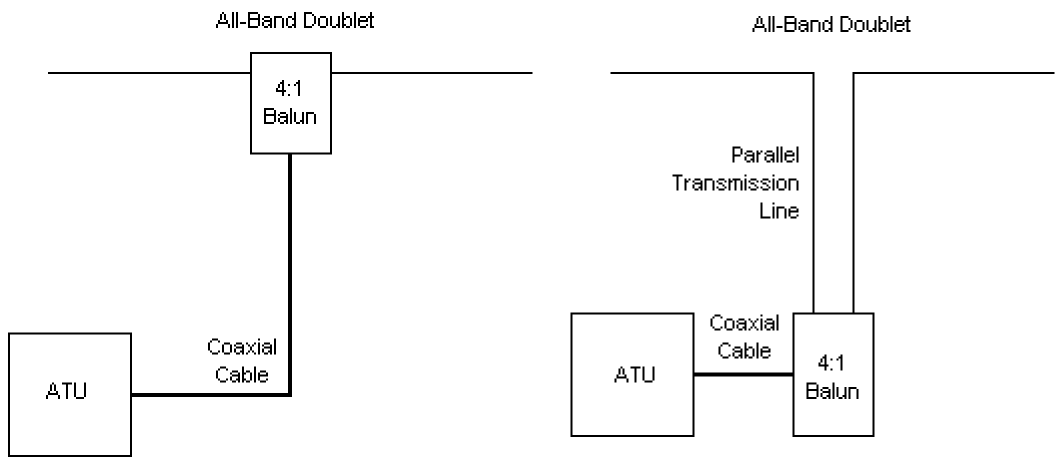
The Impedance-Transformation Properties of Common 4:1 Balun Types
Part 1: Essential Background

L. B. Cebik, W4RNL

One of the most ubiquitous antenna-system accessories among radio amateurs is the 4:1 balun. Theoretically, these devices are designed to transform a 200-Ω load impedance value to a 50-Ω input impedance level. The normal design frequency range is (more commonly) 3.5-30 MHz or (less commonly) 1.8-30 MHz. Despite the specifications, amateurs employ (or misemploy) 4:1 baluns in a number of circumstances in which the device has little hope of matching its output to the actual load. **Fig. 1** presents only two of numerous scenarios.



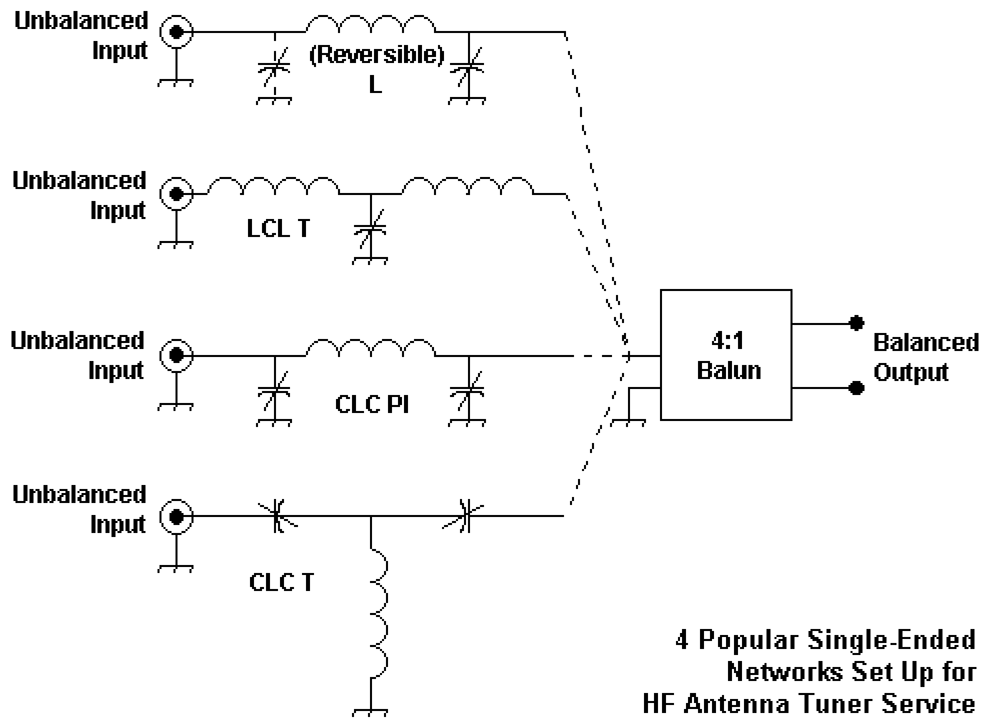
Two Commonly Used All-Band Amateur Antenna Systems
Fig. 1

