About this Article

This material was included with the downloadable supplemental content accompanying the *ARRL Antenna Book*.

You may print a copy of this material for personal use. Any other use of the information requires permission from the ARRL.

Active Loop Aerials for HF Reception, Part 2: High Dynamic Range Aerial Amplifier Design

Want to build an effective low-impedance preamplifier? Try an augmented common-base circuit.

By Chris Trask, N7ZWY

The performance of any receiving system is highly dependent on the first few stages, and very often the aerial itself is not given consideration as being a part of that system, let alone being recognized as the stage that determines the minimum noise figure (*NF*) that can be realized. Aerials having poor efficiency or that are not properly matched to the receiving unit can cripple the ability of the operator to receive low-level signals. Electrically small aerials, regardless of their configuration, are especially vulnerable to low efficiencies and hence become the critical element in a receiving system where larger aerials with good efficiency are impractical for any of a variety of reasons. With many radio amateurs and shortwave broadcast (SWBC) listeners living in apartments or subject to property zoning restrictions, small aerials having good performance, both for transmitting and receiving, have become increasingly in demand. This two-part series will describe the theory and practical aspects of a high-performance active receiving loop aerial design.

Sonoran Radio Research
PO Box 25240
Tempe, AZ 85285-5240
ctrask@ieee.org

Loop Aerials—A Brief Review

In the first part of this series, compact aerials for limited space applications were discussed, along with a few options such as short vertical monopoles, short dipoles and loops.[1] Afterwards, the various design aspects of loop aerials were examined using a variety of analytical and simulation methods to evaluate the efficiency, impedance and radiation patterns of single-turn and multiturn loop aerials. A single-turn loop having a diameter of 1 m using ¼-inch copper tubing was examined in detail both analytically and experimentally, showing that the aerial was usable for frequencies from roughly 5 MHz to 15 MHz. In this, the second and last part of the series, the aerial amplifier, tuner and control unit will be described.

[1]Notes appear on page 48.

Active Aerials—An Historical Perspective

Electrically small aerials are well known for their low impedance characteristics. The bulk of literature on their design and performance focuses on the preamplifier rather than the aerial element itself since the low resistance of the aerial represents a significant performance limitation.[2] Since reception of signals in the 10 kHz to 30 MHz spectrum is strongly hampered by external atmospheric, man-made and galactic noise, there is little reason to design a receiving system that has a noise contribution far below the received external noise (see Note 2).

It is, however, essential that the active aerial amplifier is designed with the maximum possible dynamic range, which suggests that both NF and IMD performance be considered in the design. Most active aerial amplifier designs tend to focus on the NF performance while giving IMD performance little attention. There are some notable exceptions, such as that proposed by Nordholt and van Willigen.[3]

Aerial Amplifier and Tuner

A complete schematic of the aerial amplifier and tuner is shown in Fig 1. Balun transformer T1 is specifically designed for low impedances. It couples the balanced loop aerial to an unbalanced tuner consisting of varactor diodes D2 and D3 and inductor L1. An augmented common-base amplifier, consisting of Q1 and Q2 and T2 with very low input impedance, a low *NF*, and a high *OIP3* then follows this. This amplifier couples the low-impedance loop aerial to the higher impedance of the coaxial cable by way of a common-base amplifier consisting of Q3, T3 and T4. The voltage regulator U1 provides a stable bias voltage for the amplifier stages while Zener D1 provides a prescribed drop from the supply voltage to the tuner unit, allowing the varactor diodes to have a tuning voltage of approximately 0.5-12 V. The theory and design of the balun transformer and augmented amplifier follow in detail.

Low-Impedance Wide-Bandwidth Transformers

As we noticed in Part 1 of this series, a very low resistance in series with an inductance characterizes the loop aerial impedance. We also learned that it is best to operate the loop aerial with a balanced feed to enjoy the full frequency range available and retain the radiation-pattern nulls that give this compact aerial ideal directivity performance. To maintain this balance, it would be preferable that the antenna be coupled to the tuner by way of a broadband balun transformer before applying any tuning. The reason being that it is both difficult and expensive to go about matching varactor diodes to achieve a balanced tuning capability. Such configurations are best left to motor-driven dual variable capacitors, an even more expensive option that need not be considered for an active receiving aerial. We must also keep in mind that to maintain the efficiency of the aerial, the balun as well as the entire tuning section needs to be designed to minimize loss.[4, 5]

