## Technology Special:

# ANTENNAS

BY KENT BRITAIN, WA5VJB

## A Deep Dive into End-Fed Half-Wave Antennas

BY BOB GLORIOSO,* W1IS AND BOB ROSE,# KC1DSQ (GUEST COLUMNISTS)

*WA5VJB was unable to complete his column for this issue, so we once again asked W1IS and KC1DSQ to fill in. This time, Bob and Bob were trying to optimize an end-fed half-wave antenna for multiband use when they realized that the antenna's basic design assumptions had not been closely examined in decades. Here are the results of their research. - W2VU*

Virtually all hams know dipole antennas for their simplicity and the fact that the impedance of a dipole, about 70 ohms, is a good match to our commonly used 50-ohm feedlines. A dipole is most likely the first HF antenna that most of us still use. Over time, we learn about other configurations like the Off-Center-Fed, or OCF[1], multiband dipole whose impedance of around 200 ohms doesn't match our coax and needs a balun to provide a match. If you can feed a dipole from a point off-center, why can't you feed the antenna from the end?

You can, of course, but we need to start with some basics about antennas.

1) The end of an antenna has a dangerously high voltage so we have to put insulators at the ends to isolate them.

2) The large electric field from the end of an antenna will couple to surrounding objects, especially the ground, making the tuning of the dipole sensitive to height. The lower the antenna the lower the resonant frequency and its proxy, the frequency of lowest SWR. This tells us that the impedance at the end of an antenna (voltage / current) is high, anywhere from 450-4,000 ohms depending on the length of the radiator, requiring a transformer to match our 50-ohm feedlines and radios.

3) An OCF dipole is unbalanced because the lengths of the two legs of the antenna are not equal. The unbalanced current intended to go out the antenna easily finds its way down the feedline to ground through our rig, causing all kinds of havoc. An end-fed antenna also has this problem.

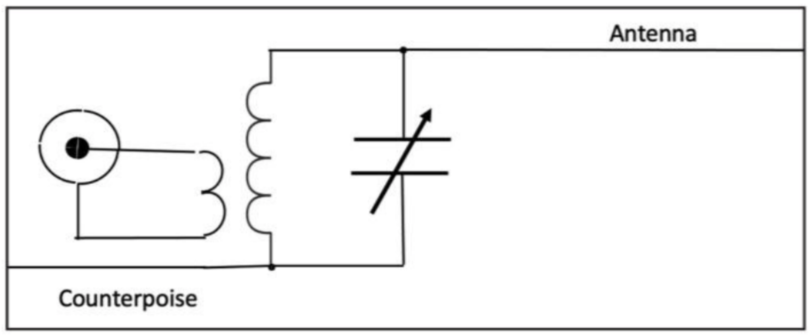


*Figure 1. Single-band end-fed antenna.*

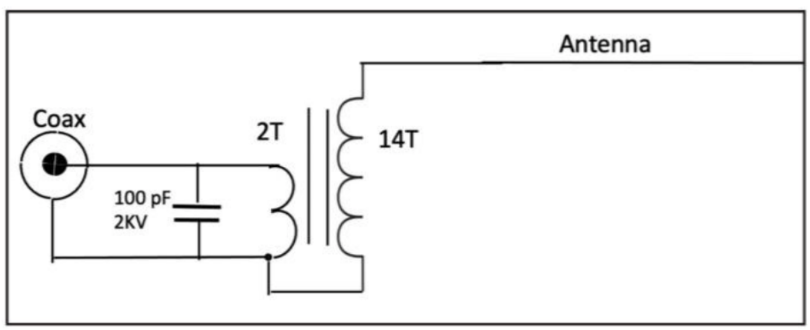


*Figure 2. Conventional configuration of a multiband end-fed antenna with a 49:1 transformer.*

All electrical devices, including antennas, must have two poles for current to flow, so what constitutes the other pole for an antenna fed from only one end? The solution here comes from the high impedance at the end, giving us two alternatives:

1) provide a separate wire connected to one side of the transformer secondary, or

2) Use the outer surface of the shield on the coax feedline.

To use the feedline, one side of the transformer is connected to the coax shield. A 1:1 balun is then necessary to suppress the RF before it enters the shack. The good news here is the counterpoise only has to be about 5% of the wavelength at the lowest frequency of the antenna. Therefore, for an 80-meter end-fed antenna, the counterpoise has to be approximately 0.05 x 80 = 4 meters = 13.12 feet.

