Measurements on a Multiband R2Pro Low-Noise Amplifier System—Part I

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December 30, 2006

1. Introduction

This report documents the performance of a manually-switched, five-band, low-noise amplifier (LNA) for the HF amateur bands. I am nearing completion of a direct-conversion (DC) receiver that is based on the R2Pro design, as conceived by Rick Campbell, KK7B[1]. The basic LNA circuit discussed here is copied directly from that design. Since there is a great deal of interest in the R2Pro and its derivatives, this report may serve as a benchmark for expected performance of the front end.

A schematic of my RF front-end appears later in this report[2]. Its heart is a set of five R2Pro LNAs with a conventional multi-deck rotary switch to select the band (10, 15, 20, 40, and 80 meters). This amplifier is a grounded-gate JFET design with a typical gain of 10 dB, a third-order highpass, and an eighth-order lowpass. In general, this simple design has a good noise figure, high IP3, excellent reverse isolation and muting capability. We start off with an overview of my project and then look at lots of performance data.

Part II of this report will address improvements to output return loss that are otherwise problematic in a multiband front-end.

2. Construction

My RF front end was constructed “ugly style” on copperclad board. I used a Moto-Tool with a sharp carbide cutter to create pads. The LNA for each band was separately built and tested on its own small board, about 1x3 inches. Inductors were measured before installation, though the results show that at least one of them was probably out of tolerance (consider this a work in progress!). All boards were then soldered on edge to a common “mother board,” which also holds the power supply and muting circuit.

I included a bypass position on the band switch whereby the RF input and output are directly connected. This makes it easy to test experimental amplifiers, or to see how receiver performance changes when there is no LNA at all.

The enclosure chassis is fabricated from 50-mil brass sheet with 0.2 x 0.4 inch brass barstock along the edges to support tapped holes for securing the cover, which was fabricated from 10-mil brass. Joints were torch soldered. A coat of Staybrite Brass Lacquer was applied over all exterior surfaces. Panel lettering is freehand ink. I built my

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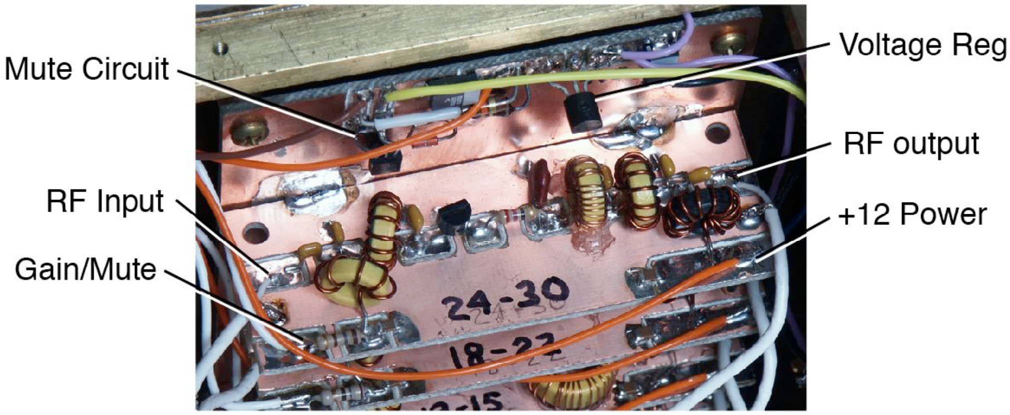
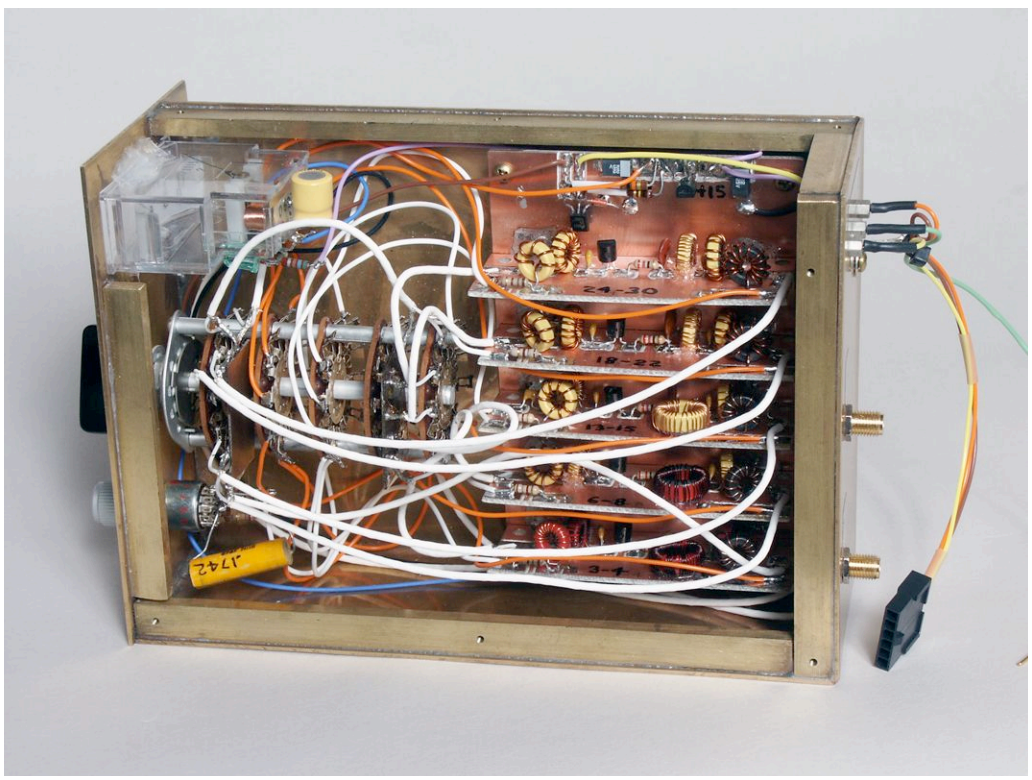
[1] Information and kits available at http://www.kangaus.com/kk7b_designs.htm.
[2] Note that I still prefer to maintain my drawings in pencil on notebook paper. It’s faster, easier, and more versatile than a computer, for me.

receiver in a modular fashion, using a standard module height of 5.5 inches. Each module is the bolted to the bottom of a common chassis.





DC power and control signals are routed through 1 nF feedthrough capacitors, and RF via SMA jacks. Internal signals are wired with 50-Ohm subminiature Teflon coax that I got at a surplus sale. Power connections on all modules are standardized and use an AMP Micro Mate-n-Lok 6-pin connector. The enclosure also holds an S meter, the subject of a future article.