In the design of broadband transformers, several details need to be considered. To begin, the ferrite or powdered-iron material in the core must be appropriate for the operating frequency range. Choosing the wrong material can lead to either insufficient coupling at low frequencies, or excessive core losses at high frequencies. For a broadband transformer being used at low impedances, either of these can prove fatal. Generally, the choices for HF can be cobalt-nickel-zinc ferrites such as Ferronics mix K or a high permeability carbonyl-powdered-iron material such as Micrometals mix 8. For low HF frequencies, nickel-zinc ferrites such as Ferronics mix J or Fair-Rite mix 61 are good choices, while for frequencies below HF, manganese-zinc ferrite materials such as Fair-Rite mix 44 will give good performance. Remember that powdered-iron

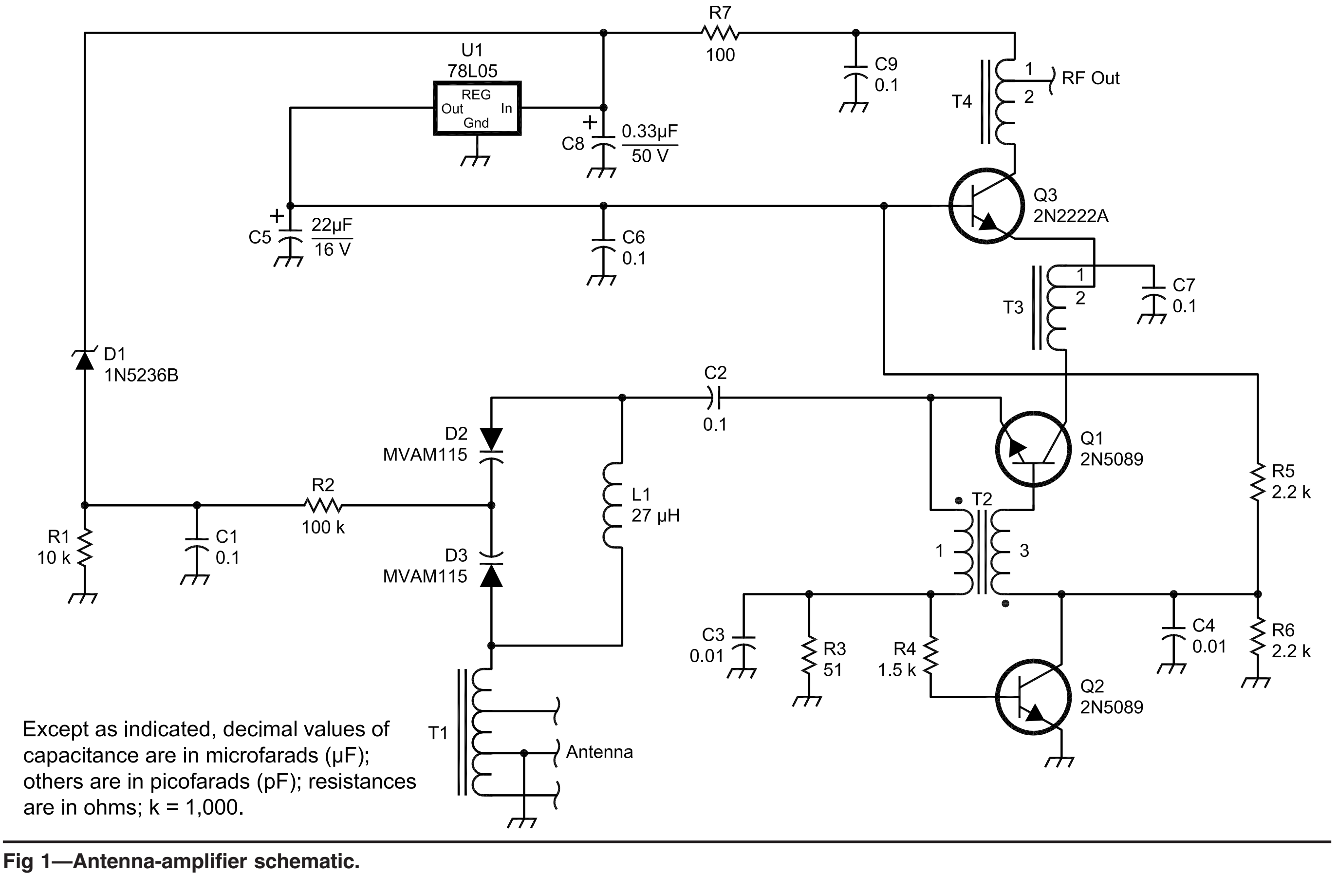

Fig 1—Antenna-amplifier schematic.

materials are "lossier" than ferrites,[6] but they are preferable for broadband transformers at upper HF and beyond.