One of the advantages of an end-fed antenna is that it can be mounted near

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*Photo A. Conventional matching transformer for multiband end-fed antenna.*

or on the side of the building closest to the shack with the other end on a pole or in a tree. It can easily be configured as an inverted-V, sloper, or inverted-L. Flexibility erecting end feds was recognized in the 1930s, when some articles first described single-band end-feds (see *Figure 1*). These antennas used tuned air-coupled transformers, two coils near each other, with a variable capacitor to tune the antenna. The coils had a few turns on the coax side and many turns on the secondary, antenna side, to provide the step-up from 50-ohms to several thousand ohms and used a short wire as a counterpoise. Because the voltage on the secondary can be several thousand volts, the capacitor must be capable of withstanding that voltage.

The lengths of both the long wire and counterpoise varied depending on the band and matching network. With the right tuning parameters, any length radiator and counterpoise can be made to work on any frequency. A resonant length isn't a requirement for an effective antenna. The downside — it only works on a single band without retuning.

Through the years, as the need for multiband antennas connected to 50-ohm radios became a requirement, two contenders have become popular: Off-center-fed and end-fed harmonic antennas. These antennas start with a half-wave antenna on the lowest frequency, usually 160, 80, or 40 meters, and depend on resonance at the harmonics to work on multiples of the lowest frequency.

Most current end-fed designs for both single and multiband antennas use transformer ratios between 9:1 and 64:1. They all work because the impedance of a half-wavelength wire approaches infinity asymptotically. *Table 1* shows the length required for a min SWR on 3.75 MHz with a 13-foot, 2-inch counterpoise at different transformer ratios. As the impedance increases, the length approaches one-half wavelength.

The length of a multiband wire for low SWR on the harmonics constrains the impedance at the end of the antenna to 1,800-4,000 ohms. Knowing that, the impedance ratios needed to match an end-fed wire to our 50-ohm feeds should be in the range of 36:1 to 64:1. This match is usually provided by a broadband transformer built using ferrite toroids. Conventional wisdom says to wind the primary, 50-ohm, side twisted together with the first few turns of the secondary as illustrated schematically in *Figure 2*. *Photo A* shows a typical matching transformer with the primary and secondary windings twisted together at one end of the secondary.

The 100-pF capacitor compensates for the leakage inductance of the primary, improving the high frequency response of the transformer. The ends of the primary and secondary are tied together, exposing one end of the capacitor to the high voltage on the secondary. We know that all antennas must have two elements to make a complete circuit, so the coax is in fact part of the antenna, acting as the counterpoise forcing current to flow on the outside of the coax. It is our experience that this can cause serious problems with end-fed antennas. Techniques like tying the coax to ground along the run and / or putting a choke/balun[2,3] at the entrance to the building, a good practice, can mitigate the problem but don't always eliminate RF feedback. Our goal was to avoid this hit or miss method of eliminating stray RF currents and radiation.

## Typical End-Fed Designs

Multiband antennas using harmonics for the high bands require some compromises because the harmonics do not line up with the bands very well. As discussed in our off-center-fed dipole article in the June 2020 issue of *CQ* magazine,[1] the harmonics occur at slightly higher frequencies than integer multiples of the fundamental. This aggravates the alignment problem. Typically, the length of the antenna is cut for resonance at the bottom of the fundamental band. Then the higher band resonances occur above the top of their respective bands. Many designs use a small coil near the end of the antenna to electrically lengthen the antenna for the 20-, 15-, 12-, and 10-meter bands to improve the placement of the resonances for those bands. Although some designs offer a choice of using a separate wire counterpoise or using the coax outer shield as the counterpoise, current designs and commercial versions use the feedline no matter the length as a counterpoise, leaving it up to the user to keep RF from finding its way to the rig.

## Our Design for an 80-Meter Half-Wave End-Fed Antenna Load Cap vs. Load Coil

We simulated the design with the small loading coil to aid placement of the high bands and found that we got better band

