

EE432/532 Microwave Circuit Design II: Lab 1

1. Introduction

This lab investigates the design of conditionally stable amplifiers using the technique of jointly matched terminations.

2. Design Specifications

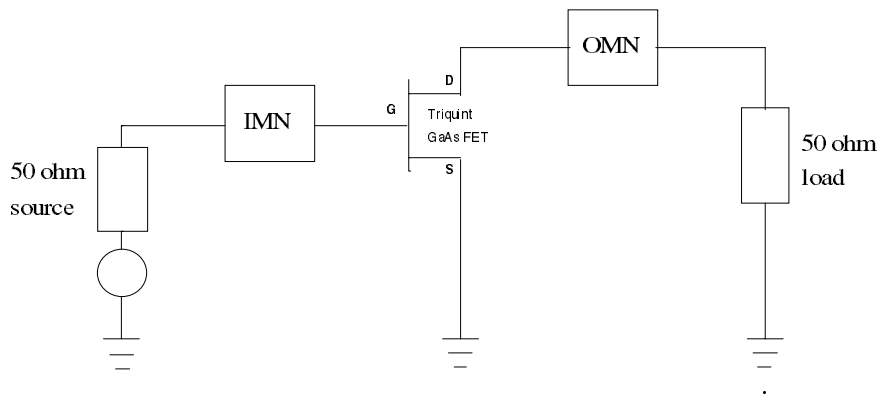


Figure 1: Block diagram of a FET amplifier

You are to design a single-stage amplifier using a transistor that is conditionally stable at the design frequency of $f = 15$ GHz. The process is outlined in the paper “A Deterministic Approach for Designing Conditionally Stable Amplifiers”¹.

The core of the amplifier is a field effect transistor (FET) in common-source configuration. In MDS, there is a built-in model library for the Triquint GaAs (gallium arsenide) FET. This model has parameters that define the bias level for the FET, so you do not have to implement DC bias circuits. You may also omit the coupling capacitors.

There is a 50Ω source impedance on the input side of the FET and a 50Ω load on the output. To keep things simple, use ell circuits (i.e., capacitors and inductors) instead of microstrip to construct the input and output matching networks.

3. Jointly Matched Terminations Method

The basic task is to define a region inside the Γ_s plane such that any Γ_s within this region automatically results in a stable Γ_L . The output stability circle is mapped into the Γ_s plane. Depending on the device parameters, this translates into three different configurations (Figs. 4, 7, and 8 from the Edwards, Cheng, and Sinsky paper). The upper bound on gains resulting from jointly stable terminations is $G_{MSM} = 2 \cdot k \cdot G_{MSG}$. For $G_A \rightarrow 0$, the constant gain circle overlaps with the Smith chart unit circle. For

¹ Authored by M. L. Edwards, S. Cheng, and J. H. Sinsky.
IEEE Transactions on Microwave Theory and Techniques, VOL. 43, NO. 7, July 1995

$G_A \rightarrow \infty$, the constant gain circle overlaps the input stability circle. Moreover, the centers of the input stability circle, unit circle, and all the constant gain circles are collinear.

Procedure:

1. Compute k (preferred: $0.5 < k < 1$)
2. Compute $D_1 = |S_{11}|^2 - |\Delta|^2$ where $\Delta = S_{11}S_{22} - S_{12}S_{21}$
3. Compute $K_1 = |C_1|^2 - D_1^2$ where $C_1 = S_{11} - \Delta S_{22}^*$
4. Compare your results against Figs. 4, 7, and 8 from the Edwards, Cheng, and Sinsky paper. All conditions must be simultaneously met; otherwise, this method cannot be used.
5. Compute $G_{MSM} = 2 \cdot k \cdot \left(\frac{|S_{21}|}{|S_{12}|} \right)$
6. Choose $G_A \leq G_{MSM} - 2$ dB for design robustness (allowing for parameter variations).
7. Draw the $G_A = \text{const.}$ circle.
8. Choose Γ_s on the $G_A = \text{const.}$ circle.
9. Design the input matching network (IMN).
10. Attach the IMN to the transistor and simulate/measure Γ_{OUT} .
11. Design the output matching network for $\Gamma_L = \Gamma_{OUT}^*$.

