The Impedance-Transformation Properties of Common 4:1 Balun Types
Part 2: The Dual-Ferrite-Bead HF Balun: Some Preliminary Measurements

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In the course of examining some basic properties of isolated off-center-fed antennas, I encountered two reports on the use of a pair of W2DU ferrite bead chokes tied together to form a 4:1 HF balun. The earlier occurs in a *QST* article by John Belrose, VE2CV, and Peter Bouliane, VE3KLO ("The Off-Center-Fed Dipole Revisited: A Broadband, Multiband Antenna," August, 1990, pp. 28-34). The second appearance of the design is in an article by Frank Witt, AI1H on volume 3 of *The ARRL Antenna Compendium* ("How to Design Off-Center-Fed Multiband Wire Antennas Using the Invisible Transformer in the Sky," pp. 66-75). I wondered about the effectiveness of such an arrangement and so decided to measure the source-side impedance relative to a collection of primarily resistive loads. The AIM4170 seemed to be a very good instrument to conduct such tests. These notes report on the results of the initial tests.

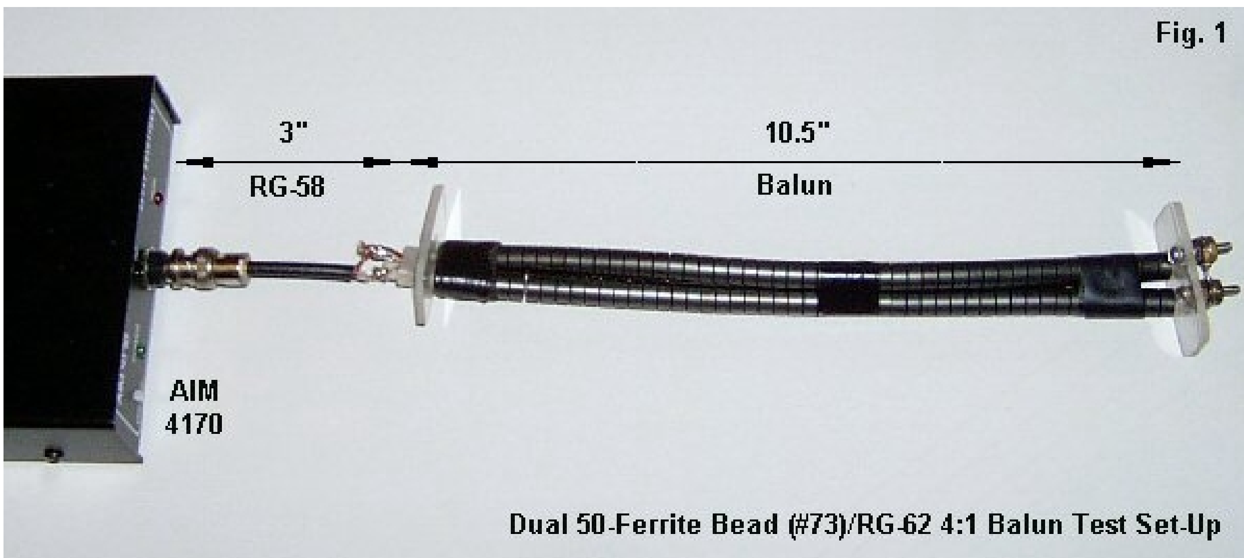
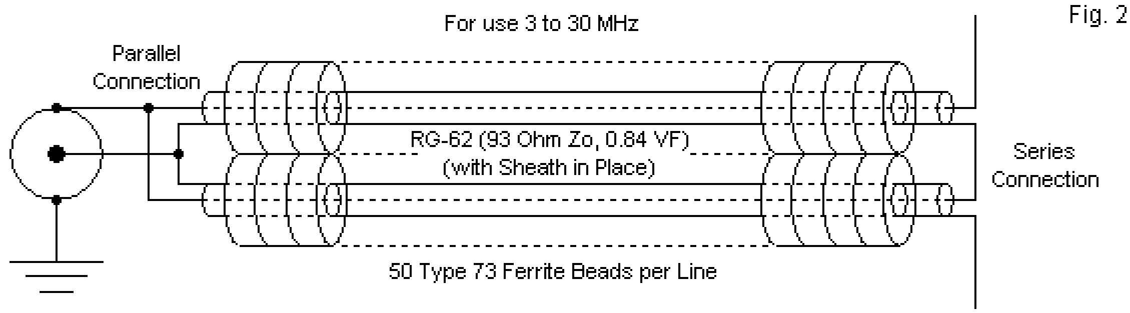


Fig. 1 photographs the test set-up. I constructed the baluns for minimal practical lead length, although the 3" section of RG-58 with a BNC connector already attached was a concession to convenience. Although the connecting line is less than 1% of a wavelength at the highest frequency scanned, I calibrated it out of the test set-up. The Plexiglas spacers at the two ends of the balun both limit bead slippage along the RG-62 cables and provide terminals for load connections (2 #6 nut-bolt-washer assemblies).