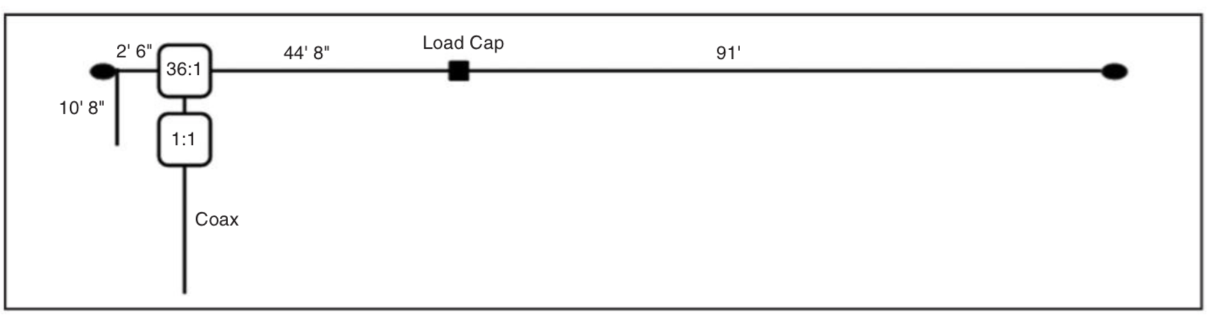


*Figure 3. Wire counterpoise 80-meter half-wave end-fed antenna.*

| Transformer Ratio | Impedance (ohms) | Length (feet) | Length λ |
|---|---|---|---|
| 9:1 | 450 | 109 | 0.417 |
| 16:1 | 800 | 110.13 | 0.420 |
| 25:1 | 1250 | 113.36 | 0.432 |
| 36:1 | 1800 | 117.29 | 0.447 |
| 49:1 | 2950 | 120.42 | 0.460 |
| 64:1 | 3200 | 122.36 | 0.467 |

*Table 1. Length of end-fed radiator for minimum SWR on 3.75 MHz at different transformer ratios.*

| Power (Watts) | Voltage (Volts) | Current (Amps) |
|---|---|---|
| 150 | 240 | 0.80 |
| 800 | 560 | 1.85 |
| 1,200 | 680 | 2.25 |

*Table 2. Voltage and current required for load capacitor at different power levels.*

alignment by cutting the length for good placement on the high bands and adding a loading capacitor to electrically shorten the antenna for the low bands. Placing the 80-meter resonance in the middle of the band is a priority because of its relatively wide bandwidth. We found that placing a 150-pF capacitor at 32% of the length puts 80-meter resonances near the middle of the band. The capacitor has less effect on the higher bands because its reactance decreases with frequency, so those resonances move a little but remain well placed. With careful tuning, we achieved low SWRs for 80, 40, 20, 15, 12, and 10 meters, and 3:1 or less on 30 meters.

## 36:1 Transformer Ratio

Steve Yates, AA5TB[2], published a chart showing that a 36:1 transformer ratio and a 0.05-wavelength counterpoise provides an operating point where the load is resistive, resulting in the lowest SWR. Because he was building a single-band antenna, he could use other ratios and tune out the reactance using his tuned secondary. However, a multi-band antenna requires a broadband matching network. Using a broadband transformer, we found that the 36:1 ratio and 0.05-wavelength counterpoise works well. Interestingly, the 0.05-wavelength counterpoise on an 80-meter end-fed causes a resonance around 32 MHz which helps lower the SWR at the top of the 10-meter band.

## Counterpoise & Feedline Radiation

Both the separate wire and coax counterpoise methods were implemented and evaluated. A 1:1 balun with sufficient isolation effectively mitigates RF feedback and feedline radiation. For the wire counterpoise case, the 1:1 it is placed at the feedpoint, right after the transformer. For the coax case, it is moved down the feedline to the desired counterpoise length.

## Wire Counterpoise

The antenna with wire counterpoise is shown in *Figure 3*. The lengths shown are for #14 Flexweave from RF Davis or

*Photo B. (1) PC board with load; (2) Silicone-potted load; (3) Load mounted on an insulator.*

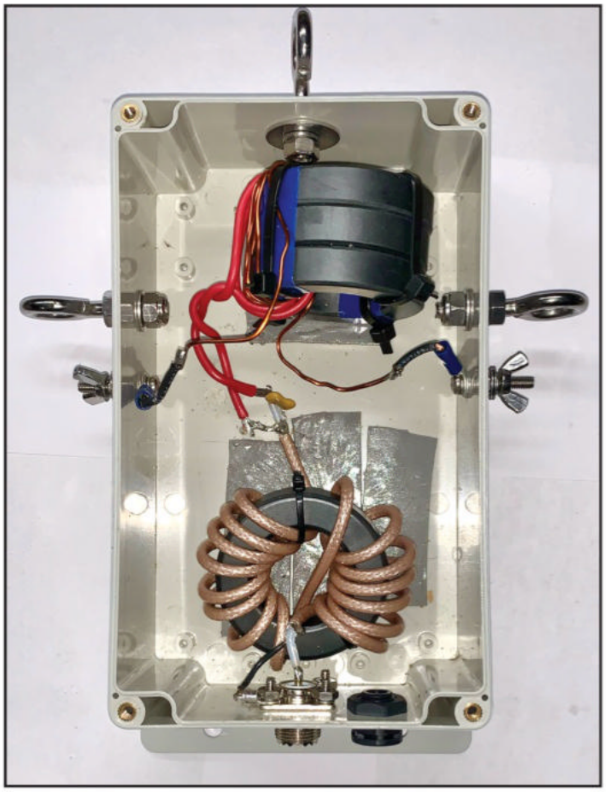

*Photo C. Transformer and balun isolated in same box.*


*Photo D. Isolation of the transformer from the 1:1 balun in separate boxes coupled together with a dual PL-259 connector to avoid unwanted coupling to the feedline.*

#14 THHN wire from the local home improvement store. The total length of the radiator is 136 feet 6 inches. The distance from the feedpoiint to the load capacitor is 43 feet 8 inches. The load capacitor is 150 pf. Its voltage and current requirements depend on the design power as shown in *Table 2*.