3. Circuit Description

The basic LNA circuit is thoroughly discussed in the R2Pro kit, and also in EMRFD[3]. My main addition is variable RF gain. Gain of this JFET amplifier is directly proportional to drain current. To adjust this current, you can regulate the voltage and/or current at the grounded end of the 180-Ohm source resistor in the regular R2Pro design. This is also the place where you can mute the amplifier by pulling the voltage to +12.

I first built a constant-current source to verify the response, and found that a range of at least 40 dB (linear with current) was achievable. Then I did a quick experiment with a variable resistor instead of an active current source, and found that quite satisfactory. You could use a reverse-log taper pot (100 K or more works fine). In my case, I used a miniature rotary switch and fixed resistors to obtain semi-calibrated 6 dB steps. External muting acts on the RF gain circuit by pulling it to ground for *operate* mode, and up to +12 for *mute*. Note that the calibration on the RF Gain knob is relative gain, where zero refers to maximum gain, which is typically 10 dB.

One issue with this muting scheme is that when the gain is set very low, a long un-muting time occurs. This is because of the RC time constant formed by the RF gain resistor and the 0.1 µF bypass near L101. A solution is to add a speedup capacitor (0.17 µF was optimum) across the gain resistors to quickly transfer charge. The result is fast muting

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[3] Wes Hayward, Rick Campbell, and Bob Larkin, *Experimental Methods in RF Design*, ARRL, 2003. I don't know what I would do without this book.

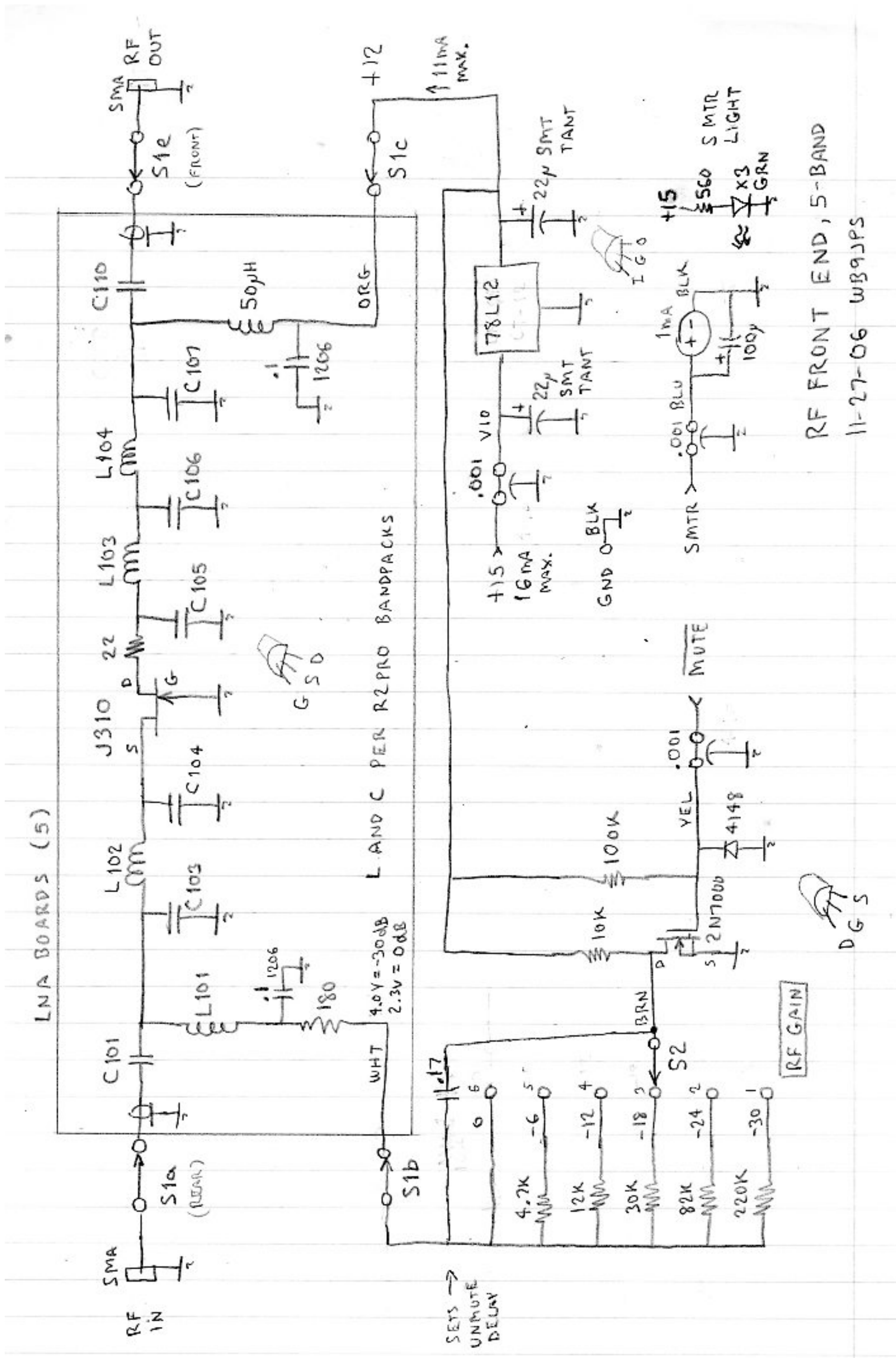
(<25 μs) and an un-muting time on the order of a few milliseconds for the lower gains. When tested with the complete receiver, I found that muting and un-muting sound instantaneous and free of audible clicks.

One may be tempted to use this adjustable gain capability as part of an AGC circuit. There are two problems with this in a DC receiver. First, in order for an AGC system to have constant response time regardless of signal level, the amplifier's gain adjustment must logarithmic with respect to the control signal. Put another way, the gain in dB must be linear with the control signal. But in the present amplifier, gain is linearly proportional to current. One option is to control the gate-source *voltage* instead. Be warned that it only varies over about a 3 V range, and it's easy to end up with the FET running destructively hot. Second, audio-derived AGC (the only way you can do it in a DC receiver) tends to have serious issues with response time because of all the delays in the various filters. This results in an unpleasant transient *pop* when a strong signal suddenly appears. For these reasons, I stayed with manual RF gain.

A better solution for AGC in a DC receiver is to build an audio compressor/limiter, which is standard fare in the recording and musical instrument industry. Some future articles will show you how.

Important note: There is an even bigger problem with this amplifier when you reduce the operating current: Distortion, particularly intermodulation, grows rapidly to an unacceptable level as current is reduced (see Section 10). This I did not discover until after the initial build of my front end. In Part II of this report, a revised approach will be discussed in detail.

Prime power in my receiver is ±15 V and +5. For this amplifier, a 12 V regulator provides a stable source that is well filtered by a 22 μF low-ESR surface-mount Tantalum capacitor. The amplifier actually has very good power supply rejection, even without a fancy regulator.