Fig. 2 provides a general sketch of the balun design. Press Jones, N8UG (The Wireman), graciously sent me his Model 835 parts kit used in his Model 824 complete balun. The kit consisted of 100 type 73 ferrite beads and about 2' of RG-62 coaxial cable. Each bead has an outer diameter of about 3/8" with an inner diameter of about 3/16". Although RG-62 has some standard listings of the outer diameter of the sheath in the vicinity of 0.26", the Wireman version of the cable has a sheath diameter of about 3/16" for a tight fit of the beads over the sheath. In practice, you would leave longer leads beyond the limits of the 50 beads per line, because you would normally provide a weatherproof housing plus suitable connectors for both the source and load ends of the assembly. Note that my terminology is transmitter oriented, although the balun works equally well (or poorly) in transmitting and receiving applications.



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

The keys to impedance transformation in the dual-choke arrangement include the use of a series connection on the load end of the system and a parallel connection on the source end. Equally important is the use of a cable characteristic impedance that is the geometric mean between the source and load target impedances. The usual conception of a 4:1 balun rests on the source-end impedance: normally 50 Ω. The target load-end impedance under a 4:1 impedance transformation is 200 Ω. The geometric mean is, of course, 100 Ω. The 93-Ω cable is close to but not exactly the ideal value for the task. Nevertheless, I wondered how the materials in this balun would affect the impedance transformation characteristics of the subject design.

The original W2DU choke employed type 73 beads with RG-303/141/142 50-Ω coaxial cable. These cables use a Teflon dielectric with a #18 center conductor and have a maximum voltage rating of 1400 v rms. RG-62 uses a #22 or #24 center conductor and has a voltage rating of 750 v rms. As a result, The Wireman rates the maximum power for the 4:1 balun at 100-200 watts. In practice, at higher power levels with the original choke, heating of the beads closest to the load has tended to form the power limit of the device and occasioned versions of the 1:1 ferrite choke balun using larger cables and beads. However, in the 4:1 balun case, excess power may show up as cable failure. I am not equipped to test the power limits of the test version—and indeed I have no desire to destroy it.

Almost all of the tests employ pre-measured ¼-w resistors as loads to check the impedance transformation characteristics of the balun from 3.5 to 30 MHz. (There is a sample additional test at the end of these notes.) The test instrument is an AIM 4170 antenna analyzer with a frequency range of 0.1 to 170 MHz. The AIM indirectly measures the impedance magnitude and phase angle of the device under test and employs associated software both to graph the results over a specified frequency range and to convert the results into other values of interest, such as the series resistance and reactance and the SWR relative to a user-set reference value. The specifications limit the magnitude to 2000 Ω, but these tests do not approach the limit. As well, the phase angles will generally be quite low, assuring good accuracy in the conversion to resistance and reactance values. The instrument is accurate by specification to 1 Ω +/- 5% of the reading. The data tables will provide numbers well beyond accuracy limits, because part of our interest lies in the trends in value progressions across the frequency range of the tests.

My resistor collection does not include any precise 200-Ω values. However, it does include a range of values that will provide an interesting overview of the balun's impedance transformation properties with resistive loads. The basic tests include values close to optimal on either side of the 200-Ω value and more distant values simulating the use of the balun with less than ideal loads. I used resistors from 100 Ω to 560 Ω for the tests.

Test 1: 180 Ω: The most basic test employed a resistor of 181.2 Ω, close to the target 200-Ω value. The test provides an opportunity to explain both the graph lines in **Fig. 3** and the table labels.