Because the capacitor is out in the elements and is likely to experience high-voltage static build up, we protect it by placing a resistor across it to drain built-up static charge while handling the voltage and power it experiences in operation. For less than 500 watts, a 1-megohm, 1-watt, non-inductive resistor works well. For higher power levels, a 2-watt, 2.7-megohm non-inductive resistor is needed.

Mounting the capacitor and resistor on a 1- x 1-inch PC board makes assembly and potting easier, especially for the high-power surface-mount parts. These are large surface-mount parts that are easily soldered to a 1x1 PC board with a slot cut out of the middle with a Dremel tool, as shown in *Photo B(1)*. Further, though not absolutely necessary, we like to protect our capacitor and resistor with a layer of modeling silicone or a non-conductive epoxy coating, as shown in *Photos B(2)* and *B(3)*.

The wire counterpoise is 13 feet 2 inches long and will interact with the feedline if it gets too close, so we ran it horizontally for 30 inches before allowing it to droop towards the ground. The wire should be stabilized to maintain a constant distance between it and the feedline and other objects, making isolated coax a more desirable configuration. The matching network is a 36:1 transformer followed by a 1:1 balun[4] with at least 30-dB isolation to suppress common mode currents. In order to reduce the interaction between the matching transformer, the two coils should be separated as in *Photo C* or use two separate boxes coupled with a dual PL-259 coupler, *Photo D*.

## Coax Counterpoise

The coax counterpoise is shown in *Figure 4*. This is basically the same antenna as the wire counterpoise version with the wire removed and the 1:1 balun in a separate box placed 13 feet, 2 inches down the feedline. The outer surface of the coax shield serves the counterpoise and the 1:1 balun / choke constrains RF from flowing on the rest of the feed line. Thus, the 1:1 position defines the length of the counterpoise and prevents feedline radiation below it. We were able to achieve comparable performance with both counterpoises.

## The Matching Transformer

The matching transformer is fundamental to building a truly multi-band end-fed antenna. It determines the match on all bands and limits the amount of power the antenna can safely handle. The design of the matching transformer starts with the parameters of the core material to determine:

1. Impedance of the primary at the lowest frequency. Too low and there will be a mismatch and high SWR. The imped-


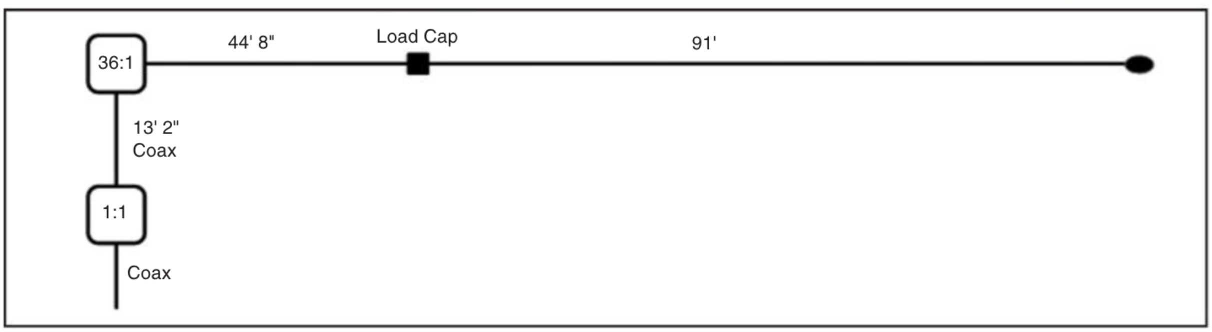


*Figure 4. Coax counterpoise 80-meter half-wave end-fed antenna.*

ance is determined by the type of core material, number of cores, and the number of turns.

2. Losses are determined by the resistance of the wire and core losses. Core losses are a function of the material and the flux density. Flux density is proportional to the number of turns and the current in the wires, making fewer turns desirable.

3. Heat. Losses show up as heat in the core/s, limiting the power that the transformer can handle. Also, if you overheat the core beyond its Curie Point (a temperature at which a material's magnetic properties change sharply), it will fail and recover as the temperature decreases.

