EE431/531 Microwave Circuit Design I: Lab 3

1. Introduction

This lab delves into the principles of amplifier design under the constraints of either maximum transducer gain or a specific operating power gain. In addition, the relationship between constant gain circles and the frequency is explored. You will also learn how to create a circuit layout in MDS.

2. Design Specifications

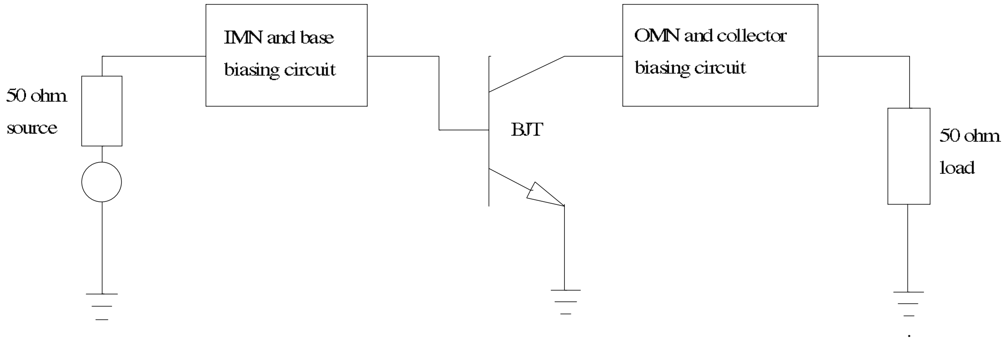

Figure 1: Block diagram of a single stage BJT amplifier

You are to design two different single-stage transistor amplifier circuits. For the first circuit, the design constraint is to achieve maximum transducer gain $G_{T,max}$. In the second circuit, the amplifier must obtain a specified operating power gain G_p. The design frequency is $f = 1$ GHz.

The input matching network (IMN) and output matching network (OMN) are to be constructed from microstrip. The substrate is Duroid ($\varepsilon_r = 2.23$ and height $H = 0.7874$ mm). The matching networks should use balanced stubs (either open-circuited or short-circuited) and a series transmission line.

The core of the amplifier is a bipolar junction transistor (BJT) in common-emitter configuration. For this lab, the transistor is a Siemens BJT (MDS Part# "siemens_10bfq196_s"). This particular device is parameterized at a fixed bias of $V_{CE} = 5$ V and $I_C = 70$ mA.

Technically, the parameterized BJT does not need external biasing for simple *S*-parameter and gain measurements. However, you are required to design base and collector biasing circuits (including DC voltage sources) and add them to your amplifier. You may use high-impedance microstrip, inductors, and capacitors. Although the bias circuits do not actually power the parameterized BJT, they may still have an impact on the amplifier due to non-ideal component effects.

The input port of the BJT needs to be matched to a 50 Ω source, while the BJT's output port is to be matched to a 50 Ω load. In the actual circuit, the source and load impedances are represented by S-ports. Coupling capacitors should be placed between the source and the IMN, and also between the OMN and the load.

For a good example of what your completed amplifier circuit design might look like, refer to page 167 of the Gonzalez textbook (2nd edition).

3. Circuit Layout

If a circuit design is to be manufactured, then you need to create a layout for the circuit. The layout procedure converts a schematic drawing to a set of detailed instructions that tell how to arrange the circuit for actual fabrication. MDS has layout models for many circuit components, which are used to define and constrain the physical layout of the components. For devices with no built-in models, you can create your own definitions that describe how to perform the component layout.

In MDS, the layout procedure can be performed automatically or interactively. In *auto-layout* mode, MDS examines the schematic, applies the appropriate models, and then generates the circuit layout. This is convenient for the engineer, but the resulting layout might not conform to certain design guidelines (especially if the models are incomplete). In this case, interactive mode is appropriate. With the MDS layout editor, you can edit a layout to fix minor problems or even create new layouts from scratch.

When a circuit layout is produced, MDS creates a layout icon in the workbench. Double-clicking this icon opens its associated layout page. What you see on the layout page is a proportionally scaled view of how the circuit will be constructed.

When the layout is finished, it can be saved as a UNIX file and imported into special software that validates the layout. Once verified, the layout can be used as a guide to make PC boards or IC masks that implement the original circuit design.

3.1 Layout problems with the Siemens BJT

The Siemens 10bfq196_s BJT does not have a built-in layout model. If you attempt to perform an auto-layout of a schematic that contains the Siemens BJT, MDS will use a default component layout that makes no sense. To get around this problem, you will define a new layout model for the BJT.

If package specifications for the Siemens BJT were available, you could create a realistic layout that takes into account the actual dimensions of the device. Since we do not have that information, you will create a simplified BJT layout instead, which consists of a 70 mil diameter circle with four terminals in the proper orientation.

3.2 Creating a new BJT layout

Here is the procedure for creating the simplified BJT layout:

- Create a new workbench called Lab3 within the MW_Labs project file (or whatever your project file is called).
- Click [SUI:Layout] to create a new layout. Type `70mil` in the input box of the 'New Layout' dialog window and press RETURN (or click [OK]). MDS should create a layout icon called 70mil in the Lab3 workbench.
- The '70mil: DRAWING 1' window appears, along with a 'Momentum' Palette that pops up on the left side of the screen. You will not use Momentum for this lab, so you can close the palette window or simply ignore it. Make sure the layout page is still the active window.

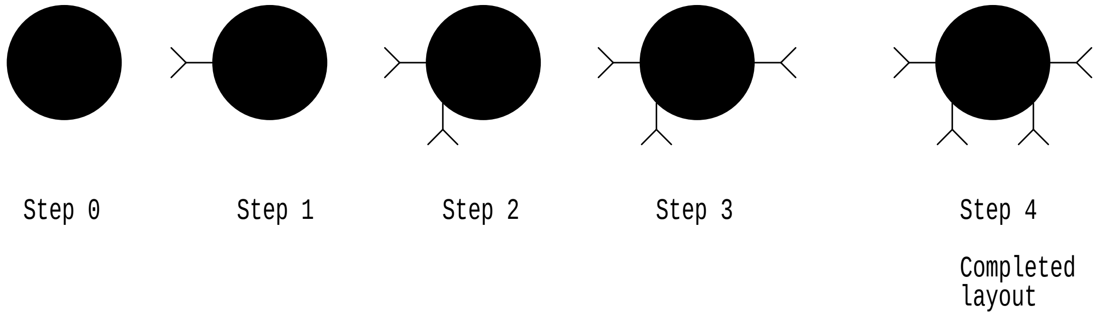

Figure 2: Step-by-step layout procedure for the Siemens BJT

- **STEP 0**: Draw the circle (Step 0 of Figure 2).

