0[\text{dB}] + G_L[\text{dB}] = 4.249 + 8.974 + 1.634 = 14.857\text{dB}$$

A deviation of 0.439dB is obtained from the bilateral value MAG obtained with the MaxGain controller, but to smaller values, so the design in unilateral approximation will provide some margin for error.

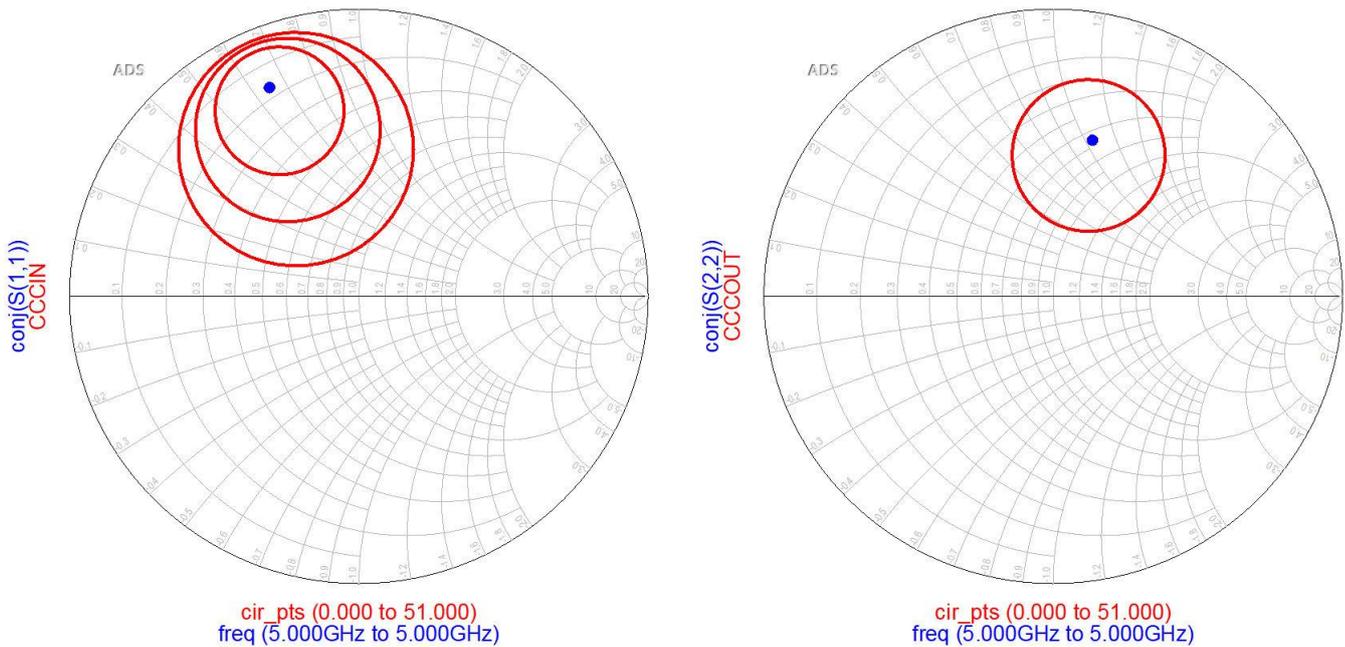
We represent (and critically interpret) on Smith Charts the input/output stability circles, the input/output constant gain circles and the constant noise figure circles. Since the stability circles expand outside the Smith Chart (recall that the Smith Chart is a circle of radius 1 in the complex plane), it is necessary to unselect Plot Options > Y Axis > Auto Scale and fix the maximum at 1. Since $NF_{min} = 0.7$ all 5 requested circles of constant noise figure {1,1.5,2,2.5,3} are plotted. $G_{Smax} = 4.249\text{dB}$ which allows the three requested input constant gain circles {1,2,3} to be plotted. $G_{Lmax} = 1.634\text{dB}$ so only one of the three requested output constant gain circles will be plotted, the one for $G_L = 1\text{dB}$. The single points corresponding to the optimum for gain and noise ($\Gamma_S = S_{11}^*, \Gamma_L = S_{22}^*, \Gamma_S = \Gamma_{opt}$) are also plotted. As the plot of a single point might be hard to see, it might be necessary to change the representation type: Trace Options > Trace Type > Scatter.