We built and tested several transformers to find the most effective match with the widest bandwidth by testing them with resistive loads. We then measured the losses in each of the transformers to determine their power-handling ability. An 80-meter test antenna was launched to validate our modeling and learn the peccadillos of the high-impedance feed. We placed temperature-sensitive strips on the cores to measure the highest temperature reached under continuous power for 1 minute at powers proportional to the power-handling capability of each of the transformers, calculated from the loss tests. We also used each of the transformers on-

| | Low | Medium | High |
|---|---|---|---|
| Digital | 50 | 250 | 400 |
| CW | 100 | 500 | 800 |
| SSB | 150 | 750 | 1,200 |

*Table 3. Power ratings for three transformer configurations.*

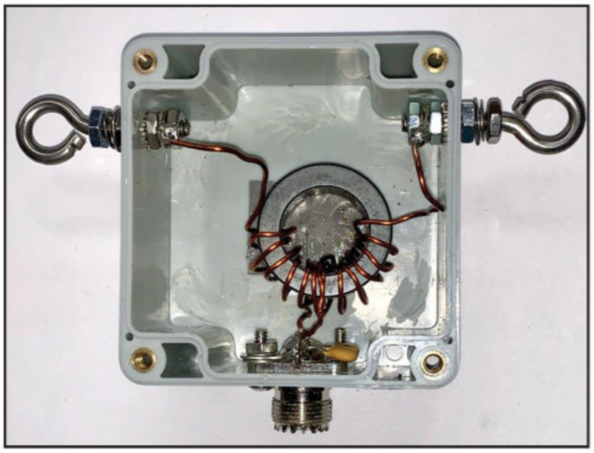

*Photo E. Transformer for low power (150 watts): One 140-43 core, wire counterpoise.*

**Parts List**

175 ft, #14 stranded wire, Davis RF or THHN from home improvement store
1 – End insulator for coax counterpoise
2 – End insulators for wire counterpoise
1 – Insulator to hold the R-C load PC board
1 – 1- x1-inch PC board
1 – 1-watt, 2.7-megohm non-inductive resistor (high power); 1-watt, 1-megohm non-inductive resistor (low power)
1 – (<750 watts) mica capacitor, 150 pF, CDV16FF151J03F, Mouser 598-CDV16FF151JO3F
1 – (1.2-kilowatt) ceramic capacitor, 150 pf, 3 kilovolt, Knowles-Syfer 222523K00151GQTAF9LM, Digi-key 1608-1588-1-ND
1 – 56 pF 3 kilovolt capacitor, CC45SL3FD560JYNNA, Digi-Key 445-15996-ND

Cores:
1 – (<150 watts) 140-43 core, FairRite, 5943002701, Mouser 623-5943002701
2 – (<750 watts) 240-43 cores, FairRite, 5943003801, Mouser 623-5943003801
3 – (<1200 watts) 236-52 cores, FairRite, 5952003801, Mouser 623-5952003801

1:1 Balun choke (see Balun Basics[3]):
#18 Polyamideimid solid copper wire, Remington Industries, 18H200P.12, <remingtonindustries.com>
Potting - Silicone – see text, or MG Chemicals, 834FX, black, flexible, thermally-conductive potting compound, Amazon.com
Box vent, Amphenol, VENT-PS1YBK-N8001, Mouser 523-VENT-PS1YBKN8001
Transformer box, Thomas & Betts E989NNJ PVC molded screw cover junction box, 4-inch x 4-inch x 2-inch, Carlon or Awclub 4.52-inch x 3.54-inch x 2.16-inch both on Amazon
8 – 10-24 stainless steel hex nuts (local HW store)
8 – #10 stainless steel flat washers (local HW store)
8 – #10 stainless steel lock washers (local HW store)
2 – #10 ring terminals (local HW store)
Scotch® outdoor double-sided mounting tape, (local HW store)

Kits with pre-mounted and potted capacitors and resistors are available on the authors' website, <www.ocfmasters.com>

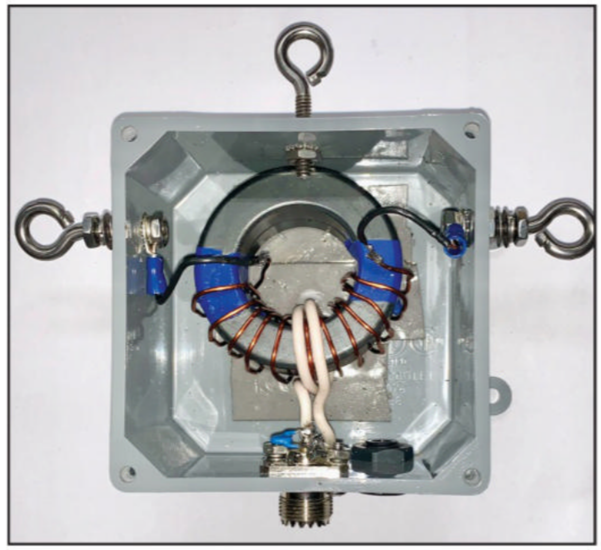

*Photo F. Transformer for medium power (750 watts): Two 240-43 cores, wire counterpoise.*

