Medium Frequency Amplifier Circuits Compared

Mark Connelly, WA1ION – 12 AUG 2003

Low-noise RF amplifiers are often needed in receiving applications when using antennas substantially smaller than what is considered efficient for a specified frequency range. Levels obtained from a given antenna may be on the verge of adequate if the antenna was being routed directly to the receiver, but when an intermediary phase-shift network is required to combine two or more antennas to form a directional pick-up pattern, the insertion loss of these additional components can bring weaker signals below the receiver's noise floor. Either as single elements or as components of a phased array, small antennas are being used quite often in receiving situations nowadays. These antennas are typically transformer-matched verticals (or dipoles) less than 1/10 of a wavelength and broadband loops enclosing an area whose square root is less than 1/10 wavelength

At frequencies of about 7 MHz (the 40 m amateur band) and lower, a compact-size receiving antenna is commonly used to reduce local electrical noise (versus what's present when using a transmitting antenna). Often something small is all that can be accommodated on an urban or suburban piece of land. Rooftop installations are common. Mobile DXpeditions, common among medium wave (0.5 to 2 MHz) DX listeners, make use of small loop and whip antennas mounted on vehicles when it is not feasible to run out a longwire (such as at beach sites near densely populated areas).

Terminated loops like the Flag, Pennant, K9AY, Ewe, and Kaz / Delta designs are quite popular for their directive properties, but output levels are often quite a bit less than from a longwire or Beverage. Even a Beverage, at a rural location during pre-sunset or post-sunrise conditions, could use a little assistance from a low-noise amplifier.

The main emphasis of this article is broadband amplification rather than tuned solutions. High-Q narrowband tuned amplification will give the ultimate in signal-to-noise and spur-free performance, but this approach is not often compatible with real-life DXing that employs practices such as using phasing to null interference, checking parallel channels quickly to verify a broadcast logging, and hearing the greatest number of stations in the least amount of time.

Many ways to achieve broadband gain have been developed over the years. Different radio enthusiasts have their "pet" methods. I figured that it was about time to step back and evaluate a few of these, both in a laboratory setting using standard test methods and with actual antennas of types likely to need amplification.

Usual laboratory tests for amplifiers include small-signal gain over a given frequency range, power compression at one or more frequencies of interest, and analysis of distortion (simple harmonics as well as two-tone intermodulation distortion). Noise figure or minimum discernable signal could also be tested in a laboratory setting, but I chose to do that end of the dynamic range equation with actual antenna and receiver "field" tests instead.

The bench test equipment consisted of a Rohde & Schwarz SMIQ-06 signal generator, a Hewlett-Packard (now Agilent) HP-8563E spectrum analyzer, an Allen Avionics F4281-1P0 bandpass filter (1 MHz, used to ensure a pure input tone for harmonic tests), an Agilent E3616A

DC power supply, and various coaxial adaptors, pads, and cables from Pasternack, Mini-Circuits, and Astrolab. For two-tone tests, additional equipment was used: Rohde & Schwarz SML-01 signal generator, a resistive power combiner, and a Narda 4745-69 step attenuator. C-language software in a LabWindows PC programming environment controlled instruments by means of a National Instruments GPIB card.

"Field tests" were done in the car with a Drake R8A receiver and two roof-mountable antenna types: a telescoping whip measuring 1.8 m / 6 ft., and a square single-turn loop of wire 2 m / 6.6 ft. per side mounted in the vertical plane and fed at the wire's only break, located at the midpoint of the bottom side.

The whip was coupled to test subject amplifiers #2 through #6 through a 100:1 homebrew step-down transformer at the antenna end of an approximately 3 m length of coaxial cable. This transformer consisted of 70 turns autotransformer-wound on an FT140-J core with a low impedance output tap 7 turns from the common ground connection. At the other end of the cable, the transformer associated with a given amplifier, as noted in the list below, was also in the path ahead of the active device. Test subject #7 consisted of the whip being fed directly to a high input impedance amplifier (BUF-E1) for reference purposes.

The broadband loop's two leads were connected directly to the low-impedance winding of the indicated transformer (see list below) ahead of test subject amplifiers #2 through #5. Test subject #1, requiring +24 VDC, was only tested in the laboratory setting.

Antenna to receiver testing primarily dealt with medium wave (0.5 to 2 MHz) performance at the two extremes of dynamic range: the ability to process very small signals (without covering them with noise) and to handle large signals (in-band and out-of-band) without creating harmonics and IMD products ("the signals that shouldn't be there"). Some of the antenna-based testing was performed in the driveway at my home location in Billerica, MA (25 km NW of Boston) and some tests were done at the Granite Pier DXpedition site in Rockport, MA.