RF FRONT END, 5-BAND
11-27-06 WB9JPS
LNA BOARDS (5)
L AND C PER R2PRO BANDPACKS
RF IN
SMA
S1a
(REAR)
C101
L101
.1
1206
180
4.0V = -30dB
2.3V = 0dB
WHT
S1b
L102
C103
C104
J310
S
D
G
22
C105
L103
C106
L104
C107
C110
50μH
ORG
S1c
+12
11mA MAX.
S1e
(FRONT)
RF OUT
22μ SMT TANT
78L12
+15
16mA MAX.
.001
V10
GND
BLK
SMTR
BLU
1mA
100μ
560
X3 GRN
S MTR LIGHT
MUTE
YEL
4148
100K
10K
2N7000
BRN
S2
RF GAIN
.47
0
-6
-12
-18
-24
-30
4.7K
12K
30K
82K
220K
SETS UNMUTE DELAY

4. Frequency Response

Most of the measurements shown here were taken on an HP8568B spectrum analyzer with HP8444A tracking generator. Figure 1 shows the basic frequency response and confirms nominal 10 dB forward gain and the expected bandpass response for each band. My 14 MHz filter apparently has a component out of tolerance, as you can see by the slope in the passband. I'll eventually get in there and find the culprit, though it really won't have much affect in normal use. Table 1 lists the exact gains and frequencies.

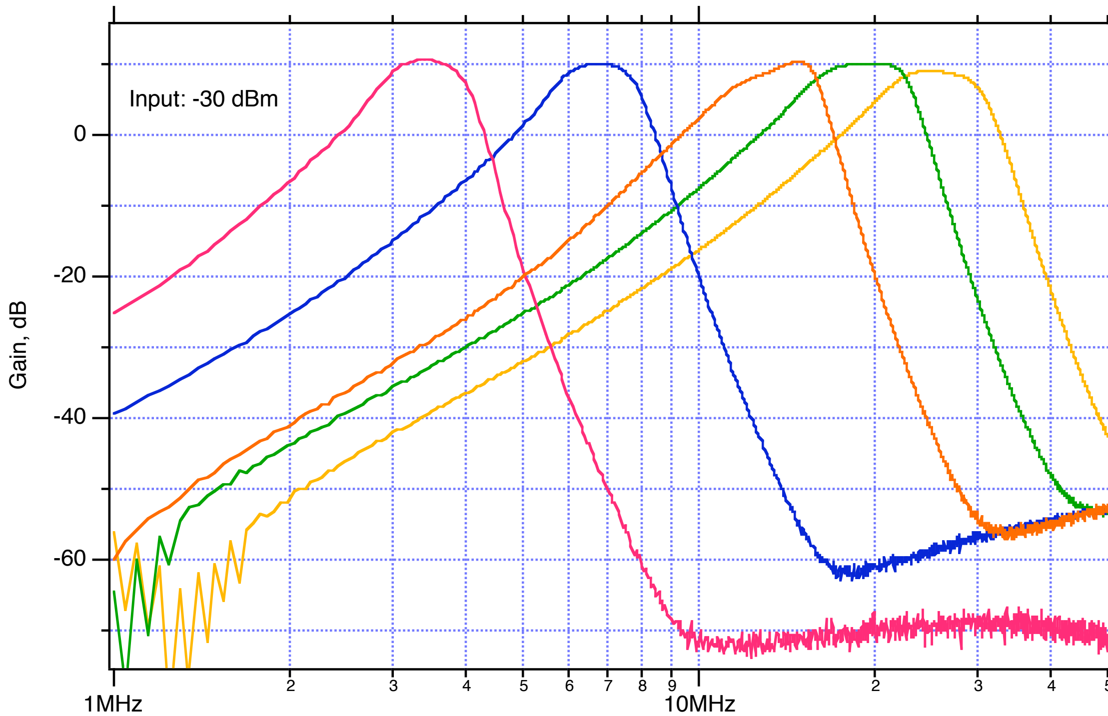


Figure 1. Frequency response for each band.

Table 1. Frequency Response Details

Band (m)	Peak Gain (dB)	Peak Freq. (MHz)	-3dB Freqs (MHz)
80	11.1	3.466	3.3036-4.074
40	10.2	6.737	5.770-7.931
20	10.2	14.971	12.015-16.064
15	10.0	21.128	15.538-22.948
10	9.0	24.371	20.788-30.358

Variation of gain versus drain current is shown in Figure 2. It is linear below about 1 mA. Accuracy of the 6 dB RF gain steps appears in Figure 3. The actual steps at the peak of the 40 meter passband are -6.5, -10.9, -16.8, -23.9, and -32.3 dB. (Again, note that these are relative to the amplifier's full gain of about 10 dB.) No attempt was made at optimizing these steps, and they do vary by 1 dB or so on each band. I picked 6 dB steps because they correspond to one S unit and the changes in audible volume are comfortable. More importantly, amplifier frequency response is affected by changes in gain. This is probably because the JFET source impedance is changing (it increases as the drain current decreases), which in turn changes the load seen by the input filter section.

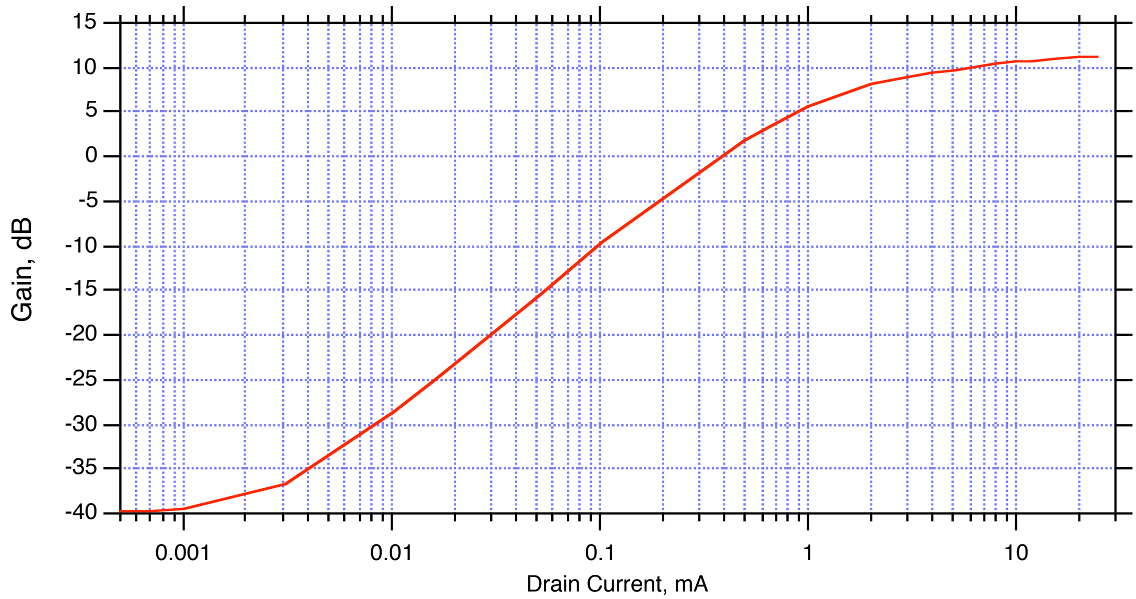


Figure 2. Variation in gain with changed in FET drain current. It's fairly linear below about 1 mA.