3.1 Questions

1. Figure 3.3.9 on page 228 in the Gonzalez textbook (2nd edition) shows three different types of resistive loading configurations. Which one provides the best compromise? Think of noise and output power.
2. For each of the following design methods, list some of their advantages and disadvantages:
 - a) Resistive loading
 - b) Designing for G_A
 - c) Jointly matched terminations.

4. FET Characteristics

4.1 Assignment

In this section, you will determine the operating characteristics of the Triquint FET.

4.2 Circuit construction

```

EQUATION del=s11*s22-s12*s21      EQUATION mdel=mag(del)
EQUATION K=(1-mag(s11)^2-mag(s22)^2+mag(del)^2)/(2*mag(s12*s21))
EQUATION U=(mag(s12)*mag(s21)*mag(s11)*mag(s22))/((1-mag(s11)^2)*(1-mag(s22)^2))
EQUATION U_dB=10*log(U)
EQUATION Gmsg=mag(s21)/mag(s12)   EQUATION Gmsg_dB=10*log(Gmsg)
EQUATION Gmsm=2*K*Gmsg           EQUATION Gmsm_dB=10*log(Gmsm)

EQUATION C1=s11-del*conj(s22)
EQUATION D1=mag(s11)^2-mag(del)^2
EQUATION K1=mag(C1)^2-D1^2
EQUATION Rs=mag(s12*s21/(mag(s11)^2-mag(del)^2))
EQUATION Cs=conj(s11-del*conj(s22))/(mag(s11)^2-mag(del)^2)

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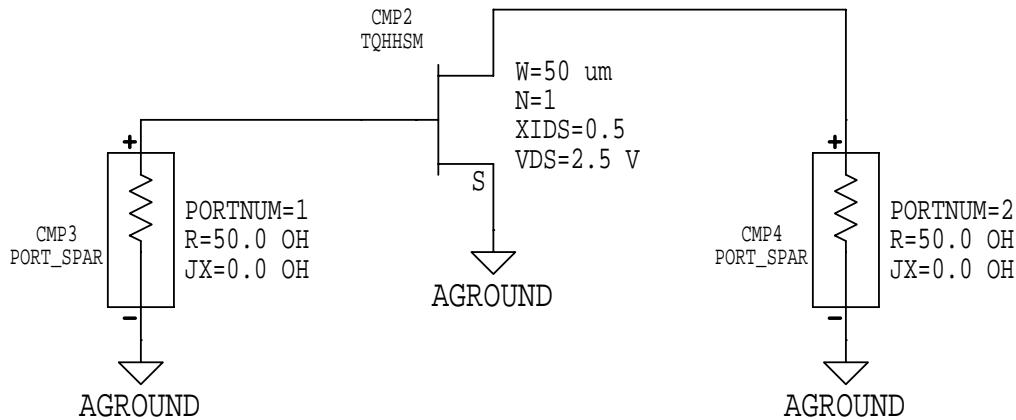


Figure 2: FET characterization test circuit

- Construct the circuit shown in Figure 2. To access the Triquint FET, click [MB:INSERT/MDS COMPONENTS/TRIQUINT - HA/FET MODEL/LINEAR HHSM].

Next to the FET symbol on the circuit page are four changeable transistor parameters. W is the width of a single gate finger and N is the total number of interdigitated gate fingers. VDS and $XIDS$ set the DC bias level for the FET. VDS is the drain-source voltage. $XIDS$ determines the ratio of drain current to the maximum allowed drain current, i.e. $XIDS = I_{DS} / I_{DSS}$. For the test circuit, $XIDS = 0.5$ means that the drain-source current is at half the maximum value.

4.3 Simulation & Output

- Configure MDS for an S -parameter simulation. Linearly sweep the frequency from 1 to 21 GHz. Use a step size of 1 GHz.

In the 'Simulation Setup' window, define the equation variables K , $mdel$, $Gmsg_dB$, $Gmsm_dB$, U_dB , $D1$, $K1$, Rs , and Cs as output variables.

- When the simulation is finished, use the template method to plot each S -parameter on its own Smith chart. On the same presentation page, use a template to create a tabular listing of the S -parameters versus the frequency. Finally, on the same presentation page, add listing columns for frequency, K , $mdel$, $Gmsg_dB$, $Gmsm_dB$, U_dB , $D1$, $K1$, Rs , and Cs .

4.4 Items to turn in

- Turn in a printout of the FET characterization circuit.
- Submit a printout of the presentation page containing the S -parameter plots, tabular listing, etc.

4.5 Questions

1. At the design frequency of 15 GHz, verify that the Triquint FET meets the requirements for using the jointly matched terminations method. Which configuration (Fig. 4, 7, or 8 from the Edwards, Cheng, and Sinsky paper) does the Triquint FET match?
2. Comment on the magnitudes of S_{11} and S_{22} . What are the important characteristics of a FET that would cause S_{11} and S_{22} to have such values?

5. Device Parameter Variation and Stability Boundaries

5.1 Assignment

You will examine how device parameter variation affects the input stability circle and gain circle, which then impacts the choice of Γ_s and G_A .

Parameter variations (sometimes as high as $\pm 20\%$) naturally occur in the manufacturing process. Thus, not all devices are identical. Accounting for this yields a more robust design. For this lab, assume that the gate width of the FET can vary by $\pm 10\%$ about its nominal value of $50 \mu\text{m}$.

5.2 Circuit construction