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)



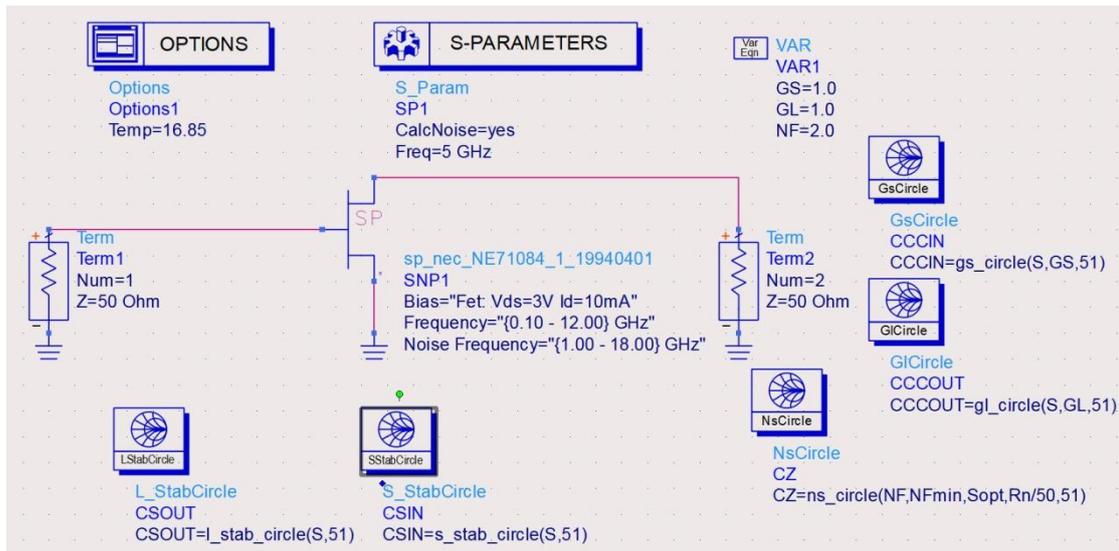
The NE71084 transistor is a good candidate for the design. $MAG > 11$ dB with a 4dB margin, sufficient for deviations and optimization, $NF_{min} = 0.7$ dB, and the 2dB constant noise figure circle (the middle one) is large enough not to impose too strict conditions when designing the input matching circuit. **Very important:** the constant noise figure and input constant gain circles are located in the same area of the Smith Chart, so we can simultaneously meet the noise and gain requirements when designing the input matching circuit.

Note: This schematic could be reused later (in your own Project/Design) as it allows for rapid investigation of different transistors by changing the device and quickly calculating the parameters for the new one.

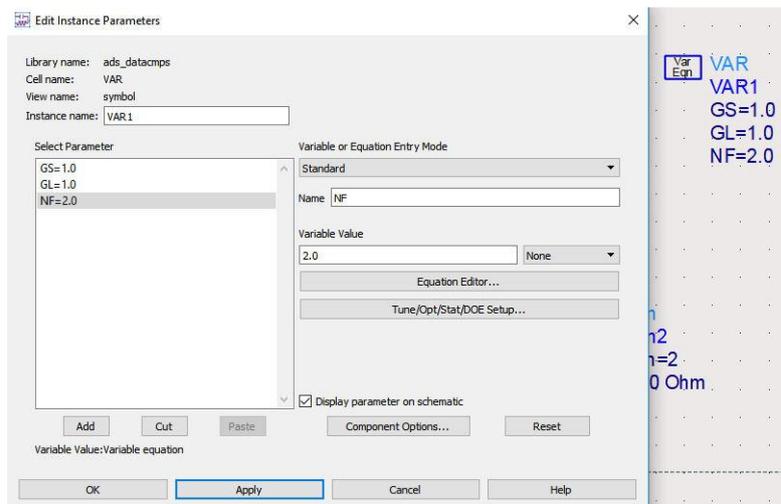
5. Schematic 2 – Target circles simulation

The circles required as target when positioning the reflection coefficients in the design of the matching circuits are computed by ADS for an entire two-port schematic. We save the previous schematic to a similar one (only the transistor connected between the two 50Ω terminals corresponding to the ports) but we reduce the data we compute to the strictly necessary values. The circles will be computed for the whole schematic and will then be used in later simulations where needed, for example in the following section (section 6). If we save this schematic with the name "sch2", the circles can be accessed by modifying the Dataset to "sch2" when choosing the measurements to be displayed.