The shape of the core is also an important factor. Broadband transformers wound on toroidal cores have the highest degree of leakage inductance, which lowers the maximum usable frequency of the transformer and lowers the high end of the aerial's tuning range. The balun (or binocular) core is generally the best shape for all practical purposes. For low frequencies, pot cores give even better performance because their leakage inductance is lowest and they deliver inductors and transformers of much higher *Q*.[7] Not all materials are available in all shapes; this further decreases the options available. The materials mentioned earlier are all available as balun cores, while additional materials are available in the form of toroids and pot cores.

Then there is the matter of the wire. For both good balance and coupling, the wires should all be twisted together. This implies that each strand will be of the same length. Also, the number of wires should be chosen so that the inter-wire coupling is uniform.[8] Fig 2 illustrates the reason for this last statement. In the first case there are only two wires, and obviously the inter-wire capacitance, hence the coupling, is uniform. In the second case, there are three wires, and the inter-wire capacitances are equal between all three wires, again making the coupling uniform between all the wires. In the third case where there are four wires, the capacitances are not equal. For immediately adjacent wires, the inter-wire capacitance is of value *C*, but for the diagonally opposite wires the capacitance is reduced to 0.707 *C*, which means that the coupling is not equal between all four wires.

From this, it should be obvious that for uniform coupling in broadband transformers, the number of wire strands should be limited to either two or three. Since we want to make a balun transformer, this brings our choices down to three wires, for which there are two configurations available, (see Fig 3). In the first case, the balun has a balanced-to-unbalanced impedance ratio of 4:1. Since the loop aerial already has very low impedance, reducing it by a factor of four will make the design of the broadband transformer and the aerial amplifier more difficult. The second balun has a balanced to unbalanced impedance ratio of 1:1, which although it doesn't improve the low-impedance situation, does not make it any worse. In addition, the direct coupling between the unbalanced and balanced terminals of the second case will improve the coupling at lower frequencies, allowing us to use less wire and core materials. This helps in lowering both the resistive losses and the leakage inductance.[9]

Taking all of these details into consideration, balun transformer T1 consists of two turns of trifilar #32 AWG enameled wire, having twelve twists per inch, on a Fair-Rite 2861002402 balun core. The remaining transformers also use this core. T2 consists of two turns and six turns of #32 AWG wire. T3 and T4 each consist of two turns and four turns of #32 AWG wire. With these transformers, the aerial amplifier gives good performance up to 20 MHz, after which increasing core losses cause the *Q* of the tuner to deteriorate. Constructing the transformers using Ferronics K material cores gives good performance up to 24 MHz, but these cores are both difficult and expensive to obtain.

Tuning Section

The tuning section of the aerial amplifier consists of varactor diodes D2 and D3 and inductor L1. The MVAM115 hyper-abrupt varactor was chosen so as to give a wide tuning range. These are difficult to find now, and the NTE618 makes a good substitute. The tuning voltage is derived from the supply voltage passing through the coaxial cable, which is dropped 7.5 V through the 1N5236B Zener diode D1. This drop is necessary because the 78L05 (U1) voltage regulator requires a minimum of 8.0 V to provide adequate regulation for the amplifier 5-V bias. The tuning voltage is applied to the varactors through R2. The dc ground for the varactors is by way of the input balun transformer and L1, the value of which is chosen to provide a parallel-resonant trap for AM-broadcast signals when tuning at the low end of the range.

Carefully choose C2 because it is in series with the antenna and the amplifier input stage, both of which have low impedance. This capacitor should have an exceptionally low equivalent series resistance (ESR) so as to minimize additional losses in the initial stages of the active aerial. Ceramic capacitors made with materials such as Y5V and Z5U will cause the gain, *NF* and tuning *Q* to deteriorate with increased frequency because of their relatively high ESR. Instead, use high quality porcelain capacitors such as the 200B series from American Technical Ceramics (ATC). In a simple test, the performances using a Y5V ceramic disc versus an ATC 200B porcelain chip capacitor were evaluated. The difference was an additional 15 dB of gain and a fivefold increase in the tuning *Q* at 15 MHz.