Some amateurs install 4:1 baluns at the feedpoint of multi-band antennas in the mistaken belief that the input impedance may be compatible with the standard 50-Ω coaxial cable. Alternatively, some amateurs install the 4:1 balun at the entry point to the equipment building. Parallel transmission line runs from the balun's balanced output terminals to the antenna feedpoint, while coaxial cable does indoor duties. A few amateurs actually install a 4:1 balun under optimal conditions. They transform an actual 200-Ω antenna feedpoint impedance value to a match for the 50-Ω main feedline.

A number of radio amateurs do run parallel transmission line from their multi-band wire antennas to an antenna-tuning unit (ATU). In many instances, the ATU employs a single-ended network against a ground that is also common to the case. To obtain a balanced output—or at least an output in which neither output terminal is connected to ground—designers have long used a 4:1 balun between the network and the connections for a parallel transmission line. **Fig. 2** shows some sample tuner configurations, all of which share in common the 4:1 output balun.

There have been numerous reports in amateur literature on the power capabilities of available balun designs and commercial as well as homebrew implementations of them. However, I have not seen a report on the precision with which various available balun designs actually transform the load impedance to the target input impedance across the intended use range, namely, the HF spectrum from 3 to 30 MHz. The availability of an inexpensive but quite adequate antenna analyzer, the AIM 4170, has not only eased the task of making at least some preliminary measurements, but doing so very accurately.

Fig. 2

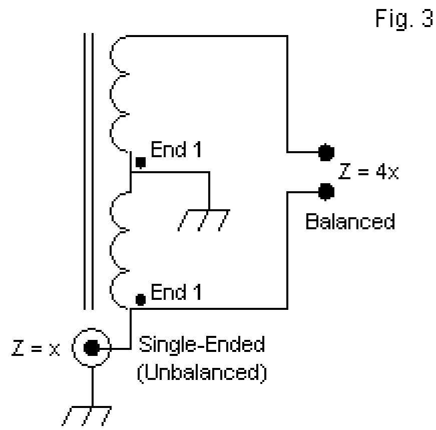


This collection of notes makes a start—but by no means a finish—of the task. Handbooks note—usually without verification—that current baluns are better at the task of impedance transformation than voltage baluns, and so up to now, we have had to accept the reports or undertake a significant learning curve to follow the mathematical analyses that have appeared from time to time in support of the handbook claims.

An alternative approach is to use an antenna analyzer, a select group of non-inductive resistors, and a small collection of 4:1 baluns and then perform HF scans to determine their actual ability to transform impedances according to specification. Where possible the balun collection should contain at least two samples (more would be better) to separate unit idiosyncrasies from trends that are functions of the design and the construction strategies.

We normally divide baluns into two groups: voltage baluns and current baluns. In each category, there are design variations. The many articles and books by Jerry Sevick, W2FMI, provide ample reading for those interested in balun design options. Our task is simpler, since most of the 4:1 balun units used in amateur service show very little variation.

Perhaps the most common 4:1 balun is the voltage type, shown schematically in **Fig. 3**. The unit consists of two series windings, with a ground (common to the input connector ground) at the junction. The dots in the photo indicate the start of a bifilar winding, a parallel run of two wires around the core. In the past, many voltage baluns used air cores, but since the advent of the age of easily available ferrite and powdered iron cores, most voltage baluns have used them to produce compact devices that are relatively free of unwanted coupling. The most usual core for the task is the T200-2 powdered iron core where $\mu = 10$ (or for coverage down to 1.8 MHz, the T200-1 for which $\mu = 20$). We can easily recognize the core by its red paint job. (Mixture 1 is normally blue.) The core has a 2” outside diameter and is about 0.5” thick.