  Choose [MB:INSERT/CIRCLE/BY X-Y VALUES/BY CENTER & RADIUS]. The first dialog window asks for the circle's center, so enter `0,0` in the input box (you must type the comma between the zeroes). The second dialog window asks for the radius, so type `35`. The final dialog window asks for the line width. You can just click [OK]. MDS now draws a filled circle on the layout page.
- **STEP 1**: Add the first terminal connector (Step 1 of Figure 2).

  Choose [MB:INSERT/CONNECTOR/BY X-Y VALUES]. The first dialog window asks for an X-Y point pair, so type `-35,0` in the input box (remember to type the comma). The next dialog window wants to know the pin angle, so type `180`. The last dialog window requests a number for the connector. Type `1` in the input box. MDS now adds the first connector to the circle.
- **STEP 2**: Add the second terminal connector (Step 2 of Figure 2).

  Repeat Step 1 with these values: (X-Y point pair: `-24.7,-24.7`), (Angle: `270`), (Number: `2`)
- **STEP 3**: Add the third terminal connector (Step 3 of Figure 2).

  Repeat Step 1 with these values: (X-Y point pair: `35,0`), (Angle: `0`), (Number: `3`)
- **STEP 4**: Add the fourth terminal connector (Step 4 of Figure 2).

  Repeat Step 1 with these values: (X-Y point pair: `24.7,-24.7`), (Angle: `270`), (Number: `4`)
- You have finished creating a simplified BJT layout called 70mil. Close the layout page window.

3.3 Accessing the new BJT layout

You have to make a few changes to your circuit schematic in order to access the simplified layout. Essentially, you insert transistor attribute statements onto the circuit page which explicitly tell MDS to use the new 70mil layout instead of the default component layout. The procedure for doing this is outlined in the next section.

4. BJT Characteristics

4.1 Assignment

As the first step in the amplifier design, you will determine the characteristics of the Siemens BJT. From the resulting *S*-parameter data, you can instruct MDS to find the reflection coefficients for a bilateral simultaneous conjugate match and compute the corresponding maximum transducer gain. The test circuit consists of the BJT, two S-ports, and no matching or bias networks.

4.2 Circuit construction

- In the Lab3 workbench, create a new circuit page called BJT_char. Figure 3 shows what your completed circuit should look like.

```
EQUATION del=s11*s22-s12*s21
EQUATION mdel=mag(del)
EQUATION K=(1-(mag(s11))^2-(mag(s22))^2+(mdel)^2)/(2*mag(s12*s21))
EQUATION U=(mag(s12)*mag(s21)*mag(s11)*mag(s22))/((1-(mag(s11))^2)*(1-(mag(s22))^2))

EQUATION Gmsg=mag(s21)/mag(s12)                    EQUATION Gmsg_dB=10*log(Gmsg)
EQUATION h21=(-2*s21)/((1-s11)*(1+s22)+s12*s21)
EQUATION h21ms=(mag(h21))^2                        EQUATION h21ms_dB=10*log(h21ms)
EQUATION s21ms=(mag(s21))^2                        EQUATION s21ms_dB=10*log(s21ms)

EQUATION B1=1+(mag(s11))^2-(mag(s22))^2-(mdel)^2
EQUATION B2=1+(mag(s22))^2-(mag(s11))^2-(mdel)^2
EQUATION C1=s11-del*conj(s22)
EQUATION C2=s22-del*conj(s11)

EQUATION Gamma_Ms=(B1-(B1^2-4*(mag(C1))^2)^0.5)/(2*C1)
EQUATION Gamma_ML=(B2-(B2^2-4*(mag(C2))^2)^0.5)/(2*C2)

EQUATION num=(1-(mag(Gamma_Ms))^2)*(mag(s21))^2*(1-(mag(Gamma_ML))^2)
EQUATION den=(mag((1-s11*Gamma_Ms)*(1-s22*Gamma_ML)-s12*s21*Gamma_ML*Gamma_Ms))^2
EQUATION GTmax=num/den
EQUATION GTmax_dB=10*log(GTmax)
```

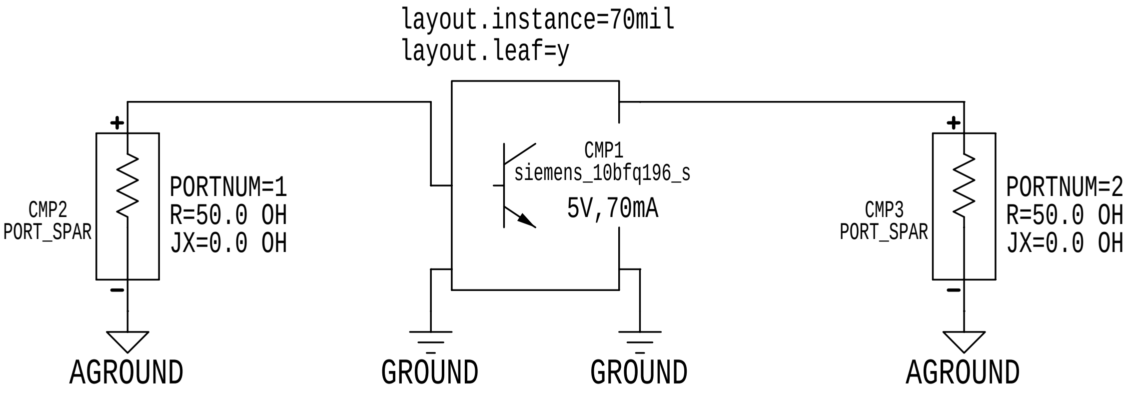

Figure 3: BJT characterization test circuit

- To access the Siemens BJT, click [Library …] on the Components Palette. In the Library Browser, click [Select by Type] and choose the “Select by Library” option. In the left-most panel of the ‘Library Browser’ window, scroll down the list and select the “siemens” option. In the middle panel, select “BFQXXX”. In the right-most panel, select “10bfq196s”. Click [OK] to exit the browser. MDS may tell you that the siemens library needs to be loaded. Answer “Yes” when prompted.
- Note that the substrate and emitter terminals of the BJT are attached to global grounds. While functionally similar to analog grounds, MDS has built-in models for global grounds that are vital when performing an auto-layout.

