EE133 - Lab 6
RF Amplification: The Power Amplifier and LNA (revisited)

1 Introduction

There will be no formal Prelab 6 handout. This does not mean that there is no work to be done prior to coming into lab, however. Please read through this handout to determine what items you must complete before coming into lab.

In this lab, you will be building and testing a monolithic power amplifier from Mini Circuits. This power amplifier is the last stage of your transmitter before the antenna. This is what will allow you to get much higher distance performance out of your FM system. In addition, you will be revisiting your LNA with some further characterization and impedance matching. We will also look at an important characteristic of almost any analog circuit, linearity.

2 Linearity and The Third-Order Intercept Point

Although there are multiple ways to measure linearity, the ones most commonly used are the third-order intercept point and the 1-dB compression point. Section 16.5 in the text has a good explanation of these two characteristics.

If we can represent the output of an amplifier as a series expansion in terms of the input voltage, then the output voltage might be written in this form:

$$V_o(t) = AV_i(t) + BV_i(t)^2 + CV_i(t)^3 + ...$$

If we assume that 4^{th} and higher order terms won't cause much error, then we can truncate the series after the 3rd term. Now, if we assume an input of the following form,

$$V_i(t) = \cos(2\pi f_1 t) + \cos(2\pi f_2 t)$$

then the output will have a number of harmonic and what are called inter-modulation terms (that is, terms that involve more than one different frequency). As stated in the book, these terms will appear as follows:

- Second harmonics: $2f_1$, $2f_2$ (from V_i^2 term)
- Third harmonics: $3f_1$, $3f_2$ (from V_i^3 term)
- Second-order intermodulation products: $f_1 \pm f_2$ (from V_i^2 term)
- Third-order intermodulation products: $2f_1 \pm f_2$, $2_f2 \pm f_1$ (from V_i^3 term)

The third-order intermodulation terms are the ones of concern to us because they appear close to our desired signal and because they tend to grow more quickly than the 2^{nd} order terms as the input power increases. We can test to see how linear an amplifier is by combining two different tones (that is, two signals of different frequencies) at the input, and measuring the levels of the intermodulation products as we increase the input power signals. In theory, the third order terms will increase 3dB for every 1dB change in input power (On a linear scale, these terms increase as the cube of the input voltage). In reality, however, both the fundamental frequency terms and third order intermodulation terms will slope off at high input powers. An example plot of fundamental and third-order power as a function of the input power is shown in Figure 1. The point at which the output fundamental power falls off by 1dB from the extrapolated power is known as the 1dB compression point. Therefore, when you measure IP3, you will have to extrapolate the actual value from values at lower frequencies.

Input vs. Output IP3: There are two ways to specify IP3, by referring to the input power (IIP3) or by referring to the output power (OIP3) at which the extrapolated first and third-order power lines intersect. Data sheets will often quote OIP3 but list it as simply IP3. This is a marketing ploy to make a component look like it has better performance than it does, since OIP3 will tend to be a bigger number than IIP3 (if it weren't, you wouldn't have a very good amplifier). Therefore you must be careful when selecting components based on these specifications.