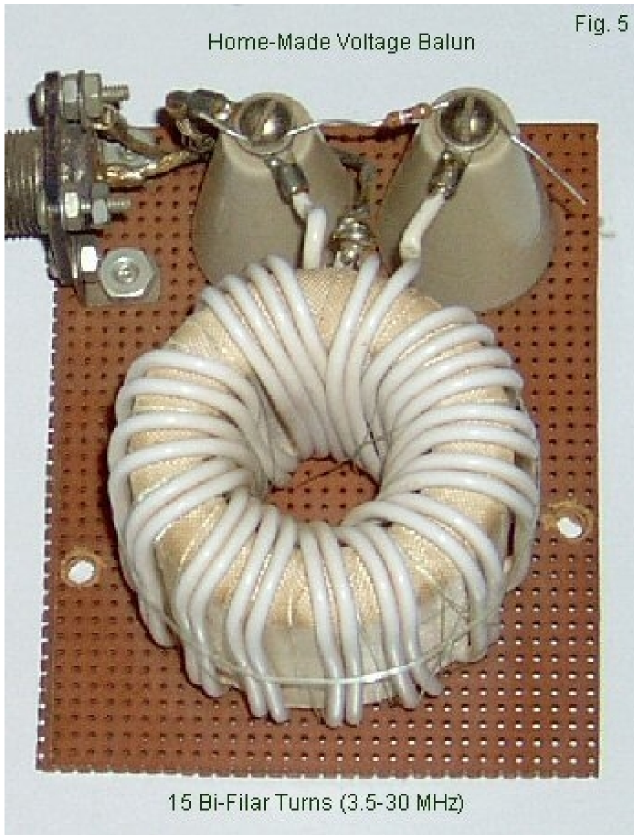


Conventional 4:1 Voltage Balun

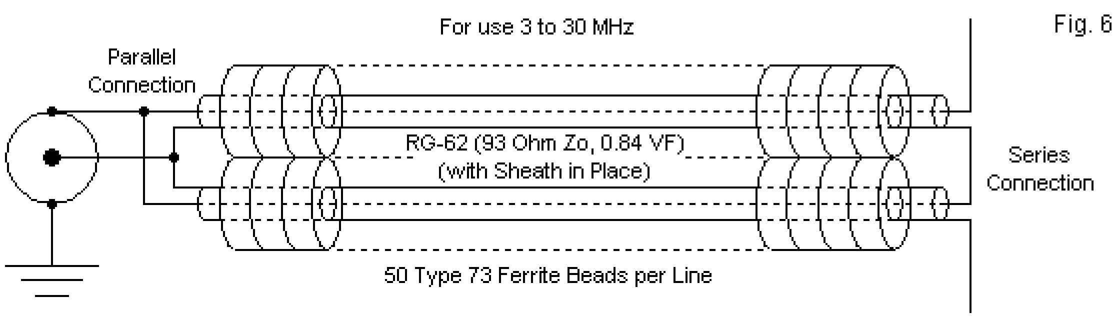
The operation of the balun is straightforward. The voltage across the input terminal appears also across the lower winding in the schematic. Close coupling of the upper winding via the bifilar winding technique creates an equal but opposite polarity voltage at its "hot" end. With twice the voltage of the input at the output terminals and assuming that the current is halved in the process, the impedance at the output terminals is 4 times the input impedance. (The assumptions about current have been the subject of very extensive discussion in balun literature.)

The standard voltage balun has a structural advantage over some other designs. It requires only a single core, although we often find stacked cores for increased power handling ability. **Fig. 4** shows one example, which happens to be an MFJ-912 unit of considerable age. The red T200 cores (a stack of 2) are readily apparent, as are the 18 turns of the winding. The phenolic hold-down plate is missing to expose the windings.