Augmented Amplifier

Earlier, I mentioned that a major limiting factor in the noise performance of an active aerial is the low antenna resistance, so low that even a theoretical fourfold increase will not offer any significant performance improvement (see Note 2). From this, it is obvious that the burden for designing high-performance active aerials lies in the design of the aerial amplifier itself. The characteristics that define a suitable amplifier include, but are not limited to, low input impedance, low noise figure and low distortion. Most aerial amplifiers answering to these criteria generally fall into the configurations of grounded-grid, common-gate and common-base. Of these,

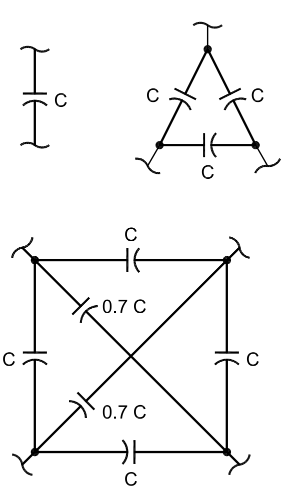

Fig 2—Inter-wire capacitances for twisted-wire transmission lines.

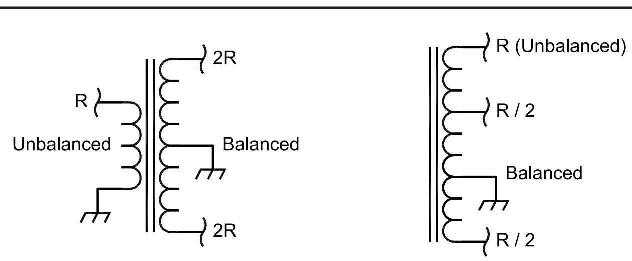

Fig 3—Balun configurations using three twisted wires.

common-base amplifiers offer the best opportunity as they tend to have much lower input impedances than their common-gate counterparts, and a low NF is easily obtained. One drawback, however, is that the input impedance is actually the nonlinear emitter-base junction, which is the primary source of distortion in common-base amplifiers. This nonlinearity problem and the already low input impedance can be substantially improved by the application of linearity augmentation.

Augmentation is a recent entry in the methods available for amplifier linearization.[10, 11] The emitter input impedance of a common-base amplifier is reduced in value and made more linear by detecting the signal voltage at the emitter, and then applying an amplified and inverted signal voltage to the base. Since the emitter signal voltage is a measure of the nonlinear emitter input resistance, connecting the inverted and amplified signal voltage to the base serves to increase linearity of the emitter input resistance as well as decrease it, thus improving the linearity of the common-base amplifier. There are both passive and active forms of augmentation, and in this design both are used in tandem in the input stage of the aerial amplifier. To gain an understanding of the augmentation process, let's begin by considering the emitter input resistance of a common-base amplifier:

$$r_e = \frac{V_E}{I_E} = \frac{V_E}{I_0\, \varepsilon^{\frac{q V_E}{kT}}} \qquad \text{(Eq 1)}$$

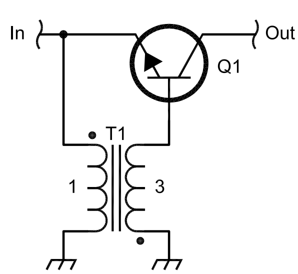

Fig 4—Input stage (high frequency).

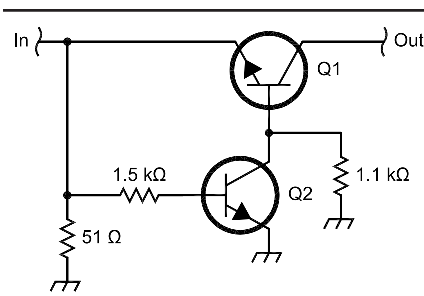

Fig 5—Input stage (low frequency).