The home tests concentrated on steady-state daytime signal-to-noise and gain evaluations and looking for any spurious signals. These "spurs" are usually caused by super-local WRKO-680 (50 kW at 4.4 km) mixing with strong stations on 850, 1030, 1510, and other channels.

The Rockport tests mostly concentrated on the broadband loop. Receiving was done in the critical 1 hour before sunset to 1 hour after sunset period. This was real-life DXing at a time of day when, with lesser grade amplifiers, spurious intermodulation distortion mixing signals from HF utility stations and from powerful 49 and 41 meter shortwave broadcasters are likely to show up on the medium wave band before the skip below 2 MHz has a chance to get up to full night-time strength. Adding to potential mixes are some super-strong groundwave signals including the WBZ-1030 big rig in Hull, MA (total waterpath), the Nantucket LORAN station on 100 kHz, and several of the coastal DGPS stations in the 325 kHz region. They're all "front end benders".

Evaluations at both sites provided several "acid tests" that showed some amplifiers to be superior to others.

Test Subjects (see Appendix for schematics)

1. Mini-Circuits ZHL-32A (schematic not available)
2. 1:1 transformer to W7IUV amplifier (active device: 2N5109)
3. 1:9 transformer to BBVA-A amplifier (active device: VN10KM)
4. 1:36 transformer to BUF-E1 amplifier (active device: LM6221N)
5. AD9632 op-amp based amplifier (includes 1:4 input transformer)
6. amplifier using Mini-Circuits ERA-5SM “pillpack” RF IC
7. BUF-E1 fed by whip antenna (used for comparative antenna tests)

Gain / sensitivity

One of the first amplifier specifications of interest to most users is gain: how much more signal do I get out from what I put in. This is usually specified at input signal levels that are small, since that’s when employing an amplifier is necessary. In the laboratory, measurements were taken at a number of frequencies with an input level of about –25 dBm. Evaluated amplifiers gave results as follow.

1. Mini-Circuits ZHL-32A: Gain was about 28.5 dB over the 0.3 – 30 MHz frequency range. Response was flat within +/- 0.2 dB.

2. W7IUV amplifier: Gain was in the 19 to 21 dB range between 0.3 and 17 MHz. Response rolled off smoothly to 14.5 dB at 30 MHz. *A variant of this amplifier, the ECP-1 Elbert County Preamplifier (made by Lance Johnson Engineering, e-mail: lance@diac.com) was given a gain test as well: it has lower gain (11 dB typical). To test ECP-1 below 1.8 MHz, its high-pass filter had to be removed.*

3. BBVA-A amplifier (after 1:9 step-up transformer): Better than 24 dB of gain below 4 MHz, response rolls off to about 20 dB at 9.5 MHz, 15 dB at 20 MHz, and 10 dB at 30 MHz.

4. BUF-E1 amplifier (after 1:36 step-up transformer): 18 dB gain up to 2 MHz, about 16 dB at 4 MHz, 10 dB at 10 MHz, 6 dB at 16 MHz, and no gain (or some loss) above 26 MHz. Changing the input transformer to a 1:16 affected gain to get about 13 dB below 9 MHz, 10 dB at 16 MHz, and 7 dB or less above 20 MHz.

5. AD9632 amplifier (with included 1:4 step-up transformer): 27 dB (or slightly better) below 8 MHz, gradually rolling off to 25 dB at 18 MHz and 22.5 dB at 30 MHz.

6. Mini-Circuits ERA-5SM amplifier: 18 dB or slightly better gain below 10 MHz, rolling off slowly to about 16.8 dB at 30 MHz.

Field tests of gain produced results similar to those noted in the laboratory setting. Gains at 1 MHz and at a few other frequencies were evaluated against a passive version of the antenna: broadband loop to receiver via 1:1 transformer, or whip to receiver via 100:1 step-down transformer. Mini-Circuits ZHL-32A was not tested. A previous check of this with a receiver showed a fairly high noise floor. Of amplifiers tested, the AD9632 and 1:9 + BBVA-A circuits showed the most gain, about 23 dB, the W7IUV came in at about 19 dB, and the 1:36 + BUF-E1 and the ERA-5SM were in the 14 dB range. The lower numbers versus the lab tests probably have more to do with Drake R8A S-meter accuracy than anything else. The 1.8 m whip directly to a BUF-E1 amplifier (high impedance configuration) had about 17 dB of gain over the whip being coupled passively to the receiver through the 100:1 transformer. This does show that a passively-coupled whip with amplification at the operating position, when required, can compete gain-wise with the traditional active whip having the high impedance to low impedance buffer amplifier at the “head end” out in the weather.

