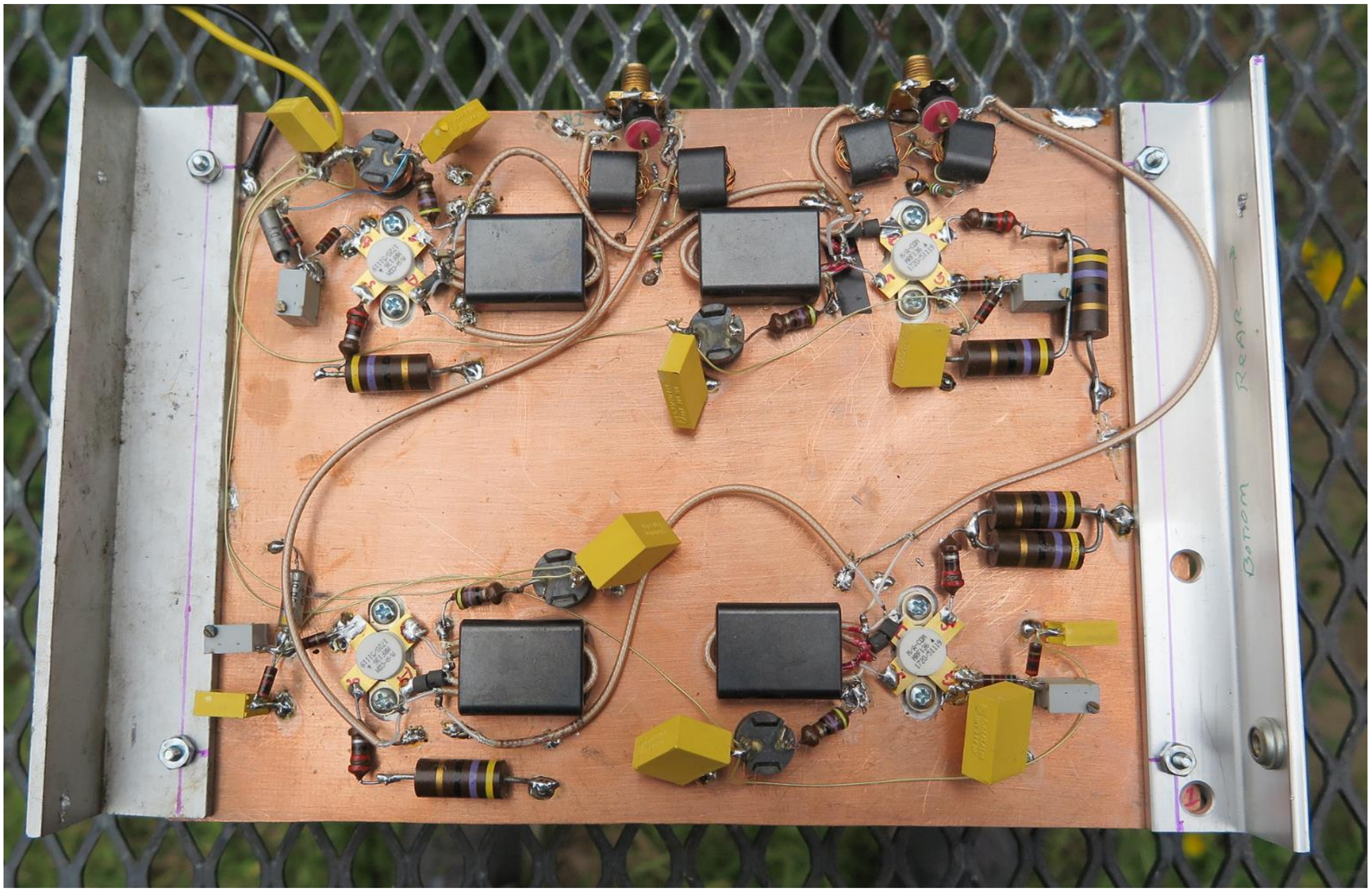


HF LNA

High Dynamic Range 1.5 → 30 MHz Low Noise Amplifier.