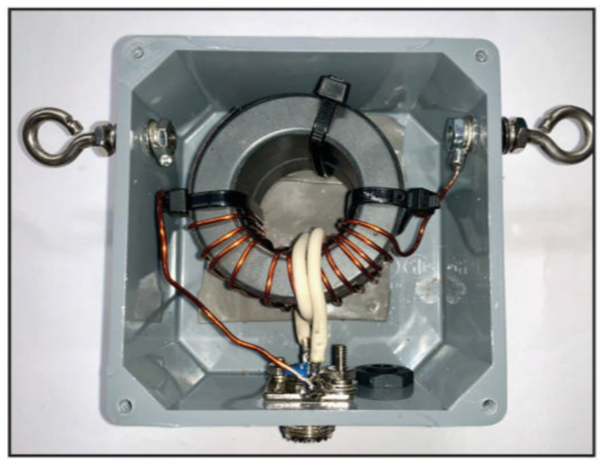

*Photo G. Transformer for high power (1,200 watts): Three 236-52 cores, coax counterpoise.*

the-air for ragchews, DX chasing, and CQ contests in both CW and SSB.

The 1-minute test is a good proxy for digital operation. The losses show up as heat that can make the box housing the transformer get quite hot[5]. For example, a transformer with a loss of 0.5 dB with 100 watts applied dissipates 12 watts, and driven with 1 kilowatt dissipates 120 watts, a lot of power to get out of a small box. So we use Amphenol Vents to improve the heat dissipation from the boxes (see parts list).

Recognizing that the goal of the transformer is to provide a high voltage to match the high impedance at the end of the antenna, it seemed odd that most transformers were wound with the low impedance primary wires wrapped tightly around a high impedance side of the secondary. Winding wires tightly around each other capacitively couples them, much like a "gimmick capacitor," putting an unneeded load on the secondary and likely limiting the high frequency response of the transformer. That is exactly what it does because winding the primary in the middle of the secondary requires a smaller capacitor while delivering a better match above 20 MHz.

Many articles and ads claim the use of large diameter wire on both the primary and secondary of the transformer, but a simple calculation shows that the maximum current in the secondary is less than one amp at 1,200 watts, so difficult-to-wind wire was abandoned for #18 solid copper wire with a Polyamideimide coating (see parts list). On the other hand, the primary must handle more current, 4.9 amps at 1,200 watts, requiring a larger diameter wire. We found wire stripped from 14-2 Romex from a recent home project proved adequate for high power and #18 wire for both primary and secondary on the low-power transformer.

The broadband transformers are wound on one or more ferrite cores: one 140-43 core for low power, two 240-43 cores for medium power, and three 236-52 cores for high power (see *Photos E*, *F* and *G*). For two or more cores, tape or ty-wrap them together. Power ratings for the three transformers for different modes are in *Table 3*.

The 12-turn secondary windings are wide-spaced about 180° around the core, and the 2-turn primary windings are close spaced on the middle of the secondary with a 56-pF capacitor across the primary to compensate for leakage inductance as shown in the photos.

The transformer is mounted in a waterproof plastic box that has the SO-239 coax connector and eye rings mounted, as seen in the photos. The core is held to the box bottom with double sided mounting tape (see parts list). To test the transformer, put an 1,800-ohm non-inductive low-power resistor across the secondary and use an antenna analyzer to measure the SWR from 3.5 to 30 MHz. Do not short the primary and secondary. If it is not less than 2:1 up to 30 MHz, adjust the spacing of the secondary windings.

## Installation, Tuning and Operating

When installing the antenna, ensure that the end of the counterpoise, wire or coax / balun, cannot contact people or pets.