The difference in minimum discernable signal (on weak stations) versus self-generated noise was not drastic among the amplifier types tested. BUF-E1 is about the quietest, but its gain is a bit lower too. The AD9632, with the highest gain, is also somewhat noisier than the others. The ERA-5SM is rather noisy. The W7IUV seems to be the best compromise in gain versus signal-to-noise and the BBVA-A does a reasonable job, too.

Strong signal handling

A low noise floor and lots of gain is of minimal value if the spectrum of received frequencies is polluted by mixing products and harmonics caused by an amplifier’s inability to cope with large signals elsewhere in the band of interest, or even outside of the band. There are several ways to evaluate the ability of amplifiers to maintain linear response under large signal conditions.

Gain compression is one test that is fairly easy to do in a laboratory setting on automatic test equipment. As an input signal is increased, amplifier output increases by the same amount until it reaches a large enough level that clipping or other “running out of headroom” begins to occur. An amplifier that, for a given frequency small-signal input, has a gain of 20 dB, will have a gain of 1 dB less, i.e. 19 dB, at some larger input level. The test equipment is programmed to find the “1 dB compression point” by incrementing the RF generator level up in small steps, 0.1 or 0.2 dB typically, until the point is reached where amplifier gain is 1 dB less than it is for a “small signal” at the same frequency. Amplifiers with a higher compression point can generally pass larger signals with less distortion. Compression points at 1 MHz found for the test subject amplifiers, from best to worst, are:

• Mini-Circuits ZHL-32A	+5.5 dBm in	+32.5 dBm out
• W7IUV	+4.7 dBm in	+24.0 dBm out
• 1:36 + BUF-E1	+3.5 dBm in	+19.8 dBm out
• 1:9 + BBVA-A	-1.2 dBm in	+23.2 dBm out
• Mini-Circuits ERA-5SM	-3.7 dBm in	+13.5 dBm out
• AD9632 (with 1:4)	-8.7 dBm in	+18.0 dBm out

The ZHL-32A runs on +24 V with a current drain of 450 mA, so a comparison with amplifiers running on nominal +12 V DC supplies with less current isn't a completely fair comparison. It has a higher noise floor since its primary role is jacking up the output level of RF signal generators rather than being a device to place ahead of a sensitive receiver.

Harmonic suppression is another important strong-signal test worth doing. The signal source being used must be spectrally pure to keep its own harmonics out of the amplifier. The Rohde & Schwarz sources, though quite expensive, only suppress second harmonic output by 40 to 45 dBc (dB relative to the fundamental carrier). This isn't good enough by any means. To improve source harmonic suppression by another 70 dB or so, a narrow bandpass filter centered on 1 MHz (Allen Avionics F4281-1P0) was used ahead of the input to the amplifier-under-test. Each amplifier was driven by a –20 dBm bandpass-filtered 1 MHz tone. A Narda step-attenuator was used between the amplifier output and the spectrum analyzer input to verify that harmonics observed were not the result of overloading the spectrum analyzer's front end.

In the following list, "supp2" means second harmonic suppression and "supp3" means third harmonic suppression. The harmonic suppressions of the amplifiers, from best to worst, are:

• Mini-Circuits ZHL-32A	74.0 dBc supp2	77.8 dBc supp3
• W7IUV	67.7 dBc supp2	72.7 dBc supp3
• 1:36 + BUF-E1	61.3 dBc supp2	69.8 dBc supp3
• AD9632 (with 1:4)	48.7 dBc supp2	73.0 dBc supp3
• Mini-Circuits ERA-5SM	38.2 dBc supp2	69.0 dBc supp3
• 1:9 + BBVA-A	37.7 dBc supp2	59.8 dBc supp3

Two-tone intercept testing gives true-to-life evaluations of amplifier performance in the presence of multiple strong signals. For input tones at f1 = 0.9 MHz and f2 = 1.1 MHz, the levels of second order products (f2-f1) = 0.2 MHz and (f2+f1) = 2.0 MHz were checked. Third order tones at (2f1-f2) = 0.7 MHz and (2f2-f1) = 1.3 MHz were then measured. The suppressions of these mixing products were entered in formulas to compute the output second order intercept point (OIP2) and the output third order intercept point (OIP3). The higher the values of these points, the more capable an amplifier is to handle strong signals without introducing unwanted artifacts. The two Rohde & Schwarz sources were each outfitted with attenuator pads to keep one source from causing intermodulation products in the other, and vice versa. The outputs of the attenuated sources connected to a resistive combiner ahead of the input of the amplifier-under-test. That amplifier's output connected, via the Narda step-attenuator, to the spectrum analyzer. The software controlling the stimulus and measurement instruments also computed the OIP2 and OIP3 values. These are shown below in order of OIP3 merit:

Mini-Circuits ZHL-32A	+33.2 dBm OIP3	+60.2 dBm OIP2
W7IUV	+33.1 dBm OIP3	+55.7 dBm OIP2
1:36 + BUF-E1	+32.5 dBm OIP3	+51.2 dBm OIP2
1:9 + BBVA-A	+31.7 dBm OIP3	+41.8 dBm OIP2
AD9632 (with 1:4)	+27.9 dBm OIP3	+62.0 dBm OIP2
Mini-Circuits ERA-5SM	+25.5 dBm OIP3	+33.1 dBm OIP2

Antenna testing for strong signal performance is the truest test of "where the rubber meets the road".

During the daytime tests at the home QTH, I checked 1360 kHz for an amplifier-produced second harmonic of super-local WRKO-680. Mixes such as 170 kHz (WEEI-850 minus WRKO-680), 350 kHz (WBZ-1030 minus WRKO-680), 510 kHz (2*680, minus 850), and others were also used to rate amplifiers on a scale ranging from "crunchproof" on one end to "feeble" on the other. The 1:36 + BUF-E1 and the W7IUV had the best performance, BBVA-A and AD9632 were a bit less bulletproof, and the ERA-5SM came in last.

Sunset-period tests at Rockport, MA largely involved suppression of IMD products in the medium wave band that were caused by shortwave signals. The 1:36 transformer + BUF-E1 has gain which rolls off above 5 MHz. This, no doubt, helped in keeping the medium wave band "spur free". The W7IUV amplifier, being more broadbanded, showed some threshold-level shortwave IMD products, but was still very "clean" overall. The 1:9 transformer + BBVA-A, having decreasing gain above 10 MHz, also did reasonably well, though it was somewhat more susceptible to harmonics of LORAN – 100 kHz. The AD9632 amplifier fell down on the job by comparison: quite a few shortwave mixing products intruded into the medium wave band. The ERA-5SM amplifier was not evaluated in the sunset-period testing at Rockport. Its previous last place finish in the two-tone intercept lab tests and the strength of the 680*2 = 1360 harmonic in the home-based antenna tests didn't bode particularly well for its serious DXpedition use anyway.

Conclusions

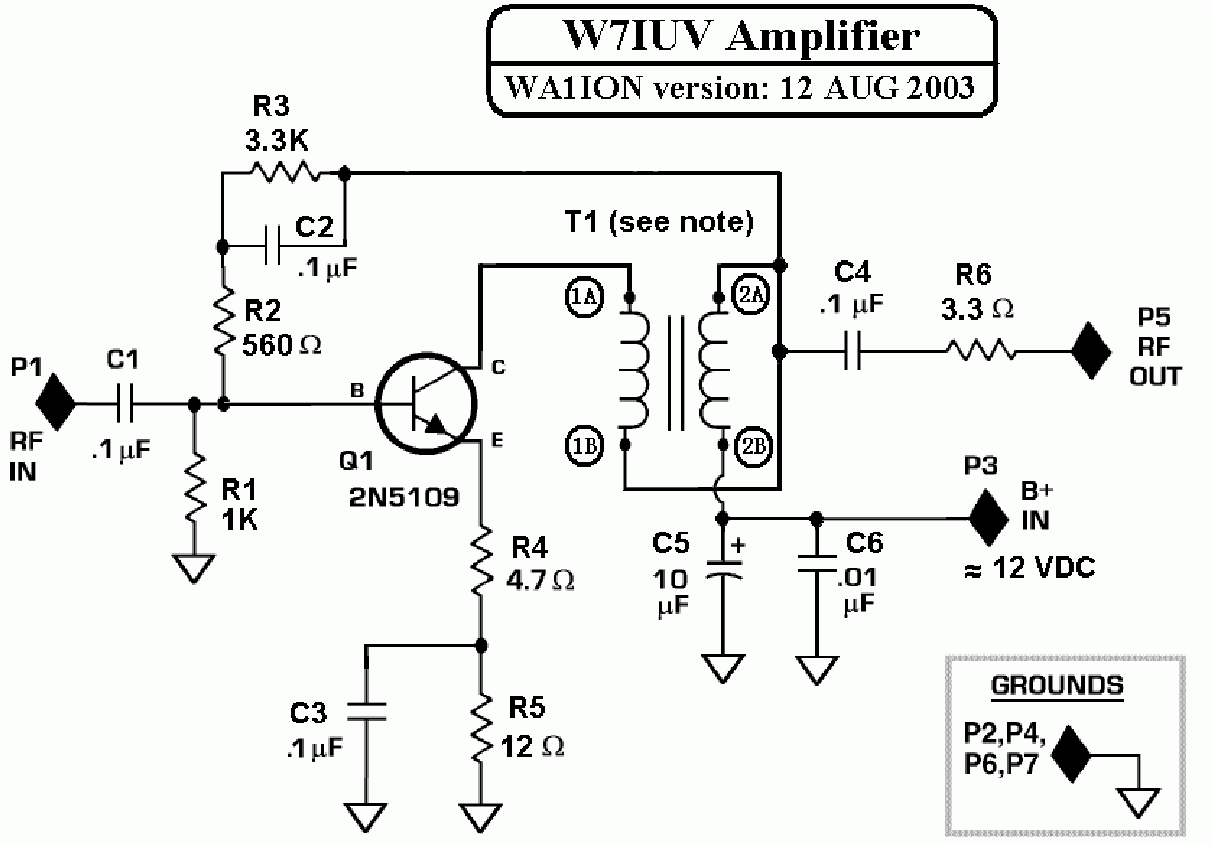
For good coverage of the entire 0.3 to 30 MHz range, the W7IUV amplifier has a lot to recommend it. Those who are mostly interested in frequencies below 7 MHz will have comparable results with the 1:36 transformer to BUF-E1. This has substantially lower current drain. BBVA-A is also worth considering for its high gain, though it's a bit down the ladder in the area of distortion-free performance. The ERA-5SM and AD9632 based amplifiers have some "niche" uses, but these usually aren't going to be your first or second choice.