  To access the global grounds, click [More parts …] on the Components Palette. From the ‘Parts’ list window, select the “Global connectors” option. The Components Palette will then have an icon with the floating label *Gnd, digital*. Use that icon for the global grounds.
- Place S-ports (R = 50.0 OH, JX = 0.0 OH) on the circuit page. MDS ignores the S-ports when performing a circuit layout, so they can still use analog grounds.
- Insert *EQUATION* statements on the circuit page and edit them to look like Figure 3.

  In the first group of equations, K is the stability factor, *mdel* is $|\Delta|$, U is the unilateral figure of merit, *Gmsg* is the maximum stable gain G_{MSG}, *h21ms* is $|h_{fe}|^2$, and *s21ms* is $|S_{21}|^2$.

  In the next group of equations, *Gamma_Ms* and *Gamma_ML* are Γ_{Ms} and Γ_{ML}, respectively, which are the source and load reflection coefficients required for a bilateral simultaneous conjugate match. Finally, *GTmax* is the maximum transducer gain $G_{T,max}$.

  MDS’s built-in dB function assumes an amplitude ratio for its argument (i.e., dB(A)=20log(A)). For this lab, a power ratio is more appropriate (i.e., dB(P)=10log(P)).

  Additional *EQUATION* statements have been defined to do the proper decibel conversion, and those equation variables (*Gmsg_dB*, *h21ms_dB*, *s21ms_dB*, and *GTmax_dB*) are the correct output variables.
- The *layout.leaf* and *layout.instance* statements are the transistor attribute statements mentioned earlier. They are not simple text statements. You have to enter them using an attribute viewer.

  Choose [MB:INSERT/ATTR VIEWER]. Although nothing seems to happen, MDS is waiting for you to select a component whose attributes you want to change. Select the BJT with the mouse.

  A dialog window appears that asks you to insert the attribute name. Type `layout.leaf` in the input box and press RETURN (or click [OK]). A new dialog window appears and asks if it should create *layout.leaf*, to which you should type `y` in the input box. The final dialog window asks you to insert the attribute value for *layout.leaf*. In the input box, type `y`. An outline of the attribute now tags along with the mouse pointer. Position the pointer where you want the attribute statement to go and click the mouse to drop it onto the circuit page.

  The dialog window that asks for an attribute name automatically appears again. Repeat the previous procedure to place the *layout.instance* statement on the circuit page. Type `70mil` when asked for the attribute’s value. To exit the attribute viewer, click [OK] when the dialog window asking for the attribute name appears again.

  For your information, *layout.leaf=y* instructs MDS to ignore the transistor’s built-in layout (which the Siemens BJT does not have anyway). The statement *layout.instance=70mil* tells MDS to use an instance of the layout called 70mil, which happens to contain your simplified BJT layout.

4.3 Circuit layout

- Since the test circuit has no matching networks, you do not have to create a full circuit layout yet.

4.4 Simulation and output

- Configure MDS for an *S*-parameter simulation. Linearly sweep the frequency from 0.9 to 1.1 GHz with a step size of 10 MHz. In the 'Simulation Setup' window, define the equation variables *K*, *mdel*, *U*, *Gmsg_dB*, *h21ms_dB*, *s21ms_dB*, *Gamma_Ms*, *Gamma_ML*, and *GTmax_dB* as output variables.

  IMPORTANT: Change the default dataset name to `DS_BJT` before running the simulation.

- After the simulation, create a tabular listing of the *S*-parameters versus the frequency. Add listing columns for *K*, *mdel*, and *U*. Insert additional listing columns for *Gamma_Ms* and *Gamma_ML* (display them in linear magnitude and phase format). Finally, add a listing column for *GTmax_dB*.
- Perform another simulation, but this time use a logarithmic frequency sweep. Set *Sweep type* to "Log", *Start*=10 MHz, *Stop*=6 GHz, and *Pts/decade*=20.
- Using the new data, make a LIN-LOG plot of *Gmsg_dB*, *h21ms_dB*, and *s21ms_dB* versus the frequency. They should all be plotted on the same graph.

4.5 Items to turn in

- Turn in a printout of the BJT characterization circuit.
- Submit the listings and the gains versus frequency plot.

4.6 Questions

1. Is the Siemens 10bfq196_s BJT unconditionally stable at the design frequency of 1 GHz? From the simulation results, explain why the transistor does not fulfill the unilateral criterion.
2. Discuss the significance of the gains versus frequency plot.
3. Determine the frequency at which the transistor becomes potentially unstable.
4. Determine f_β, f_T, and f_s. Explain why you are not asked to find f_{max}. (Refer to Fig. 1.11.10 in the textbook for definitions of these frequencies.)
5. What is the maximum transducer gain at the design frequency? How does $G_{T,max}$ vary with frequency?

5. Amplifier Circuit 1: Designing for $G_{T,max}$

5.1 Assignment

Using the Γ_{Ms} and Γ_{ML} values that were computed in the previous section, design the microstrip input and output matching networks of the amplifier to achieve maximum transducer gain ($G_{T,max}$) at the 1 GHz design frequency.

5.2 Circuit construction

- In the Lab3 workbench, create a new circuit page called Amp_GTmax. The circuit you need to build looks like Figure 4 (insert your own matching networks and bias circuits).