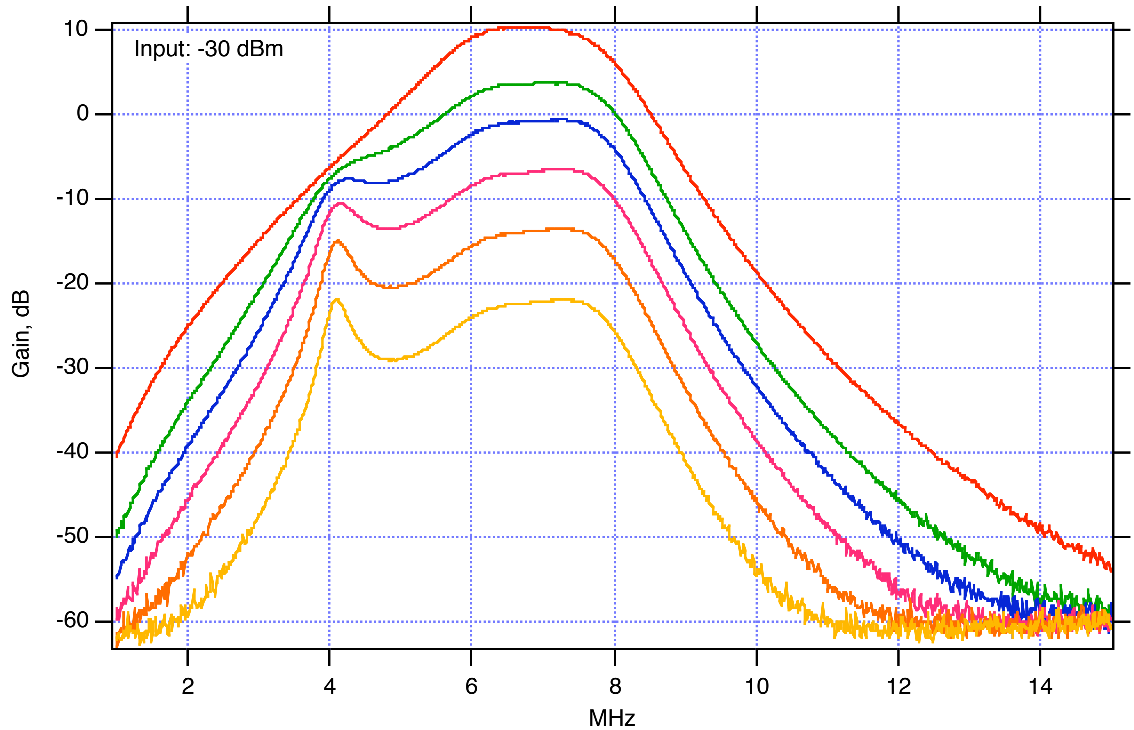


Figure 3. Effect of RF gain settings for 40 m band. Steps are about 6 dB. Note that this graph uses a linear frequency scale for clarity.

Figure 4 shows the system response into the VHF region. Since conventional point-to-point wiring was used along with ordinary leaded components, we expect to see feedthrough of these higher frequencies. Loss is acceptably high, even at 250 MHz, and I would not expect any trouble from VHF energy in my receiver. It's interesting to manipulate coaxial cables and poke your fingers around in an amplifier like this while watching the spectrum analyzer display. *Everything* makes a difference at VHF, and one should not expect predictable performance up there with such simple fabrication techniques.

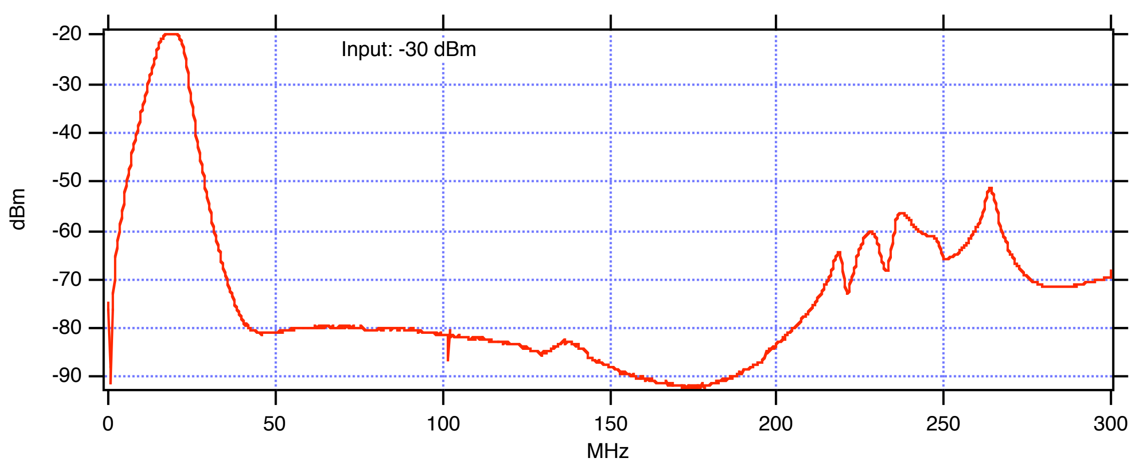


Figure 4. VHF response of the RF section. 10 m band selected.

5. Reverse Isolation

An important performance factor in the LNA for a DC receiver is reverse isolation, or reverse gain. Local oscillator energy and mixer products leak out of the mixer's input and can be radiated and/or reflected back into the mixer. In Figure 5, you can see that the reverse gain is pleasingly low at -29 dB or better in the passbands and much lower at other frequencies. This value can be added to the LO-RF isolation of the mixer to calculate radiated LO power.