The schematic is quite similar to the previous one. In order to keep uncluttered the graphs on which we will design the matching circuits, we will choose only one target circle of the same type instead of the family of circles computed in the previous section. The stability circles already are unique. For the gain circles, we previously calculated $G_0 = |S_{21}|^2 \approx 9$ dB so in order to meet the 11dB gain requirement we will need an additional 2dB gain, which should be split between the two matching circuits. Because $G_{S_{max}} = 4.249$ dB and $G_{L_{max}} = 1.634$ dB it would seem natural to affect most of the 2dB extra gain to the input matching circuit. However, noise is strictly dependent on the input matching, and there is a possibility that obtaining lower noise may require sacrificing some gain in the input match. We will thus choose $G_S = G_L = 1$ dB. For the constant noise figure circle we choose the one for the design noise factor (2dB).



Because there is a possibility that these choices need to be changed later based on stability/gain/noise results, we will define some variables with these requirements. A VAR type controller (VAR1) is inserted in the schematic, to allow changes to all circles in a single place (instead of "chasing" them around the schematic) and you can see that the circle controllers have their formulas changed to automatically compute for the values indicated in the VAR controller: $CCCOUT=gl_circle(S,GL,51)$, $CCCIN=gs_circle(S,GS,51)$



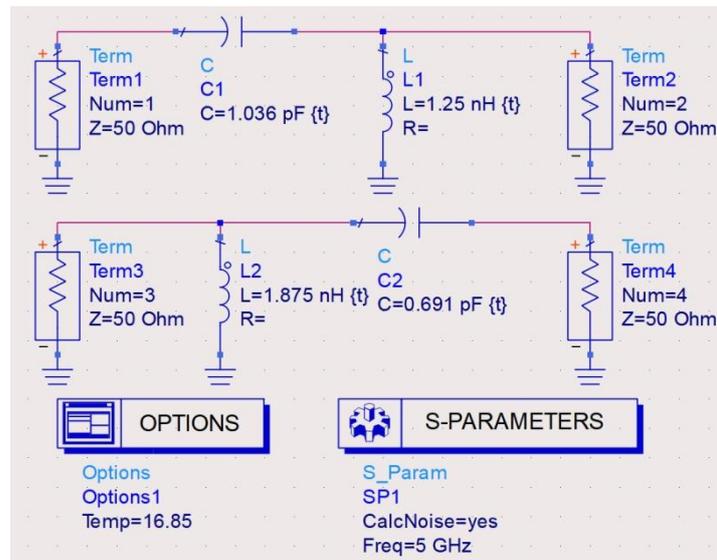
Note: You need to simulate this schematic but do not require displaying anything in its Data display window. The computed circles will be needed at section 6 Data display. However, if you want to check the correctness of the schematic at this time, display and check the correct placement of circles as shown in figures in section 6.

6. Schematic 3 – Design of the input/output matching circuits

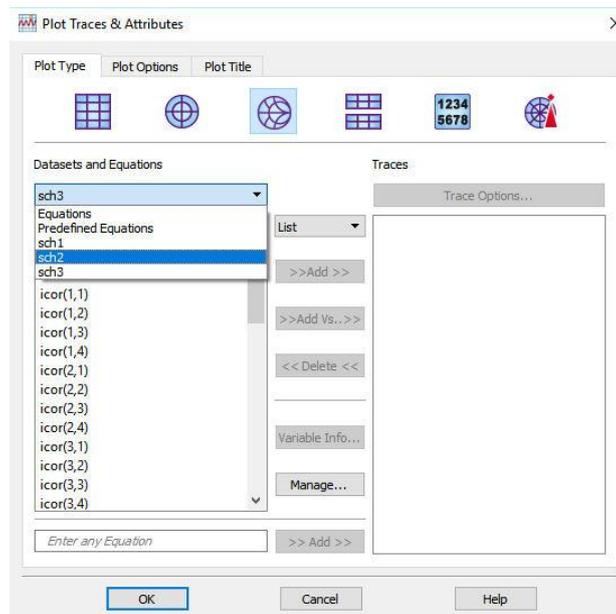
The design of the matching L-networks involves the calculation of the reflection coefficients Γ_S and Γ_L (first figure in section 2, looking from the transistor towards the source and the load) and the correct positioning of these values against the noise/gain/stability circles. For reasons of simplicity in this lab assignment, matching is achieved with LC circuits, but as mentioned, more often in microwave frequency range (including for the MDCR project/design) the matching is achieved with sections of transmission lines and stubs.