Chances are good that comparable, or better, performance could be had from some other amplifier circuit topologies such as common-gate FET, push-pull, noiseless feedback, or global negative feedback (a la Dallas Lankford). In all probability, at some future date, a sequel to this article will be written, either by me or by someone else. That could be a good opportunity to showcase some of the other good amplifier designs out there.

Appendix: Schematic Diagrams of Amplifier Test Subjects

Web links were accurate at the time of publication. These may change over time.

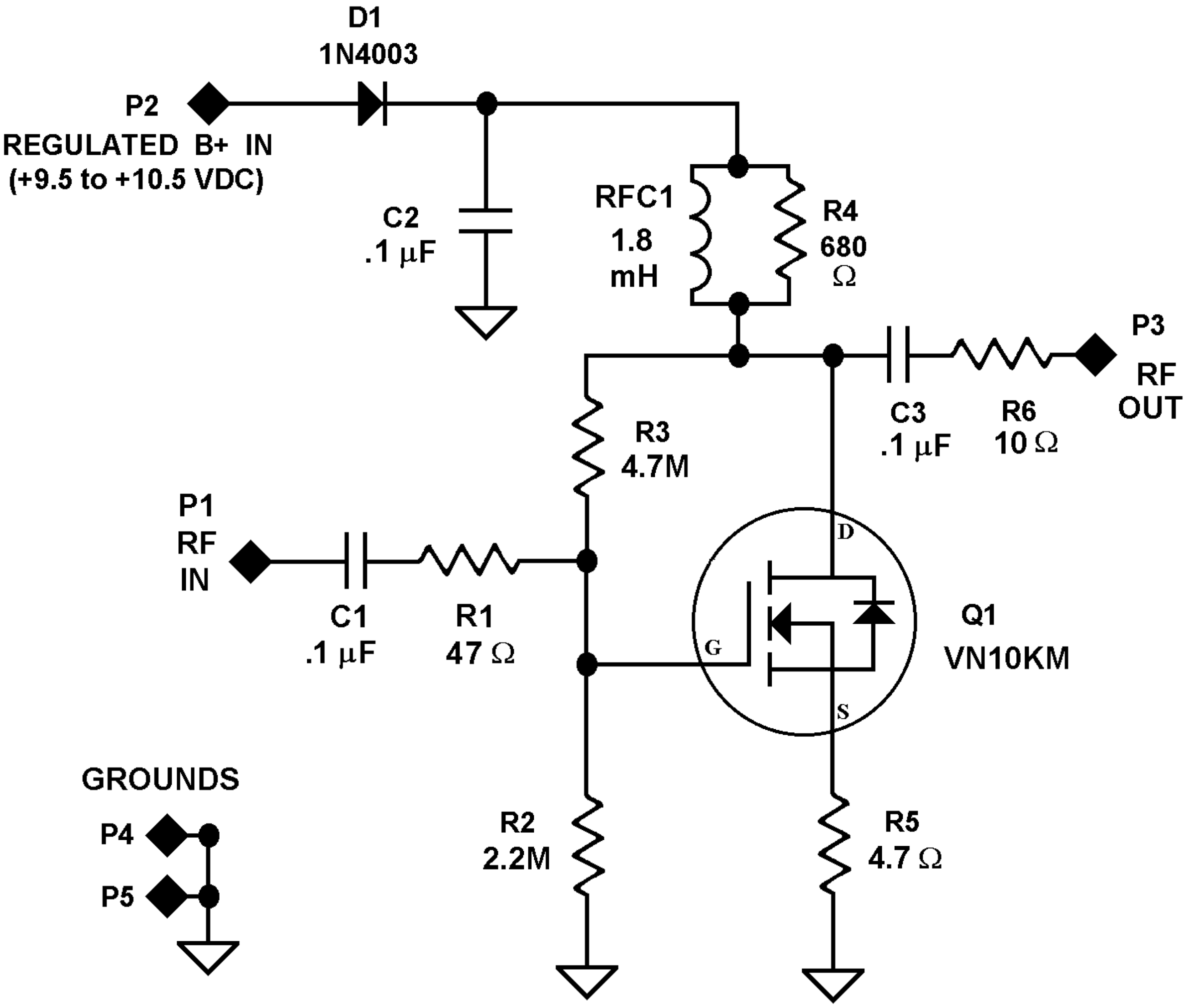
W7IUV amplifier (2N5109-based)
Web Link "http://www.qsl.net/wa1ion/amp/w7iuv_amp.htm"
Current drain about 80 mA. Used after a Mini-Circuits T1-6-X65 transformer (balanced in, unbalanced out) for **Test Subject #2**. A 2N3866 may be substituted for the 2N5109.