Tuning the antenna with a 13-foot 2-inch coax / balun counterpoise only requires adjusting the far end so the lowest SWR on 20 meters is above the middle of the band and the

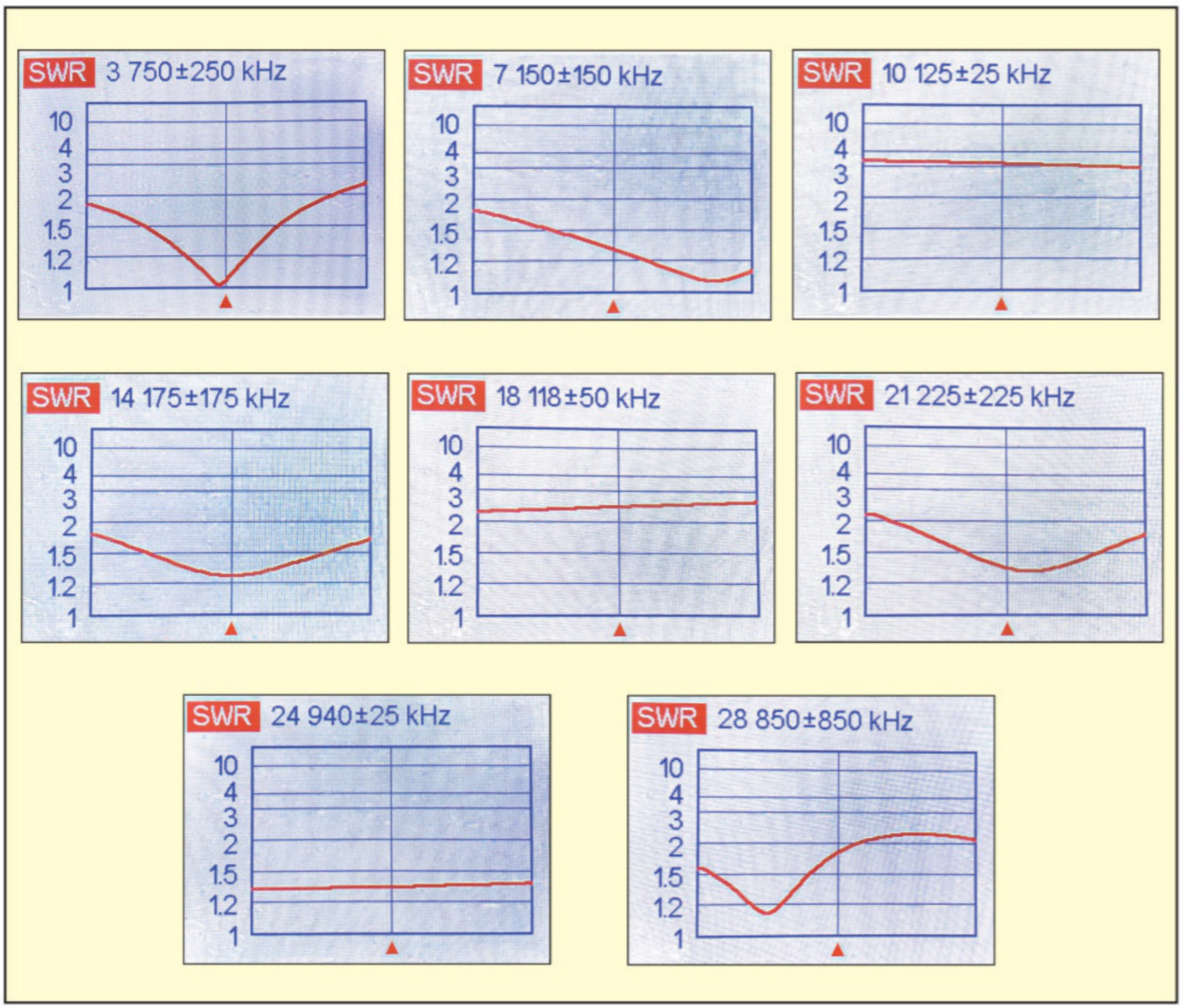


*Figure 5. A typical set of SWR curves measured with 100 feet of RG-8x on each HF band between 80 and 10 meters (except 60 meters).*

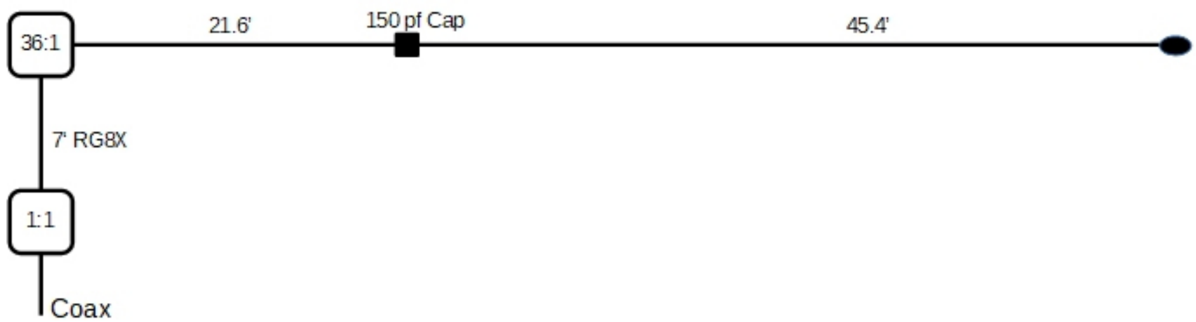

*Figure 6. Dimensions of 40-meter end-fed antenna with coax counterpoise, tunable for higher-frequency bands as well.*