The two proposed matching circuits are introduced into schematic 3 (bellow). Choosing the right L-network of the four possible LC circuits (shunt C series L, series C shunt L, shunt L series C, series L shunt C) might require some trial and error steps to find the schematic that causes the reflection coefficient to shift in the

desired direction. In the following schematic, the input matching L-network is inserted between ports 1 and 2, and Γ_S will be S_{22} . The output matching L-network is introduced between ports 3 and 4, then Γ_L will be S_{33} .

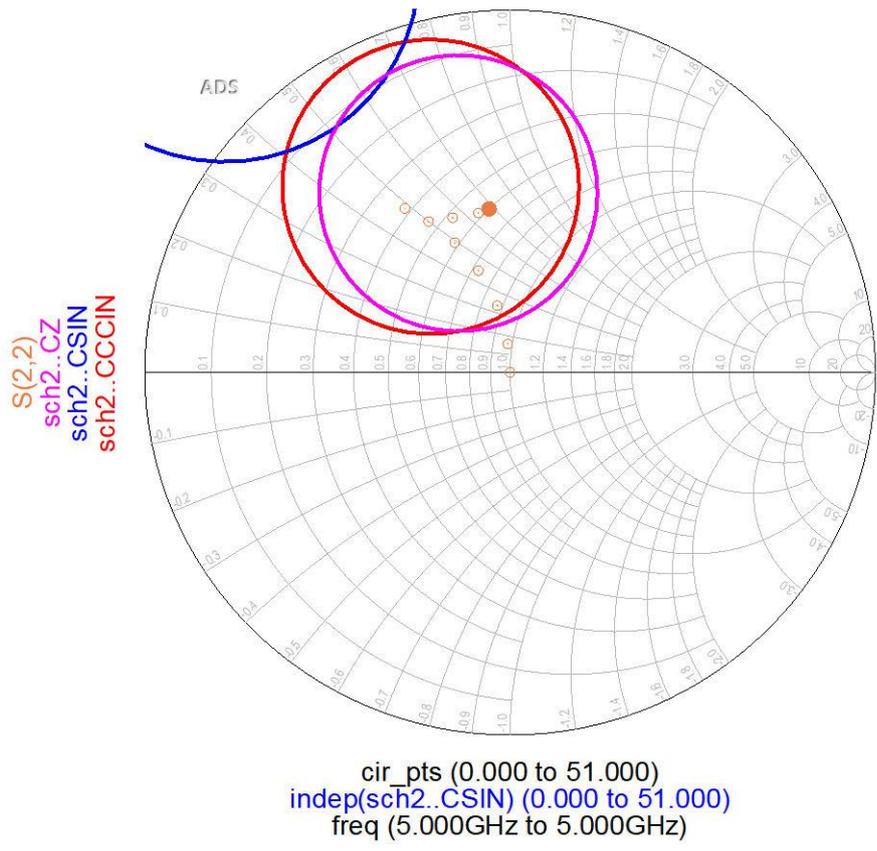
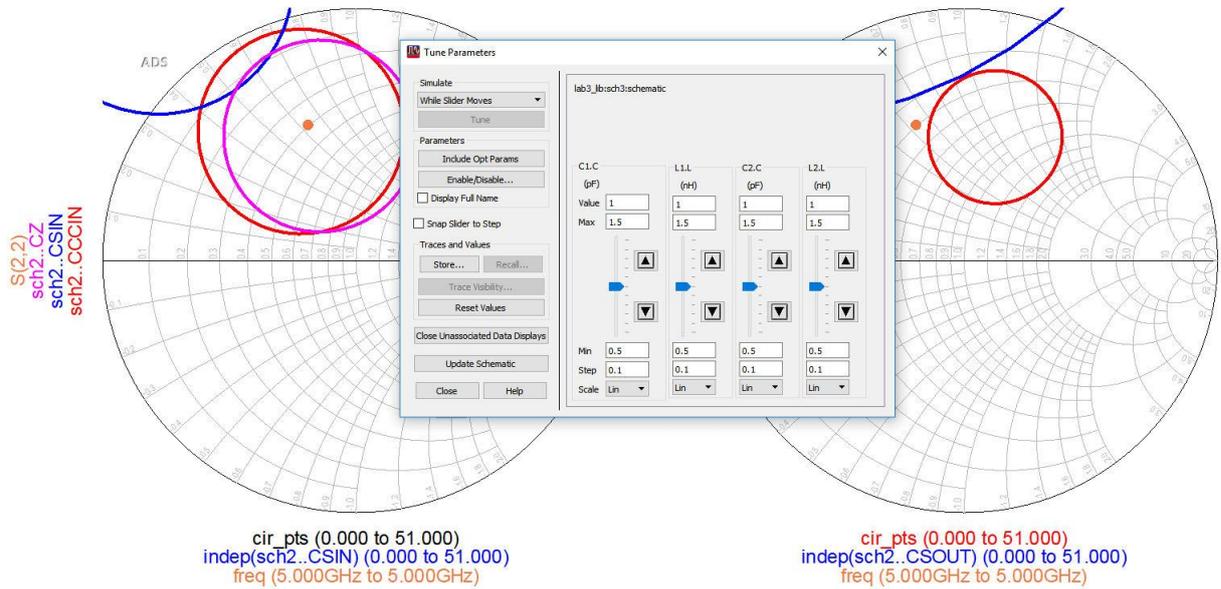