Fig. 5 shows an alternative version, a homebrew open frame version using a stack of 3 T200 cores wrapped in glass tape. The 25-year-old test unit uses minimal hardware, since its place was indoors. It has 15 bifilar turns for 3.5-30-MHz coverage. Like the commercial unit, the output terminals show a test load resistor.



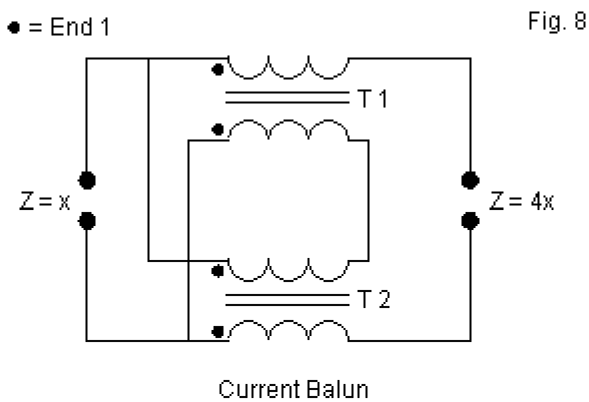
When we turn to current baluns, we encounter a subdivision. The lesser-used type is an adaptation of the W2DU ferrite-bead choke that places a large number of small ferrite beads over a length of coaxial cable. The beads present high impedance to currents that might extend along the outside of the coax braid. The choke thus becomes a 1:1 current balun.



General Features of a 4:1 Balun Composed of Two Ferrite Bead Chokes

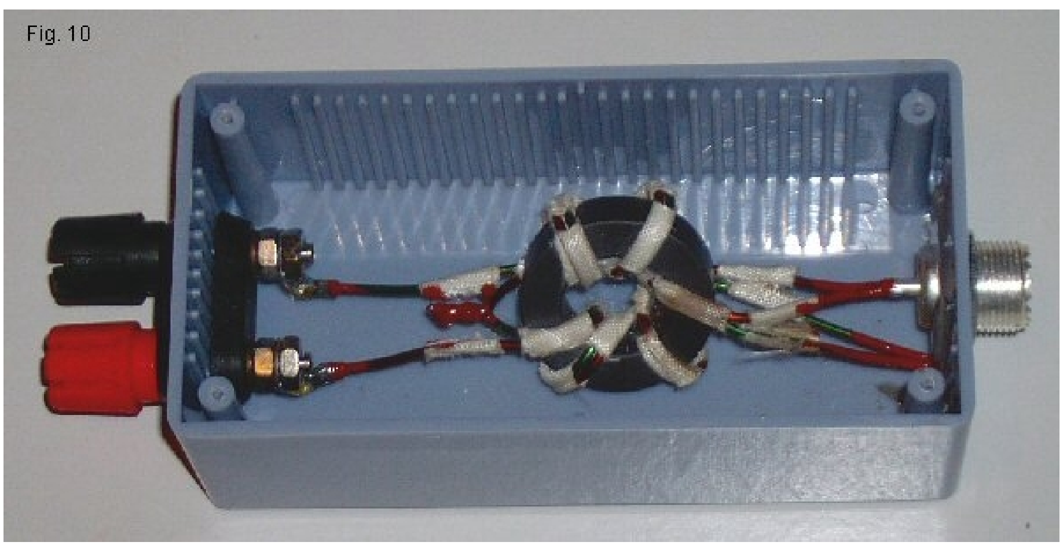
To create a 4:1 balun, we take two such chokes and place them side-by-side, as shown in **Fig. 6**. We connect the input ends in parallel to force a current division into the two legs. We connect the output ends in series at the antenna feedpoint. The series connection shows half the input current, and by assuming that the terminal voltage is twice the input value, we arrive at a 4:1 impedance ratio. Current baluns are somewhat sensitive to the impedance of the lines. The best characteristic impedance is the geometric mean between the intended input and output impedance values. For a balun intended to convert a 200-Ω load to a 50-Ω main feedline, the optimal value is 100 Ω. 93-Ω RG-62 is very close to the desired value. **Fig. 7** shows a pre-encasement layout of the Wireman's kit for the balun. Like the voltage baluns, the configuration is for testing purposes. The advantage of the dual ferrite bead configuration among current balun designs is the simplicity of construction.