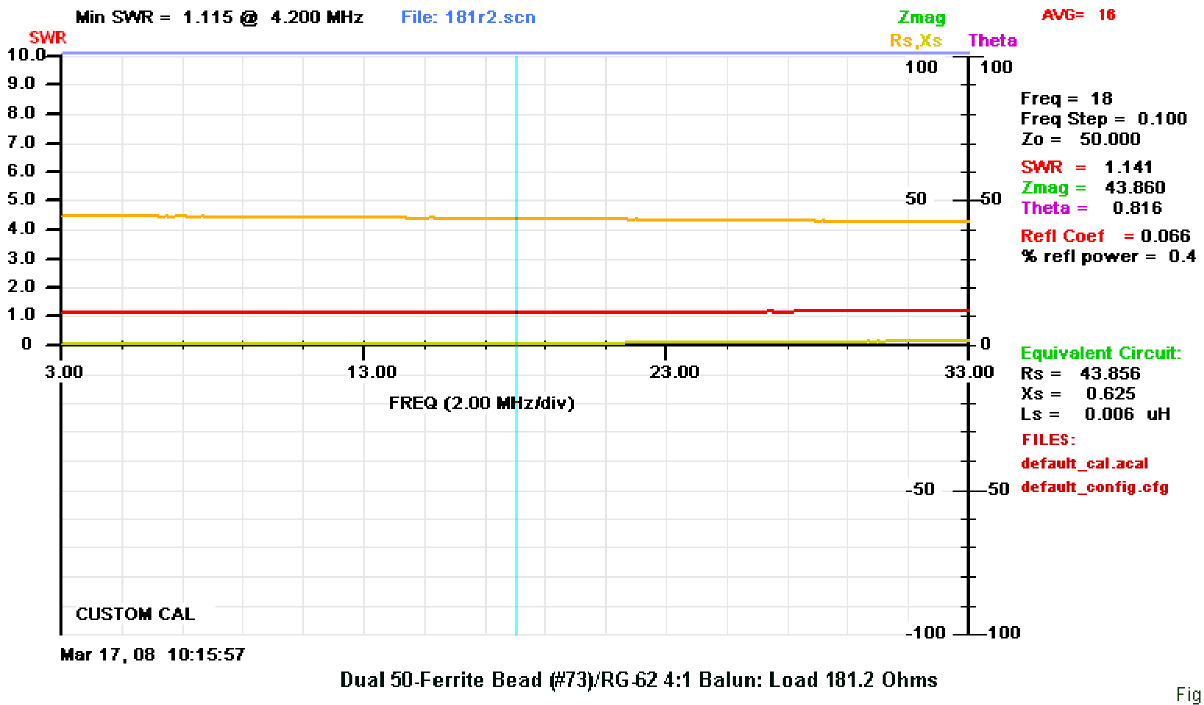


Fig. 3

Test 1: Balun with resistive load of 181.2 Ohms					
Load R	Ideal In R	Ld SWR	In SWR		
181.2	45.300	1.026	1.104		
Freq	SWR50	R	X	Adj Id R	Adj Id X
3.5	1.12	44.73	0.56	45.54	-0.19
7.0	1.12	44.67	0.38	45.52	-0.37
14.0	1.14	44.06	0.45	45.50	-0.74
28.0	1.17	42.97	1.25	45.46	-1.49
Delta	0.05	1.76	0.69		

The column headings SWR50, R, and X correspond to the lines on the graph at the designated frequencies. The entries contain sufficient decimal places to allow easy identification of trends. 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.

The graph lines for the resistive (orange) and reactance (ochre) impedance components are very close to flat across the frequency range. The SWR line (red) is very close to 1:1 across the scanned spectrum. The graph confirms that the balun performs well at all HF frequencies tested with a resistive load close to optimal. However, the graph can also obscure some trends in the numbers. Therefore, the table provides sample numbers at traditional amateur frequencies. Although the increments are small, the "delta" values show that with increasing frequency, the source-end resistance grows smaller while the reactance becomes more inductive. As well, the 50-Ω SWR at the source end of the balun increases with frequency, due to the reduction in resistance, which is below 50 Ω throughout.

Test 2: 220 Ω: Increasing the resistance to 20 Ω above the target load impedance (200 Ω) does not yield identical results in the scan, since the ideal impedance for the balun is about 186 Ω. However, as shown in **Fig. 4**, the balun functions quite well under the conditions. The same lines overlap as in the previous test, and the SWR line is barely above the 1:1 marker.