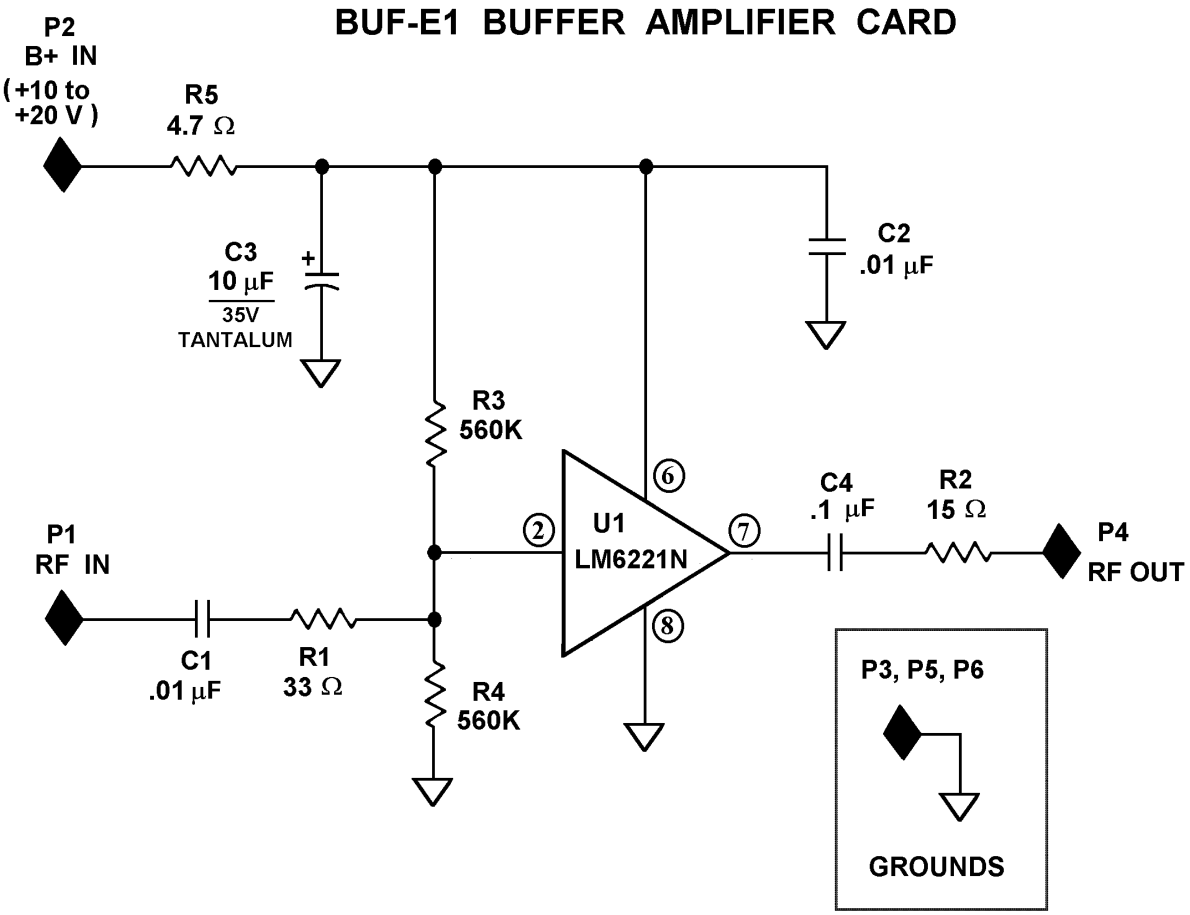
Notes:
T1 = 10 turns bifilar on Amidon FT82-43
Gain ≈ 18 to 20 dB
1 dB compression ≈ 20 to 24 dBm
OIP3 ≈ 33 to 39 dBm