```

EQUATION ang=0
EQUATION del=s11*s22-s12*s21
EQUATION K=(1-mag(s11)^2-mag(s22)^2+mag(del)^2)/(2*mag(s12*s21))
EQUATION C1=s11-del*conj(s22)

EQUATION In_Stab_Circ=polar(Rs,ang)+Cs
EQUATION Rs=mag(s12*s21/(mag(s11)^2-mag(del)^2))
EQUATION Cs=conj(s11-del*conj(s22))/(mag(s11)^2-mag(del)^2)

EQUATION Gmsm_Gain_Circ=polar(Rmsm,ang)+Cmsm
EQUATION Gmsm=2*K*mag(s21)/mag(s12)
EQUATION ga1=Gmsm/mag(s21)^2
EQUATION Cmsm=ga1*conj(C1)/(1+ga1*(mag(s11)^2-mag(del)^2))
EQUATION Rmsm=nom1/den1
EQUATION nom1=(1-2*K*ga1*mag(s12*s21)+ga1^2*mag(s12*s21)^2)^0.5
EQUATION den1=mag(1+ga1*(mag(s11)^2-mag(del)^2))

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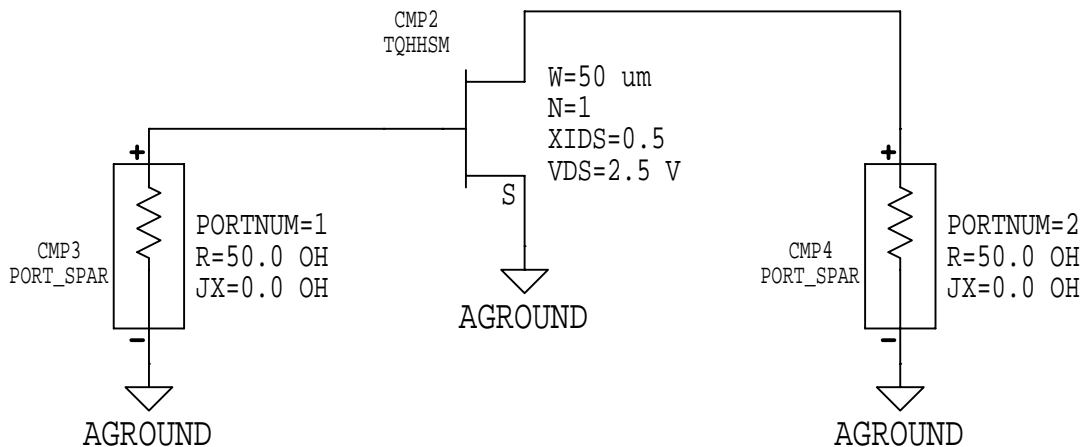


Figure 3: Device parameter variation test circuit

- Construct the circuit shown in Figure 3. This is essentially the same circuit as in Figure 2, but the equations are different. Record the component number (*CMP#*) of the FET; you will need it later.