More common than the ferrite-bead version of a 4:1 current balun is a very old design updated for ferrite core use. The Guanella balun usually requires two transformers and therefore two cores, as shown in the schematic diagram in **Fig. 8**. Each core has a bifilar winding (as indicated by the end dots), with the wire spacing set for a characteristic winding impedance of 100 Ω. The ferrite core is often type 43 (μ = 850), although other types also serve. The two transformers should not directly interact (except via the connections shown), a requirement vastly eased by the use of toroidal ferrite cores.



We can easily recognize the parallel input connections and the series output connections that effect the impedance transformation. The diagram actually shows balanced input and output terminals. In practice, some builders add a 1:1 balun at the input, while others simply connect one side of the input to ground to achieve a single-ended input.

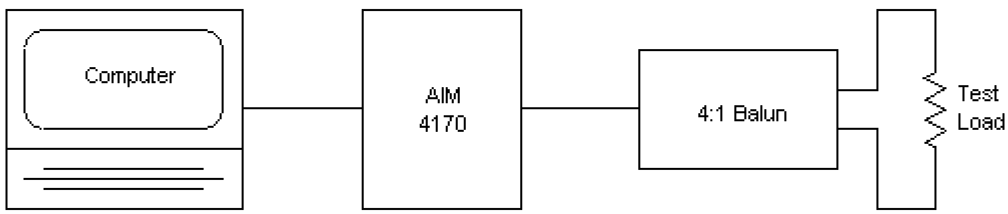
The MFJ-911 indoor 4:1 current balun adheres to the simplified input, as shown by the inside view in **Fig. 9**. The maker rates the unit at 300 Watts with a "relatively flat response from 1.8 to 30 MHz." Clearly evident on the photo are the two side-by-side ferrite (black) cores that are about 1.5" outside diameter and 0.375" thick. Although the maker does not specify the ferrite mix, type 43 is most likely. Each core has 16 bifilar turns. The input uses an SO239 connector, while the output uses standard plastic binding posts.



The photo (**Fig. 10**) shows a version of the same basic balun concept, but with a much higher permeability core. Clear Signal Products produces this balun (and a fully sealed outdoor version) using a single core, for which μ = 1500, from Ceramic Magnetics. The high-μ allows a single 1.375”-diameter by 0.375”-thick core to carry both windings, which require only 3 turns each with wire spacing set for a 100-Ω characteristic impedance. The case uses gray UV-resistant PVC, normally with a compatible sealant.

The photos actually show the array of baluns at my disposal for testing. The test set-up itself appears in **Fig. 11**. The test instrument is an AIM-4170 antenna analyzer that measures the relative strengths and the phase angle between the voltage and current at the test terminal and converts these values into values for impedance magnitude and phase angle. Computer software uses these values to determine such commonly desired quantities as the series resistance and reactance, reflection coefficient, and SWR, among other parameters. The instrument is accurate up to 170 MHz, although our use will not press its limits, since we shall scan from 3 to 30 MHz. (The software will automatically extend the scan to 33 MHz to obtain neat subdivisions for the scan graph.) Even though we shall only show a few quantities in the graphics that we use, the instrument saves the data for all initially calculated parameters of the test antenna or device.