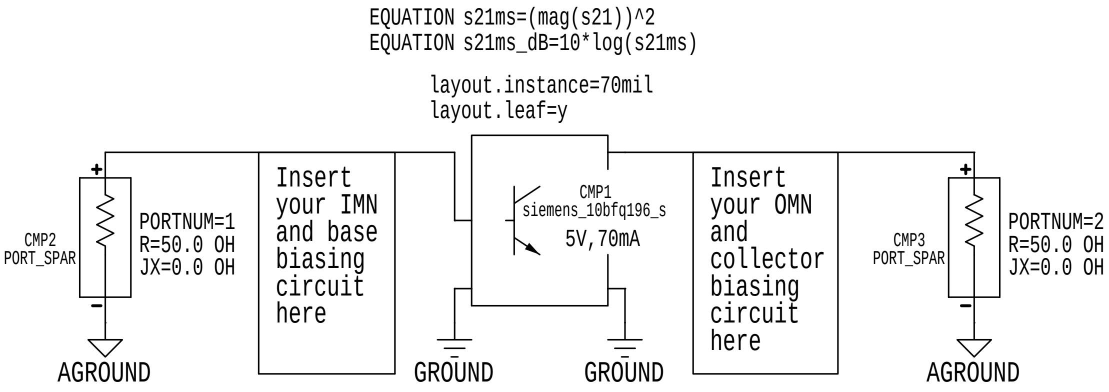

Figure 4: $G_{T,max}$ amplifier circuit

Here are some general hints that may be useful:

- Make a copy of the BJT characterization circuit and use it as the starting point for your new circuit. Notice that only two equations are required for the $G_{T,max}$ circuit.
- **IMPORTANT**: Construct the IMN and OMN as subcircuits.
- Use global grounds in your matching networks and biasing circuits.
- The ideal capacitor component does not have a built-in layout (MDS uses a default component layout). Try using a chip capacitor instead, which does have a built-in layout. The ideal inductor faces the same problem, but there is no readily available alternative.
- The coupling capacitors should provide a low impedance path for ac signals at the design frequency.
- Since the bias circuits do not really power the parameterized BJT, the exact values you use in their design are not critical. However, do make an attempt to choose reasonable values.

5.3 Circuit optimization

Before attaching the IMN and OMN subcircuits to the main amplifier circuit, test them individually first. Verify that the IMN transforms Γ_{Ms} to the 50 Ω source and that the OMN transforms Γ_{ML} to the 50 Ω load.

Use the MDS optimization feature to tune the matching networks at the design frequency. When you are done, the output port of the IMN should not deviate more than a few percent from the required Γ_{Ms} value. Likewise, the input port of the OMN should be as close as possible to the required Γ_{ML} value.

5.3.1 Tuning the IMN

- Figure 5 shows the test circuit you need to construct in order to optimize the IMN.

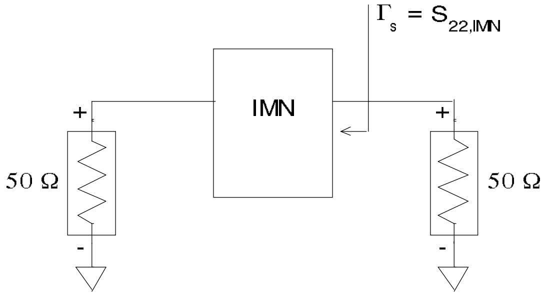

Figure 5: IMN test circuit

- On the output port of the IMN, the required reflection coefficient is Γ_{Ms}, which has a specific magnitude and phase. For the circuit in Figure 5, notice that by optimizing the value of S_{22} (i.e., S[2,2]) at the design frequency, you are also tuning the value of Γ_{Ms} as well.

  To tune the IMN, you need to perform a two goal optimization. The first goal sets limits on the magnitude of S_{22}, while the second goal sets limits on the phase of S_{22}. In the goal editor of the optimization setup window, you can enter multiple design goals, and MDS will try to optimize the circuit to achieve the desired result. There is no guarantee that MDS can meet all of the stated goals simultaneously, so you have to be careful how you define the goals.

  Refer to Lab 2 for a reminder of how to access the optimization feature of MDS. The only thing different in this lab is that you now have two goals instead of a single goal. By clicking the [Add] button in the goal editor window, you can enter additional goals. If you do click [Add], MDS automatically uses the parameters of the previous goal for your new goal. You can then edit the new goal and change the settings to what you really want. There are arrow buttons that allow you to browse forward and backward through the list of defined goals.

  As an example, suppose the required value for Γ_{Ms} is $0.430 \angle -120.5°$ (use your own computed value). For the first goal, set *Expression*="mag(S[2,2])", *Min*="0.425", and *Max*="0.435" (be careful in choosing your own limits). For the second goal, set *Expression*="phase(S[2,2])", *Min*="-121.0", and *Max*="-120.0". For this example, MDS will try to optimize the circuit parameters (such as microstrip lengths) to make S[2,2] as close as possible to $0.430 \angle -120.5°$. (Actually, you can also add a goal to optimize S[1,1] so that its magnitude is near zero. You can try this if you have time.)

- The optimization should be performed at the design frequency of 1 GHz. After MDS is done, check the computed value of S[2,2] to see if it meets the goal. If it does, then try making the limits even tighter for a better match (a relative error of less than 1% or 2% between the circuit's S[2,2] value and the required Γ_{Ms} value is very good). However, don't waste too much time doing the optimization. Be sure to update your circuit with the optimized microstrip length values.

IMPORTANT: After you have finished optimizing the IMN, you need to collect some *S*-parameter versus frequency data that will be used later in the lab. Follow this procedure:

- Configure MDS for a standard *S*-parameter simulation of the IMN test circuit. Linearly sweep the frequency from 0.9 GHz to 1.1 GHz in 10 MHz steps.
- Change the default dataset name to DS_IMN before running the simulation.

5.3.2 Tuning the OMN

- Figure 6 shows the test circuit you need to construct in order to optimize the OMN.

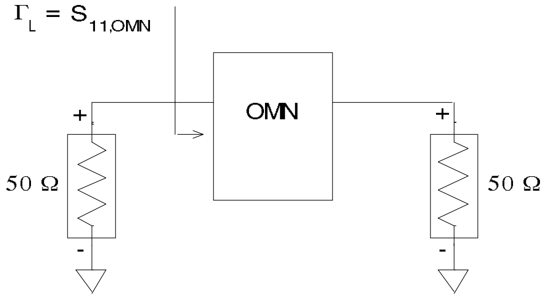

Figure 6: OMN test circuit

- The OMN optimization procedure is basically identical to the IMN procedure. In this case, you are tuning Γ_{ML} by optimizing S[1,1] on the input port of the OMN. The two goal expressions are now “mag(S[1,1])” and “phase(S[1,1])”.

