Case Study: Amp1
Narrowband Linear Amplifier Design

Presented by Michael Steer

Reading: Chapter 17, Section 17.10

Index: CS_Amp1

Design Specifications

- Gain: maximum gain at 8 GHz
- Topology: three two-ports (input and output matching networks, and the active device)
- Stability: broadband stability
- Bandwidth: maximum that can be achieved using two-element matching networks
- Source impedance: \( Z_S = 50 \, \Omega \)
- Load impedance: \( Z_L = 50 \, \Omega \)

Block diagram of an RF amplifier including biasing networks.
Linear amplifier with input and output matching networks

Transistor Choice
Transistor technology: Depletion-mode pHEMT.
Model: FPD6836P70 from RFMD, Inc.
Description: Low-noise, high-frequency packaged pHEMT. Optimized for low-noise, high-frequency applications.
Synopsis:
22 dBm output power (1dB).
15 dB power gain (G1dB) at 5.8 GHz. Useable gain to 18 GHz.
0.8 dB noise figure at 5.8 GHz, 32 dBm output IP3 at 5.8 GHz.
45% power-added efficiency at 5.8 GHz.
Useable gain to 18 GHz.

A pHEMT is a JFET (JFET), junction field effect transistor.

JFET

- Applying a voltage at the gate (a gate-source voltage) closes off the channel by extending the space-charge region (i.e. no charge region) of a reverse-biased junction.
- The GS voltage changes the resistance of the channel.
  - Not quite accurate as for high DS voltages it changes the drain current.
- This is called an depletion mode of operation.
- A GaAs JFET is called a MESFET (Metal-Epitaxy Semiconductor Field Effect Transistor.) Largely replaced by pHEMT.
There are n-type and p-type JFETs but the performance of a pJFET is poor. So designs mostly use only nJFETs.

There is not a useful p-type pHEMT but there are p-type JFETs but they do not work well.
**pHEMT pseudomorphic High Electron Mobility Transistor**

- Generally depletion-mode
- Enhancement-mode possible
- Only n-type

**JFET summary**

Two modes of operation
- Enhancement mode
- Depletion mode

**Current-voltage characteristic of pHEMT**

Scattering parameters of an enhancement mode pHEMT transistor biased at:

- $V_{DS} = 5\, V$
- $I_D = 55\, mA$
- $V_{GS} = -0.42\, V$

Extract from the data sheet of the FPD6836P70 discrete transistor.
Amplifier classes

- **Input characteristic**
- **Output characteristic**

**Conventional load line**

**High efficiency load line**

- **Quiescent point**
  - A: Class A amplifier
  - B: Class A amplifier
  - AB: Class A amplifier
  - C: Class A amplifier

Extract from Manufacturer’s Datasheet

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S parameters of pHEMT transistor at \( V_{DS} = 5 \, \text{V}, \, I_D = 55 \, \text{mA}, \, V_{GS} = -0.42 \, \text{V} \).

So many definitions are needed as it is necessary to describe the amplifier before the matching networks have been designed and to know the ultimate performance at different stages.
**Definition of gains**

- The input and output matching networks are lossless so that the actual device input signal power, $P_{inD}$, is the power delivered by the source.
- Similarly, the actual output signal power delivered to the load, $P_L$, is the power delivered by the active device.

**Most useful gains**

- **System Gain**
  
  \[ G = \frac{P_L}{P_{in}} \]

  Power actually delivered to the load relative to the input power delivered by the source.

- **Power Gain**

  \[ G_P = \frac{P_L}{P_{inD}} \]

  G but with the effect of $M_1$ removed.

- **Transducer Gain**

  \[ G_T = \frac{P_L}{P_{Ai}} \]

  G with optimum $M_1$.

- **Available Gain**

  \[ G_A = \frac{P_{A0}}{P_{Ai}} \]

  G with optimum $M_1$ and $M_2$.
**Most useful gains**

![Diagram of amplifier gain](image)

- **Transducer Gain**
  
  \[
  G_T = \frac{P_L}{P_{Ai}}
  \]

  - \(G\) with optimum \(M_1\).

- **Unilateral Transducer Gain**
  
  \[
  G_{TU} = G_T \text{ with } S_{12} = 0.
  \]

- **Maximum Unilateral Transducer Gain**
  
  \[
  G_{TU\text{max}} = G_{TU} \text{ with optimum } M_1 \text{ and } M_2.
  \]

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**Development of gain expressions**

- Developed using generalized scattering parameters (which can be defined different and complex load and source impedances).
- Then refer back to using transistor’s \(50-\Omega\) \(S\) parameters.
- Different gains useful at different stages of design.
- E.G. \(G_{TU\text{max}}\) used in selecting transistor, estimating design challenge.