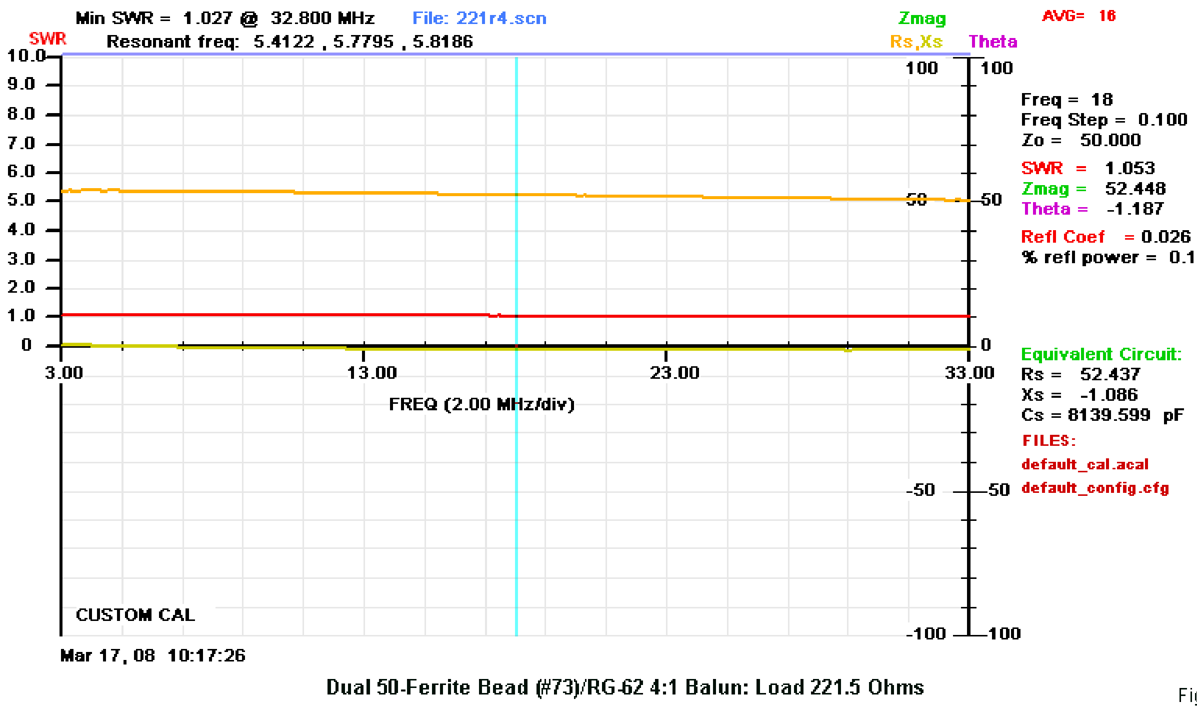
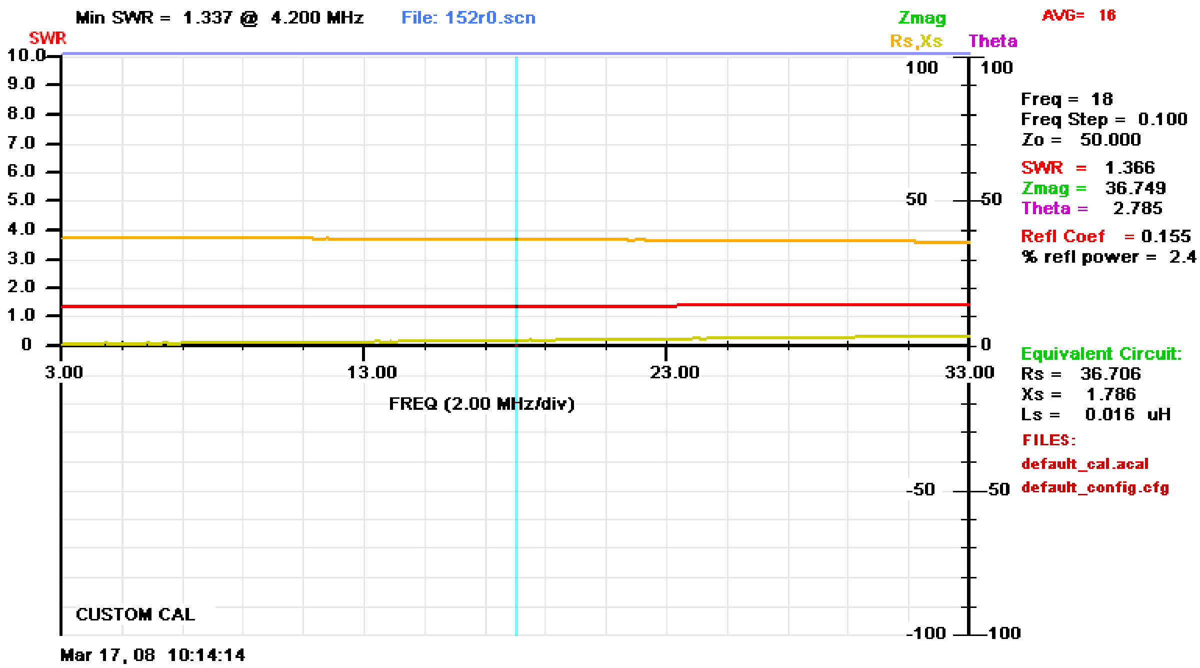


Fig. 4

Test 2: Balun with resistive load of 221.4 Ohms					
Load R	Ideal In R	Ld SWR	In SWR		
221.4	55.350	1.190	1.107		
Freq	SWR50	R	X	Adj ld R	Adj ld X
3.5	1.08	53.74	0.47	55.11	-0.36
7.0	1.07	53.68	-0.22	55.09	-0.70
14.0	1.06	52.85	-0.93	55.05	-1.39
28.0	1.03	51.12	-1.24	54.97	-2.76
Delta	0.04	2.62	-1.71		

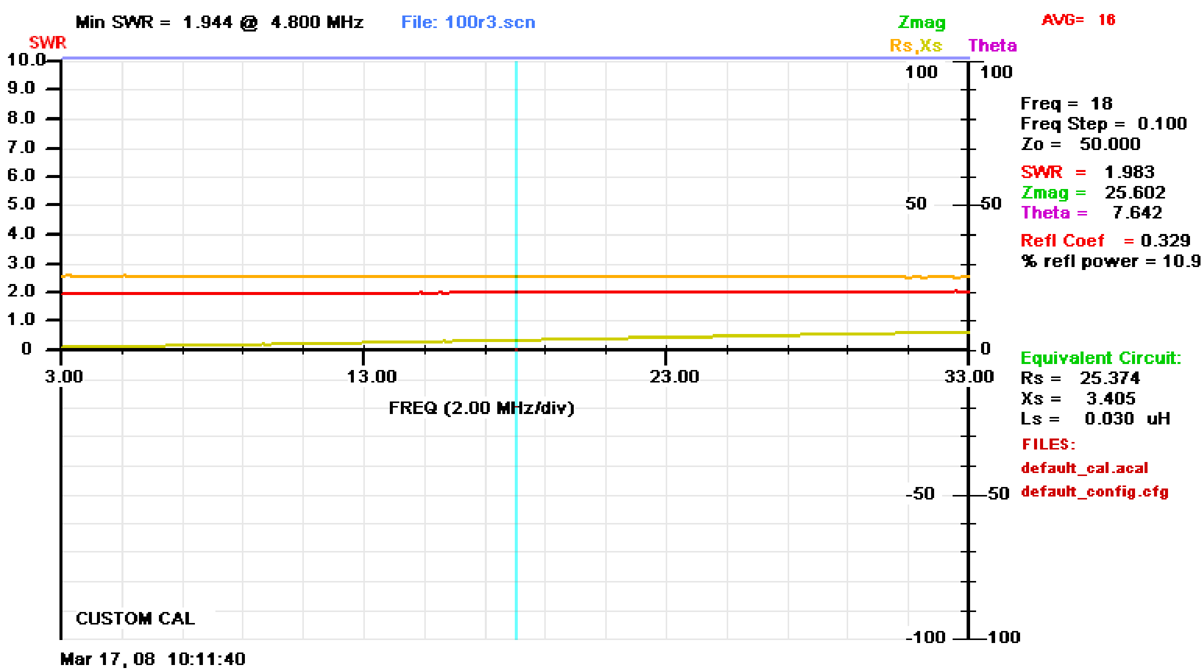
As in the first test, the resistance decreases with frequency, but the reactance becomes more capacitive. Since the loads resistors become more capacitively reactive with rising frequency, the actual reactance may run from about j0.3 Ω to j1.1 Ω from 80 through 10 meters. Because the resistance is above 50 Ω throughout, the 50-Ω SWR decreases with rising frequency. Above and below the ideal impedance, the trends in resistance, reactance and 50-Ω SWR show reverse tendencies. Let's examine the tests below 180 Ω to determine if these trends continue to hold.