IMPORTANT: After you have finished optimizing the OMN, you need to collect some *S*-parameter versus frequency data that will be used later in the lab. Follow this procedure:

- Configure MDS for a standard *S*-parameter simulation of the OMN test circuit. Linearly sweep the frequency from 0.9 GHz to 1.1 GHz in 10 MHz steps.
- Change the default dataset name to `DS_OMN` before running the simulation.

5.4 Circuit layout

- Click [SUI:Layout] to create a new layout. Type `Amp_GTmax` in the input box of the ‘New Layout’ dialog window and press RETURN (or click [OK]). By using a layout name that is identical to the name of an existing circuit page, MDS will automatically use that circuit page’s schematic when performing the layout.
- The ‘Amp_GTmax: DRAWING 1’ window appears. Either close the ‘Momentum’ Palette or else just ignore it. Make sure the layout page is still the active window.
- Choose [MB:PERFORM/AUTO-LAYOUT]. After a few seconds, the completed circuit layout will be drawn on the layout page.
- If you find that the circuit layout has a glaring error, correct the problem and then choose [MB:PERFORM/AUTO-LAYOUT/RE-INSTANTIATE] to restart the auto-layout process.

5.5 Items to turn in

- Include the by-hand Smith charts you used to design the microstrip matching networks. Explain briefly your design choices. List the major equations you used.
- Turn in printouts of the main $G_{T,max}$ circuit and its subcircuits. Also submit a printout of the final circuit layout.

6. Amplifier Circuit 1: Using MDS to find G_T vs. *freq*

6.1 Assignment

For the $G_{T,max}$ amplifier circuit, determine the transducer gain G_T as a function of frequency. Compare G_T and $G_{T,max}$ at the 1 GHz design frequency.

6.2 G_T computation issues

At first glance, calculating the transducer gain using the equations in the textbook seems like a simple task. However, on closer examination, there are several subtle points that complicate the situation.

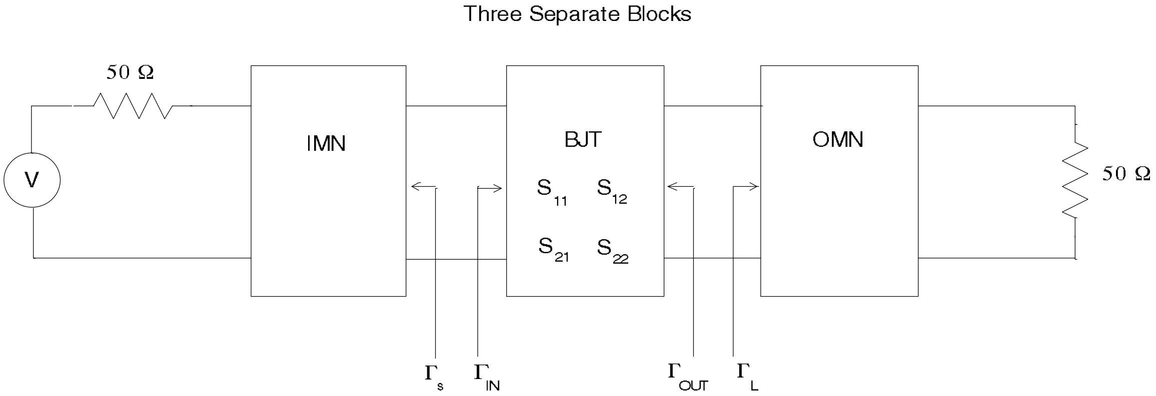

Figure 7: *S*-parameter and reflection coefficient definitions for a general amplifier

Figure 7 shows the reference positions for specific reflection coefficients as defined in the textbook. Notice that S_{11}, S_{12}, S_{21}, and S_{22} are the *S*-parameters for the BJT. The transducer gain formula is

$$G_T = \frac{1-|\Gamma_s|^2}{|1-\Gamma_{IN}\Gamma_s|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \quad \text{where} \quad \Gamma_{IN} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L} \tag{1}$$

Hence, to compute G_T , all you need to do is plug in the correct *S*-parameters and Γ values.

So what is the problem? Well, there are actually two potential difficulties:

1. The transducer gain equation is implicitly dependent on the frequency. For each frequency at which you want to compute G_T , you must re-measure the BJT *S*-parameters and the reflection coefficients and then plug those new values into the gain equation.

2. In MDS, S-ports cannot be inserted between circuit blocks. They can only be placed on the input and output ports of the overall circuit. Figure 8 illustrates this situation. Notice that in the prime reference system, the *S*-parameters are for the overall circuit and not for the BJT alone.

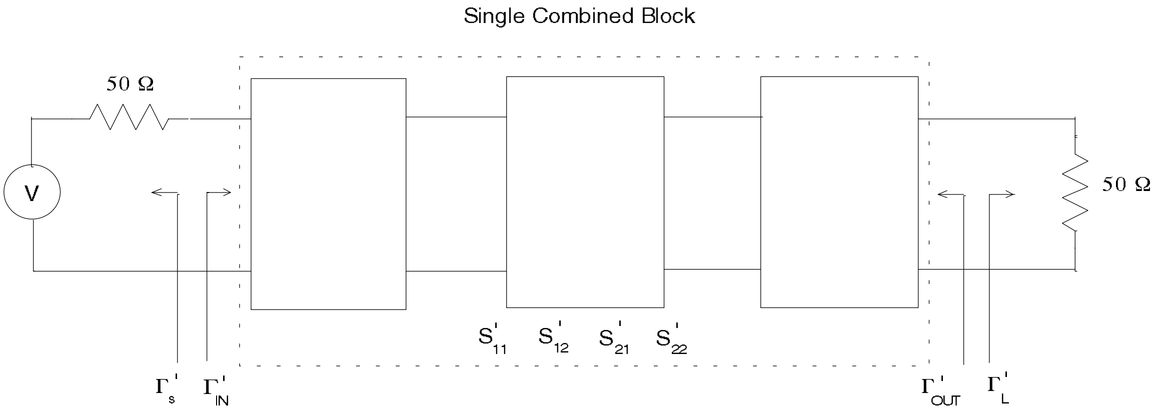

Figure 8: How MDS calculates *S*-parameters and Γ values.