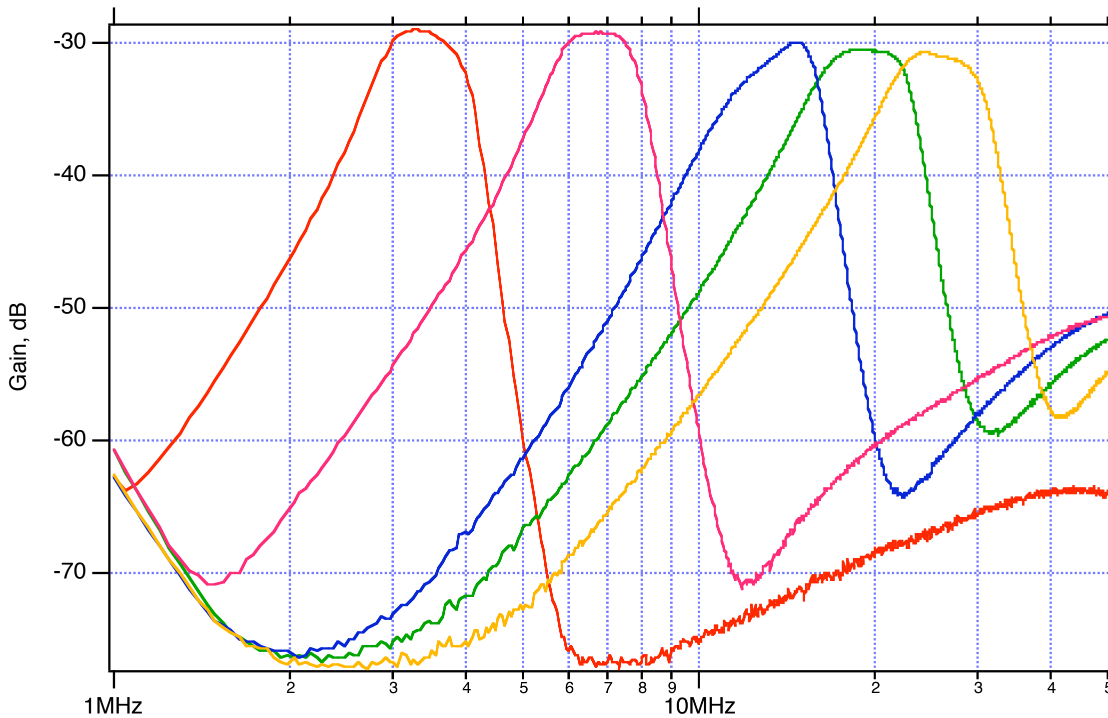


Figure 5. Reverse gain (isolation) for each band.

6. Frequency Response When Muted

Another useful property of the common-gate amplifier is that it provides a convenient way of muting the input of your receiver. Using the same control method as RF gain adjustment—in this case, cutting off the FET's drain current—the amplifier turns into a healthy attenuator. Figure 6 shows the frequency response for each band. Loss ranges from 40 to 50 dB in the passbands and much more at other frequencies. As I mentioned earlier, muting action is quick and clickless. It's also better than disconnecting or shorting the mixer input on a DC receiver because that sudden change in impedance almost always results in a nasty click.

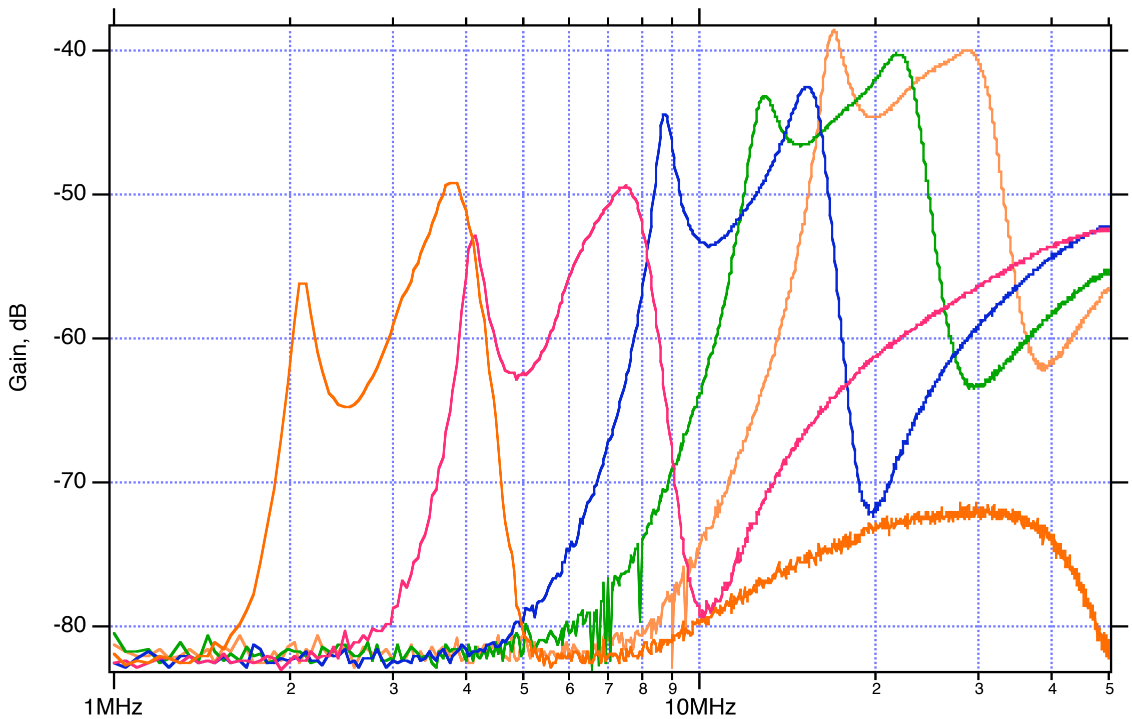


Figure 6. Frequency response for each band when muted.

7. Input Matching

Return loss at the input for each band is plotted in Figure 7. The match to 50 Ohms is fine in the passbands. A return loss of 10 dB corresponds to a VSWR of 1.92. Further optimization of this match would not significantly improve receiver performance.

