The Dual-Ferrite-Bead 4:1 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 preliminary tests. These notes report on the results of the initial tests.

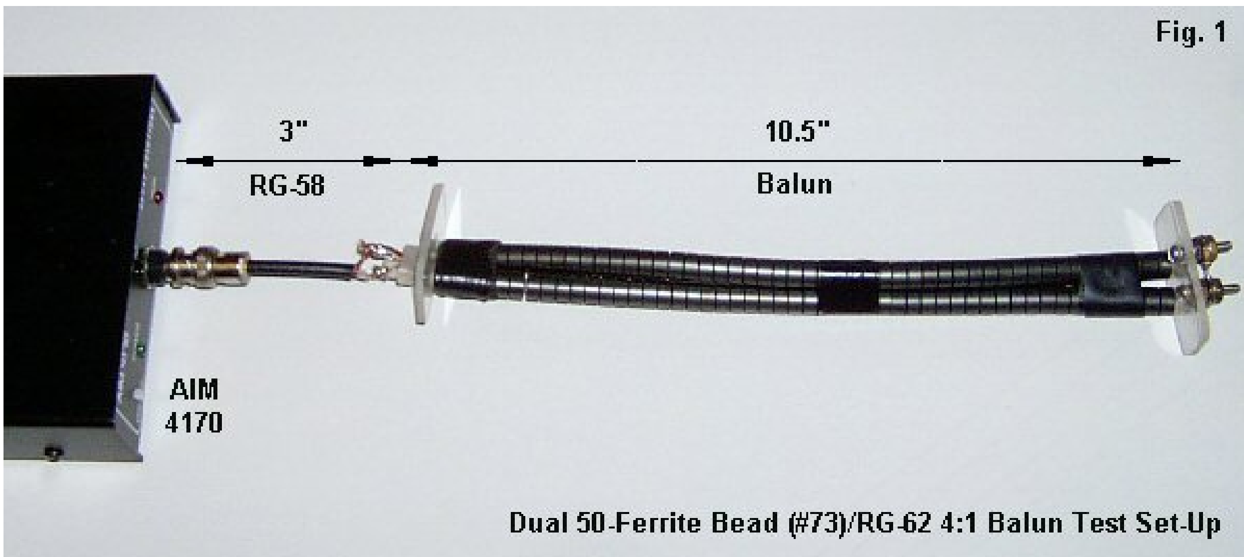
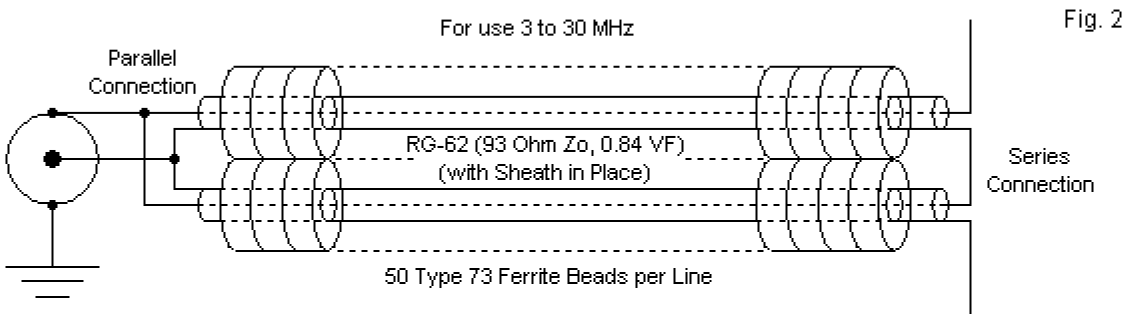


Fig. 1 photographs the test set-up. I constructed the baluns for minimal practical lead length, although the 3" section of RG-58 with a BNC connector already attached was a concession to convenience. I did not try to compensate for the RG-58, since the length was well under 1% of a wavelength at the highest surveyed frequency. 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. However, windings that I have seen applied to single-core (or core stack) versions of functionally equivalent current baluns tend only to approximate a consistent 100-Ω characteristic impedance, and in some baluns, the approximation can be fairly careless. 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 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 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 200-Ω precise 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: 181.2 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.