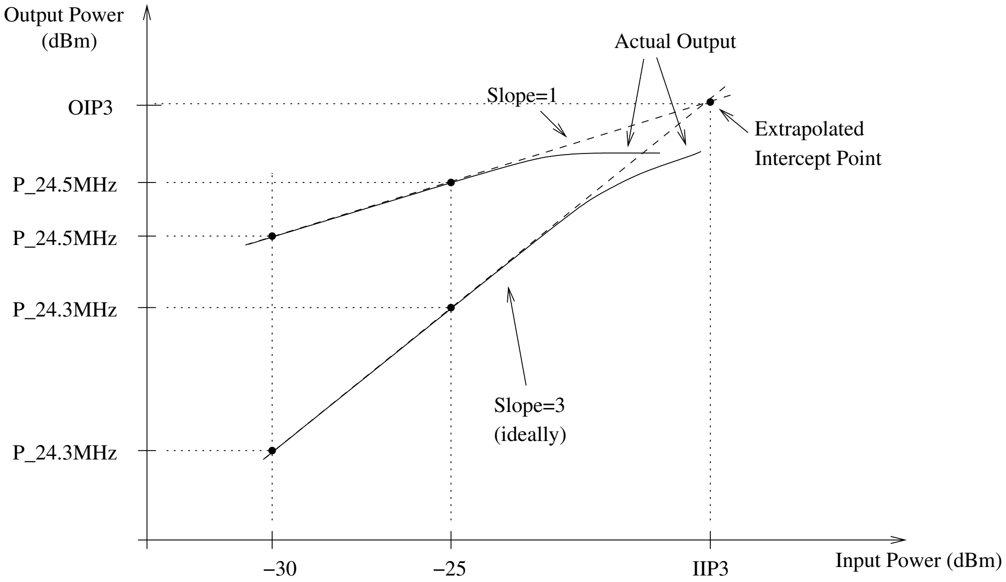

Figure 1: Determining IIP3

3 The Power Amplifier

3.1 Building the Power Amplifier

Ask your TA for a power amplifier chip and solder mount board. This chip is a surface-mount part, so we're going to have to use a slightly different soldering technique to put it on our board. As you can see, the part itself is too small to fit onto our boards directly, so we've made up a header board to solder the part to. Once you've soldered the surface-mount part on, you can then solder the rest of the circuit to the board.

1. **The GALI-5:** Look at the data page for the GALI-5 (there is a link from the EE133 website) and note down important specifications for the amplifier. Some things to look for are power gain, frequency range, input and output impedances, power consumption, etc.

2. **Chip Layout and Connection:** The chip has three pins and one tab on top. The middle pin and tab are to be connected to ground, the left pin is the input, and the right pin is the output (this will be connected to the power supply through an inductor and bias resistor).

3. **Orienting the Board:** Notice that the solder mount board has three plate-through holes, one for the input and two for the output. This will allow you to connect a coupling capacitor to the input, and it will allow you to connect the RF choke and coupling capacitor to the output. The middle pin and top pad are connected to the small copper ground plane. This ground plane should be connected to the ground of your circuit. Figure 2 shows the general circuit layout.

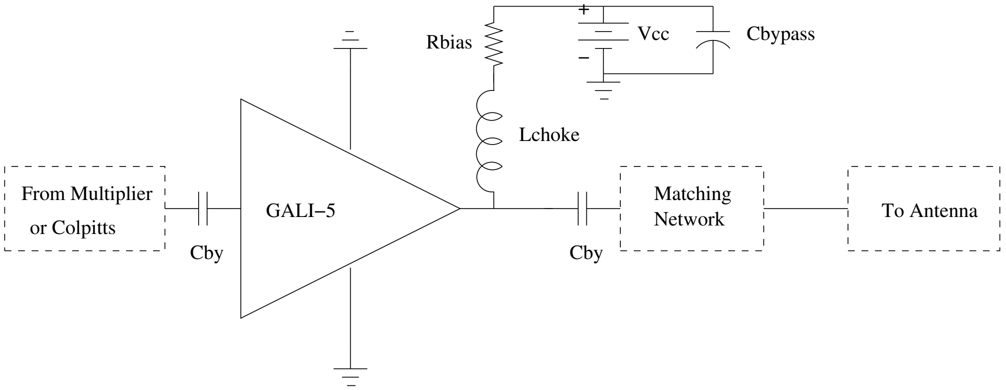

Figure 2: MiniCircuits GALI-5 Amplifier Circuit

4. **Soldering a Surface Mount Part:** Soldering surface-mount parts takes a slightly different approach than soldering normal parts. First, without putting the part on the mounting board, place a small dab of solder on each of the traces where you want the pins to be soldered to the board (this includes the ground tab and middle pin, which connect to the ground plane on the board). Then place the MiniCircuits part on top of the cold solder. You may want to use a pair of tweezers to hold the part in place. Now heat up the trace with the soldering iron until the solder melts and the pin is secured to the board. *Be careful not to overheat the part.*

5. **Building the Rest:** Note in Figure 2 that the output of the amplifier is connected through an inductive RF choke (so-called because it presents a high-impedance to RF signals and so 'chokes' them off) and a bias resistor. This resistor is necessary for the chip to operate correctly. *Do not connect the output of the chip to power without this bias resistor.* The value of this resistor should be about 60Ω, and should be made from a few resistors in parallel, because it has to dissipate a large amount of power. For a Power Supply voltage of 8-9V, the effective value of Rbias should be between 55Ω and 65Ω (this is because the actual voltage at the output of the amplifier is around 5V). For more information on this, see 'Biassing MMIC Amplifiers', which is linked off of the GALI-5 web page. As for L_{choke}, you can choose any value of inductor that will present a high impedance at 24MHz (20-100uH is probably fine - just be sure to measure your actual inductor value at the correct frequency). The bypass capacitors should be the usual high-frequency values. Don't forget to solder a connection from the ground plane to the ground of your board. For now, don't worry about the matching network.