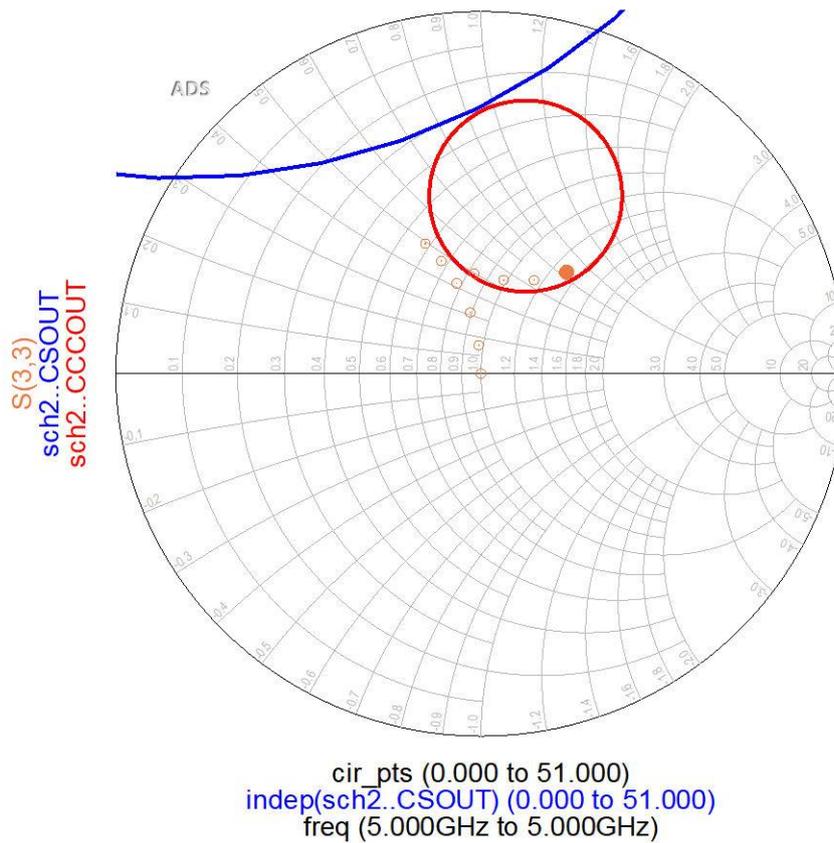
We need to activate the Tune tool, successively for every L-network. Unlike the situation in lab 1, it might be useful to press the "Store" button extensively, possibly storing and displaying a larger number of points to visualize the movement of the reflection coefficient towards the target circles during components' variation.



$S(2,2)$ is displayed along with the input stability, noise figure and gain circles taken from the previous target analysis (Dataset > sch2). The current schematic result (one point) should be placed **on** the constant gain circle (red), **on** the constant noise figure circle (pink), **as far away** as possible from the stability circle (blue). As mentioned before, the particular position of the gain and noise circles in this case allows positioning the $S(2,2)$ point closer to the center of the noise circle (better, less than 2dB noise figure) and inside the gain circle (also better, higher gain than 1dB). The further approach to the minimum noise and maximum gain points would mean the possible dangerous approach to the stability circle.

If a more accurate estimation of the gain/noise performance is desired, repeat the analysis of the target schematic (section 5) with other specified values for the noise and gain circles ($NF \approx 1\text{dB}$, $GS \approx 2.5\text{dB}$) and modify them until $S(2,2)$ lies **on the intersection** of the two circles.