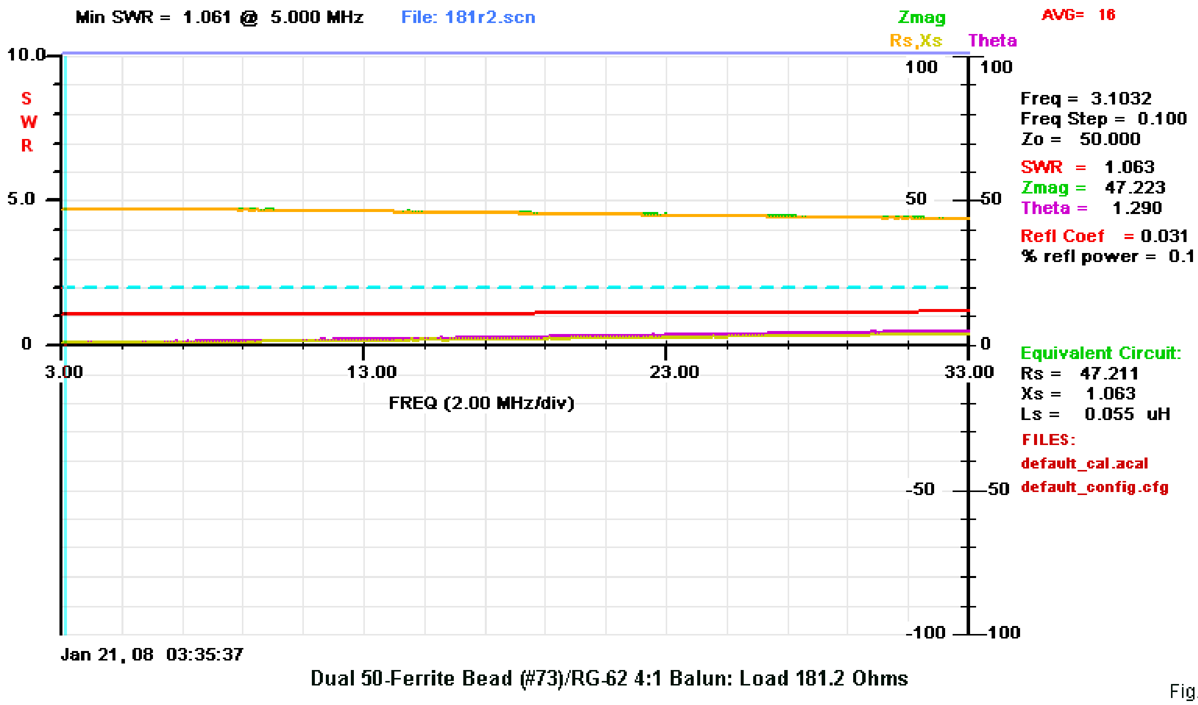
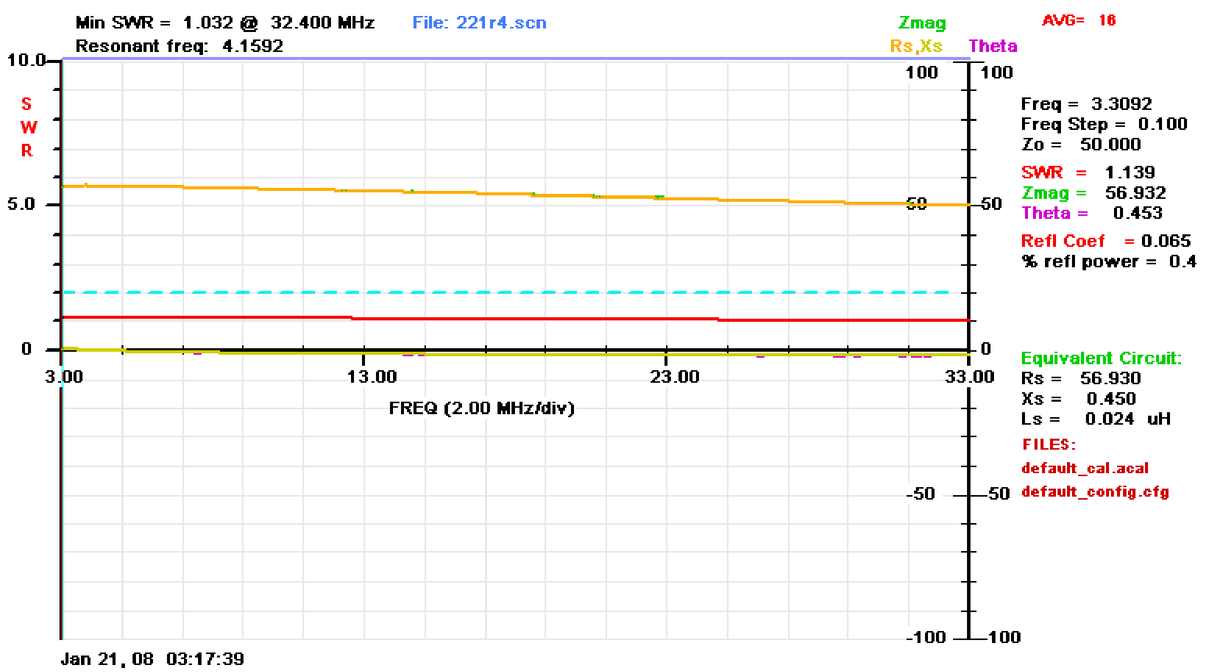