By Doug Ronald, W6DSR

I have always had an interest in building high-performance receivers and transmitters for HF. An expected performance metric for receivers is dynamic range. The receiver should not add noise of its own for weak signal reception, and at the same time, remain linear with a high amplitude signal in or out of the receive information bandwidth.

My station's transceive lineup starts with a log periodic dipole array (LPDA) antenna, then a short 58 foot run of 1-5/8 inch air core heliax transmission line to the shack, a high-power transmit/receive switch, and then for the receive path, by an LNA with 10.5 dB of gain. Next in the shack is a switched bandpass filter bank with a bandpass filter for each of the HF ham bands in the 1.5 through 30 MHz span. Following that is a switched attenuator, then another LNA with the same characteristics as the antenna's LNA, and following that in the receive path, is a 30 MHz brick wall filter, a 20 dB amplifier of respectable spec, and on into a 16 bit analog-to-digital converter (ADC). For the transmit path, the same LNA which on receive is connected to the antenna, is switched to the output of the DAC after its sine-x-over-x filter which provides the RF signal to be transmitted. The same filter bank which is used in the receive path is now in the path for the transmit function, followed by the second LNA which is now providing about 1 Watt to the exciter. So this LNA I'm describing here is not only a low noise, high IP3 amplifier in the receive path, but also a low distortion exciter linear amplifier in the transmit path.

This article addresses the design of the LNA located at the antenna's output port, and the identical LNA after the switched attenuator.

LNA Specification Derivation

The noise figure (NF) of a typical ADC is on the order of 30 dB. With a preamp preceding the ADC, that noise figure can be brought down to a reasonable 10 dB or so, where at the lower frequencies, atmospheric noise will dominate anyway. In the 17, 15 and 10 meter bands, however, a lower noise figure is desirable. I chose to have my overall noise figure no greater than 5 dB at up to 30 MHz.

For gain, I needed to overcome the line loss from the antenna to the shack, and the bandpass filter loss. Since there is another 20 dB of gain before the ADC, 10 to 12 dB of gain in the LNA would be adequate.

The real challenge for my LNA design was the required IP3 spec. My LPDA was not designed to be efficient in the AM broadcast band of 550 kHz through 1650 kHz, but it makes an excellent antenna in that band. I measure signals of -25 dBm! Simultaneously with the constant AM station signals, I'm trying to receive signals in the -135 dBm range. Since there is no filter which would have inconsequential insertion loss before the LNA to not spoil the noise figure, that amplifier has to have phenomenal linearity over the entire HF bandwidth. I decided any design I could finalize on, must have an OIP3 of > 60 dBm.

Final Measured LNA Performance Specification

- Noise Figure – My measured noise figure is 3.1 dB worst case. Surprisingly, this occurs at the low frequency end of the bandwidth. At 28 MHz, the measured noise figure is 2.2 dB.
- Gain – The gain is quite flat from 1.5 MHz through 50 MHz at 10.5 dB. I deliberately roll-off the gain above 50 MHz to prevent amplifying the FM band stations from 88 MHz through 108 MHz. With simple modification to the design, flat gain may be had through 150 MHz, and as a bonus the NF stays around 2 dB.
- OIP3 – I have a challenge measuring the IP3 since it is so high, but I can state that it is > 61.5 dBm.
- S11 – Expressed as SWR, at 1.5 MHz it is 1.06:1. At 50 MHz it is 1.05:1 with the output terminated in a 50 Ohm load. It is flat across that range with very little energy reflected back into the antenna.
- The 1 dB amplifier gain compression happens at just about 2 Watts with 250 mA on the final two push-pull transistors, and 40 VDC drain-to-source bias. Because these amplifiers remain linear at this power level, I have used the LNAs in the transmit path where the final LNA needs to provide ~1 Watt to the exciter.

The Long Road to Success

For at least 10 years, I have been trying to design an HF LNA with decent specs. All of my previous designs have been push-pull, all with current and voltage feedback, originally using 2N5109s, then MRF-586s, and finally zeroing-in on the MRF-136 MOSFET. The Norton / Podell designs had the most success, so my final design is of that nature. The 2N5109s had a high noise figure, and terrible IP3. Using MRF586s got the noise figure down to 5 dB, but the IP3 was still unacceptable. Running the transistors at 50 mA, and 20 VDC, I achieved 53 dBm IP3, the best of the designs, but not anywhere good enough.