SWR on 15 is less than 2:1 across the band. Tuning a wire counterpoise is similar, but if the SWR on 10 meters is not below 2.5:1 between 28 and 28.5 MHz, adjust the length of the counterpoise. The high impedance affects the tuning because the frequency is more susceptible to surroundings and environmental conditions such as moisture. The combined effect means resonances may not be exactly where they are expected, but the bandwidth is wide enough to cover the variation. A typical set of SWR curves measured with 100 feet of RG-8x is in *Figure 5*. Note that the low-power version works well at two-thirds power on 6 meters while the core loss of the higher-power versions precludes 6-meter operation. Also, any end-fed antenna with a native SWR above 2.5:1 should be run at two-thirds power.

## How About 40-Meter Multiband or a 60-Meter Single-Band Antennas?

A broadband matching transformer makes these antennas possible. A 40-meter end-fed (*Figure 6*) is a simple modification of the 80-meter antenna made by changing the lengths of the wires. The resulting configuration is:

- Total Length: 67 feet
- Distance to 150-pF load: 21.6 feet
- Counterpoise Length: 6.6 feet
- Tuning is similar to the 80-meter version as verified in our tests.

For 60 meters or any single band end-fed half-wave antenna, you don't need a capacitor.

1. Calculate the length of the counterpoise, wire or coax / balun, as 0.05% of the wavelength. For 60 meters, it is 3 meters or 9.84 feet.

2. Calculate the length of a half-wave wire, L=468/F; for 60 meters, 5.36 MHz, the length is 87.5 feet, but with a 36:1 transformer, the length will be slightly shorter so 87.5 feet is a good place to start. Adjust the length for minimum SWR at 5.36 MHz to cover the 60-meter band.

## Summary

We found that the wire counterpoise and the coax counterpoise have essentially the same performance. We prefer the coax counterpoise because it is less fussy mechanically and less likely to get tangled in tree branches. For the wire counterpoise, a 1:1 balun should be used following the transformer. For the coax counterpoise, the 1:1 balun is put in a separate box and positioned on the feedline to define the length of the counterpoise. This effectively eliminates RF feedback. It is our practice to use another 1:1 balun at the entrance to the shack to suppress any RF picked up by the feedline.

We found that we could achieve good positioning of the resonances by cutting the length for the high bands and raising the lower bands' resonant frequencies with a capacitive load of 150 pf at 32% of the length. This worked better than the common practice of cutting the length for the low bands and using a small coil near the end of the antenna to lower the resonant frequency for the high bands.

We achieved the lowest SWRs by using a 36:1 transformer and a counterpoise length of 5% of the wavelength at the lowest frequency. The transformer is the most crucial aspect of the design. The common practice of building the transformer with the primary twisted with the first few secondary windings is not the best design. Instead, a transformer with the primary centered on the secondary has better high frequency performance. We found that one or two type-43 cores worked well for low- and medium-power designs, and that three type-52 cores worked well for high power designs.

The flexibility of using a broadband transformer was demonstrated by the simplicity of making a 40-meter multiband version or a 60-meter single-band version with the same transformer.

All these antennas performed well on the air with no detectable RF in the shack. We consider the results and performance to be similar to our OCF designs[1] with more flexibility in deployment while sacrificing only the 60-meter band.

## Acknowledgements

We thank our spouses Dee Glorioso, W1MGA, and Barbara Rose for their support throughout this long project, along with Colin Brench, W1DJR, and Allison Parent, KB1GMX, for sharing their experiences with end-feds.

**References**

1. "Multiband Off-Center-Fed Dipoles for 160 & 80 Meters," Bob Rose, KC1DSQ and Bob Glorioso, W1IS, *CQ* magazine, June 2020

2. "The End-Fed Half Wave Antenna," Steve Yates, AA5TB, <www.aa5tb.com/efha.html>

3. *Understanding, Building & Using Baluns*, Jerry Sevick, W2FMI, CQ Communications, <https://tinyurl.com/ubw5e9p>

4. "Balun Basics: What's a Balun? Why a Balun? How Do I Make a Balun?" By Bob Glorioso, W1IS and Bob Rose, KC1DSQ, *CQ* magazine, January 2021

5. "The End-Fed Half Wave Antenna," Steve Dick, K1RF, <https://tinyurl.com/3cdm9jr2>