Fig. 3

Test 1: Balun with resistive load of 181.2 Ohms						Table 1
	Load R	Ideal In R	Ld SWR	In SWR		
	181.2	45.300	1.026	1.104		
	Freq	SWR50	R	X		
	3.5	1.063	47.234	1.055		
	7.0	1.068	46.998	1.044		
	14.0	1.091	46.324	1.884		
	28.0	1.151	44.354	3.366		
	Delta	0.088	-2.880	2.311		
Load R = Value of test resistor in Ohms						
Ideal In R = Ideal transformed resistance in Ohms						
Ld SWR = Load SWR relative to series-connected RG-62 (186 Ohms)						
In SWR = SWR relative to 50 Ohms of ideal transformed load						
SWR 50, R, X = Measured values at indicated frequencies in MHz						
	R and X in Ohms					

The graph lines for the impedance magnitude and the resistive component of the impedance overlap in this case because the phase angle is close to zero. As well, the phase-angle and reactance lines also overlap for the same reasons. The dashed line is a 2:1 SWR reference line (relative to 50 Ω), while the SWR line itself 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, **Table 1** 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: 221.4 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.



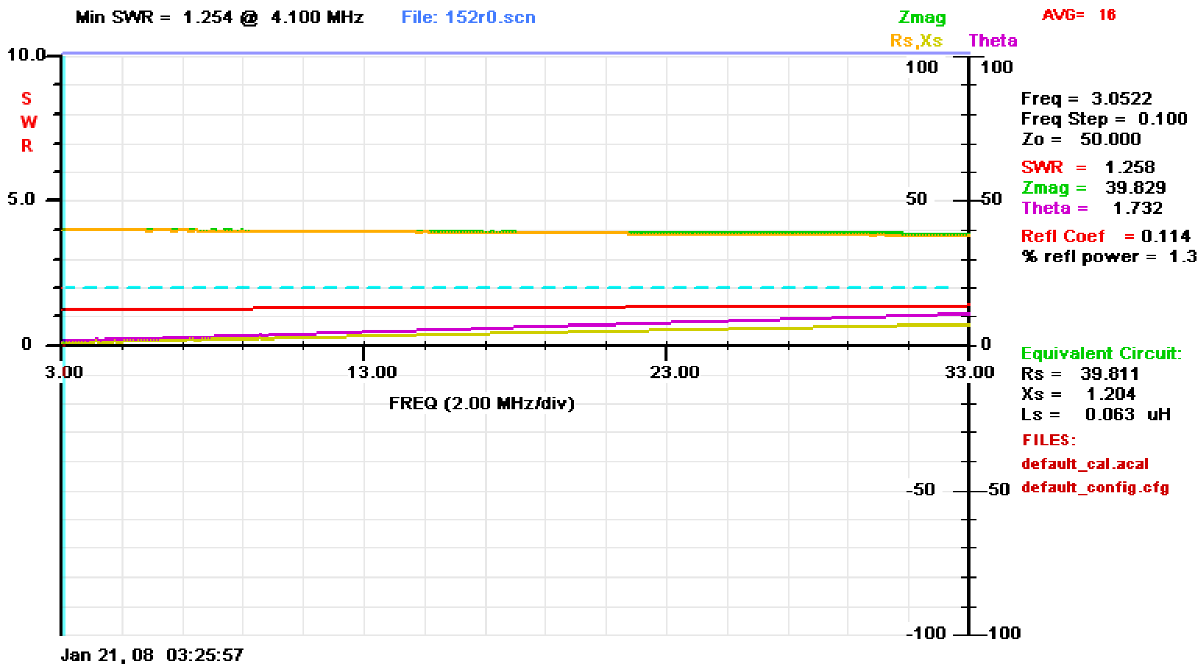
Dual 50-Ferrite Bead (#73)/RG-62 4:1 Balun: Load 221.5 Ohms