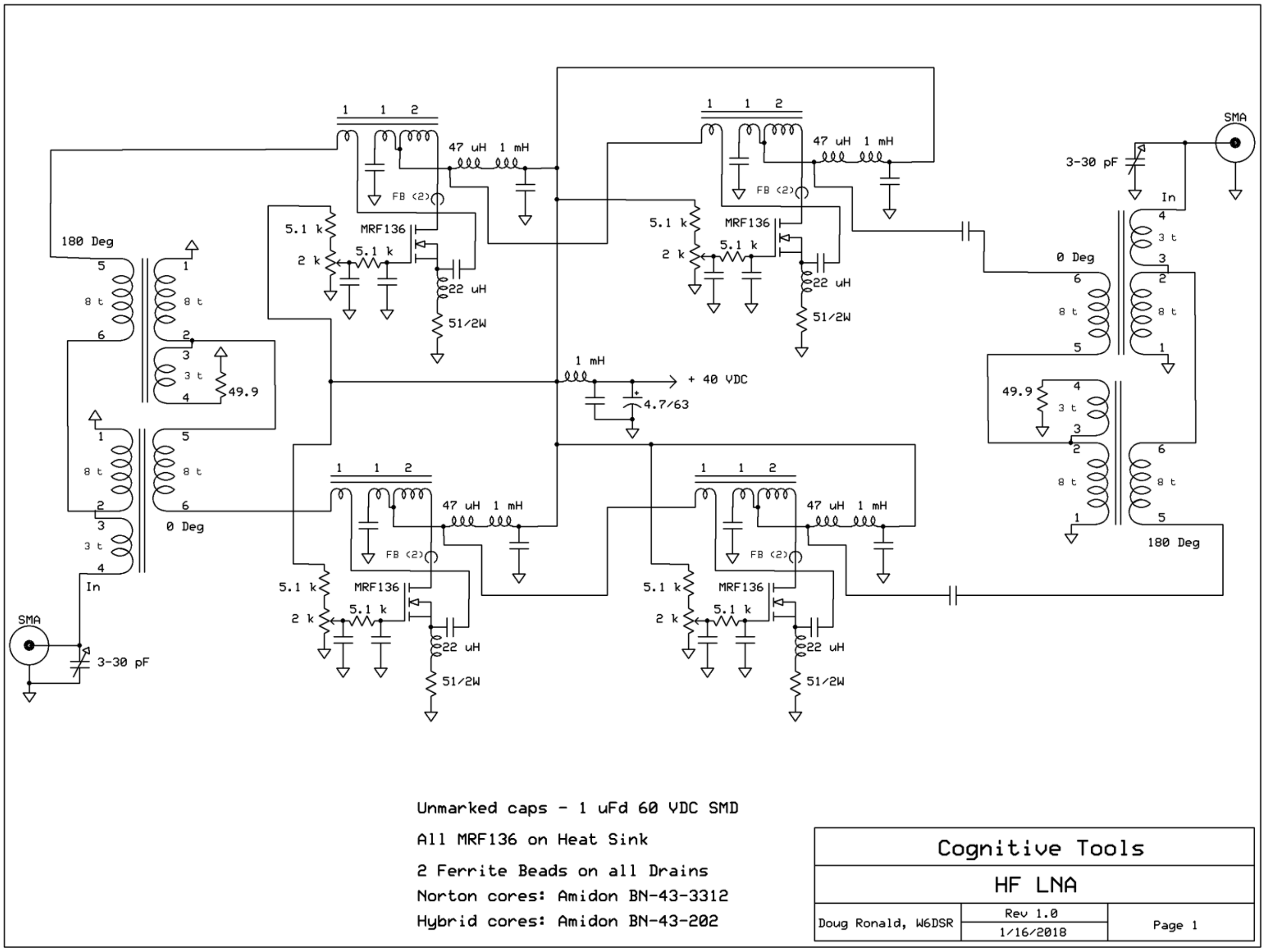
One thing most experimenters notice with the Norton Lossless Feedback Amplifier is that the achievable gain falls short of the theoretical gain. I found that mostly due to ignoring the emitter resistance of the transistors in the analysis leads to optimistic estimates for the gain. Also, any loading on the collectors which have high impedance will reduce the gain. The transformer design also needs to have tight coupling for good amplifier performance.