Test 3: 150 Ω and Test 4: 100 Ω: The graphs for the third and fourth tests appear in **Fig. 5** and in **Fig. 6**. The resistive component line continues to be quite flat for both lower resistive loads. The reactance grows more rapidly with decreasing resistive values as loads, but any contribution by the load resistor itself is minuscule. The source-end SWR relative to 50 Ω continues to increase, but the rate is not consistent with the target 200-Ω load-end value. However, SWR values are consistent with a load-end ideal of about 186 Ω.



Dual 50-Ferrite Bead (#73)/RG-62 4:1 Balun: Load 152.0 Ohms

Fig. 5



Dual 50-Ferrite Bead (#73)/RG-62 4:1 Balun: Load 100.3 Ohms

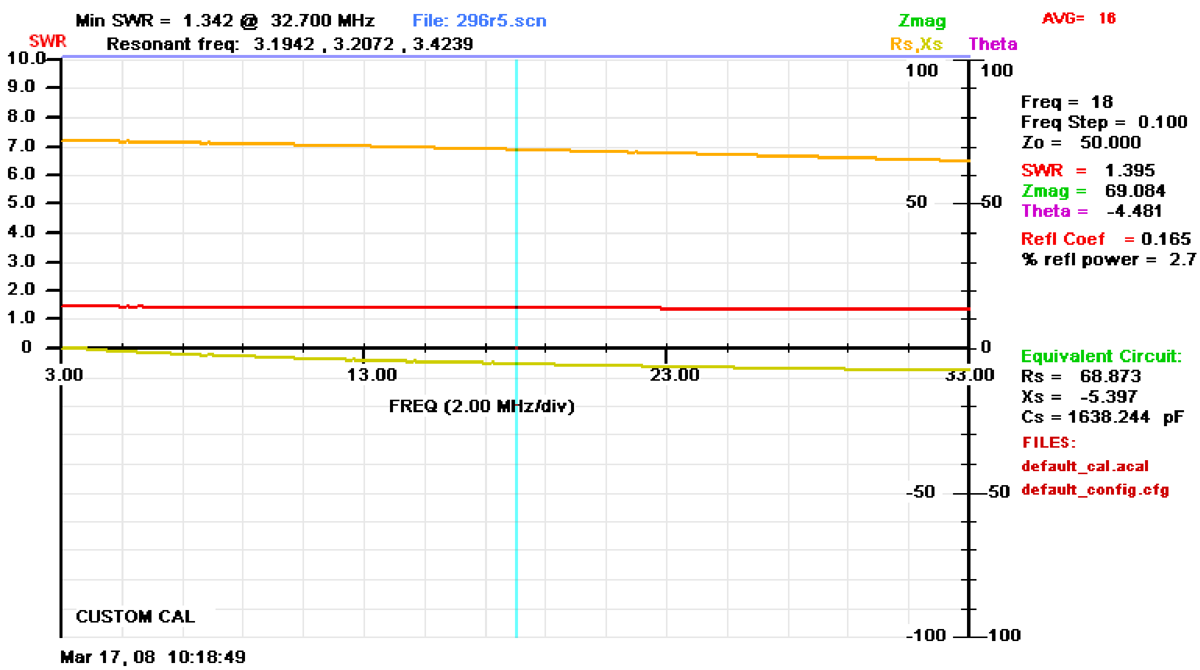
Fig. 6

Test 3: Balun with resistive load of 152.0 Ohms					
Load R	Ideal In R	Ld SWR	In SWR		
152.0	38.000	1.224	1.316		
Freq	SWR50	R	X	Adj Id R	Adj Id X
3.5	1.34	37.41	0.80	37.86	-0.15
7.0	1.35	37.21	0.86	37.85	-0.22
14.0	1.36	36.88	1.35	37.83	-0.38
28.0	1.39	36.14	2.90	37.78	-0.68
Delta	0.06	1.27	2.10		