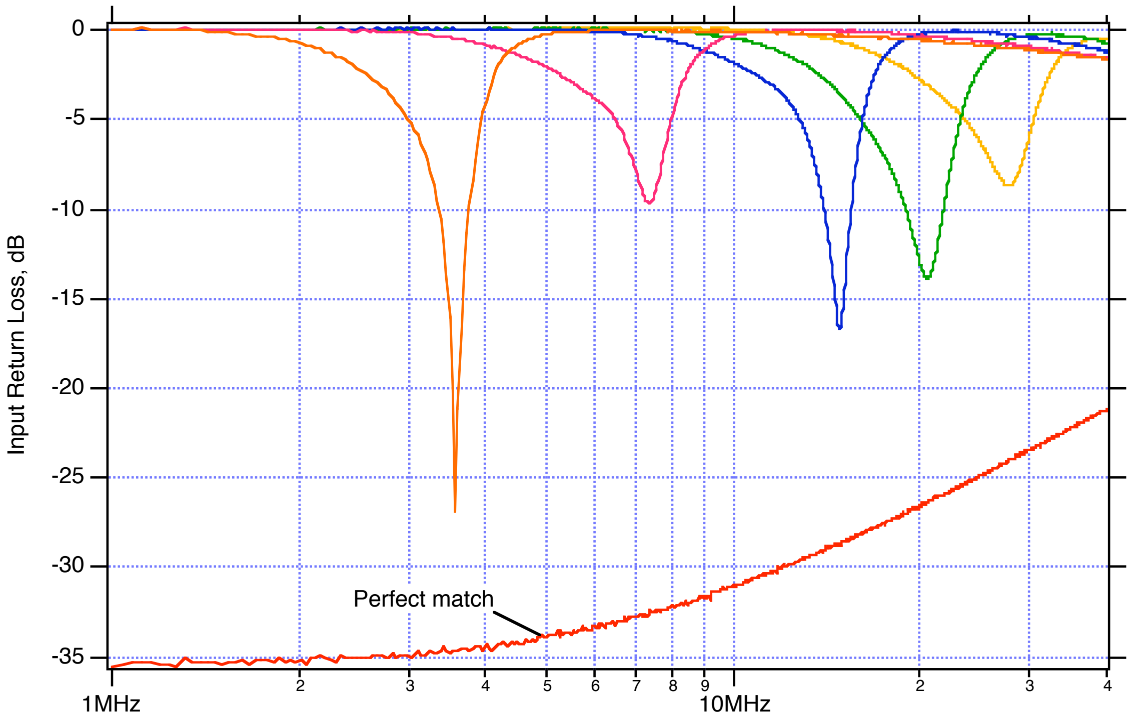


Figure 7. Input return loss. Match is pretty good in the passbands.

8. Output Return Loss

Another important requirement for optimum performance in a DC receiver is that the mixer must operate in a pure 50-Ohm environment on all three terminals at all frequencies. Meeting this requirement on the RF side is probably the hardest of the three. The amplifier at hand comes up short in this respect as you can see in Figure 8. Return loss in the amateur bands is only about 2 dB. As I mentioned before, energy leaking out of the mixer's RF input is reflected back into the mixer, and this energy re-mixed unpredictably with desired signals. Furthermore, an image-reject DC receiver is highly sensitive to phase variations in the received signal. Variations in phase directly affect opposite-sideband rejection. The reflected signal is returned with an unpredictable phase, and this problem is especially troublesome when you switch bands. Figure 9 shows that return loss also varies slightly with operating current.

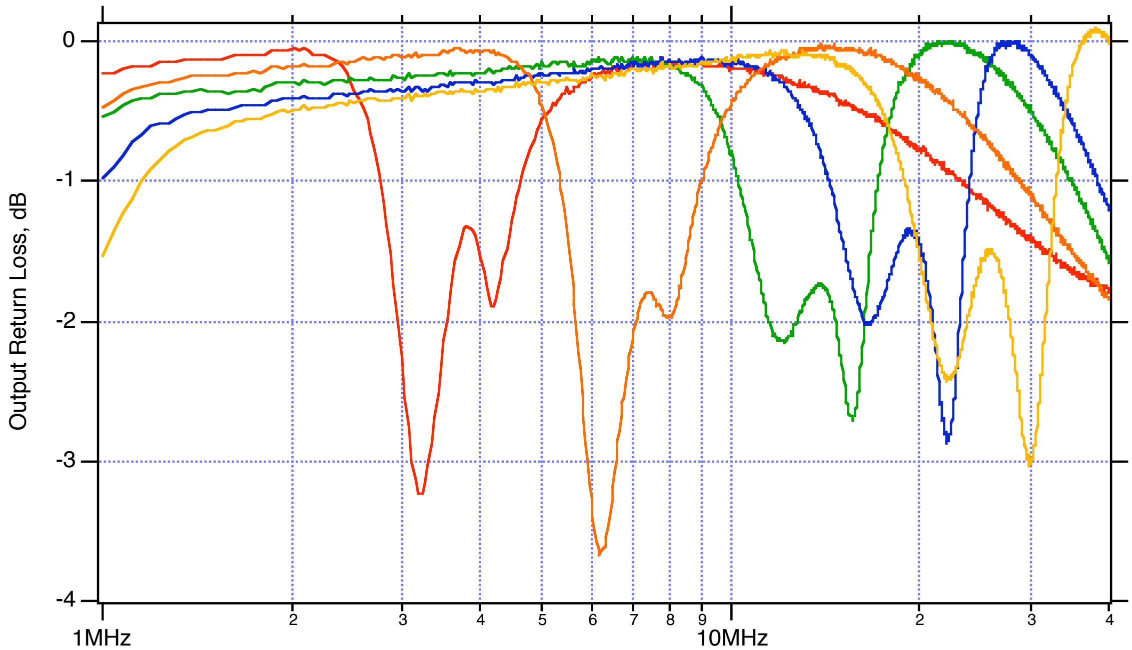


Figure 8. Output return loss. This can be improved by adding an attenuator.

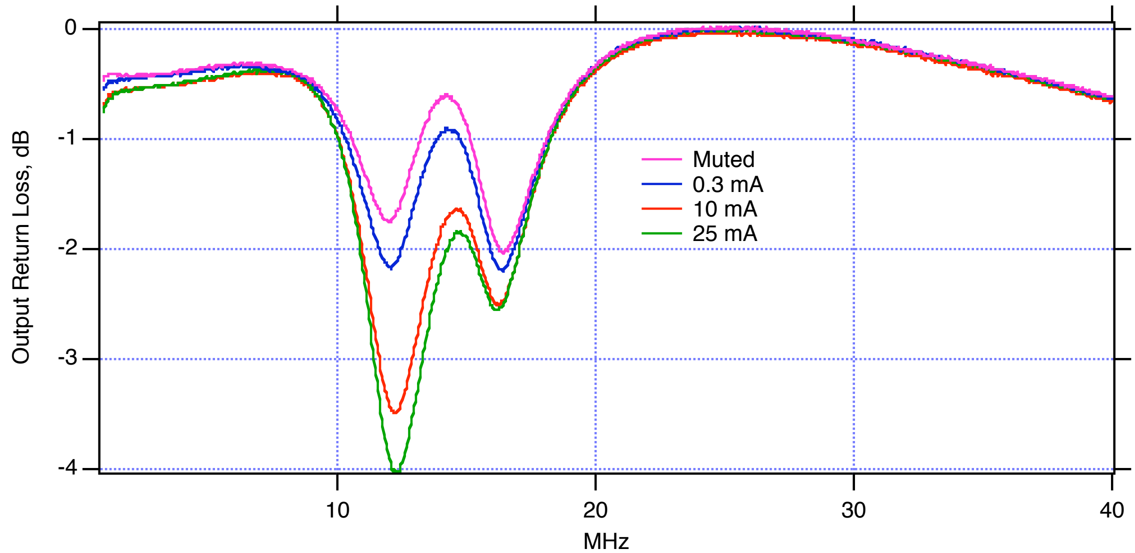


Figure 9. Output return loss changes slightly with operating current.