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**Amplifier Gain in Terms of Transistor \(S\) Parameters**

- Transducer Gain
  
  \[
  G_T = |S_{21}|^2 \left( \frac{1 - |\Gamma_s|^2}{1 - |\Gamma_s S_{11}|^2} \right) \left( \frac{1 - |\Gamma_L|^2}{1 - |\Gamma_L S_{22}|^2} \right)
  \]
- For a unilateral two-port \(S_{12} = 0\)
  - Unilateral transducer gain
    
    \[
    G_{TU} = |S_{21}|^2 \left( \frac{1 - |\Gamma_s|^2}{1 - |\Gamma_s S_{11}|^2} \right) \left( \frac{1 - |\Gamma_L|^2}{1 - |\Gamma_L S_{22}|^2} \right)
    \]
  - Maximum unilateral transducer gain
    
    \[
    G_{TU\text{max}} = |S_{21}|^2 \left( \frac{1}{1 - |S_{11}|^2} \right) \left( \frac{1}{1 - |S_{22}|^2} \right)
    \]

- \(G_{TU\text{max}}\) is the most important figure of merit that guides initial design (design is very hard if required gain is greater).

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**Maximum unilateral transducer gain, \(G_{TU\text{max}}\), of the pHEMT transistor**

<table>
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<tr>
<th>Frequency (GHz)</th>
<th>(G_{TU\text{max}}) (dB)</th>
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<td>3.61</td>
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Even more gains

**甚至更多的增益**

![电路图](image)

- **Transducer Gain**
  \[ G_T = \frac{P_L}{P_{Ai}} \]
  传递函数 $G$ 与最优 $M_1$ 有关。

- **Maximum Available Power Gain**
  \[ G_{MA} = \left| \frac{S_{21}}{S_{12}} \right| (k^2 - k - 1) \]
  $G_{MA}$ 与边缘稳定性 $k = 1$ 相关。

- **Maximum Stable Gain**
  \[ G_{MS} = \left| \frac{S_{21}}{S_{12}} \right| \]

Amplifier stability

- **不稳定**
  \[ |\Gamma_S\Gamma_{IN}| > 1 \]

- **稳定**
  \[ |\Gamma_L\Gamma_{OUT}| > 1 \]

- **对于稳定的放大**
  - \[ |\Gamma_S\Gamma_{IN}| \] 必须小于1
  - \[ |\Gamma_L\Gamma_{OUT}| \] 必须小于1
  - 对于被动的源和负载 \[ |\Gamma_S| < 1, |\Gamma_L| < 1 \]
  - 因此为了无条件的稳定性需要
    - \[ |\Gamma_{IN}| < 1 \]
    - \[ |\Gamma_{OUT}| < 1 \]

Stability consideration

- **输出匹配网络**
  \[ \Gamma_{OUT} \]

- **输入匹配网络**
  \[ \Gamma_{IN} \]

- **噪声**
  \[ \Gamma \]

- **不稳定**
  \[ |\Gamma_L\Gamma_{OUT}| > 1 \]

** Amplifier Stability**

- **传递函数**
  \[ |\Gamma_{IN}| = \frac{S_{11} + S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \]

- **输出传递函数**
  \[ |\Gamma_{OUT}| = \frac{S_{22} + S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} \]

- **放大器是不稳定的**
  \[ |\Gamma_S\Gamma_{IN}| = \frac{S_{11} + S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} > 1 \]

  or \[ |\Gamma_L\Gamma_{OUT}| = \frac{S_{22} + S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} > 1 \]

- **无条件的稳定性**
  \[ |\Gamma_{IN}| = \frac{S_{11} + S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} < 1 \]
  and \[ |\Gamma_{OUT}| = \frac{S_{22} + S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} < 1 \]

- **注**：复数的模描述了在复平面上的圆。

- **公式**：已开发出稳定性圈（中心和半径）的公式。
Amplifier Stability

- Amplifier is unstable if \( |\Gamma_{IN}| = \left| S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \right| < 1 \)
- Output stability circles on the \( \Gamma_L \) plane:
  - \( |S_{11}| < 1 \)
  - \( |S_{11}| > 1 \)

\( \Gamma_L \) must be in stable region for amplifier to be stable

Representations of stability circles

- Using shading to indicate the unstable region
- Stability circle of an unconditionally stable two-port
- Using a dashed line to indicate the unstable region

Output stability circles for \( |S_{11}| < 1 \)

- 1 GHz
- 8 GHz
- 16 GHz

Input stability circles for \( |S_{22}| < 1 \)

- 1 GHz
- 8 GHz
- 16 GHz

\( \Gamma_S \) must be in stable region for amplifier to be stable
Unconditional stability criterion

The amplifier is stable for any source and load (provided that $|S_{11}| < 1$ and $|S_{22}| < 1$.

Edwards-Sinsky Stability Criterion, $\mu$ factor

$\mu$ is the distance from the origin to the nearest point of the unstable region.

$$\mu = \frac{1 - |S_{11}|^2}{|S_{22} - S_{11}^* \Delta| + |S_{21} S_{12}|}$$

$\mu > 1$ for unconditional stability, The greater $\mu$ the more stable.