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
	3.5	1.139	56.996	0.287
	7.0	1.132	56.552	-0.551
	14.0	1.102	54.941	-1.261
	28.0	1.041	51.281	-1.604
Table 2	Delta	-0.098	-5.715	-1.891

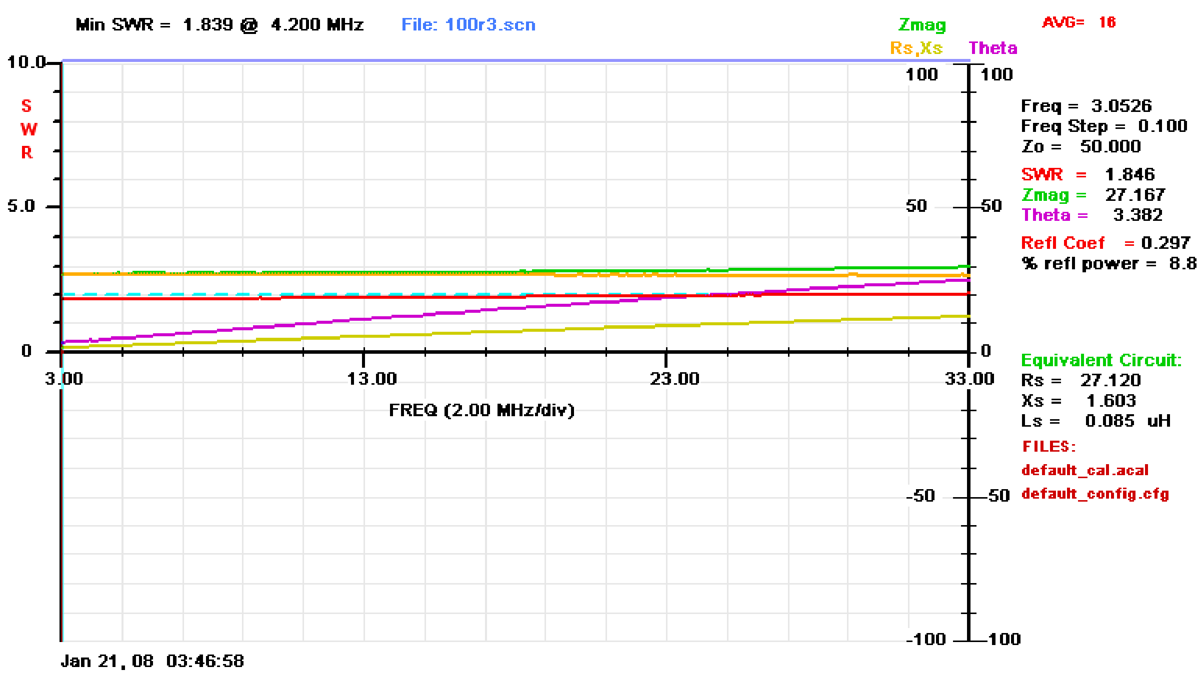
Table 2 omits the explanations of the headings, which are the same in all test tables. As in the first test, the resistance decreases with frequency, but the reactance becomes more capacitive. Because the resistance is above 50 Ω throughout, the SWR decreases with rising frequency. Above and below the 50-Ω standard, the trends in resistance, reactance and 50-Ω SWR show reverse tendencies. Let's examine the tests below 181.2 Ω to determine if these trends continue to hold.

Test 3: 152.0 Ω and Test 4: 100.3 Ω: The graphs for the third and fourth tests appear in **Fig. 5** and in **Fig. 6**. The impedance magnitude and resistive component lines continue to overlap (within the limits of the line thickness), but we find a small divergence between the phase-angle (theta) line and the reactance. The divergence grows as we continue to decrease the value of the load and present the load-end of the balun with a higher SWR. 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. The numerical data appear in **Table 3** and in **Table 4**.