- *In_Stab_Circ* defines the input stability circle, while *Gmsm_Gain_Circ* defines the maximum single-sided matched gain circle.

5.3 Simulation & Output

- Configure MDS for an *S*-parameter simulation. In the ‘Simulation Setup’ dialog window, set *Sweep type* to “Single Point”. The frequency should be changed to 15 GHz.
- Click [Sweeps/control...] on the ‘Simulation Setup’ window to get the ‘Sweeps and Control’ window. Select “Parameter Sweep” and then click [OK]. The ‘Simulation Setup’ window should now change its appearance to allow you to set up the parameter sweep.
- Set *Parameter Name* to “ang”. This is the same as the equation variable *ang* (angle) on the circuit page. Set *Sweep type*=“Linear”, *Start*=0, *Stop*=360, and *Step-size*=5. The multipliers should all be “x1.0”. MDS will then sweep the *ang* variable a full 360 degrees in 5 degree increments, which is used to plot the input stability circles and gain circles.
- Click [Sweeps/control...] again to get the “Sweeps and Control’ window. In the subpanel labeled *Apply this sweep/control:*, select “Parameter Sweep”. In the subpanel labeled *To this simulation:*, select “SWEEP:sweep1”. Click [OK]. The *Simulation Sequence* panel on the left side of the parameter setup window should look something like this:

```
SWEEP:sweep2
  SWEEP:sweep1
    SP:sim1
```

If you don’t see the nested sweeps in the *Simulation Sequence* panel, then you will need to try again.

- In Figure 3, the component number of the FET is *CMP2*. Set *Parameter Name* to “cmp2.W” (use your own *CMP#*). Set *Sweep type*=“Linear”, *Start*=45, *Stop*=55, and *Step-size*=2. The multipliers should all be “micro”. MDS will then sweep the *W* (gate finger width) variable of *CMP2* from 45 to 55 μm in 2 μm increments.

The net effect of the two-level nested sweep is this: For each FET gate width (six values from 45 to 55 μm), MDS will compute the points needed to plot the input stability circle and gain circle for the given *W* value.

- In the *Simulation Sequence* panel, click “SP:sim1” to return to the standard ‘Simulation Setup’ dialog window. Define the equation variables *In_Stab_Circ* and *Gmsm_Gain_Circ* as output variables. Run the simulation.
- Once the simulation is done, create a Z-Smith chart on a new presentation page. Plot the variables *In_Stab_Circ* and *Gmsm_Gain_Circ* on that same Smith chart.

5.4 Items to turn in

- Turn in the Smith chart plot showing how the device parameter variation affects the input stability circle and gain circle.

5.5 Questions

1. Briefly explain the behavior of the stability and gain circles as a function of the transistor’s gate width.

6. Choosing Γ_s

6.1 Assignment

Find the appropriate source reflection coefficient (Γ_s) value for a design frequency of 15 GHz and an available gain of $G_A = G_{MSM} - 2$ dB (to allow for parameter variations).