<u>**BBVA-A amplifier**</u> (VN10KM-based)
Web Link "http://www.qsl.net/wa1ion/bbva/bbva_a.htm"
Current drain about 110 mA. Used after a homebrew 1:9 step-up transformer (Fair-Rite 2873000202 or Amidon BN73-202 binocular core: 3 turns: 9 turns) for **Test Subject #3**.

SCHEMATIC: BBVA-A BROADBAND AMPLIFIER CARD

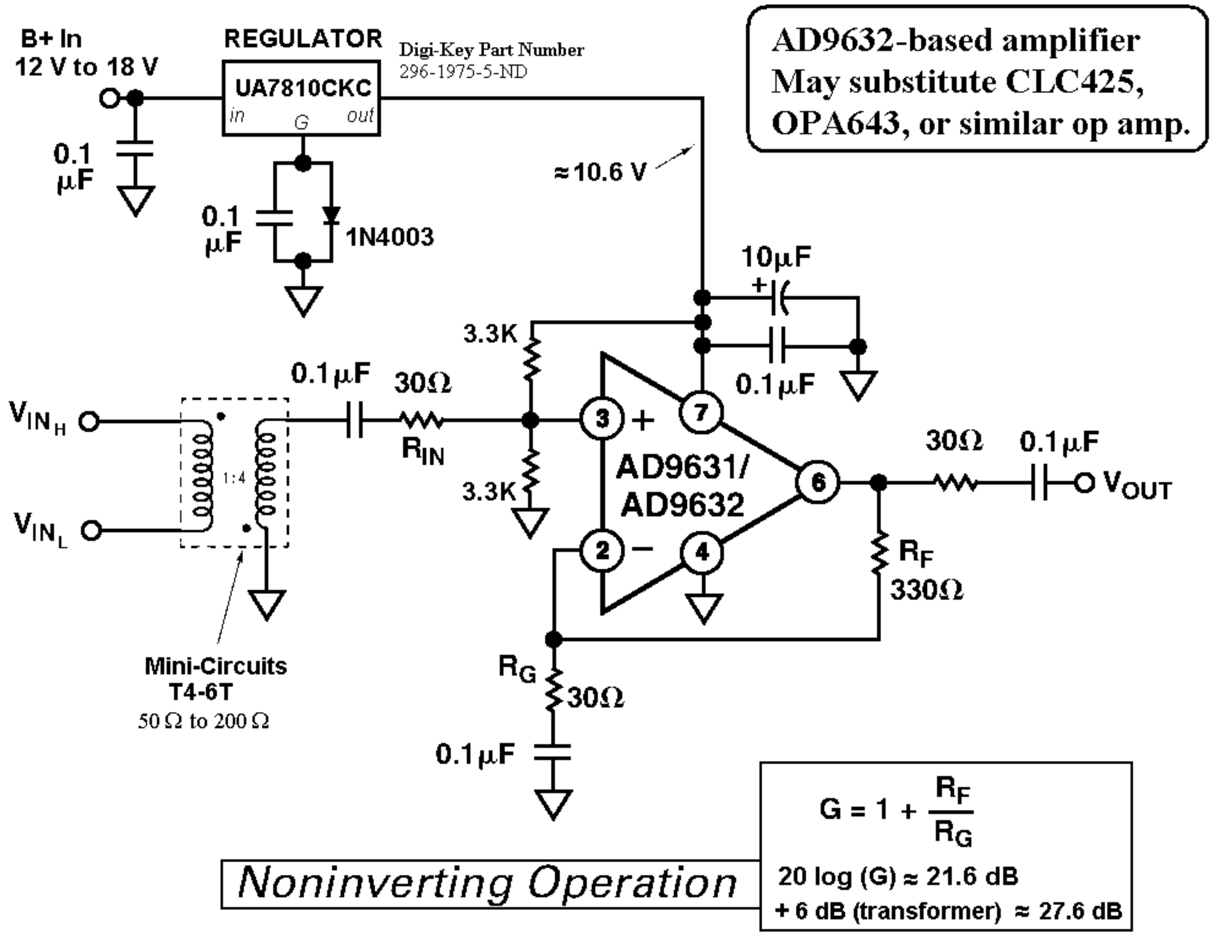


BUF-E1 (National LM6221-based)
Web Link: "http://www.qsl.net/wa1ion/buffers/buf-e1.zip"
Current drain about 20 mA. Used after a Mini-Circuits T36-1-X65 transformer in step-up mode for **Test Subject #4** and straight from output of 1.8 m / 6 ft. whip