Test 4: Balun with resistive load of 100.3 Ohms					
Load R	Ideal In R	Ld SWR	In SWR		
100.3	25.075	1.854	1.994		
Freq	SWR50	R	X	Adj Id R	Adj Id X
3.5	1.95	25.65	0.90	25.06	0.03
7.0	1.96	25.59	1.45	25.06	0.09
14.0	1.97	25.45	2.63	25.06	0.20
28.0	2.01	25.22	5.26	25.05	0.42
Delta	0.06	0.43	4.36		

Placing the tables side by side allows us to compare the rate of change in the delta values as well as to confirm the trends in the initial tables. Resistance decreases with rising frequency, while the reactance becomes more inductive. The SWR also steadily increases with frequency in both cases. Notably, as we mismatch the load impedance to the balun's load end with values below the ideal, the rates of change with frequency increase with the increasing mismatch. We may also note that the frequency at which the theoretical input-side SWR occurs increases with the increasing mismatch for loads less than about 186 Ω.

Test 5: 295 Ω and Test 6: 390 Ω: To determine whether the opposing trends are also general, **Fig. 7** graphs the data for a load of 295 Ω, while **Fig. 8** does the same for a load of 390 Ω. The side-by-side tables provide the associated numerical data for the two extensions of the initial load of 220 Ω. The most general trend that we can immediately observe with higher load resistance values is the almost linear decline in resistance and the rising capacitive reactance with the rising frequency and load value.

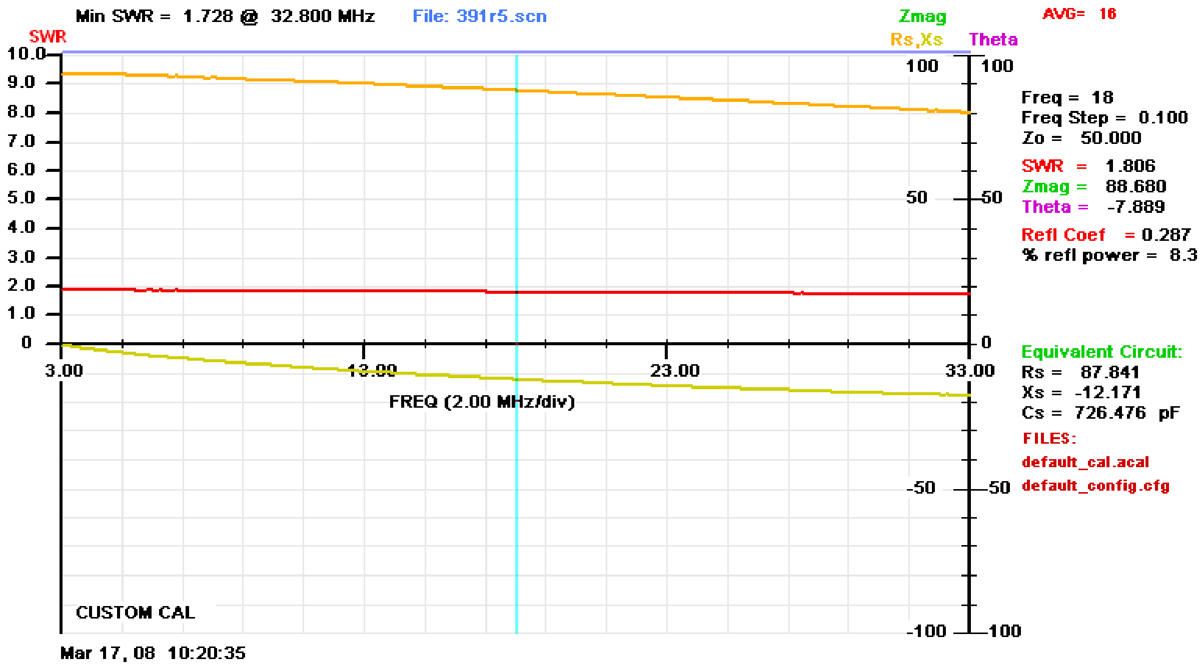


Dual 50-Ferrite Bead (#73)/RG-62 4:1 Balun: Load 296.5 Ohms

Fig. 7

Test 5: Balun with resistive load of 296.5 Ohms					
Load R	Ideal In R	Ld SWR	In SWR		
296.5	74.125	1.594	1.483		
Freq	SWR50	R	X	Adj Id R	Adj Id X
3.5	1.44	71.76	-0.13	73.91	-0.42
7.0	1.43	71.27	-2.13	73.86	-1.10
14.0	1.41	69.77	-4.29	73.75	-2.46
28.0	1.36	66.24	-7.13	73.55	-5.19
Delta	0.08	5.52	-7.00		

Test 6: Balun with resistive load of 391.5 Ohms					
Load R	Ideal In R	Ld SWR	In SWR		
391.5	97.875	2.105	1.958		
Freq	SWR50	R	X	Adj Id R	Adj Id X
3.5	1.87	93.31	-1.07	97.40	-1.37
7.0	1.86	92.38	-5.07	97.27	-2.61
14.0	1.83	89.72	-10.18	97.01	-5.08
28.0	1.75	82.66	-16.22	96.50	-10.03
Delta	0.12	10.65	-15.15		



Dual 50-Ferrite Bead (#73)/RG-62 4:1 Balun: Load 391.5 Ohms

Fig. 8

Although the resistance increments might suggest SWR values corresponding to those for the lower resistance tests, the values are higher, since the ideal load is less than 200 Ω. However, in both supplementary tests, the SWR decreases with frequency, just as does the resistive component of the source-end impedance. As well, the reactance becomes more capacitive as we increase the scanned frequency.