6.2 Circuit construction

```

EQUATION ang=0
EQUATION del=s11*s22-s12*s21
EQUATION K=(1-mag(s11)^2-mag(s22)^2+mag(del)^2)/(2*mag(s12*s21))
EQUATION C1=s11-del*conj(s22)
EQUATION Gmsm=2*K*mag(s21)/mag(s12)
EQUATION Ga_dB=10*log(Gmsm)-2

EQUATION In_Stab_Circ=polar(Rs,ang)+Cs
EQUATION Rs=mag(s12*s21/(mag(s11)^2-mag(del)^2))
EQUATION Cs=conj(s11-del*conj(s22))/(mag(s11)^2-mag(del)^2)

EQUATION Ga_Gain_Circ=polar(Ra,ang)+ca
EQUATION Ga=10^(Ga_dB/10)
EQUATION ga2=Ga/mag(s21)^2
EQUATION Ca=ga2*conj(C1)/(1+ga2*(mag(s11)^2-mag(del)^2))
EQUATION Ra=nom2/den2
EQUATION nom2=(1-2*K*ga2*mag(s12*s21)+ga2^2*mag(s12*s21)^2)^0.5
EQUATION den2=mag(1+ga2*(mag(s11)^2-mag(del)^2))

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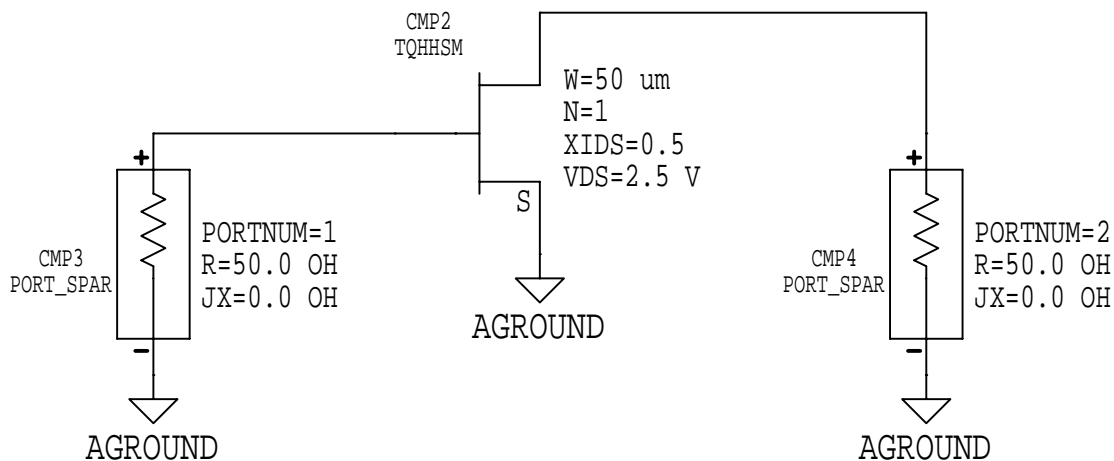


Figure 4: Γ_s test circuit

- Construct the circuit shown in Figure 4. This is essentially the same circuit as in Figure 3, but the equations are slightly different.

- In_Stab_Circ defines the input stability circle, Ga_Gain_Circ defines the constant available gain circle, and Ca is the center of the constant gain circle.

6.3 Simulation & Output

- Configure MDS for an S -parameter simulation. In the ‘Simulation Setup’ dialog window, set *Sweep type*=“Single Point” and *Frequency*=15 GHz.
- Set up a 0 to 360 degree parameter sweep on the *ang* equation variable (just like the previous section). The step size should be 1 degree for better resolution. The is just a one-level sweep, so the FET’s gate width should initially be fixed at 50 μm (do not sweep W).
- Define the equation variables In_Stab_Circ , Ga_Gain_Circ , and Ca as output variables. Run the simulation.
- After the simulation is complete, create a new presentation page and plot the output variable In_Stab_Circ on a Z-Smith chart. Add Ga_Gain_Circ as a trace on the same Smith chart. Add Ca as another trace on the same Smith chart.
- In this step, you will draw a line on the presentation page that connects the center point of the Smith chart to the center point Ca of the constant gain circle.

Choose [MB:INSERT/LINE/SOLID/.01"]. Position the mouse pointer directly over the center of the constant gain circle (where the Ca point is located). Click the left mouse button, hold it down, and drag the mouse until the pointer is directly over the center of the Smith chart. When you release the mouse button, MDS will draw a line connecting the two points. If the line does not quite go through the desired points, just delete the line and try again.