3.2 Characterizing the Power Amplifier

Now we will take a look at how well this amplifier performs compared to its purported datasheet values. Note that this amplifier works in a very large frequency range, and we are using it in the very low end of its range, so some of the datasheet values might not apply directly to our application. They should give us a good idea of its general behavior, however.

1. DC Power: What is the DC power consumed by your amplifier?

2. S-parameters: Using the 8712E Network Analyzer (be sure it's been calibrated correctly), measure the S-parameters of this amplifier by connecting the input and output through BNC connectors to the analyzer. What are the input and output impedances (use the Smith Chart format)? What is the power gain ($|S_{21}|^2$)? How much do these values change over a frequency range of 10-40MHz? Sketch the S-parameter responses over this range.

3. Power Efficiency: Power efficiency of power amplifiers is often characterized by this equation: $\eta = (Powerdeliveredtoload)/(DCPowerconsumed)$. Measure the power that your amplifier delivers to a 50Ω load. What is the Power efficiency of your amplifier?

4. Two-Tone Measurement Setup: Now we will measure the IIP3 and 1-dB Compression Point for this amplifier, and obtain a plot similar to Figure 1. There should be a spectrum analyzer and two function generators set up to do a two-tone test on your amplifier. Ask your TA for help with the set-up.
   - You will need the following: 2 RF function generators, a power splitter/combiner, and the 4395A Spectrum Analyzer.
   - Connect the RF output from the two function generators to the power combiner inputs (if there are extra inputs, you must terminate them with a 50Ω termination.) Connect the output of the combiner (marked with an 'S') to the A or B input of the Spectrum Analyzer.
   - Set one RF generator to produce a 24.5MHz signal at -28dBm. Set the other RF generator to produce a 24.7MHz signal at -28dBm.
   - On the 4395A Spectrum Analyzer, select the following options:
     - Select Spectrum Analyzer: Format ⇒ Spectrum Analyzer
     - Select Input A or B: Measure ⇒ A or B
     - Set Center Frequency: Center ⇒ 24.6MHz
     - Set Frequency Span: Span ⇒ 1MHz
     - Set Peak Threshold: Search ⇒ Peak ⇒ Peak Def Menu ⇒ Threshold on, Threshold Value ⇒ -80dBm (or just above the noise floor)
     - Set Multiple Markers to Measure Multiple Peaks: Search ⇒ Multiple Peaks ⇒ Peaks All
     - Display Marker values: Marker Utility ⇒ MKR List ON
5. **Measuring IIP3 and 1-dB Compression Point:** Now, increase both function generators by 1dB(m) increments (the power output of both should be the same) and watch the display on the spectrum analyzer. When you start to see intermodulation products appear above the noise floor, you should start taking measurements (you should see two peaks at 24.5 and 24.7, with a smaller peak on either side at 24.3MHz and 24.9MHz). You may have to re-select the peak detecting markers so that you get measurements for all four signals. Don't forget to record the input power as well as these output power levels (you should verify that the power reading on the function generator is the actual power being delivered to the input of your amplifier). You may want to take sparse measurements at lower powers, but you should take more narrowly spaced points as the signal powers begin to slope off.
6. **Plotting and Extrapolating IIP3:** Plot the fundamental and third-order output powers vs. input power for your amplifier. Extrapolate lines from the linear portion of the graph to estimate IIP3. At what input power is your output power 1dB less than the extrapolated value?

4 Low Noise Amplifier

In Lab 3, we designed and implemented a shunt-shunt feedback Low-Noise Amplifier. Now we will revisit the concept of noise and the Low-Noise Amplifier.

In a cascaded system, the noise contribution of the first stage is the most crucial to the overall performance of the system. Chapter 14 discusses the various sources of noise, the concept of Noise Figure, and noise in cascaded systems. In essence, the noise of the first stage contributes directly to the total noise of the system, while the noise of each successive stage is divided by the product of the gains of the preceding stages.

There are a few parameters to control when trying to minimize noise: bandwidth, impedance matching, and amplifier contributions. Because we have already picked an active element (the 2SC3302) for our input gain stage, this parameter is fixed. We do have control over bandwidth and impedance matching, however. Limiting bandwidth greatly reduces noise, since white noise power has a linear dependence on bandwidth (Noise = kTB). Therefore, we will include an input filter on our LNA to filter out noise outside of our signal bandwidth. In addition, proper impedance matching can reduce noise as well. As is explained in Section

14.10 in the book, there is an optimum impedance match that will minimize noise at the input to an amplifier. It turns out that this is not always equal to the impedance match that will maximize power transfer into a load. For our situation, however, these two optimal values are relatively close to each other, and so we will deal with trying to get maximum power transfer rather than attempt a complex noise matching calculation.