As we depart further from the ideal load resistance, the amount of increase with rising frequency also grows. Moreover, the frequency at which the theoretical SWR actually occurs becomes lower as we increase the mismatch between the load and the balun's load end. Nevertheless, the dual ferrite bead 4:1 balun appears to provide quite good impedance transformation service across the HF range for load SWR values up to 2:1 in either direction from the ideal—at least in applications that do not challenge the power-handling capabilities of the choke assemblies. In the scans, we find no anomalous frequencies, although the 0.1-MHz increments between test steps are small enough to detect almost any spike that might occur.

Test 7: 560 Ω: I used a 560-Ω load that provided the load end of the balun with an SWR value outside the desirable (2:1) range. The load SWR is just over 3.0:1, although the source-end of the balun should show a 50-Ω SWR below about 2.8:1. **Fig. 9** provides the graph of values, with the Y-axis scale expanded to handle impedance magnitude and resistance values greater than 100 Ω.

Nevertheless, in this low power test situation, the graph shows no visible anomalies. The trends that we saw in tests with resistive loads higher than the ideal balun input impedance simply continue to grow with the increasing mismatch between the balun's load end and the load itself. However, not all of the lines may be as linear as they initially appeared with smaller load values. For example, the reactance begins to level off at higher frequencies, as borne out by the data in the test table. It is possible that the capacitive reactance of the load resistors may provide up to 1/3 of the total measured capacitive reactance. On the other side of the coin, above 7 MHz, the rate of resistance decrease is almost linear.

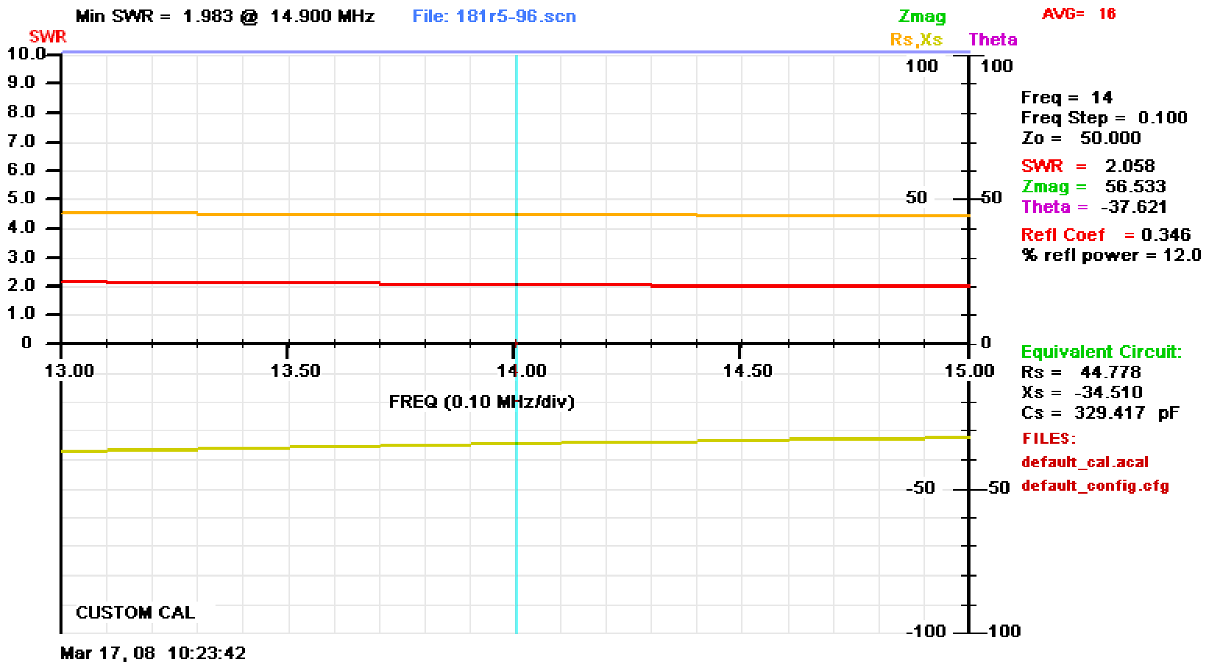
Test 7: Balun with resistive load of 561.0 Ohms					
Load R	Ideal In R	Ld SWR	In SWR		
561.0	140.250	3.016	2.805		
Freq	SWR50	R	X	Adj Id R	Adj Id X
3.5	2.65	132.45	-3.28	139.82	-2.61
7.0	2.63	130.29	-12.31	139.40	-5.13
14.0	2.56	122.75	-23.38	138.56	-10.16
28.0	2.43	107.11	-35.50	136.87	-20.23
Delta	0.22	25.34	-32.22		

With a high SWR (>3:1) on the load side of the balun, the input-side impedance may prove to be less predictable than we like to expect of a balun as we change the operating frequency from one end of the spectrum to the other. The tests themselves do not permit a determination of all of the factors involved, although speculative calculations may turn up several potential sources including balun losses. (Common-mode currents are unlikely, since I added about 17" of RG142 in the form of an additional common-mode ferrite bead choke, and the measured values at the test frequencies were consistent with the calculated impedance transformation created by the length of added cable.)