The transformer design is critical to the performance of the Norton configuration. I experimented with various designs where the ratios of 1:M:N determine the gain. The only ratio which yielded low noise, wide bandwidth, and high IP3 was the 1:2:1 ratio using RG-178 coax for tight coupling. Unfortunately, the gain is only 6 dB, so I had to cascade two stages in order to get near 12 dB of gain.

I never got a decent IP3 until I researched the lot of transistors available, and found the MRF-136 MOSFET. The input resistance of the common gate configuration is approximately 1/Gm, and since this transistor’s Gm is 400 mmhos, the input resistance is small, and the Norton’s gain is closer to the 6 dB theoretical. This transistor also can take 65 VDC drain-to-source along with a couple Amps of drain current. Another amazing statistic of this transistor is the noise figure of 1 dB at 150 MHz with an Amp of drain current. The transistor is in a 211-07 package and needs to be heatsinked, but the case is isolated from the transistor’s elements, and is easy to interface to.

Initial experiments with a single stage were very encouraging. I had 5.8 dB of gain, NF of 2 dB, and 55 dB of IP3 using 40 VDC drain-to-source, and 100 mA of drain current.

Figure 1: Schematic of the Amplifier



The amplifier consists of four identical modules of Norton Lossless Feedback design with MRF-136 MOSFET transistors as the current gain elements. The drain-to-source supply is 40 VDC, and each stage's current is adjusted with the gate bias adjustment to 150 mA. Each push-pull pair should have the bias fine-tuned to minimize the OIP2. Simply null the sum of the two-tone test signals.

The input (and identical output hybrid) is wound on two binocular ferrite cores to provide zero degree and 180 degree isolated outputs to feed in push-pull, the gain stages. Details on winding the transformers are given below. I used this configuration in order to present a 50 Ohm source to the amplifiers, and also obtain the necessary zero-degree, and 180 degree phases for the push-pull configuration. The transformers, constructed as shown below have less than 0.2 dB of loss from 0.5 through 55 MHz. They present > 40 dB isolation between the push-pull stages, lessening any tendency to instability with those high-gain, high ft, MOSFETS. The trimmers on the input side compensate for the leakage inductance, and are adjusted for best return loss with a VNA set to measure S11 (or S22 on the output side).

The current feedback transformers are also on binocular cores, and the windings are made from RG-178 50 Ohm coax in order to obtain very tight coupling. Details of the construction are given below. The amplifier's frequency response extends well into the UHF range if the ferrite beads are left off the MOSFET drains. However, without any ferrite beads, I found the MOSFETs were unstable, and sometimes oscillated in the 630 MHz region, thus, I would recommend at least one ferrite bead to get a flat response through 155 MHz. With two beads, response through the 6 meter band was obtained, but the FM band from 88 through 108 MHz had about unity gain.

I used SMD ceramic capacitors on the gates, and also for all the coupling capacitors. A 1206 size just fits between the copper ground plane and the gate of the MRF-136s.

I worried about DC in the windings partially saturating the ferrite cores, and affecting the IMD3, but with the binocular cores specified, even 200 mA of drain current had no effect on the IMD3. The drain current was selected to obtain that 1 dB of NF from the MOSFETS, and also to obtain that terrific 61 dBm of OIP3. With lower drain currents, the noise figure increases (unexpectedly), and the IP3 decreases.

Limitations

The calculation of the overall receiver's IP3 follows this formula:

$$ip3_c = \frac{1}{\frac{1}{ip3_{N-1} \times g_N} + \frac{1}{ip3_N}}$$

Where c = cumulative IP3 up to and including stage N, N = current stage, and N-1 = the previous stage. All IP3s are in power, not dBm. This calculation illustrates that each amplifier in the chain will degrade the overall IP3, by the previous stage's gains. In my receiver chain, the last amplifier before the A/D converter has only a 47 dBm IP3, which will degrade all my efforts to improve the front-end IP3. This monolithic amplifier needs to be replaced with a copy of my earlier stage LNAs. The saving grace for the time being is that a band-specific bandpass filter precedes this amplifier stage. With this 20 dB amplifier in place, my overall IP3 is only 43 dBm. I'll have to improve that before I can brag about the overall transceiver's performance.