Fig. 11

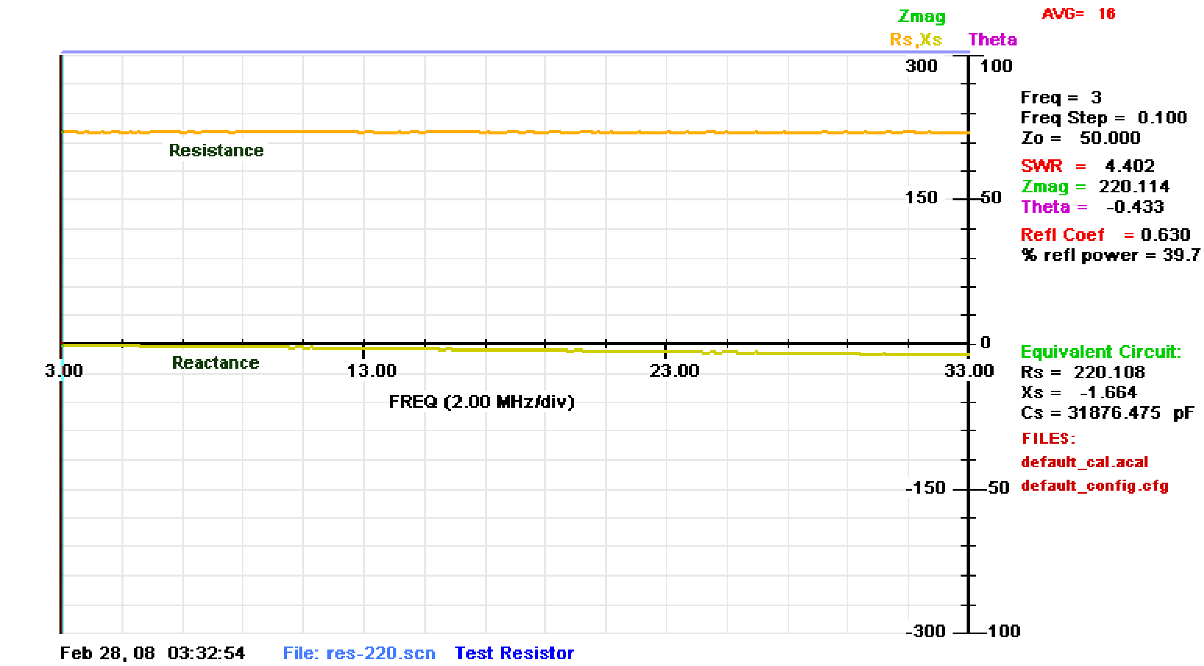


Basic Layout of the 4:1 Balun Test Set-Up

The test baluns will be the subjects of study. Each one uses a 3" length of RG58 cable between the balun and the 4170. Although the connecting cable is less that 1% of a wavelength at the highest scanned frequency, it does shift measured values at the high end of the sweep. Therefore, using procedures prescribed for the unit, I calibrated the connecting cable out of the test set-up. Essentially, the procedure for unit calibration occurs with the connecting cable in place, moving the measurement point from the input connector of the unit itself to the connector at the far end of the connecting cable.

Since the 4170 test signal to the device amounts to microwatts, it is safe to use low-wattage resistors as test loads. The test resistors are non-inductive ¼-watt carbon-film units. The test series consists of a range of values, approximated by the following corresponding values of resistance and approximate SWR relative to the ideal load impedance of 200 Ω: 100 Ω and 390 Ω (2:1), 150 Ω and 280 Ω (1.4:1), 180 Ω and 220 Ω (1.1:1), and 560 Ω (2.8:1). The values of the individual resistors will appear according to the measured resistance at DC (for example, 221.4 Ω).