$k$-factor of pHEMT

| Freq. (GHz) | $k > 1$ | $|\Delta| < 1$ |
|-------------|----------|----------------|
| 0.5         | 0.15178  | 0.62757        |
| 1           | 0.24895  | 0.58720        |
| 2           | 0.46535  | 0.46821        |
| 3           | 0.67865  | 0.37045        |
| 4           | 0.91943  | 0.29706        |
| 5           | 1.0838   | 0.24365        |
| 6           | 1.1839   | 0.18765        |
| 7           | 1.2846   | 0.14113        |
| 8           | 1.5225   | 0.092502       |
| 9           | 1.6448   | 0.056060       |
| 10          | 1.3151   | 0.072750       |
| 11          | 1.1043   | 0.11703        |
| 12          | 0.98784  | 0.16159        |
| 13          | 0.92131  | 0.18991        |

$\mu$ factor of pHEMT

<table>
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<th>Freq. (GHz)</th>
<th>$\mu &gt; 1$</th>
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Summary of stability considerations

- If an amplifier is unconditionally stable design is considerably simplified.
- Even if an amplifier is not “unconditionally stable” it could still be stable. Design is then tricky and is only done in special circumstances.
  - E.g. very high frequency operation.
  - Consider a cell phone power amplifier connected to an antenna
    - Must be stable
      - When antenna is covered by hand.
      - Phone is placed on a metal surface.
  - Severe price if amplifier goes unstable
    - In a communication system the whole EM spectrum could be polluted.
    - Amplifier could self-destruct (thermal runaway).

Back to design of the amplifier

\[
G_T = G \text{ with optimum } M_1.
\]
\[
G_{T_{\text{max}}} = G \text{ with } S_{12} = 0, \text{ optimum } M_1, M_2.
\]
\[
G_{MA} = G \text{ with optimum } M_1, M_2.
\]
\[
G_{MS} = G_{MA} \text{ but with } k \text{ set to 1 (at edge of stability).}
\]
\[
U = G_{MA} \text{ with } S_{12} = 0.
\]
\[
G_T \text{ and } G_{MA} \text{ are the only gains that do not modify the device.}
\]
Gain circles of the pHEMT at 8 GHz

Output matching network design

- Design nearly always commences with the output matching network.
- The first design step is to choose an output matching network that will provide the appropriate impedances to ensure stability below 5 GHz and above 11 GHz.
- To do this the stability circles must be considered, as the device is only conditionally stable below 5 GHz and above 11 GHz.

Output stability circles for $|S_{11}| < 1$

- $\Gamma_L$ must be in stable region for amplifier to be stable.
- Capacitive at low frequency or perhaps open or short circuit.
- Unconditionally stable at operating frequency of amplifier.
- Look like a resistor or short at high frequencies.

pHEMT at 8 GHz

$Z_{OUT} = R_S + jX_S$

$Z_L = R_L = 50 \Omega$

$Z_{OUT} = Z_0 \frac{1 + \Gamma_{OUT}}{1 - \Gamma_{OUT}} = Z_0 \frac{1 + S_{22}}{1 - S_{22}} = 36.153 - j27.447 \Omega$

However the output of the transistor really looks like a resistor in parallel with a capacitor.

$Y_{OUT} = 1/Z_{OUT} = 0.017547 + j0.013322 S$

So $R_S = 1/Y_{OUT} = 56.99 \Omega > (R_L = 50 \Omega)$

$p_{HEMT}$ at 8 GHz
Consider output stability circles.

1 GHz.

8 GHz.

16 GHz.

Output matching network design

Active device

Load

\( R_S = 56.99 \, \Omega, \, X_L = -75.06 \, \Omega, \, R_L = 50 \, \Omega \)

\( R_S = 56.99 \, \Omega, \, X_L = -75.06 \, \Omega, \, R_L = 50 \, \Omega \)

Active device

Load

\( R_S = 56.99 \, \Omega, \, X_L = 152.4 \, \Omega, \, R_L = 50 \, \Omega \)

\( L_o = 1.00 \, \text{nH}, \, C_o = 1.064 \, \text{pF} \)

Input matching network design

Now consider \( S_{12} \) and loading

\( Z_{IN} = 15.959 + j17.935 \, \Omega \)

Appropriate choice:

Almost certainly will be unstable
Input stability circles for $|S_{22}| < 1$

$\Gamma_S$ must be in stable region for amplifier to be stable

Input matching network design

Final amplifier schematic.

- 10 nH has a reactance of approximately 500 $\Omega$ at 8 GHz.
- 100 pF provides an RF short circuit at 8 GHz.
- Simulated transducer gain is 13.2 dB
  - Compare to maximum available gain of 13.96 dB
  - Error is because $S_{12}$ was ignored in synthesizing the output matching network.
- Design could also target a specified gain.

Design for a specific gain at 8 GHz

Recall that simulated gain of design here is 13.2 dB.
Final amplifier

- This is a surprisingly simple circuit.
- Bias circuit integrated into matching networks.

\[ L_1 = L_i = 681 \text{ pH} \]
\[ L_2 = L_o = 1.00 \text{ nH} \]
\[ L_3 = 10 \text{ nH} \]
\[ C_1 = C_i = 482 \text{ fF} \]
\[ C_2 = C_o = 1.064 \text{ pF} \]
\[ C_3 = 100 \text{ pF} \]