In the prime reference system, the transducer gain equation is now

$$G'_T = \frac{1-|\Gamma'_s|^2}{|1-\Gamma'_{IN}\Gamma'_s|^2}|S'_{21}|^2\frac{1-|\Gamma'_L|^2}{|1-S'_{22}\Gamma'_L|^2} \quad \text{where} \quad \Gamma'_{IN} = S'_{11} + \frac{S'_{12}S'_{21}\Gamma'_L}{1-S'_{22}\Gamma'_L} \tag{2}$$

In a 50 Ω system, $\Gamma'_s = 0$ and $\Gamma'_L = 0$. Equation (2) then reduces to $G'_T = |S'_{21}|^2$. Surprisingly, G'_T is equal to G_T (refer to your lecture notes for an explanation of why this is so). In this section, you will examine the transducer gain versus frequency relationship using both equation (1) and (2).

6.3 Computing G_T using equation (1)

In this approach, the overall amplifier circuit is broken down into three separate test circuits - IMN, BJT, and OMN. *S*-parameters and reflection coefficients are computed as a function of frequency for each test circuit separately, and the resulting values are used in equation (1) to find G_T.

6.3.1 EQ1: How to find Γ_s vs frequency

- The circuit required to find Γ_s versus the frequency is identical to the circuit in Figure 5. Hence, you have already collected the necessary data (*S*-parameters from 0.9 GHz to 1.1 GHz). The Γ_s vs *f* data are stored in the DS_IMN dataset.

6.3.2 EQ1: How to find the BJT *S*-parameters vs frequency

- The circuit required to find the BJT *S*-parameters versus the frequency is identical to the one used to characterize the BJT. Therefore, you have already collected the necessary data. The *S*-param vs *f* data are stored in the DS_BJT dataset.

6.3.3 EQ1: How to find Γ_L vs frequency

- The circuit required to find Γ_L versus the frequency is identical to the circuit in Figure 6. Hence, you have already collected the necessary data (*S*-parameters from 0.9 GHz to 1.1 GHz). The Γ_L vs *f* data are stored in the DS_OMN dataset.

6.3.4 EQ1: How to find G_T vs frequency

Now that you have all the necessary data, how do you extract the required values to compute G_T using equation (1)? In addition to evaluating equations on a circuit page, MDS also has the capability of defining equations on a display page (i.e., a presentation page). You can create new variables from scratch, or you can access data (such as *S*-parameters) that are stored in different simulation datasets. Of course, you can also perform standard mathematical operations on the variables.

```
s11x=DS_BJT.sim1.SP.S[1,1]
s12x=DS_BJT.sim1.SP.S[1,2]
s21x=DS_BJT.sim1.SP.S[2,1]
s22x=DS_BJT.sim1.SP.S[2,2]

Gamma_S=DS_IMN.sim1.SP.S[2,2]
Gamma_L=DS_OMN.sim1.SP.S[1,1]
Gamma_IN=s11x+((s12x*s21x*Gamma_L)/(1-s22x*Gamma_L))

G1=(1-(mag(Gamma_S))^2)/(mag(1-Gamma_IN*Gamma_S))^2
G2=(mag(s21x))^2
G3=(1-(mag(Gamma_L))^2)/(mag(1-s22x*Gamma_L))^2

GT=G1*G2*G3
GT_dB=10*log(GT)
```

Figure 9: Equations for calculating G_T

Figure 9 shows the equations that you need to enter on the presentation page. The variable names *s11*, *s12*, *s21*, and *s22* are reserved in MDS, so you have to use slightly different names. Unlike equations on a circuit page, there is no special *EQUATION* statement that precedes equations on a presentation page.

Notice the syntax for assigning data from a dataset to a variable name. For example, the variable *s11x* accesses a data array (S[1,1]) of type *S*-parameter (SP) from simulation 1 (sim1) within an external dataset (DS_BJT). It is important to realize that the defined variables do not contain just a single value, but an entire array of values (one value for each frequency tested). MDS performs mathematical operations on variables on an element-by-element basis. Therefore, the variable *GT_dB* is an array that contains the computed transducer gain at each tested frequency.

To add the equations in Figure 9 to a presentation page, follow this procedure:

- Click [SUI:Presentation] to create a blank presentation page. Call the new page `GT_vs_f`.
- Choose [MB:INSERT/EQUATION/FROM DATASET]. The ‘Dataset variable viewer’ dialog window appears.

  In the input box next to the label *Variables in dataset:*, type the name of the dataset you want to access. For example, to define the equation for *s11x*, you would type `DS_BJT` in the input box. In the input box next to the label *Equation name:*, type the name of the variable you wish to define (such as `s11x`). In the lower panel of the window, click the button next to the data parameter within the dataset that you want to retrieve (such as S[1,1]).

  When you are done choosing, click [OK]. An outline of the equation tags along with the mouse pointer. Position the pointer on the presentation page where you want the equation to go and click the mouse button to drop the equation onto the page. Repeat this procedure for each equation listed in Figure 9.

TIP: It is fairly tedious using the equation dialog window. It is actually faster to select an equation, copy it to the clipboard (use [MB:COPY/TO CLIPBOARD]), insert the copy onto the presentation page (use [MB:INSERT/FROM CLIPBOARD), and then directly edit the copy to achieve the desired result.

- Once all of the equations have been entered onto the presentation page, add two listing columns to the page by using [MB:INSERT/LISTING COLUMN]. Edit the header of the first listing column to show the frequency (use the DS_BJT dataset). Change the header of the second listing column to "GT_dB", which is the equation variable you defined earlier. Assuming your data and equations are correct, the listings should clearly indicate the variation of G_T (in dB) with frequency.

6.3.5 EQ1: Items to turn in

- Submit a printout of the presentation page which contains the G_T equations and the *GT_dB* versus frequency listings.