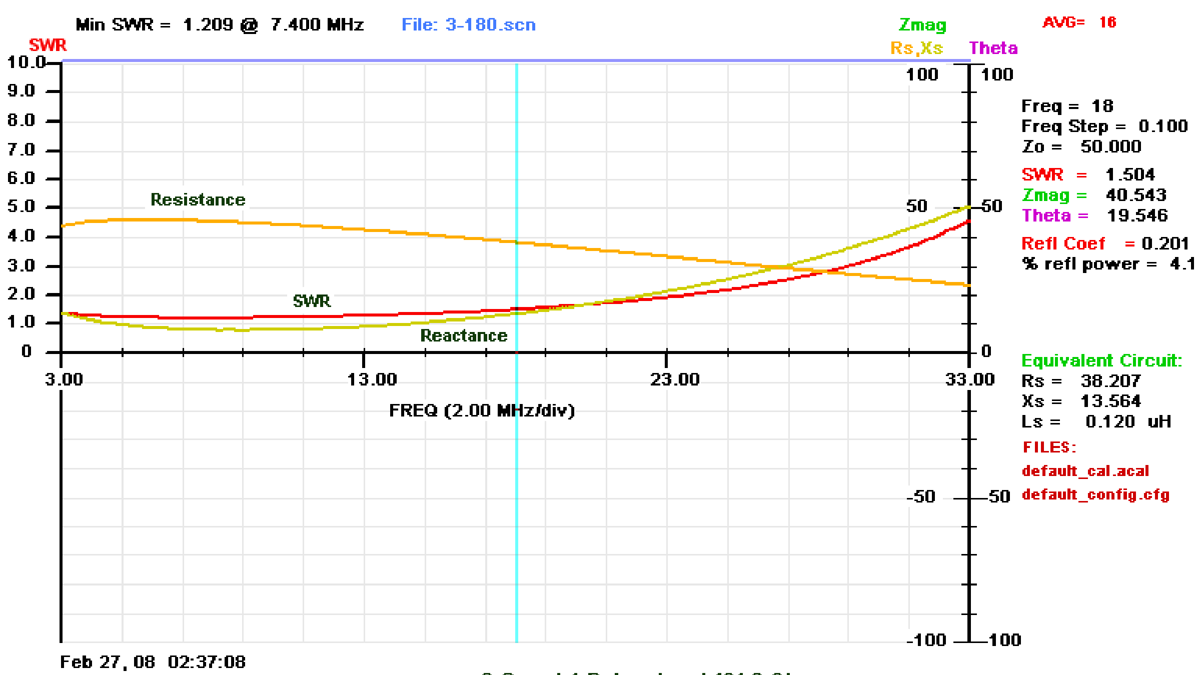
I pre-scanned each resistor to determine its characteristics at RF. All resistors showed excellent resistance stability within the passband. For example, as shown in **Fig. 12**, a sample 220-Ω resistor varied from 220.1 Ω at 3 MHz to 219.5 Ω at 33 MHz. However, with rising frequency, the units displayed a small capacitively reactive component. The test unit reactance varies from –j1.9 Ω at 3 MHz to –j11.8 Ω at 33 MHz. In general, the lower the resistor value, the smaller the reactive component. In no case did the reactance exceed 20% of the resistance value at the upper limit of the scan, and it was, of course, lower for all lower frequencies. In fact, as the resistance value decreases, the maximum reactance at 33 MHz grows lower as a relative percentage to the resistance value. As the tests will show, the characteristics of the baluns at higher frequencies will generally negate any errors introduced by the load capacitive reactance values at the upper end of the passband.



Typical Scan for a Test Load Resistor

Fig. 12

For each test run, the output will appear in two forms: a scan, such as shown in **Fig. 13**, and an associate table of values for 3.5, 7.0, 14.0, and 28.0 MHz. The sample scan graph identifies the calculated lines: orange for resistance, ochre for reactance, and red for SWR. The vertical blue line indicates the center frequency of the scan, and its values appear on the right side of the graph. Note that there is data even for the lines suppressed from view for the sake of clarity. The top line lists the minimum SWR frequency relative to 50 Ω. Had the reactance passed through the zero line, a resonant-frequencies list would also have appeared.



3-Core 4:1 Balun: Load 181.2 Ohms

Fig. 13

Test 1: Balun with resistive load of 181.2 Ohms					Fig. 14
Load R	Ideal In R	Ideal SWR			
181.2	45.300	1.104			
Freq	SWR50	R	X	Adj Id R	Adj Id X
3.5	1.33	44.97	12.51	45.54	-0.19
7.0	1.21	45.80	8.22	45.52	-0.37
14.0	1.32	41.75	9.72	45.50	-0.74
28.0	2.76	28.14	33.22	45.46	-1.49

The table samples the scan file for readings at the assigned frequencies. The column headings *SWR50*, *R*, and *X* correspond to the lines on the graph at the designated frequencies. The entries contain sufficient decimal place to allow easy identification of trends (even for some balun units that show less variation than the one used as a sample).