A simple solution, implemented by Rick in his new MicroR2 design, is the addition of an attenuator between the amplifier and mixer. Since reflected energy passes through the attenuator twice, return loss is increased by twice the value of the attenuator. Rick picked 5 dB. I did a quick test with a 6 dB attenuator, and sure enough, you can add about 12 dB to all of the data shown in the graphs. And that holds for all frequencies, from DC to VHF, limited only by the quality of your attenuator.

The drawback of this method is that the overall noise figure is degraded by a value equal to the attenuator loss. While this may be acceptable on 80 and 40 m, it is probably a poor compromise on the higher bands. A better solution is to add a broadband amplifier (probably with an attenuator) after the LNA. If properly designed with respect to IIP3 and noise, overall system noise figure may actually improve. This will be the subject of Part II of this report.

9. Noise Figure

Noise figure was measured with a calibrated noise source applied to the input of the LNA using the tools and procedures described by Sabin[4].A preamp consisting of two Minicircuits MAR-6 MMIC amplifier (20 dB gain each, NF 3 dB) was added at the LNA output to boost the signal level above the noise level of the spectrum analyzer. Accuracy of this instrumentation setup has been confirmed by tests with several amplifiers having known noise figures. By the way, it does take a great deal of care and practice to get repeatable and believable noise figure measurements when testing individual components. I had plenty of false starts and kept ending up with figures higher than expected, but eventually worked out the procedures for my particular instruments. I estimate my absolute NF accuracy at ±0.6 dB. Table 2 shows the results.

Table 2. Noise Figure

Band (m)	NF (dB)
80	4.5
40	6.0
20	4.0
15	3.7
10	6.0

In the original R2Pro article, Rick mentioned 2 dB, and then in the EMRFD version of that article, 4 dB. The easiest thing in the world is to get a poorer noise figure than expected, due to design, layout, power supply, shielding, or individual variations in FET performance. And of course there are those measurement system errors. Still, for the HF bands this is acceptable performance. I know that the band noise on my R2Pro is much greater than my receiver's self-noise at least through the 20 m band.

Noise figure does vary with FET drain current (Figure 10). I did a simple experiment at 15 MHz. Gain only varied by 2 dB over this range of current, but it still had to be accounted for in the noise figure calculations; measurement system noise figure becomes more important for lower front-end gain.

[4] W. Sabin, "A Calibrated Noise Source for Amateur Radio," *QST*, May, 1994, p. 37-40. Procedure also covered in EMRFD p. 2.20 and in ARRL Handbook. It is not hard to build and is extremely valuable for characterizing components and subsystems.

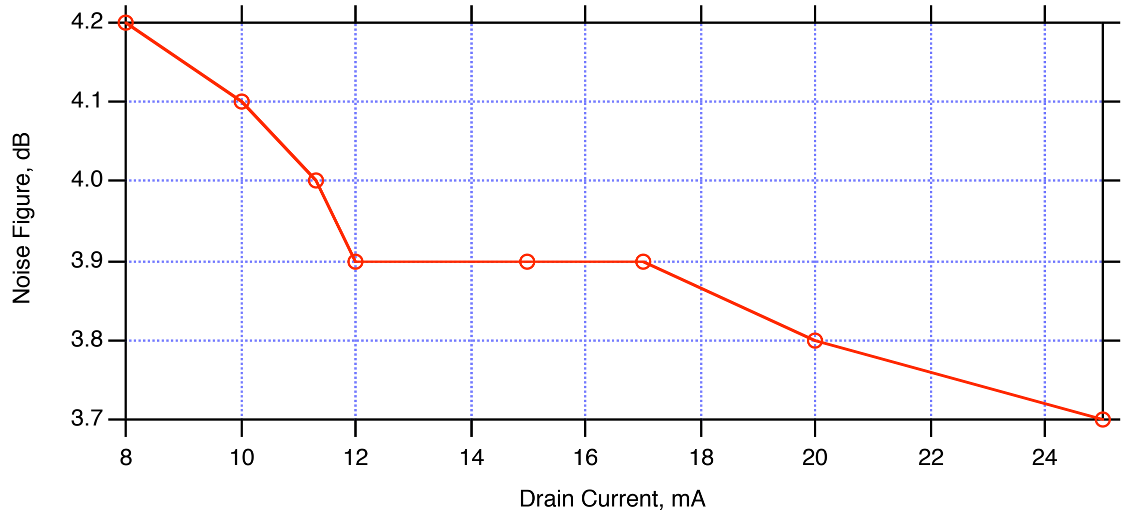


Figure 10. Variation of noise figure with drain current. Data taken at 15 MHz. Measurement resolution is 0.1 dB.

Any amplifier will have an optimum bias current range where the ratio of noise voltage to noise current (R_{opt}) is equal to the real part of the source impedance. In RF and microwave systems, this is usually treated as a reflection coefficient representing the noise match between a source and load and the term Γ_{opt}, a complex number, applies. (Some day, I may put my math skills to work again and understand how this particular amplifier behaves in that framework.) In some situations, there is no practical optimum value. For instance, very low source resistances require very high bias current in the amplifier to minimize its noise voltage. But eventually you run up against a power dissipation limit in the transistor. Perhaps that is the situation here; at 30 mA, the FET was getting rather warm, but the trend in NF still had not reached a minimum.

10. Third-Order Intercept

Input third-order intercept was measured at 14.3 MHz using a pair of crystal oscillators and the method described in EMRFD, p. 7.19. At nominal operating current, the result was a respectable +18 dBm with an estimated uncertainty of ±0.2 dB. For such a simple amplifier, this is a very respectable result.

Now for the kicker. When Rick reviewed this report, he asked for data on IIP_3 as a function of operating current because part of the lore regarding common-gate FET amplifiers is that IIP_3 degrades quickly at lower current. Figure 11 clearly shows this to be the case. Though it's not shown on the plot (due to the logarithmic current scale), intercept does recover when the FET is cut off (muted). Thus, the amplifier is fine above 8 mA and also at zero. Why does this happen? Think of this low-bias amplifier as more of a poor mixer than a good amplifier[5]. Harmonic distortion and intermodulation products are prolific at low current.

[5] Rick Campbell, private communication, Dec., 2006.

In fact, this is such a serious deficiency that I am stepping away from the whole variable gain option. Instead, I'll be looking at an ordinary attenuator. That, too, will be discussed in Part II of this report.