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

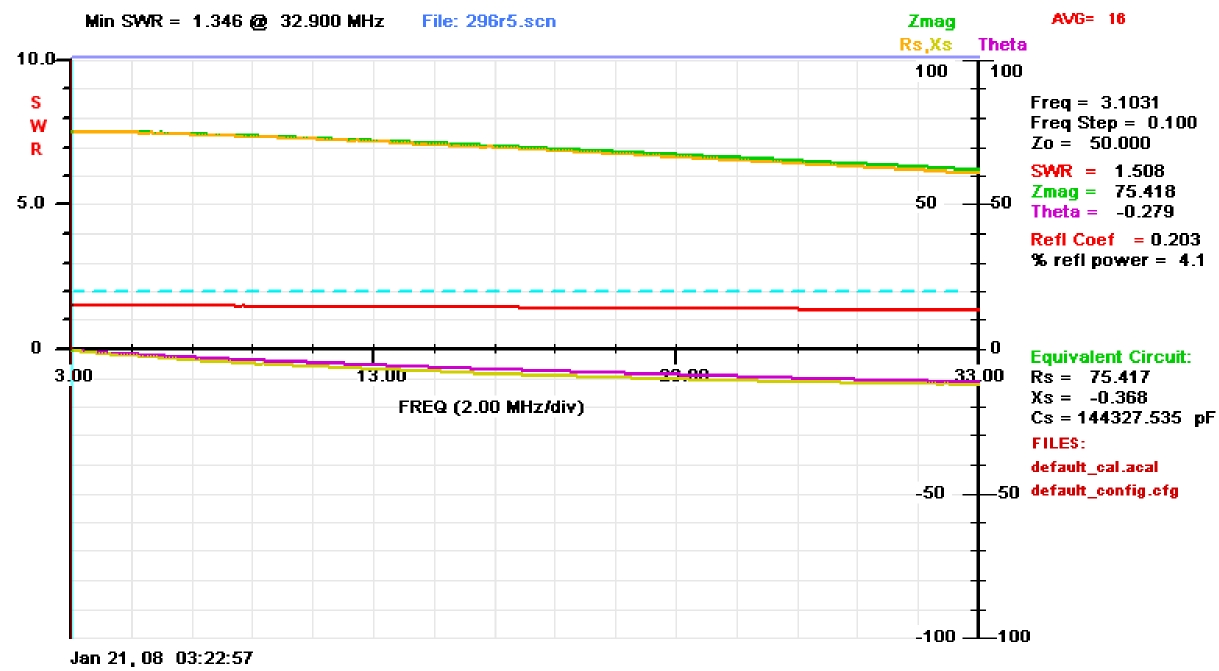
Fig. 6

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
	3.5	1.255	39.904	1.157
	7.0	1.263	39.741	1.825
	14.0	1.291	39.197	3.393
	28.0	1.357	38.195	6.318
Table 3	Delta	0.102	-1.709	5.161

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
	3.5	1.843	27.181	1.772
	7.0	1.854	27.107	3.077
	14.0	1.891	26.995	5.869
	28.0	1.991	26.721	10.794
Table 4	Delta	0.148	-0.460	9.022

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 **Table 1**. 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: 296.5 Ω and Test 6: 391.5 Ω: To determine whether the opposing trends are also general, **Fig. 7** graphs the data for a load of 296.5 Ω, while **Fig. 8** does the same for a load of 391.5 Ω. **Table 5** and **Table 6** provide the associated numerical data for the two extensions of the initial load of 221.4 Ω.



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
	3.5	1.507	75.325	-1.128
	7.0	1.494	74.318	-3.835
	14.0	1.457	71.381	-7.378
	28.0	1.372	63.695	-11.563
Table 5	Delta	-0.135	-11.630	-10.435

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
	3.5	1.958	97.757	-3.212
	7.0	1.941	95.853	-9.096
	14.0	1.888	89.691	-17.234
	28.0	1.771	74.498	-25.454
Table 6	Delta	-0.187	-23.259	-22.242