The graphs have two supplemental sets of values. At the top is the load value based on the DC resistance measurement of the test resistor. Beside it is the calculated "ideal" input resistance based on that load value followed by the 4:1 theoretical impedance transformation of the balun. The right two columns take into account the scans of the actual load resistors and create adjusted "ideal" resistance and reactance values based on simple proportional-parts calculations. The goal is to provide an estimate of the input values that might be produced by an ideal 4:1 balun at each frequency for comparison with the values actually measured at each sample frequency. For the sample case, we may correlate the measured values with the applicable points on the graph lines and compare the values with "ideal" values. The sample table illustrates the relative harmlessness of the capacitive reactance in the load resistor at higher frequencies, since the measured balun input reactance values are all considerably more inductive and show a much wider range of values across the range of frequencies in the table.

The graph and table require close correlation, since the numeric values are based on frequencies that are multiples of each, while the graph proceeds on a linear scale. Nevertheless, the unit in the sample suggests some possible shortcomings at higher frequencies in the HF range, even with a nearly ideal load impedance value. The actual tests will use a wide range of load values in order to see how the initial trends expand with loads both larger and smaller than ideal. Initially, we noted the application of baluns in antenna systems that present the balun with loads even wider than the range of load resistors that we shall use. Therefore, we shall be very interested in impedance transformation performance trends across the load-impedance spread to assess that performance.

Almost all of the baluns that we shall sample are commercial units. In most cases, the manufacturer is less important than the type of balun under test. Except for the dual ferrite bead balun, we shall look at two units per balun type. Unless we encounter radical variations from units of the same type, we may attribute the general properties to the balun design. The goal of the investigation is to characterize, as best possible with present instrumentation, the impedance transformation properties of various types of 4:1 baluns in common use within amateur radio applications. There are several other possible goals that are not part of this study. Generally, I am not interested in rating one balun superior to another. That judgment requires attention to many balun features outside the scope of the tests. For example, the tests do not include assessments of power handling capabilities or of the impedance of the units to common-mode currents. As well, determining the best balun for a given application requires evaluation of the unit's physical properties, including size, case materials relative to the operating environment, and the position and type of connections used, especially on the high-impedance side. Our attention to physical properties will extend only so far as they may be relevant to the balun's impedance transformation properties.

The following parts of this preliminary exercise in measure balun impedance transformation begin with a design that attracted my initial attention to the question. A few amateurs have adapted the W2DU ferrite bead balun to 4:1 service. Claims of good service carried no confirming measurements, leaving open the question of whether the configuration is capable of effective 4:1 transformation across the HF spectrum.

The following part of the sequence exams two voltage baluns. Although much criticized in terms of potential impedance transformation error, voltage baluns remain in very wide service, perhaps most notably as output devices to converted single-ended antenna tuner networks for use with balanced parallel transmission lines.

The final part of the sequence examines two specimens of true current or Guanella baluns using toroidal ferrite cores. The units differ in the selection of cores, the number of cores, and the number of turns per winding. Since the ferrite bead balun is also a variety of Guanella balun, we shall be interested in comparing the overall performance of it to the toroidal versions.

The samples are enough to start the measurement process for the sake of obtaining some general trends and overall characteristics of balun types. However, the number of units at my disposal is far short of the number of units on the markets, even within amateur radio circles. Although many units are simple clones of the units under test, construction and housing strategies are highly varied. Alas, many of the units come in sealed cases, defying any correlation between construction and materials on the one hand and performance on the other—at least without destructive deconstruction of the individual units. As a consequence, we shall have to be satisfied with the units at hand, all of which allow interior inspection.

Within these limitations, we may at least begin the process of characterizing the impedance transformation behavior of various types of 4:1 baluns in common use. The end of the process lies far in the future and may include not only a much larger selection of units, but as well a more complete set of measurements and improved measurement techniques. The final theme of these notes is simply a process of doing the best one can with what is at hand.