6.3.6 EQ1: Questions

1. What is the transducer gain G_T at the design frequency? How does G_T vary with frequency?
2. Does the computed value for G_T equal $G_{T,max}$ (to within a few percent) at 1 GHz?

6.4 Computing G'$_T$ using equation (2)

For this approach, you use the *S*-parameter values of the overall circuit in conjunction with equation (2) to compute G'_T. As a reminder, $G'_T = |S'_{21}|^2$.

6.4.1 EQ2: How to find *G'*$_T$ vs frequency

- This correct circuit to simulate is the one shown in Figure 4, with the IMN, OMN, and bias subcircuits in their proper positions.
- Find the overall circuit's *S*-parameters from 0.9 GHz to 1.1 GHz in 10 MHz steps. Remember to define the equation variable *s21ms_dB* as an output variable.
- Create a new presentation page and add listing columns for the frequency and *s21ms_dB.*

6.4.2 EQ2: Items to turn in

- Submit a printout of the presentation page which contains the *s21ms_dB* versus frequency listings.

6.4.3 EQ2: Questions

1. What is the value of G'_T at the design frequency?
2. Does the computed value for G'_T equal $G_{T,max}$ (to within a few percent) at 1 GHz?
3. From your simulations, does the value of G'_T (computed from eqn (2)) equal the value of G_T (computed from eqn (1)) at each frequency?

7. Amplifier Circuit 2: Designing for G_p

7.1 Assignment

In this part of the lab, you need to re-design your microstrip matching networks to obtain a specific operating power gain (G_p) at the design frequency. The requirements are a) G_p = 16 dB, b) magnitude of Γ_L is minimized, and c) $G_T = G_p$.

7.2 Circuit construction

- In the Lab3 workbench, create a new circuit page called Amp_Gp. The basic amplifier circuit is similar to the one used to test $G_{T,max}$, except you should use your re-designed matching networks. Keep the equation statements that define *s21ms* and *s21ms_dB* and make sure your IMN and OMN are well-tuned.

7.3 Circuit layout

- Create a circuit layout for your re-designed circuit. Call the new layout Amp_Gp.

7.4 Items to turn in

- Include the by-hand Smith charts and constant gain circle chart that you used to re-design the microstrip matching networks. Briefly explain the reasoning behind your design. List the major equations you used.
- Turn in printouts of the G_p test circuit and subcircuits. Submit a printout of the final circuit layout.

8. Amplifier Circuit 2: Using MDS to verify $G_T = G_p$

8.1 Finding G_T

- Determine the *S*-parameters of the overall Amp_Gp circuit. Linearly sweep the frequency from 0.9 to 1.1 GHz in 10 MHz steps. Define the equation variable *s21ms_dB* as an output variable.
- Once the simulation is done, create a tabular listing of the *S*-parameters versus the frequency. In this situation, S[1,1], S[1,2], S[2,1], and S[2,2] are S'_{11}, S'_{12}, S'_{21}, and S'_{22}, respectively. Add another listing column for *s21ms_dB* (remember that $G'_T = |S'_{21}|^2$ and $G_T = G'_T$).

8.2 Items to turn in

- Submit a printout of the *S*-parameter tabular listing and the *s21ms_dB* listing.

8.3 How to find G_p at the design frequency

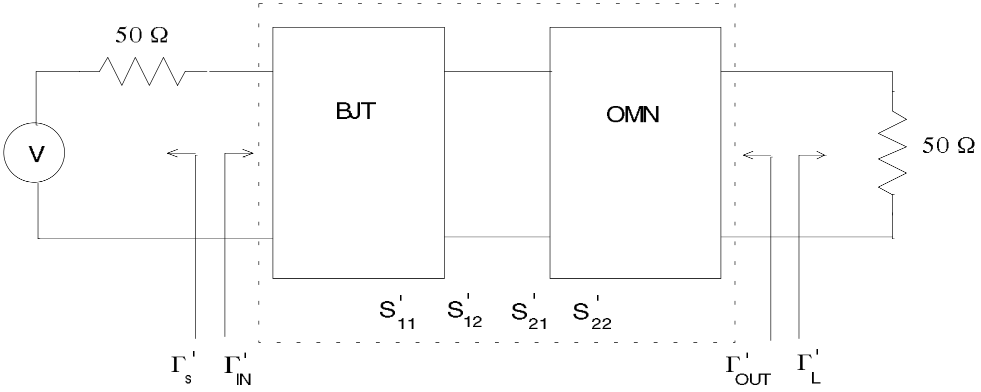

Figure 10: G_p test circuit

Figure 10 is the schematic used to determine G_p. Notice that the IMN circuit is <u>not</u> included in the overall circuit. The equation for the operating power gain is:

$$G'_p = \frac{1}{1-\left|\Gamma_{IN}\right|^2}\left|S'_{21}\right|^2 \frac{1-\left|\Gamma'_L\right|^2}{\left|1-S'_{22}\Gamma'_L\right|^2} \quad \text{where} \quad \Gamma'_{IN} = S'_{11} + \frac{S'_{12}S'_{21}\Gamma'_L}{1-S'_{22}\Gamma'_L} \tag{3}$$

In a 50 Ω system, $\Gamma'_L = 0$. This means equation (3) reduces to the simpler expression:

$$G'_p = \frac{1}{1-\left|S'_{11}\right|^2}\left|S'_{21}\right|^2 \tag{4}$$

Using an argument similar to the one that proves $G_T = G'_T$, it also turns out that $G_p = G'_p$.

- Create a new test circuit that corresponds to the schematic in Figure 10 (use S-ports for the source and load impedances). If you want to, just modify the Amp_Gp circuit by omitting the IMN subcircuit. You should add equations to the circuit page to calculate G'_p. For consistency, use the equation variable name *Gpp_dB* for the calculated G'_p value in decibels.
- Linearly sweep the frequency from 0.9 to 1.1 GHz in 10 MHz steps. Define the equation variable *Gpp_dB* as an output variable.
- Once the simulation is done, create a new presentation page with listing columns for the frequency and *Gpp_dB.*

8.4 Items to turn in

- Turn in a printout of the circuit you used to find G'_p.
- Submit a printout of the *Gpp_dB* versus frequency listing.