for **Test Subject #7**. Other buffer IC's, such as BUF634, may be used with changes to wiring as necessary.



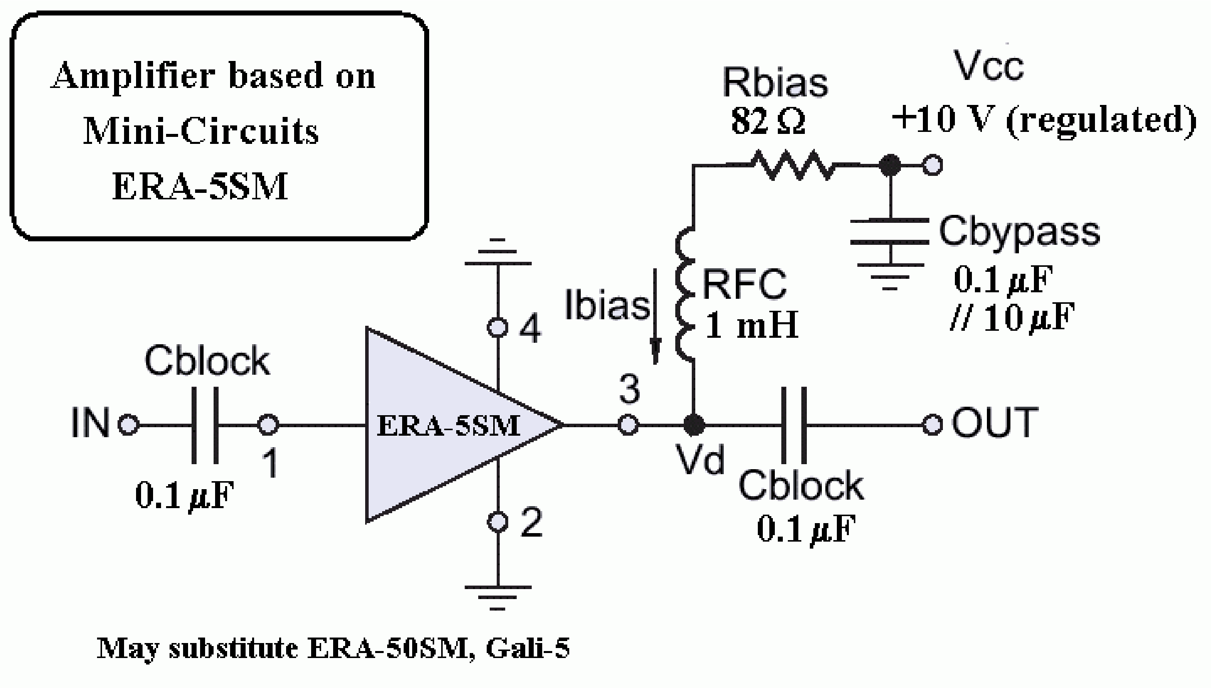
AD9632 op-amp based amplifier

Web Link "http://www.qsl.net/wa1ion/amp/ad9632_amp.gif"
Current drain about 45 mA at full output. Includes Mini-Circuits T4-6T-X65 transformer in step-up mode. Used for **Test Subject #5**.



Mini-Circuits ERA-5SM based amplifier

Web Link "http://www.qsl.net/wa1ion/amp/era-5sm_amp.gif"
Current drain about 80 mA. Used for **Test Subject #6**, bench tests and active whip tests only.



May substitute ERA-50SM, Gali-5