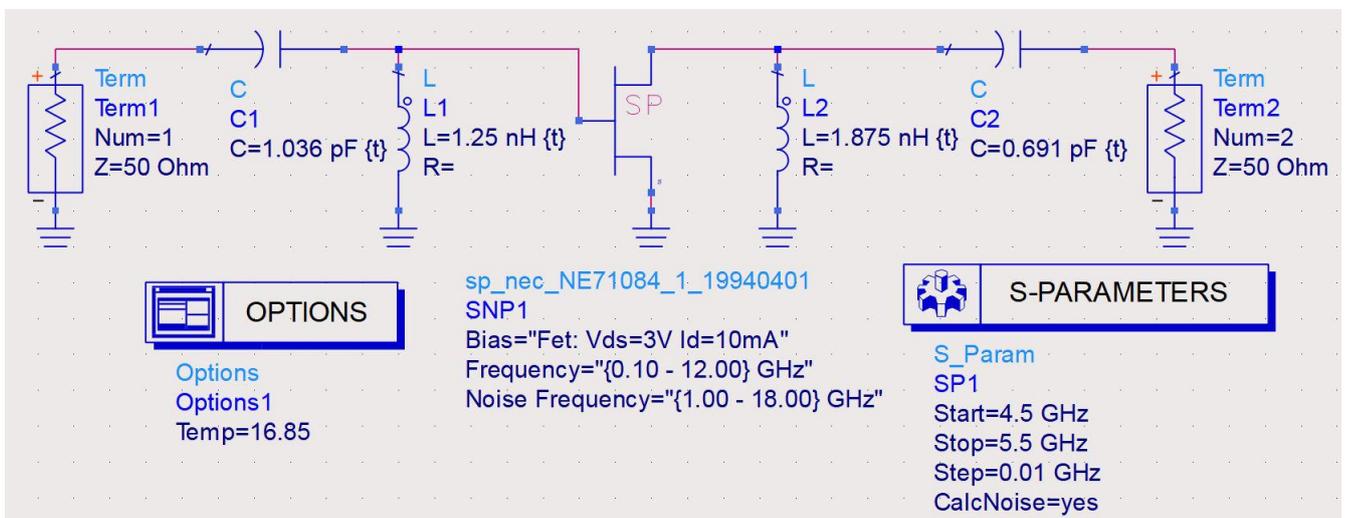




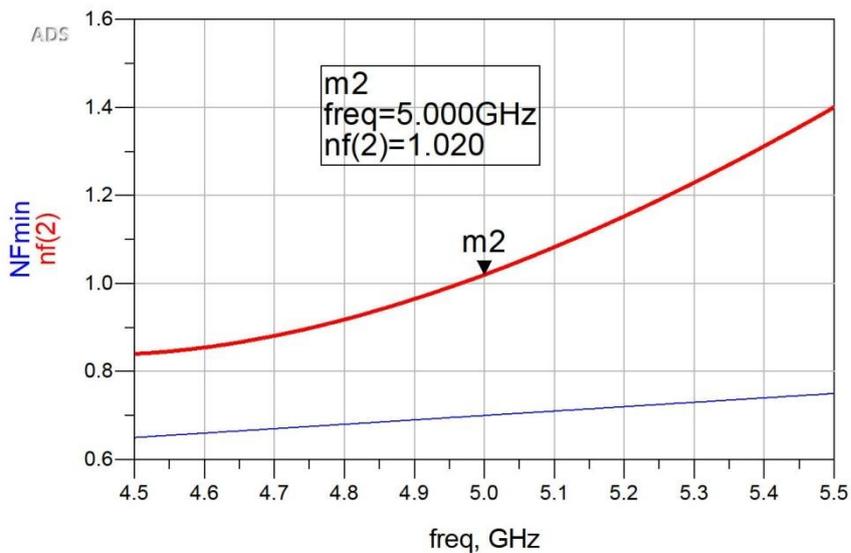
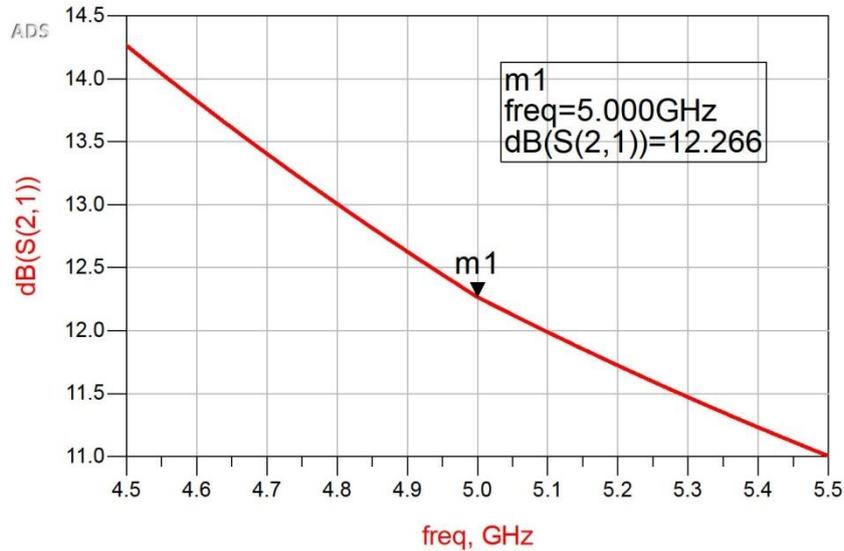
For the output matching L-network only constant gain and stability circles appear, and by adjusting the components we move the $S(3,3)$ reflection coefficient on the constant gain circle (red) **as far away** as possible from the stability circle (blue), the circles taken as well from the section 5 dataset.