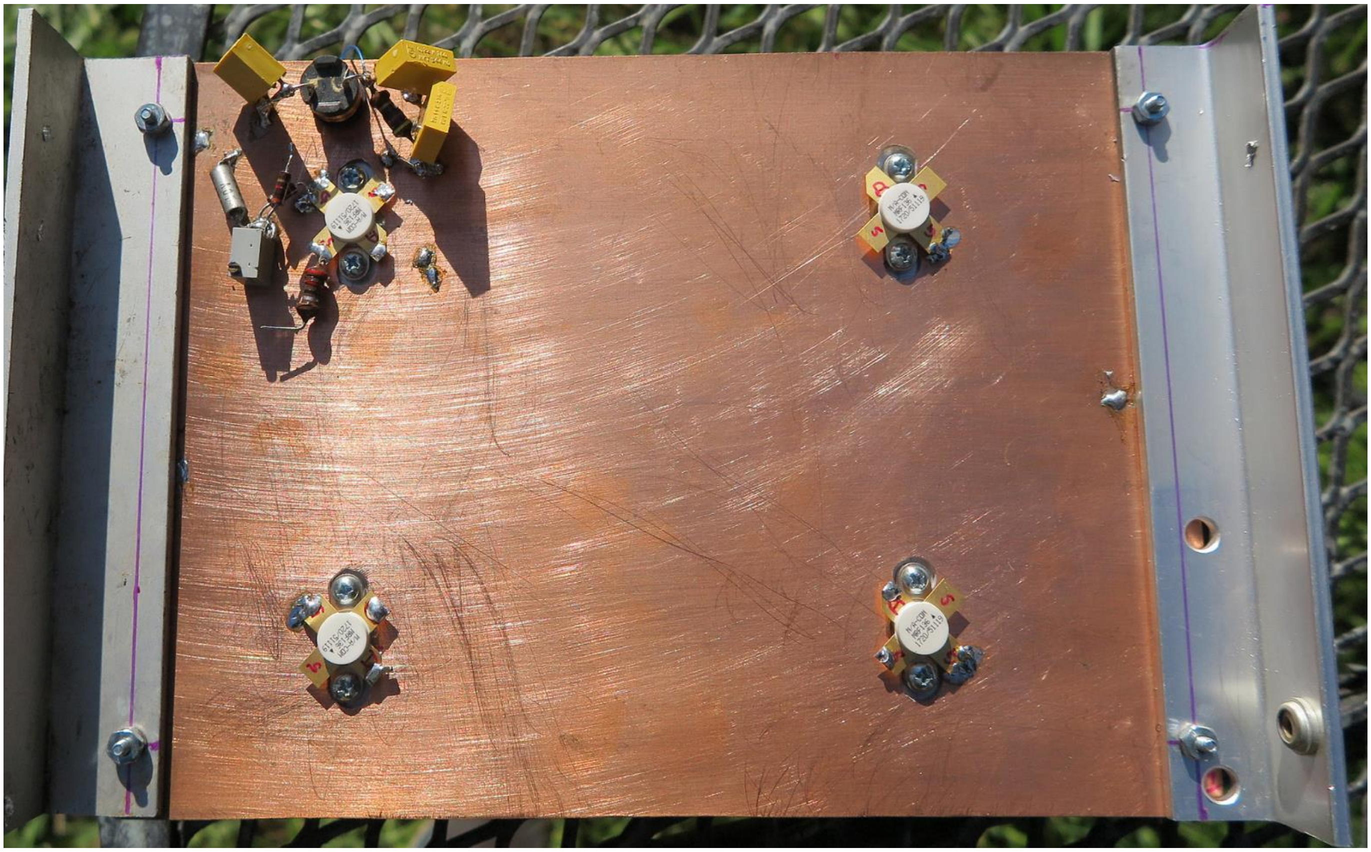
The overall noise figure is determined by the following formula:

$$Noise_{total} = 10log_{10}\left(n_1 + \sum_{i=2}^{M} \frac{n_i - 1}{\prod_{j-1}^{i-1} g_j}\right)$$

$$n_i = 10^{\frac{N_i}{10}};\ \ g_i = 10^{\frac{G_i}{10}};\ \ Gain_{total} = \sum G_i$$

My overall noise figure calculates out as 5.1 dB which is just about my original requirement.