- The desired Γ_s value occurs at the intersection between the line and the boundary of the constant gain circle. Use the intersection point that is closest to the center of the Smith chart. To make reading the Γ_s value more accurate, insert a marker on the constant gain circle trace.

Select [MB:INSERT/MARKER ON TRACE]. A message window appears that says “Select trace and drag marker to the desired location”. Click the Ga_Gain_Circ circle, hold down the left mouse button, drag the triangular marker to the intersection of the circle and the line, and release the mouse button. A data box then tags along with the mouse pointer. Place the box where you want it to go and click the mouse button to drop it onto the presentation page.

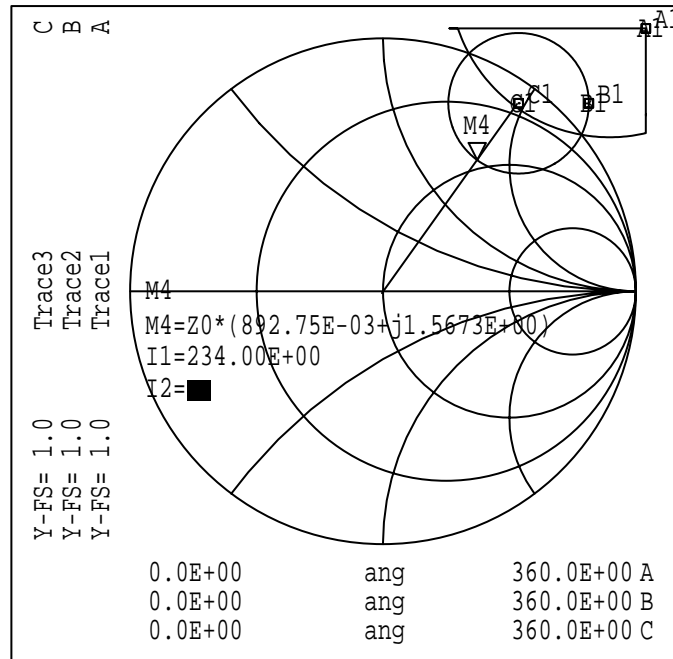
Γ_s will be given by an expression such as “ $M4=Z0*(a+jb)$ ”, where $M?$ is the marker ID, $Z0$ is the 50 ohm characteristic impedance, and a and b are the real and imaginary parts of Γ_s .

Tip: You can get a more accurate Γ_s value if you zoom into the presentation page so that the gain circle fills most of the screen.

Refer to Figure 5 for an example of what your finished plot should look like.

Dataset=DS_Gamma_S50

Qualifier=■



Trace1=in_stab_circ
 Trace2=ga_gain_circ
 Trace3=ca

Figure 5: Sample Smith chart with circles and added line

IMPORTANT: Repeat the simulation and output procedures at the extremes of the FET gate width, i.e. at $W = 45 \mu\text{m}$ and $W = 55 \mu\text{m}$. Determine the corresponding Γ_s values at each gate width.

6.4 Items to turn in

- Submit printouts of the $W = 45 \mu\text{m}$, $50 \mu\text{m}$, and $55 \mu\text{m}$ Smith charts.

6.5 Questions

1. What are the individual Γ_s values (magnitude & phase) at $W = 45 \mu\text{m}$, $50 \mu\text{m}$, and $55 \mu\text{m}$?
2. Calculate the average Γ_s and compare it to the value of Γ_s at $W = 50 \mu\text{m}$.

7. Designing the IMN

7.1 Assignment

You will design the input matching network (IMN) of the amplifier.

7.2 Circuit construction

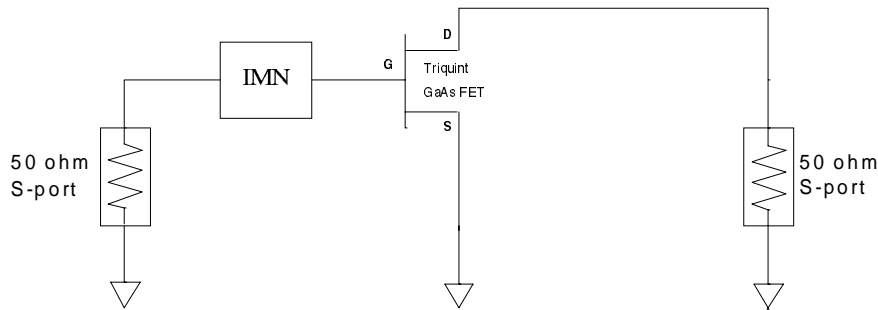


Figure 6: IMN test circuit

- Construct the circuit shown in Figure 6. The FET bias parameters are unchanged.

When designing the IMN, use the average value of Γ_s you computed in the previous section. Build the IMN using ell circuits.