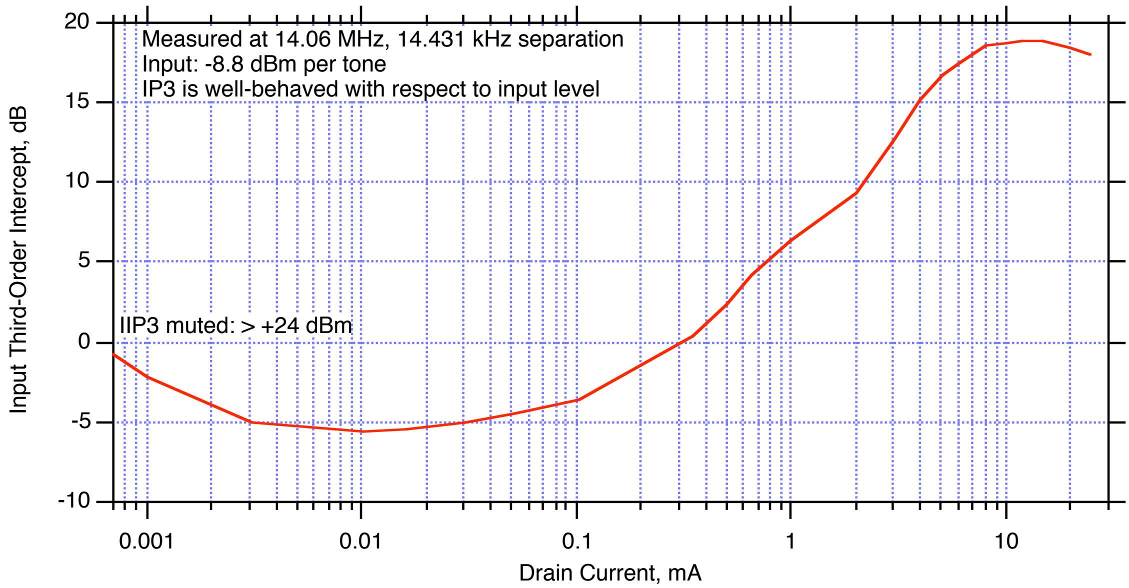


Figure 11. Input third-order intercept vs. drain current.

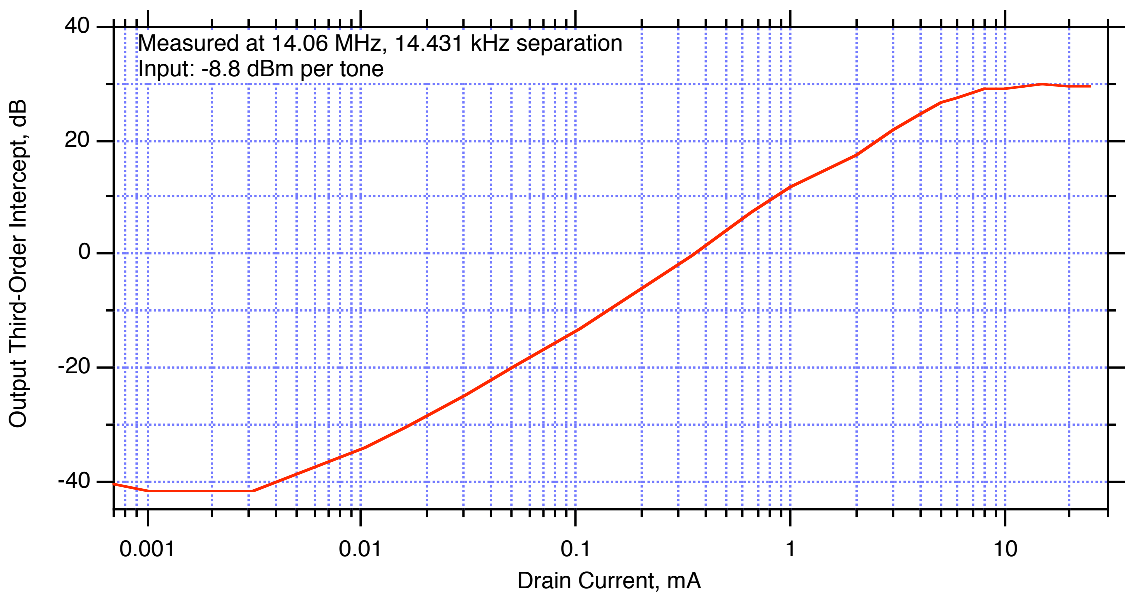


Figure 12. Output third-order intercept vs. drain current.

11. Specification Summary

Gain (typical)	10 dB
Loss when muted	-40 dB or better in passband
Reverse gain	-29 dB or better in passband
Input return loss	>8 dB in passband
Output return loss	>1.5 dB in passband
Noise figure	4 to 6 dB (band-dependent)
Third-order intercept	+18 dBm at 14 MHz
Operating power	160 mW from 15 V

12. DC Receiver LNA Design Objectives

After studying the literature, I have compiled the following list of goals for the front-end of a DC receiver. The present LNA design generally meets all of these requirements, particularly in the context of the R2Pro. There are still compromises and room for improvement, of course. For instance, in an ideal amplifier the wideband output return loss would be lower.

1. Provide a lowpass filter to prevent reception of signals at the 3rd harmonic of the LO. This implies a fairly steep rolloff above the desired band. That is pretty easy to do, regardless of how wide the bandpass is; you just need enough poles. Something around 80 dB at the 3rd harmonic seems to be realistic. Many DC front-ends are nothing more than lowpass filters, and that is often adequate.

2. Reject large, out-of-band signals to prevent overload. This implies that a bandpass is better than just a lowpass, and that a sharper bandpass may have advantages. In the limit, a sharp preselector may be the ideal solution, though it's often a nuisance to tune. If you're using your receiver during a big Field Day operation, you know all about this.

3. Provide reverse isolation to prevent the LO from radiating. If the mixer is well-balanced, this is less of a problem.

4. Add some gain with a low-noise amplifier to improve overall system noise figure. This must be done without seriously compromising overload margin (IP3).

5. Optimize gain distribution among the various elements in the receiver. This is an overall system design task. Thanks to Rick's experience, the R2Pro appears to have a good overall gain balance that provides very good dynamic range and sensitivity without too much complexity.

5. Optimize the 50-ohm match looking out of the mixer's input at *all* frequencies. This prevents mixer products from reflecting back into the mixer, which would otherwise re-mix with random phase, causing a variety of ills. This is the biggest shortcoming of the present amplifier. An output pad on the LNA is a simple answer, though you do sacrifice some NF. A better solution will be presented in Part II of this report.

6. Provide a means of muting during transmit without upsetting mixer balance. The FET makes this real easy—just remove the bias—and you can even ramp it (over a millisecond or so) to avoid nasty transients.

7. Optionally, provide a means of adjusting RF gain.

8. Optionally, minimize operating power (for portable use).

Acknowledgements

I wish to thank Wes Hayward, W7ZOI, and especially Rick Campbell, KK7B, for their valuable reviews and advice on this project, as well as their long-term contributions to the amateur radio community.

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