Lab 3 Writeup

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March 16, 2004

Abstract

In Lab 3, a low noise amplifier (LNA) with shunt-shunt feedback was designed and built to meet 50 Ohm input impedance with output matching to a SA612 mixer. A block diagram is shown in Figure 1, below. Together these parts make up the initial amplification and mix-down blocks of my FM receiver. 50Ω input impedance was achieved on the LNA, and it performed well with $16dB$ gain. Overall power gain of the LNA and the mixer was $43dBm$, with the multiplier providing a conversion gain of $g_{conv} = 10\frac{V}{V}$.

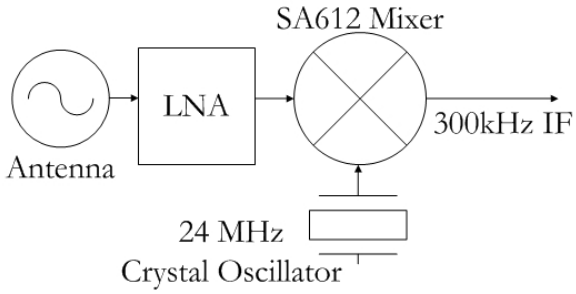


Figure 1: Lab 3 Block Diagram

1 LNA Design Specifications

The low noise amplifier was designed using the 2NSC3302 transistor to meet the following specifications:

- Supply Rails: 9V and OV
- Input Impedance (R_{in}): 50Ω
- Output Impedance (R_{out}): 50Ω
- $S_{21} > 12dB$
- Collector Current (I_c): $4mA$
- Collector-Emitter Voltage (V_{CE}): $> 1V$
- Power consumption: as small as possible

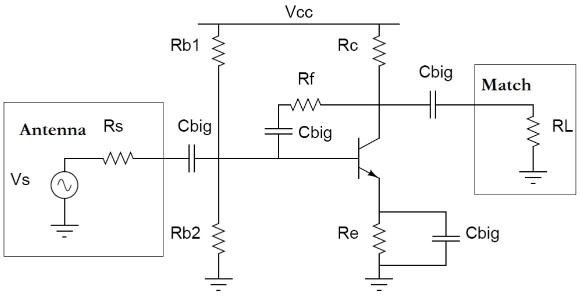


Figure 2: LNA Circuit

We wish the LNA to amplify FM signals at $24.3MHz$ received on an antenna which for this analysis we model as a voltage source (V_s) in series with a 50Ω source resistance. The LNA is connected to a matching network (R_l) between the LNA and the SA612 mixer. The matching network must transform down the $1.5k\Omega$ input impedance of the SA612 to 50Ω or to a perfect match with the LNA output impedance and resonate out the $3pF$ mixer input capacitance and whatever LNA output reactance at $24.3MHz$.

2 LNA Design Theory

The LNA is a shunt-shunt feedback amplifier, where shunt-shunt refers to the way the signal is sensed at the output and fed back to the input. In this LNA design, shown in Figure 2, the transistor collector voltage is fed back to the transistor base as a current. This is similar to placing a voltage "sensor" in parallel at the collector and a current source in parallel with the transistor base–thus the term shunt-shunt.

Such feedback has implications for amplifier noise, small signal gain, and small signal impedances, and in the following sections gain and impedance implications are discussed.

2.1 Impedance Implications

Because shunt feedback places an equivalent impedance in parallel with the input impedance, we expect it to lower the amplifier input impedance. This is desirable, because we are aiming for an input impedance of 50Ω and the open-loop transistor base input impedance is $r_\pi = \frac{\beta}{g_m} = 1k\Omega$. In fact, the feedback reduces the open-loop impedance by the loop gain, as shown in (1).

$$Z_{in} = \frac{Z_{inOL}}{1 + \frac{A}{R_f}} \tag{1}$$

Output impedance is found similarly (2).

$$Z_{out} = \frac{Z_{outOL}}{1 + \frac{A}{R_f}} \tag{2}$$

To determine the small signal open loop impedances, we must turn the circuit in Figure 2 into something we can simply analyze. First, at the frequencies of interest, all the big capacitors are shorts. Second, it turns out that with a simple resistor in the feedback loop, the amplifier ends up with R_f as a load on both sides to ground, as shown in Figure 3.

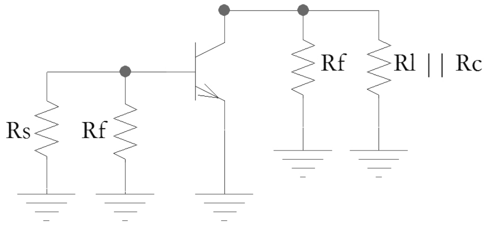


Figure 3: R_f Loading of LNA

With this simplification, we can easily calculate Z_{inOL} and Z_{outOL}, (3) and (4) respectively.

$$Z_{inOL} = R_s||R_f||R_{b1}||R_{b2}||R_\pi \tag{3}$$

$$Z_{outOL} = R_0||R_f||R_c||R_l \tag{4}$$

2.2 Gain Implications

With the above equations it is evident that $A_{ol} = g_m R_{inOL} R_{outOL}$. However, the closed loop gain A is a little bit trickier, because with shunt-shunt feedback A is actually a transresistance (5).

$$A = \frac{V_{out}}{I_{in}} = \frac{A_{ol}}{1 + \frac{A_{ol}}{R_f}} \tag{5}$$

To get voltage gain, we utilize the fact that $I_{in} = \frac{V_{in}}{R_s||R_{in}}$.