Construction details

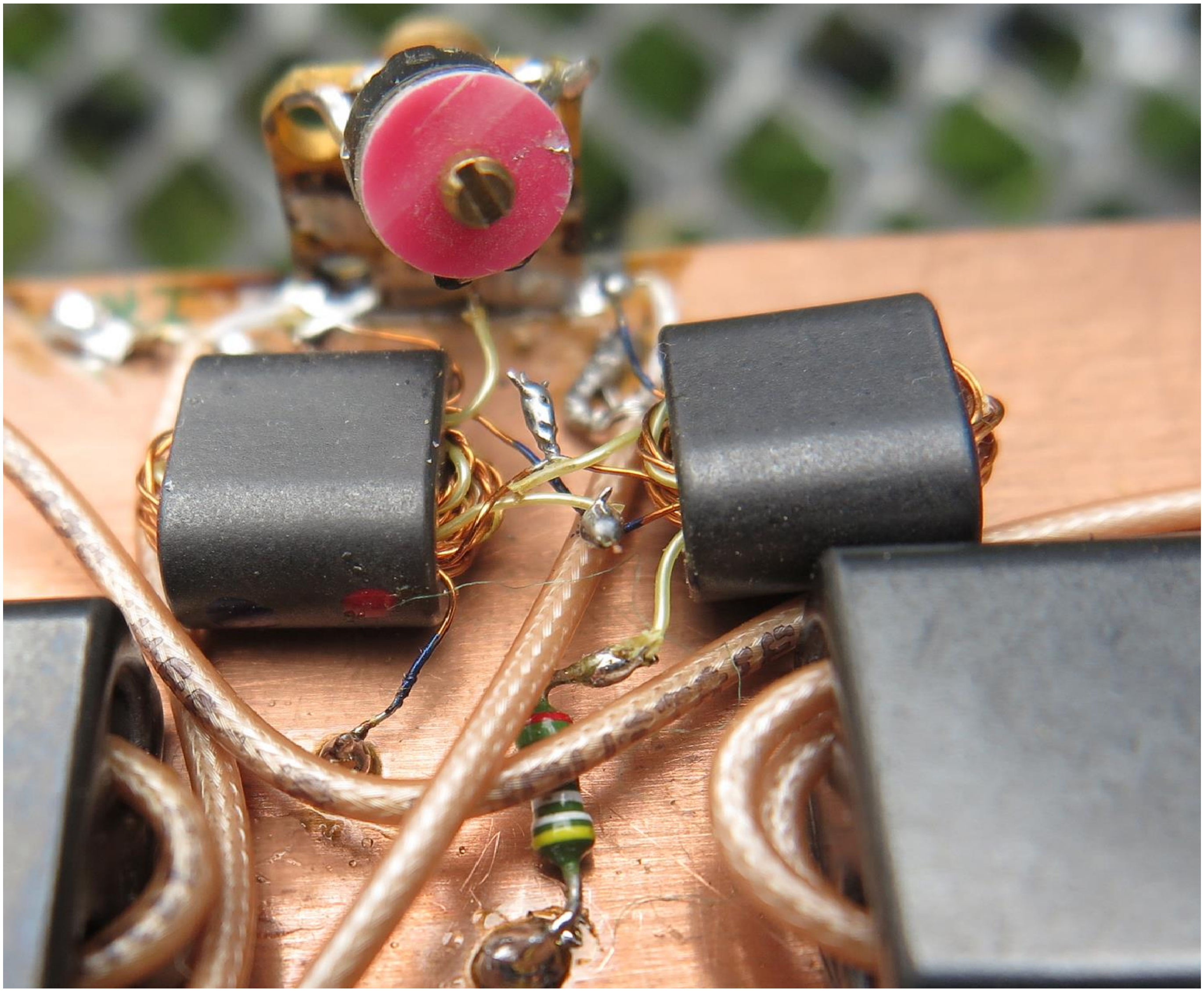


The LNA is built on a 10” x 6” x 1.5” aluminum finned heatsink. The unit if not enclosed in a tight box will not require a fan. I cut holes in the 10” x 6” copper board for the transistors, placed it over the heatsink with fasteners through some aluminum angle for mounting. I then mounted the MRF136s with a dab of heatsink compound. The fasteners for the transistors are exactly centered in-between a pair of heatsink fins. 4-40 screws with a washer just fit in the slots. I have already begun placing some of the bias and power supply components on the upper left corner FET.

Here is a close-up of one of the MRF136s illustrating how a couple 1206 size, 1 uFd, 60 VDC bypass caps just fit under the gate tab keeping it at a solid RF ground. I had used some of these FETS for other experiments, thus the residue solder on the terminals. I place these caps as soon as possible because the gates are static sensitive, and these caps provide some protection.

For the transformers, prepare the BN-43-3312 (an Amidon part number) ferrite binocular cores with a red dot to mark the polarity. Cut eight of the RG-178 coax windings to length so they just protrude from the core as shown in the image, and remove some insulation from the ends.

Next, I separate out the braid, and remove a section of the inner dielectric from the center conductor. It helps to red dot the same coax stub at both ends in order to keep straight how to make the connections. Connect the braids of one side's red dot stub with the un-dotted braid from the other binocular hole. This is the series connection for the two turn M part of the transformer. The one turn source feedback turn then connects to the source of the transistor. There are two source connections on opposite sides of the transistor, so I use one side for the 22 uH bias connection, and the other side for the transformer connection. Next I take a center conductor from the cold side of the binocular holes and bring it across to the braid of the other coax stub to form the RF output connection. I use 1 uFd, 60 VDC SMD caps to do all the bypassing, and the coupling because these caps have low series inductance, and excellent characteristics up through the GHz frequencies.