Note: We have mentioned briefly in section 1 the low-pass type native behavior of the transistor (S_{21} decreases with increasing frequency). Obtaining a bandwidth (frequency balanced) behavior for the amplifier will require that at least one of the two matching circuits to be of the high-pass type. In the example we presented, both L-networks are high-pass networks.

7. Schematic 4 – Final Simulation and Tune/Optimization

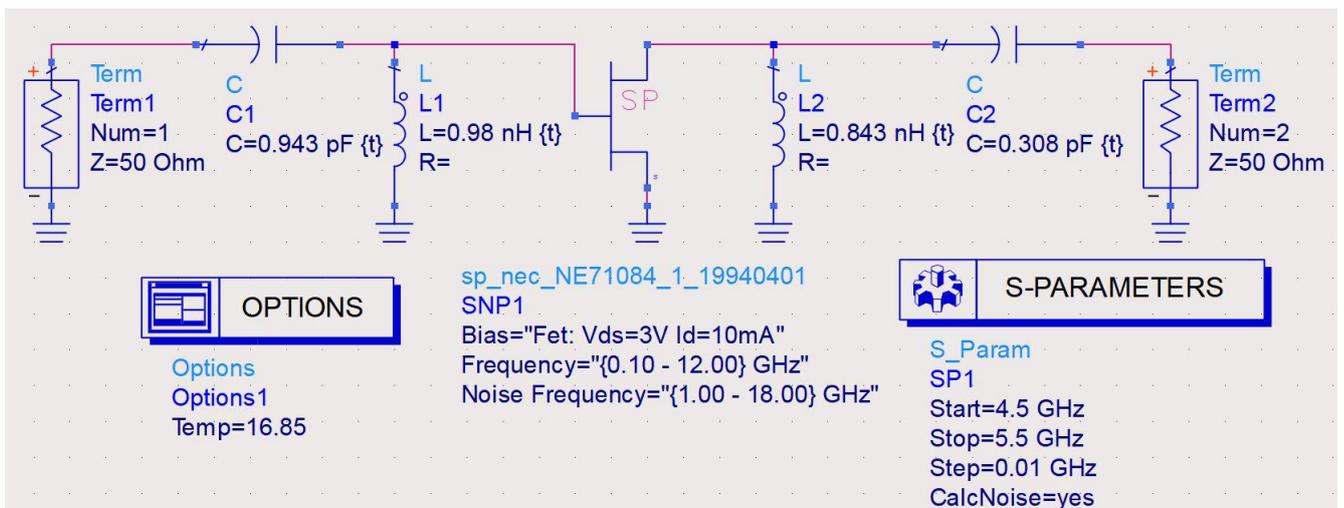
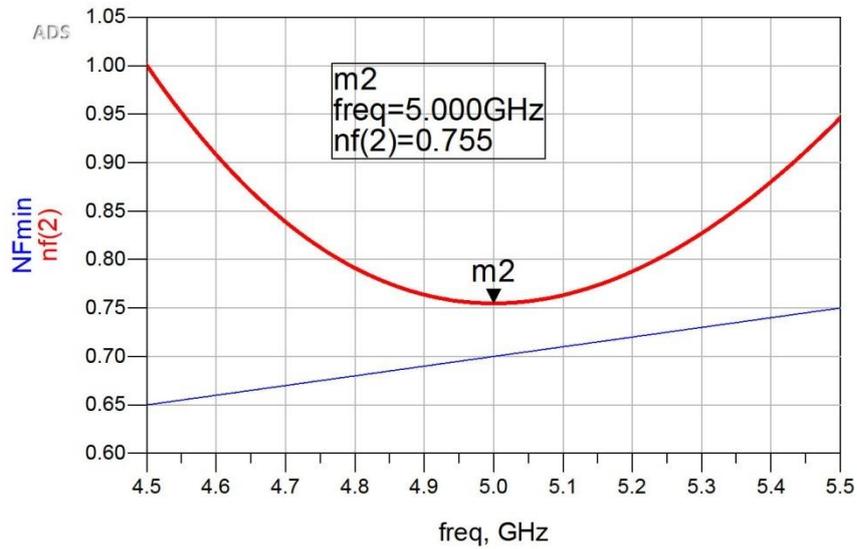
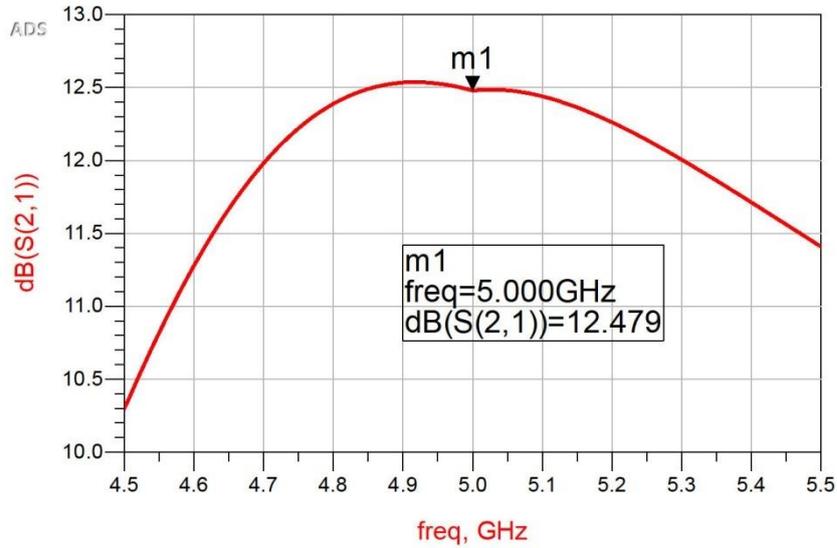