2.3 Final Design

These equations alone are not enough to choose the proper resistor values to make it happen. A little more discussion of the DC biasing is needed.

First, in biasing the amplifier, we want R_{b1}, R_{b2}, and R_c to be large in comparison to 50Ω, because all load the amplifier as they appear in the small signal input- and output- impedances discussed above.

Next, as the input signal will be on the order of μV, we do not need to center the transistor base and collector voltages between 0 and $9V$, because dynamic range and saturation shouldn't be an issue with such small signals.

Finally, we need $V_{ce} > 1V$ to keep the transistor in the linear region.

With these conditions and the above specifications in mind, I worked with a spreadsheet model of the BJT's AC and DC parameters and settled upon the values shown in Table 2, below.

R_{b1}	R_{b2}	R_c	R_e	R_f
$18k\Omega$	$10k\Omega$	680Ω	390Ω	390Ω

Table 1: LNA Resistor Values

3 LNA Simulation and LAB Results

In Table 3, the circuit characteristics of interest are shown for the results of my spreadsheet model, of HSpice simulations, and in lab. These include LNA gain (S_{21}), R_{in} (S_{11}), R_{out} (S_{22}), collector current I_c, and bias voltages V_c, V_e, V_{be}.

Characteristic	Spreadsheet	HSpice	Lab
S_{21}	$18.2dB$	$13.9dB$	$16.2dB$
S_{11}	.131	.069	.21
S_{22}	.085	.134	.131
I_c	$5.3mA$	$4.73mA$	$4.82mA$
V_c	$5.58V$	$6.02V$	$5.72V$
V_e	$2.42V$	$1.75V$	$1.89V$
V_{be}	$.794V$	$.790V$	$.78V$

Table 2: LNA Results

As the table shows, in lab I was more than able to meet the $> 12dB$ gain spec and the DC biasing was within acceptable ranges. However, I went over the $4mA$ spec and was unable to match 50 Ohms perfectly with the component values I chose. The actual impedances measured on the Agilent8712E were as follows:

- $R_{in} : 75.8\Omega - 7.6j$
- $R_{out} : 44.4\Omega - 9.6j$

The impedances, though not 50Ω, were quite easy to work with. I decided to design my matching network to match both the real and complex components of the above R_{out}. The R_{in} value was acceptable as the matching network would change the LNA loading and thus I felt confident R_{in} would change once the network was connected to the amp.

4 Matching Design Theory

Matching can be more of an art than a science, but the basic ideas are quite clear. Placing reactive elements (X_p) shunt across a resistor (R_p) lower its equivalent series resistance (R_{s-eq}) and placing reactive elements (X_s) in series with a resistor (R_s) raise its effective parallel resistance (R_{p-eq}). The following equations dictate all of the science of matching (assuming Q is reasonably large):

$$Q_p = \frac{R_p}{X_p} \tag{6}$$

$$R_{s-eq} = \frac{R_p}{1 + Q_p^2} \tag{7}$$

$$Q_s = \frac{X_s}{R_s} \tag{8}$$

$$R_{p-eq} = R_s(1 + Q_s^2) \tag{9}$$

4.1 Final Match

So, if we wish to match the $1.5k\Omega$ mixer input impedance to the 44.4Ω output impedance of my LNA, I need to place a reactive element shunt across the multiplier input.

I also need to keep in mind the reactive components in my match, for a perfect match would resonate out all such components at the $24.3MHz$, the frequency of interest. As my LNA has a $-10j$ output impedance, I need 10Ω of inductance in series with the output to cancel this out. Similarly, I need inductance to resonate out the $3pF$ input capacitance of the mixer.

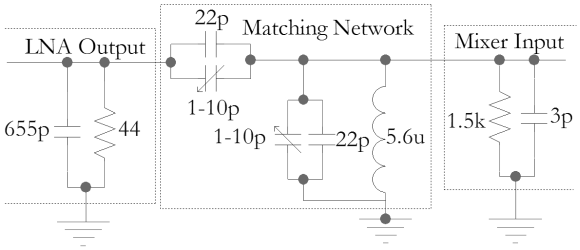
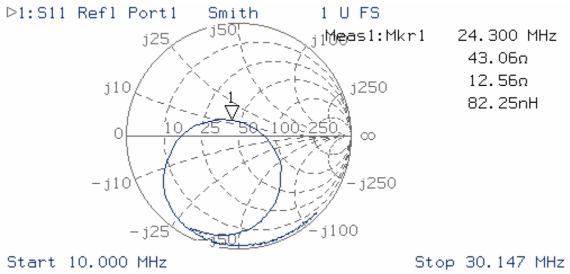


Figure 4: Matching Network

To meet these ends I employed the match shown in Figure 4. I use a variable inductor (realized by the inductor in parallel with a variable capacitor which resonates out specific amount of the inductance) to transform down the $1.5k\Omega$ real mixer impedance to the desired series equivalent 44.4Ω and resonate out the $3pf$. Next comes another variable capacitor to perfectly resonate out all but $10j$ of the remaining series equivalent inductance. Together the two degrees of freedom allow me to perfectly attain the real and complex matching impedances I need.