For the hybrids, I take three different colored wires, and with a power drill, tight twist them for a length to fit eight turns through the BN-43-202 (Amidon part number) plus for one of the wires, I leave enough for three turns free from the twisted group for the three turn part of the auto-transformer. Four total of these hybrid transformers are needed, and be careful about connecting the wires together or the hybrid will not work correctly. Above is an image of one hybrid. The yellow wire on the left transformer goes to the input SMA connector and is the three turn top of the autotransformer part. The three turn part of the other transformer, also yellow, shown on the right of the image goes to the 49.9 Ohm termination resistor.

If you want your LNA to invert, then cross-connect the hybrids from input-to-output. That is, put the 0 degree input side hybrid to the top MRF-136s, and on the output side of the top chain, put the output to the 180 degree side of the output hybrid. I prefer this inverting configuration which gives a slightly better S11 return loss.

Conclusion

The described HF LNA has finally met all of my desires; low noise, and high dynamic range. There are two downsides to the amplifier as designed:

1. The large power draw – with 40 VDC at 600 mA, these amps are power pigs, but I do not know how to design around that. Monolithic LNAs from the commercial sources are getting better all the time with respect to OIP3 and noise figure. I do not have knowledge of the internals to accomplish that, but I have not seen one yet that comes anywhere near 60 dBm of IP3.
2. The input impedance is totally reflected by the output impedance, and therefore it is imperative that the output of the amplifiers be terminated in 50 Ohms. I have tried to design an active 50 Ohm termination using various configurations. I configured a P8000 MOSFET as a common gate buffer, and got a really good match to 50 Ohms resistive, but at the drain current adjusted to optimize the Gm at 20 mmhos, the IP3 was only 47 dBm. I believe a complementary-symmetry push-pull configuration with the MRF-136 as the N-Channel device might work, but I could find no P-Channel device for the bottom half. My final solution to the matching problem was to insert 2 dB attenuators on the output of each of the amplifiers. This obviously reduces the gain, but at least maintains a decent input match.

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