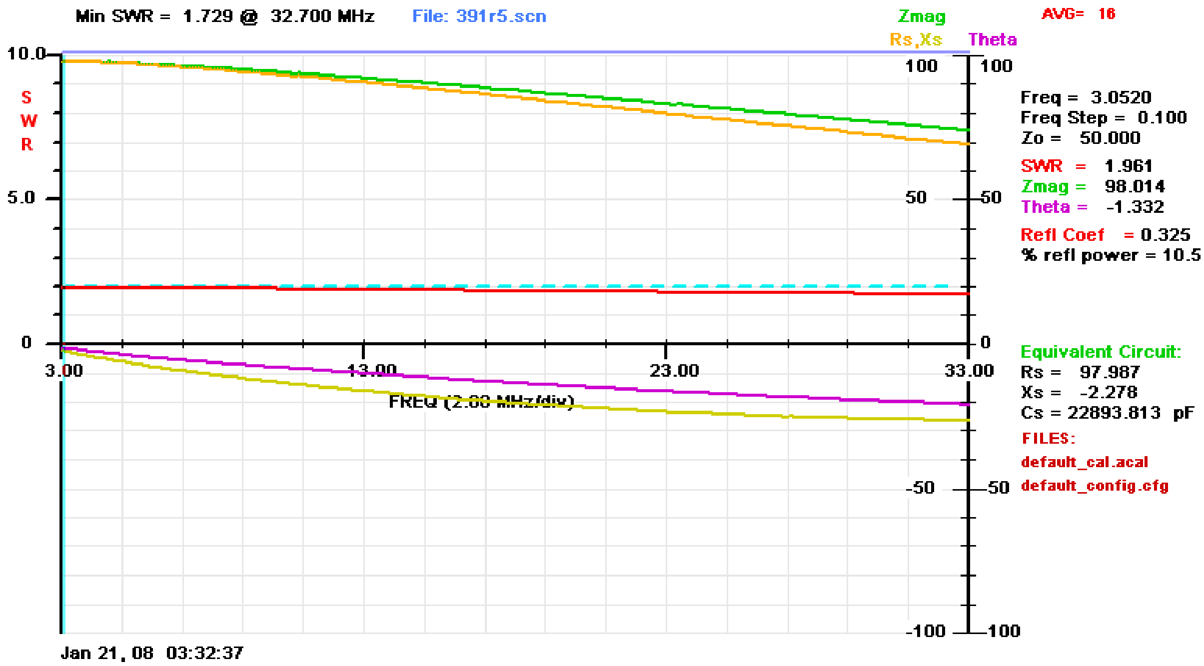


Fig. 8

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 occurs becomes lower as we increase the mismatch between the load and the balun 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: 561.0 Ω: I used a 561-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. As expected, the graphed lines for resistance and impedance magnitude and for reactance and phase angle (theta) diverge by significant amounts.

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 appear. For example, the reactance begins to level off at higher frequencies, as borne out by the data in **Table 7**. On the other side of the coin, above 7 MHz, the rate of resistance decrease is almost linear.