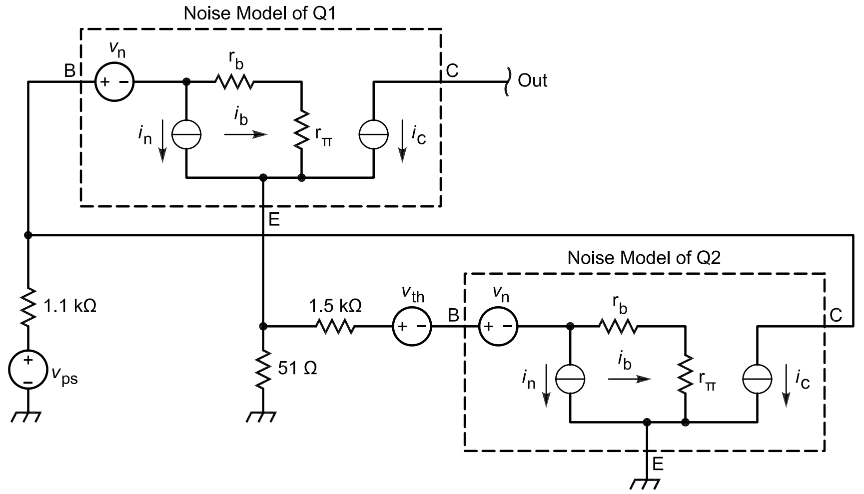

Fig 6—Input stage low-frequency noise model.

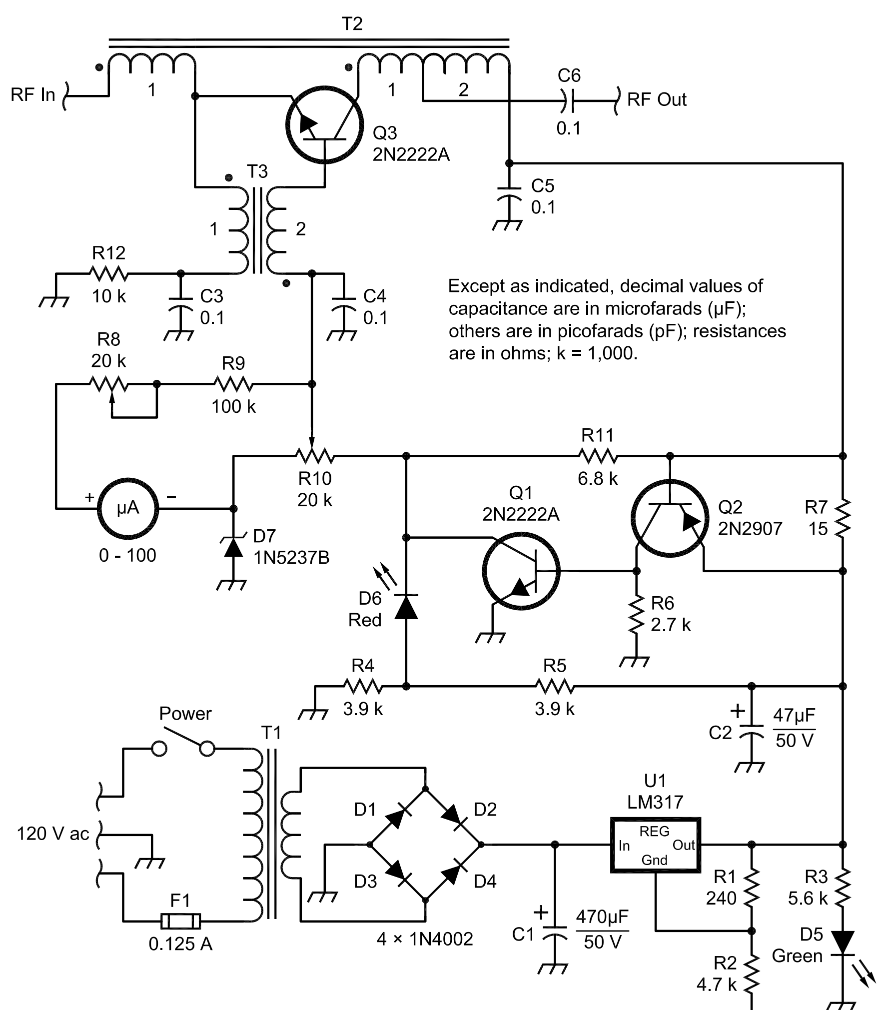

Fig 7—Control-unit schematic.