4.1 LNA: Redesign

For the final project, we will ask you to make some significant change or improvement to your LNA design. The way in which we have gone about building our LNA stage is somewhat pedagogical in nature. We first built a broadband 50Ω input and output impedance amplifier using shunt-shunt feedback, and then used impedance transformations to change the small output impedance to the larger input impedance of the multiplier, thus getting rid of the broadband match and the work we did to obtain the low output impedance. Clearly, this might not be the most efficient means of designing this circuit, but it does give you the tools for thinking about a better way for building the LNA. Your job now is to rethink this stage and get the best performance out of it that you can. You should refer back to the LNA lecture notes and discuss options with your lab partners, TAs, and classmates. Here are some options:

- **Gain:** Shunt-shunt feedback reduces gain, so you might want to design your amplifier without it. This puts your design at the mercy of the transistor parameters, however, so there is a tradeoff, and you will have to design more elaborate impedance matching. You can also design your feedback network to match 50Ω on the input and $1.5k\Omega$ on the output. If you replace Rc with a tuned load (LC tank), this helps get ride of the problem of Rc loading down your output impedance.

- **Stability:** This is probably the factor most significantly limiting the gain of your amplifier. Because of the high frequency of our signals, and because of the ease of coupling at these high frequencies, feedback loops can form between reactive components even when they're not designed into your circuit. Therefore you need to be careful about wiring, power supply bypass, and ground planes. In addition, attempting to achieve too much gain can end up creating instabilities that will turn your amplifier into an oscillator. You may find that this is especially a problem is you decide to go with a tuned load on the output.

- **Noise:** As stated above, from a noise perspective we have the options of limiting bandwidth and reducing the amount of resistance in the circuit. We can do the former by using a tuned load and placing a filter on the input. We can do the latter by reducing the amount of resistive bias we use. With shunt-shunt feedback, we can reduce the number of bias resistors by allowing the feedback resistor to provide both AC feedback and DC bias current to the base.

- **Another knob to tweak:** If you find your LNA having stability problems, the first thing to check is probably that your power supplies are properly decoupled and stable. If that fails, the addition of a small (AC) emitter resistor can help to stabilize your circuit by providing series-series feedback (note that this has the effect of countering the impedance-lowering characteristics of the shunt-shunt configuration). This will also lower the gain of your amplifier (g_m becomes $g_{meff} = g_m/(1 + g_m r_e)$), but it is an option that can help curb negative impedances and oscillations. The value of this resistor should be very small (less than 10Ω) or your LNA gain will suffer more than desired.

4.2 LNA Characterization

1. If you have made changes to your LNA, or suspect that your previous measurements were flawed, redo your measurements from Lab 1 for S-parameters, Q, gain, etc.

2. **LNA IIP3:** Repeat the IIP3 measurement from above for your LNA. You can use the tap of the output inductors for your output. Because your LNA has a tuned output, this measurement may have some error due to attenuation of the intermodulation products (just take measurements at a good enough number of points to be able to plot the IP3 curves). Therefore you should use a smaller spacing for your fundamental frequency signals (try 24.35MHz and 24.40MHz). Note that your LNA output

signals will saturate at much lower levels than the power amplifier, so you will need to use generally lower power levels for this measurement.

4.3 LNA Input Filter

Lastly, we need some way to reject the unwanted electromagnetic signals that can enter our LNA and overload it. Imagine a large signal (called a blocker) at a nearby frequency, such as $25MHz$. This signal could be so large that the LNA becomes saturated, and our desired signal would be lost. Even with smaller blocking signals, non-linearities can cause intermodulation and desensitization to occur (see the lecture notes or the textbook for details). We would like to filter out these potential blockers as soon as possible in our receiver, so we'll be adding a series LC filter at the input to our LNA. You can remove the AC coupling capacitor from your LNA input

Design a series LC filter for use at the input of your LNA. You may want to use either a variable capacitor or inductor (we have some, but not a wide variety) to tune your filter. If it turns out you need a very small value of capacitance, you can put the variable cap in series with a static cap.

1. Measuring Q: Measure the Q of your input filter separately (this is easy to do with the network analyzer).
2. Connecting to the LNA: Connect your filter to your LNA input. Characterize your newly filtered LNA.

Congratulations again on building a very impressive wireless transmitter and receiver! For the rest of the quarter, you'll be characterizing, improving, and packaging your wireless system.