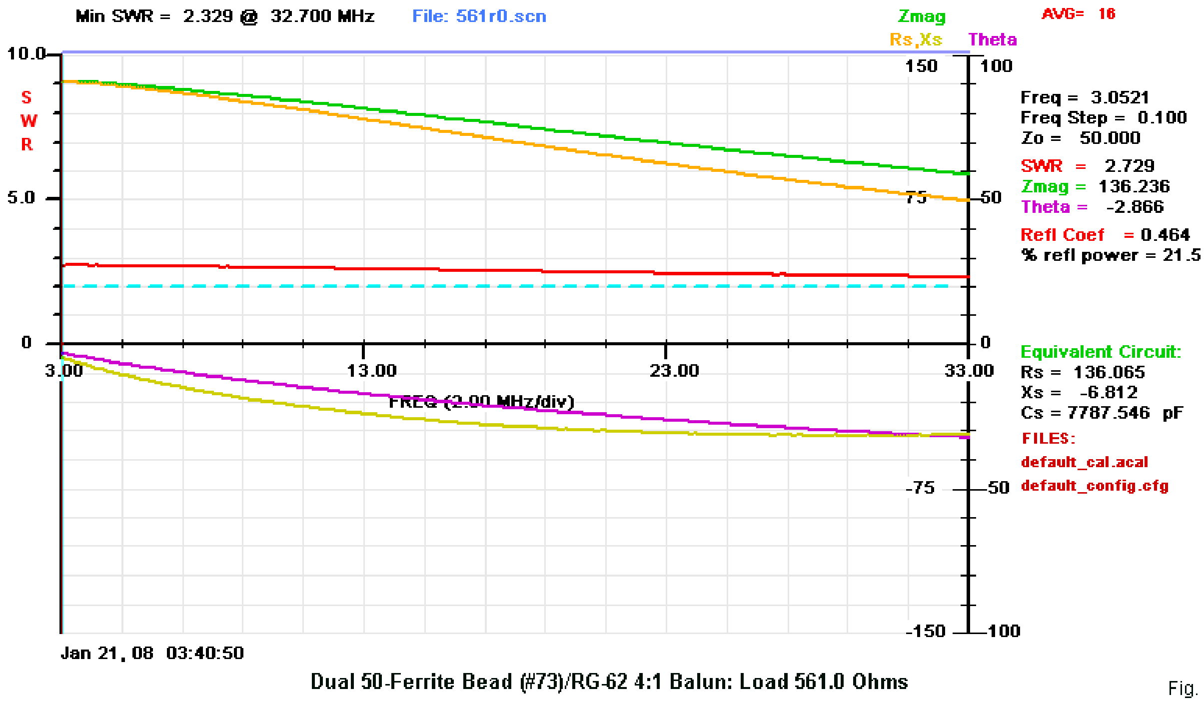


Fig. 9

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
	3.5	2.734	136.065	-6.812
	7.0	2.699	130.434	-22.455
	14.0	2.592	114.505	-37.888
	28.0	2.389	83.597	-47.405
Table 7	Delta	-0.345	-52.468	-40.593

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 the precise factors involved, although speculative calculations may turn up several potential sources including remnant common-mode currents and 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.)

Test 8: 181.5 – 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 43.72 – j31.91 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.)

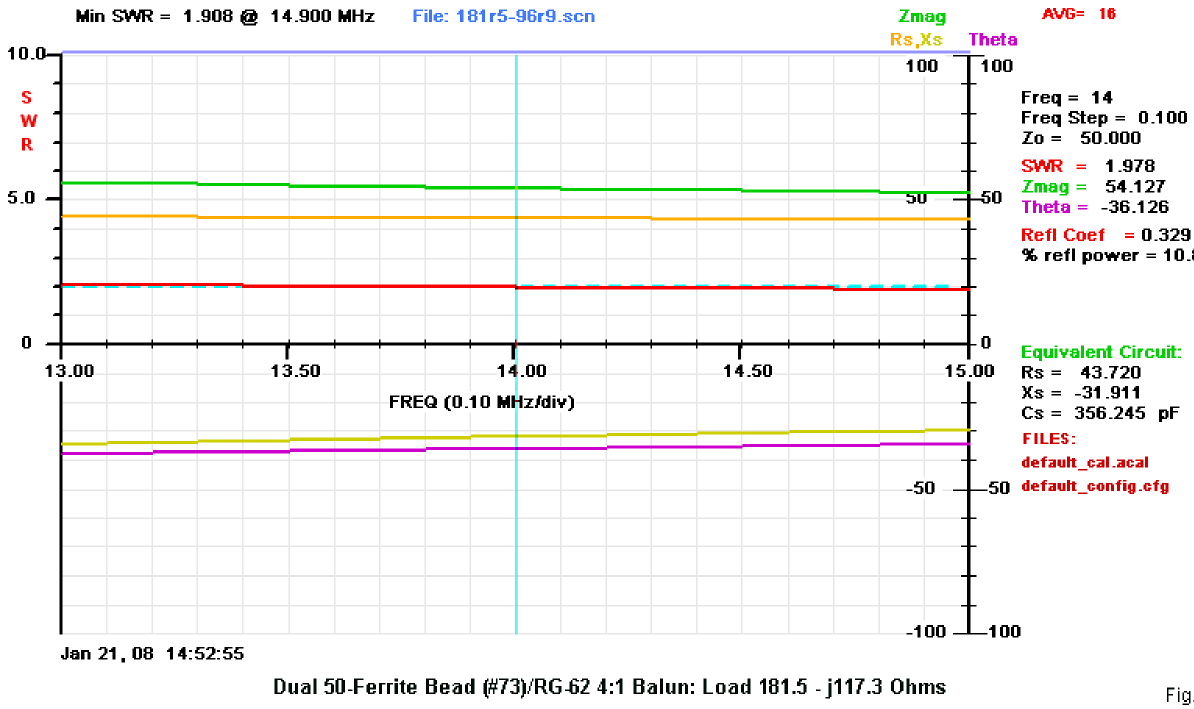


Fig. 10

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. 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.

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. 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 more interesting.

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

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