Tip: The performance of the amplifier is dependent on the accuracy of the IMN's component values. To get better results, you may wish to test the IMN by itself first. Use MDS's optimization feature to tune the IMN (just like Lab 3 from Microwave Circuits I).

7.3 Simulation & Output

- Configure MDS for an S -parameter simulation. In the 'Simulation Setup' dialog window, set *Sweep type*="Single Point" and *Frequency*=15 GHz. For the circuit in Figure 6, $\Gamma_{OUT} = S_{22}$.
- After the simulation is completed, create a new presentation page and add a listing column to view the value of S_{22} .

IMPORTANT: Perform the simulation and output procedures at $W = 45 \mu\text{m}$, $50 \mu\text{m}$, and $55 \mu\text{m}$. Determine the corresponding Γ_{OUT} values at each gate width.

7.4 Items to turn in

- There is nothing to turn in.

7.5 Questions

1. What are the individual Γ_{OUT} values (magnitude & phase) at $W = 45 \mu\text{m}$, $50 \mu\text{m}$, and $55 \mu\text{m}$?
2. Compute the corresponding transducer gain G_T for each value of Γ_{OUT} .
3. Calculate the average Γ_{OUT} and compare it to the value of Γ_{OUT} at $W = 50 \mu\text{m}$.

8. Designing the OMN

8.1 Assignment

You will finish the amplifier circuit by designing the output matching network (OMN).

8.2 Circuit construction

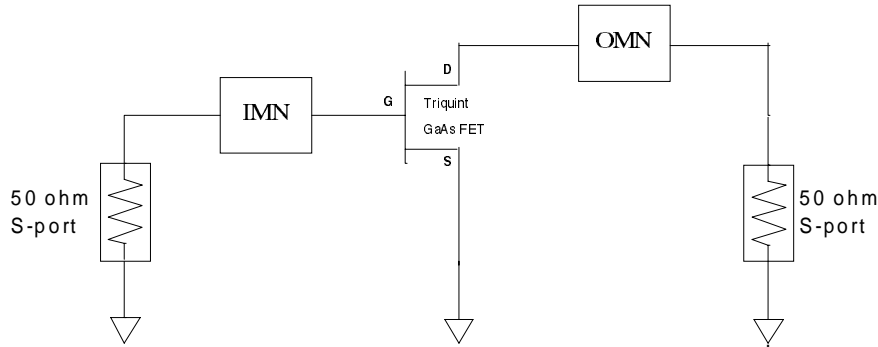


Figure 7: Final amplifier circuit

- Construct the circuit shown in Figure 7. The FET bias parameters are unchanged.

When designing the OMN, the load reflection coefficient Γ_L is given by the expression $\Gamma_L = \Gamma_{OUT}^*$. Use the average value of Γ_{OUT} that you computed in the previous section. Build the OMN using all circuits.

Tip: To achieve better results, consider testing the OMN by itself first. Use MDS's optimization feature to tune the OMN.

8.3 Simulation & Output

- Configure MDS for an S -parameter simulation. Linearly sweep the frequency from 12 to 18 GHz. Use a step size of 0.25 GHz.
- After the simulation is over, create a tabular listing of the S -parameters on a new presentation page.

8.4 Items to turn in

- Turn in a printout of your final amplifier schematic. If you used subcircuits for the matching networks, then include printouts of those, too.
- Turn in a printout of the S -parameter tabular listing.

8.5 Questions

- What is the gain at the design frequency? Does it meet the design requirements (to within 2 or 3 percent)?
- Compare the magnitudes of S_{11} and S_{22} in the amplifier circuit with matching networks to their corresponding values with no matching networks.