8.5 Questions

1. At a frequency of 1 GHz, does the computed value for G_p meet the design requirement of 16 dB (to within 1%)?

2. Does $G_T = G_p$ at the design frequency? Compare the values of G_T and G_P as the frequency moves away from the design value. What is the reason for this behavior?

3. How do the input SWR (defined as $\frac{1+|S'_{11}|}{1-|S'_{11}|}$) and the output SWR (defined as $\frac{1+|S'_{22}|}{1-|S'_{22}|}$) of the overall Amp_Gp circuit vary with frequency?

9. Constant Gain Circles

9.1 Assignment

You will examine the effect of frequency on constant gain circles. The test circuit consists of the BJT, two S-ports, and no matching or bias networks.

9.2 Circuit construction

- In the Lab3 workbench, create a new circuit page called BJT_CGC. Figure 11 shows what your completed circuit should like. There are no *EQUATION* statements.

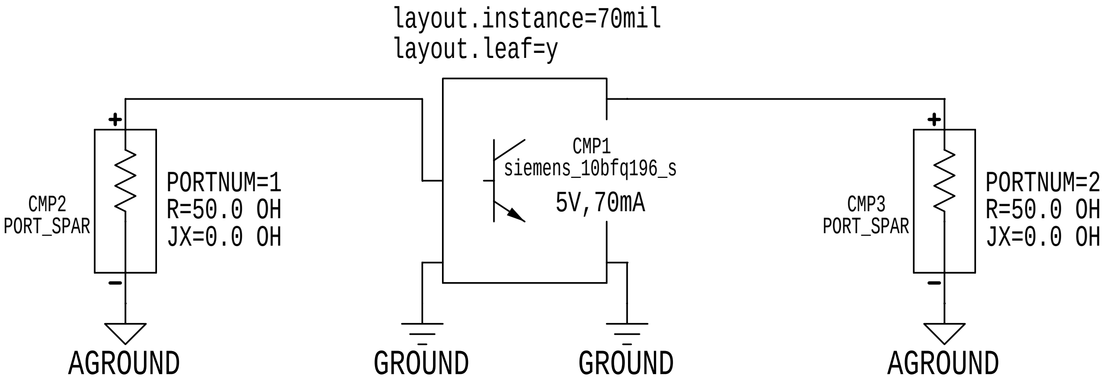

Figure 11: Constant gain circle test circuit

9.3 Circuit layout

- You do not have to perform a layout for this circuit.

9.4 Simulation

- Do a standard *S*-parameter simulation. Set *Sweep type*="Linear", *Start*=0.9 GHz, *Stop*=1.1 GHz, and *Step-size*=50 MHz. This defines five specific frequencies for constant gain circle computations. Change the dataset name to DS_BJT_CGC.

9.5 Output

- Click [SUI:Presentation] and create a new display page called BJT_CGC. Change the *Dataset=DATASET* line to *Dataset*=DS_BJT_CGC.

- Instead of creating a Z-Smith chart the standard way, choose [MB:INSERT/PLOT/Z-SMITH]. Next, define a rectangular area on the display page where the chart should be drawn. To do this, click and drag the mouse from the upper left corner to the lower right corner of the rectangular area. When you release the mouse button, MDS will draw a blank Z-Smith chart inside the area you just defined.
- To draw constant gain circles on the blank Z-Smith chart, you first have to insert a power gain circle equation on the display page. Choose [MB:INSERT/EQUATION/CIRCLES/POWER GAIN]. An outline of the equation tags along with the mouse pointer. Position the pointer outside the frame that surrounds the Z-Smith chart and click the mouse button to drop the equation onto the display page.

  Note that this only defines the gain circle setup conditions but does not actually draw the circles on the chart (that is a separate step).

  The equation you see on the display page is *G=Gcircle(S)*. The full syntax of the power gain circle equation is *G=Gcircle(S{,StartValue,StepSize,NumCircles,PointsPerCircle})*, where the braces indicate optional parameters. *S* is the two-port *S*-parameter data. *StartValue* is the initial power gain (dB) to compute. *StepSize* indicates the interval (dB) between successive gain circles. *NumCircles* tells how many gain circles to compute. *PointsPerCircle* determines the number of evaluated points per circle. The computed gain circle data is stored in *G*.

  For example, if *G=Gcircle(S, 12.5, 0.5, 3)*, MDS would compute data for three constant gain circles (12.5 dB, 13.0 dB, and 13.5 dB).
- Click inside the *G=Gcircle(S)* equation to edit it. Change the equation to *G=Gcircle(S, 15, 0, 1)*. This tells MDS to compute a single 15 dB constant gain circle. Since only one circle is requested, the step size is not important, but it still needs to be defined.
- Choose [MB:INSERT/TRACE ON PLOT]. The ‘Messages’ window asks you to select a plot for inserting the trace. Select the blank Z-Smith chart with the mouse.
- The ‘Expression Error’ dialog window appears. In the input box, type `G[*,1,*]` and press RETURN (or click [OK]). MDS now draws a set of constant gain circles on the Z-Smith chart.

  What did that cryptic expression do? *G* has the syntax *G[FrequencyIndex, CircleIndex, Angle]*. The first parameter determines which frequency to plot gain circles for (* = include all frequencies in the frequency sweep). The second parameter indicates which of the computed gain circles to plot at a given frequency (* = include all circles). The third parameter determines the angle on the circle for plotting a data point (* = include all angles, i.e., a full circle).

  Hence, the combination of *G=Gcircle(S, 15, 0, 1)* and *G[*,1,*]* causes MDS to draw five separate 15 dB constant gain circles on the Z-Smith chart, one circle for each frequency in the sweep from 0.9 to 1.1 GHz . If you had specified *G[3,1,*]* in the input box, MDS would only draw the 15 dB circle for the third frequency index (i.e., at 1 GHz).

9.6 Items to turn in

- Submit the Z-Smith chart containing the plot of constant gain circles versus the frequency.

9.7 Questions

1. What is the behavior of the gain circles as the frequency increases?
2. The *G=Gcircle(S, 15, 0, 1)* equation called for a 15 dB gain circle. What happens to the gain circles on the Z-Smith chart if you try 16 dB? What is the reason for this effect?