If we now apply an input signal voltage V_s from a signal voltage source having linear source impedance R_S, the emitter-input current I_E becomes:

$$I_E = \frac{V_S}{R_S + r_e} \qquad \text{(Eq 2)}$$

For frequencies in the aerial's range of operation, Q1 and T2 form a passively augmented amplifier, as shown in Fig 4. Here, the signal voltage appearing across the primary winding of T2, which is the emitter signal voltage of Q1, is inverted and magnified by a factor of three at the transformer secondary winding and then applied to the base of Q2. At the same time, signal current from the base of Q1 is magnified and inverted back to the primary of T2, which serves to further reduce the apparent emitter input resistance, which becomes:

$$r'_e = \frac{V_E}{I'_E} = \frac{V_E}{\left(1 - \frac{N}{h_{fe}}\right) \times I_0\, \varepsilon^{\frac{q\, V_E\, (N+1)}{kT}}} \approx \frac{V_E}{I_0 \left(\varepsilon^{\frac{q\, V_E}{kT}}\right)^{N+1}} \qquad \text{(Eq 3)}$$

which shows that the apparent input resistance r'_e of Q1 decreases rapidly as the turns ratio N of T2 is increased. With this lower resistance substituted into Eq 2, the input emitter current becomes:

$$I'_E = \frac{V_S}{R_S + r'_e} \qquad \text{(Eq 4)}$$

Since the augmented r'_e of Eq 4 is now much less than the unaugmented r_e of Eq 2, the linear source resistance R_S dominates the determination of the emitter input current and is therefore more linear. This linearization technique decreases the odd-ordered IMD products, such as third (1×2, 2×1), fifth (2×3, 3×2) and so forth, that appear immediately adjacent to the desired signals by as much as 30 dB for a transformer ratio of 1:3

Since the coupling of the augmentation transformer (T2) decreases at low frequencies, the method of passive augmentation loses its effectiveness in addressing the odd-order IMD products, such as second (1×1), fourth (2×2) and so forth, that appear at the lower baseband frequencies. These can disturb the transistor bias conditions and produce further in-band distortion products. For this purpose, active augmentation is applied by way of Q2, as shown in Fig 5. Here, the nonlinear emitter input voltage of Q1 is applied to the base of Q2, which produces a collector current, I_C, which is then applied to the base of Q1. The apparent emitter resistance for the actively augmented amplifier circuit is:

$$r'_e = \frac{V_E}{I'_E} = \frac{V_E}{\left(h_{fe1} + 1 + \frac{1}{h_{fe2}}\right) \times I_0\, \varepsilon^{\frac{q\, V_E}{kT}}} \qquad \text{(Eq 5)}$$

which is a more substantial reduction in the apparent emitter resistance than Eq 3.

This method of augmentation also has advantages in terms of noise. Referring to the low-frequency noise model of Fig 6,[12] voltage source V_{ps} represents the noise added by U1, and the voltage source V_{th} represents the thermal noise added by the resistors and other passive components. The bias conditions for Q2 are selected in favor of good IMD performance with some consideration given to NF. For Q2, the bias conditions are selected to favor NF, typically less than that of Q1. The values of R4, R5 and R6 are chosen to provide proper source resistance for good NF performance of Q1 and Q2. As the gain of Q2 increases, the output noise of the amplifier becomes that of Q2, which at low frequencies is mostly 1/*f* flicker noise. A method somewhat similar to active augmentation is used to decrease the SSB phase noise of microwave and millimeter-wave oscillators caused by 1/*f* noise.[13, 14]

The output from the input stage is connected to the emitter of common-base amplifier Q3, which serves to isolate the input stage from the varying supply voltage on the coaxial cable. Together with T3 and T4, this stage provides 24.1 dB of signal power gain.

Control Unit

A complete schematic of the control is shown in Fig 7. The power supply starts with the power transformer and continues on to C2, with LED D5 providing a power-on indicator for the front panel. Q1 and Q2, along with R4 to R7 provide current limiting in the event that the coaxial cable to the aerial amplifier is shorted, with LED D6 providing a visual fault indication on the front panel. The current limiter reduces the reference voltage at the top of tuning potentiometer R10, which should be of the 10-turn variety for adequate tuning resolution.

Q3 performs two distinct functions. First, it is the pass device that controls the voltage to the aerial amplifier through the coaxial cable, the voltage being controlled by tuning potentiometer R10. Second, it is the common-base amplifier transistor for the passively augmented loss-less feedback amplifier,[15, 16] which includes T2 and T3 wound on Fair-Rite 2861002402 balun cores. Feedback transformer T2 has windings of 2:2:6 while T3 has windings of 2:6. When constructing this amplifier, be very mindful of the phase orientation of the various windings. This amplifier provides an additional 6 dB of power gain, giving the active aerial system a total gain of about 30 dB.