The increasing slope of both the resistance and reactance curves with rising load values is moderate but noticeable. Although these notes have registered the possible effect of the capacitive reactance of higher-value resistors used as loads, the effects of the RG-62 cables used as a foundation for the balun remain unanalyzed. With rising frequency, the cable length (about 10.5") becomes slightly more significant as we also change the load to create a larger mismatch between the load impedance and the 186-Ω impedance of the balun. In addition, the ferrite beads used for the structure also have somewhat indeterminate frequency limits. While all of the noted factors may play some role in the sloping curves, the nature of the present test procedure cannot sort out the practical role of each factor.

Test 8: 181.2 – j117.3 Ω @ 14 MHz: A full test sequence would devise many loads for the dual ferrite 4:1 balun with varying levels of reactance in the load. Because all such tests are frequency specific, we shall just use one example, a load of 181.2 Ω resistance with a capacitive reactance of –j117.3 Ω representing a 96.9-pF capacitor at 14 MHz. The graph for this combination appears in **Fig. 10**, which uses a scan restricted to the region from 13 to 15 MHz. The cursor for the scan rests on the target frequency and so the values on the right side of the graph read out the measured values of 50-Ω SWR, resistance, and reactance at the input side of the balun assembly. The impedance is 44.78 – j34.51 Ω, yielding a 50-Ω SWR value of 1.978 at 14 MHz. (Note once more that reported values use excess decimal places relative to the specified accuracy limits of the AIM instrument.) Ideally, the 4:1 balun should yield values of both resistance and reactance that are close to ¼ the load values, or 45.3 – j29.3 Ω. The dual ferrite bead balun comes within a few Ohms of the ideal.

Test 8: Balun with a complex load of 181.2 - j117.3 Ohms					
	Ideal SWR: 1.978:1		Ideal R-X: 45.3 - j29.3 Ohms		
	Dual Ferrite Bead Balun				
Freq	SWR50	R	X		
13	2.15	45.38	-37.06		
14	2.06	44.78	-34.51		
15	1.98	44.40	-32.26		



Dual 50-Ferrite Bead (#73)/RG-62 4:1 Balun: Load 181.5 - j117.3 Ohms

Fig. 10

Within the boundaries of this limited test, the resulting values are quite reasonable, with a 50-Ω SWR value that approaches 2:1, as designed by the selection of components. Tests at other frequencies, of course, would require hand selection of load components to yield results that permit transparent comparisons.

Conclusions

When used within 2:1 SWR limits, the dual-ferrite bead 4:1 balun appears to perform quite normally and well for its intended purpose. The tests in this series checked only the impedance transformation and not the consequences of operating the balun near, at, or beyond its power handling limits. Nor do the present tests measure the common-mode current attenuation of the balun. Within these preliminary test restrictions, the performance is smooth across the HF spectrum, but not without some trends that show widening ranges of input-side impedance changes with increasing or decreasing operating frequencies. However, for SWR values up to 2:1, the variations fall within easily managed limits.

Special Note

Measurements show that for the dual ferrite-bead 4:1 balun, with loads higher than the ideal load impedance, the resistance value at the input decreases with rising frequency. At the same time, the input reactance becomes increasingly capacitive for the same frequency range. The higher that the load resistance is relative to an ideal load, the steeper that the curves become for both resistance and reactance. At the same time, the 50-Ω SWR values calculated for the resistance and reactance remain relatively constant, even with the 561-Ω load.

The behavior of the resistance and reactance for loads that are not matched to the balun's characteristic impedance and configuration do not represent material limitations or similar possible flaws in design. Rather, they are inherent factors in the design itself. The balun consists of approximate 1' sections of transmission line operated over a wide frequency range.

When we attach a load to a simple transmission line that is higher than the line's characteristic impedance, the input end of the line will show values of resistance and reactance follow the same patterns displayed by the balun. In fact, the calculated values for simple lines are within a few percent of the measured values for the balun. Since the load resistors for these tests are not perfect, and since the test measurements have a limited range of precision, it is not possible to separate the transmission-line impedance transformation with unmatched loads from any other source of variation. For practical purposes, the values shown by the measurements are in accord with the behavior of the loads relative to the impedance transformation properties of the transmission lines that underlie them.

The tests leave several open questions that call for further testing and comparisons. We have noted the difference between minimum power bench tests and normal operating power levels. Bead heating, especially at the load end of the balun, may result in additional performance departures from the ideal. As well, we have the matter of the source of the trends in resistance and reactance variation that call for a different set of measurements to decide—or a different test set-up—or both. In addition, it might be useful to perform an equivalent set of tests with a single-core (or core stack) balun wound with carefully spaced wires to compare the trends in impedance as we move across the HF spectrum. In the end, these notes are but a start toward full testing, but the start is sufficient to establish the basic impedance transformation function. However, the remaining questions may ultimately prove equally interesting.

My thanks go to Press Jones, N8UG, for supplying the balun materials for these very preliminary tests.