Insert the previously tuned L-networks into a new schematic, around the transistor (copy/paste from schematics 2 and 3). This time no circles are drawn, and the S-parameters simulation has to be Frequency > Sweep type > Linear in a frequency range centered on the design frequency of 5GHz (relatively narrow range, the design is a narrowband amplifier).



The simulation result shows the fulfillment of the requirements of the design ($G = 12.27\text{dB}$, $NF = 1.02\text{dB}$ at 5 GHz). However, as mentioned above, it is useful to obtain a frequency balanced behavior to improve low frequency stability of the amplifier.

A final tune process allows you to achieve this behavior and even increase the gain (up to a value of 12.48dB) and decrease the noise (down to $NF = 0.75\text{dB}$).



Note: Performing a tune action directly in the last schematic, without completion of the intermediate steps (sections 4-6) it's unlikely to achieve a good match fast (due to the existence of 4 different L/C components and 4 different possible L-networks: shunt C series L, series C shunt L, shunt L series C, series L shunt C). Passing

through sections 4-6 insures that the right L-networks are chosen and the component values are close to the needed ones.

(Most important) Note:

This lab assignment will take 2 sessions to complete. In the first session you will create the 4 schematics (sections 4-6) **exactly** for the design data in the example (a power gain of 11dB and a noise factor of 2dB at 5GHz with the NE71084 transistor). Comparing your results with those plotted in this material will ensure that your schematics are correct. Next you will receive your personal assignment (different frequency/gain/noise) and in the second session you will use and adapt your previous (known correct!) schematics to design and simulate for your individual data. You **can** use the same transistor if you wish, NE71084. At the end of the second lab session you must hand over to the teacher the results sheets that **should** contain:

1. The final ADS schematic, in which matching circuits values are clearly shown
2. Graph of the simulation results (gain and noise factor)

The teacher will simulate the schematic you handed over. Fulfillment of the requirements by the **handed over schematic** and the agreement of results with **handed over ones** are essential for a passing grade.