M1 indicates the tuning of the aerial amplifier. Potentiometer R8 is adjusted for full-scale deflection when the tuning potentiometer is set at maximum.

Synopsis

The active loop aerial described here performs more than adequately for serious DX purposes. The tuning Q ranged from 37 at 6 MHz to over 67 at 14 MHz, which decreased above 15 MHz because of the lower Q of the loop aerial itself. This makes it obvious that a 10-turn pot should be used for the tuning control. The *OIP3,* as measured at the output of the control unit, was +5 dBm at both 6 and 14 MHz, while the measured *NF* was 1.72 dB at 6 MHz and 1.63 dB at 12 MHz.

Although the aerial will tune down to 5 MHz, remember that the aerial efficiency at that frequency is probably less than 10%, which will add to the *NF* of the aerial amplifier considerably. It would be better to use a 2-meter-diameter 1-turn or a 1-meter-diameter 2-turn loop for the lower bands in order to enjoy the higher efficiency and keep the NF reasonable.

The author uses a variety of active loops for SWBC DXing, including a 2-meter-diameter 1-turn, a 1-meter-diameter 2-turn, a 1-meter-diameter 1 turn and a 0.75-meter-diameter 1-turn loop—all with equally good performance.

Notes

[1]C. Trask, N7ZWY, "Active Loop Aerials for HF Reception Part 1: Practical Loop Aerial Design," *QEX*, Jul/Aug 2003, pp 35-42.

[2]R. A. Sainati, "Active Antenna Performance Limitation," *IEEE Transactions on Antennas and Propagation*, Vol 30, No. 6, Nov 1982, pp 1265-1267.

[3]E. H. Nordholt and D. van Willigen, "A New Approach to Active Antenna Design," *IEEE Transactions on Antennas and Propagation*, Vol 28, No. 6, Nov 1980, pp 904-910.
[4]H. A.Wheeler, "Fundamental Limitations of Small Antennas," *Proceedings of the IRE*, Vol 35, No. 12, Dec 1947, pp 1479-1484.
[5]W. S. Bachman, "Loop Antenna Coupling Transformer Design," *Proceedings of the IRE*, Vol 33, No. 12, Dec 1945, pp 865-867.
[6]C. Trask, "Powdered Iron Magnetic Materials," Workshop on Passive Components for RF Applications, IEEE 2002 International Microwave Symposium (IMS 2002), 4 June 2002, Seattle, Washington.
[7]F. J. Banzi, "Higher Q from Pot Core Inductors," *IEEE Transactions on Parts, Hybrids, and Packaging*, Vol 13, No. 4, Dec 1977, pp 371-377.
[8]G. S. Pandian, "Broadband RF Transformers and Components Constructed with Twisted Multiwire Transmission Lines," Ph D thesis, Indian Institute of Technology, Delhi, Dec 1983.
[9]C. Trask, "Wideband Transformers: An Intuitive Approach to Models, Characterization and Design," *Applied Microwave & Wireless*, Nov 2001, pp 30-41.
[10]C. Trask, "Common Base Amplifier Linearization Using Augmentation," *RF Design*, Oct 1999, pp 30-34.
[11]C. Trask, "Common-Base Transistor Amplifiers with Linearity Augmentation," US Patent #6,271,721, 7 Aug 2001.
[12]K. Hartmann, "Noise Characterization of Linear Circuits," *IEEE Transactions on Circuits and Systems*, Vol 23, No. 10, Oct 1976, pp 581-590.
[13]U. L. Rohde and F. Hagemeyer, "Feedback Technique Improves Oscillator Phase Noise," *Microwaves & RF*, Nov 1998, pp 61-70.
[14]F. Hagemeyer, "Low-Noise Oscillator Circuit Having Negative Feedback," US Patent #5,900,788, 4 May 1999.
[15]C. Trask, "Distortion Improvement of Lossless Feedback Amplifiers Using Augmentation," 1999 Midwest Symposium on Circuits and Systems, Las Cruces, NM, Vol 2, pp 951-954.
[16]C. Trask, "Lossless Feedback Transistor Amplifiers with Linearity Augmentation," US Patent #6,172,563, 9 Jan 2001.