5 Matching Results

Figure 5 shows S_{11} of the match when it is loaded with the multiplier. I wanted to see $44.4\Omega + 10j$ and was able to get quite close. Note the Q of the match is not very high–all signals at $10MHz$ and $30MHz$ are still within $10\Omega < R100\Omega$ and $-75j < X < 10j$ on the Smith Chart.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▷1:S11 Refl Port1   Smith      1 U FS
Meas1:Mkr1   24.300 MHz
              43.06Ω
              12.56Ω
              82.25nH
Start 10.000 MHz                    Stop 30.147 MHz
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Figure 5: S_{11} of match and mixer

When I added all the blocks together, I was interested to see how my LNA input impedance changed with its output loading changed. To my surprise, after adjusting my variable capacitors and tuning around, a magical thing happened, shown in Figure 6. I had achieved a nearly perfect 50Ω input match with $S_{11} <= .05$, though still with an unimpressive

Q.

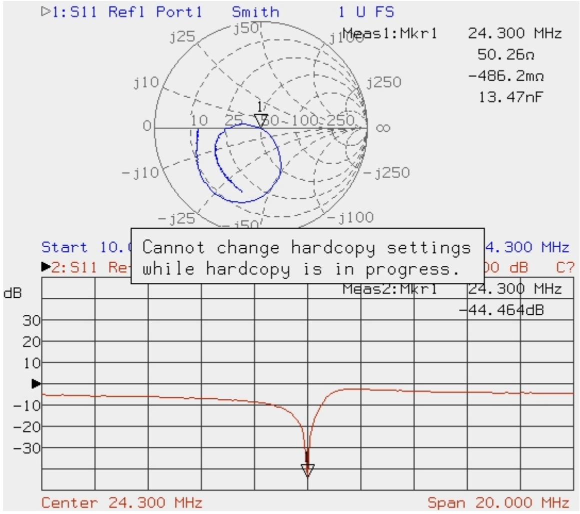
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Figure 6: S_{11} of LNA with matching network and mixer

6 Final LNA-Mixer Performance

With a well performing matching network, it was time to test the gain of the LNA-Mixer combo. I expected the $16dB\frac{V}{V}$ gain to combine with the mixer conversion gain (which the datasheet specifies is minimum $14dB$) to provide me with at least $40dB\frac{V}{V}$ gain. I connected a $-50dBm$ signal from the 8647A RF generator to the input of my LNA and measured the output with the active probe on the spectrum analyzer. The input signal was measured to be $-73dBm$ at the input to the LNA by the probe. $20dBm$ loss is due to the probe attenuation, and I can only assume the other $3dBm$ have to do with offset errors in the probe or attenuation in the BNC cable from the RF generator to the BNC input on my board. The output was measured to be at $-30dBm$ – the two blocks had provided $43dBm$ gain. Because the input impedances to the LNA and the spectrum analyzer are both 50Ω, this power gain is equivalent to the $dB\frac{V}{V}$ volage gain. Thus the mixer must be providing about $17dB$ conversion gain, $3dB$ more than the minimum datasheet value.

7 Conclusion

A low noise amplifier with shunt-shunt feedback was built with $16dB$ voltage gain and a 50Ω input impedance. It was matched to the $1.5k\Omega$ input impedance of the SA612 multiplier using a unique two-degree of freedom matching network involving an inductor and two variable capacitors. This integral initial block of the receiver functions very well, providing $43dBM$ power and voltage gain into a 50Ω load. I seem to have lucked out, for many of my classmates had difficulty with instabilities and finding a match. For this reason, I think I will choose to make as few changes to my well-functioning LNA as possible in the SPAM final project. Then again, all this work to provide a 50Ω input impedance may be futile, especially if all antennas have SWR plots similar to the one I analyzed in lab (Figure 7). We'll see just how handy my matching network is when I try my receiver out in the field.

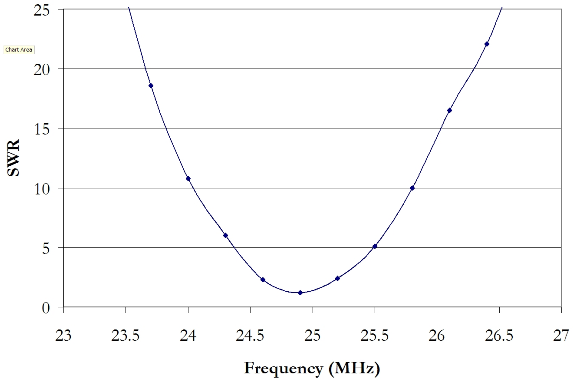

Figure 7: Standing Wave Ratio of Antenna