a new class of coaxial-line transformers

A review of transmission-line transformers and balun theory, including problems with magnetic cores — Part 1 of a two-part series

Most coaxial-fed antennas require a balun for optimum performance; many also require a matching transformer. Typically, these baluns and transformers are made with magnetic core material such as ferrite. These devices are subject to arcing and linearity problems. Simple baluns and a new class of rf transformers which are not subject to these problems use only coaxial line in their construction — and they are easy to make.

To match the low impedance of two closely spaced dipoles, I needed a broadband 4:1 transformer for some experiments on a low-band phased array. My first inclination was to go to the handbooks to design a ferrite-core transmission-line transformer. However, I decided that there had to be a better way. I had just read Doug DeMaw's article, "The Whys and Hows of Bifilar Filament Chokes" in *QST*.[1] He expressed concern about saturation of the core material and corona from the windings to the core when operated at high power. My search began for a way to make broadband transformers without magnetic core material.

background

In conventional low-frequency transformers, closely coupled primary and secondary windings of the appropriate turns ratio are used. At radio frequencies, because of inevitable leakage reactance, narrowband tuned transformers are generally used for impedance transformation. Quarter-wave matching transformers may be used but are also narrowband; they are a quarter wavelength at only one frequency.

The availability of solid-state rf power devices with their capability for broadband performance created the need for broadband interstage matching, thus causing rapid development of transmission-line transformers.[2,3,4] Development of ferrite materials also expanded rapidly during this period.

The low-frequency response of transmission-line transformers is limited by winding inductance, and the high-frequency response is limited by resonances from stray capacitance; therefore, ferrite material is used to extend the low-frequency limit of small transformers by increasing inductance. Thus broadband transmission-line transformers and baluns using ferrite cores have come into wide use in solid-state rf circuitry and Amateur antenna systems. While these cores are very useful, they have some disadvantages.

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This article shows how to build and design broadband rf transformers and baluns without magnetic cores.

problems with magnetic cores

Amateurs build or buy highly linear SSB equipment and effective lowpass filters to avoid TVI. We then subject our clean, harmonic-free signals to the uncertainties of ferrite-core transformers or baluns in our antenna systems. The cores in these devices are subject to saturation and, therefore, nonlinearity. High permeability ferrite cores are also susceptible to permanent damage at flux densities of a few hundred gauss.[5] Tune up your linear into the wrong antenna just once and the damage is done.

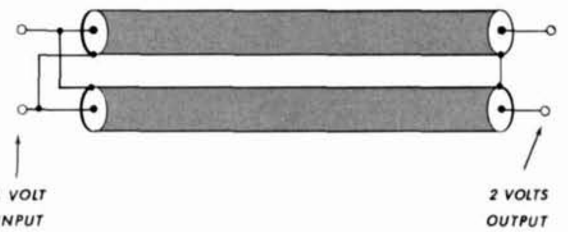

fig. 1. Broadband transmission-line transformers are made of two or more transmission lines connected in parallel at one end and in series at the other. One volt applied to two coax lines in parallel at the input results in 1 volt across *each* of the lines at the output. If these two lines are connected in series at the output as shown, the output will be 2 volts. In this way a 1:4 impedance stepup is achieved. Sufficient impedance must be provided over the length of the outside conductors to prevent the connections at one end from shorting the other end.

Magnetic materials such as ferrite, powdered iron, and specialty steel tapes have added greatly to the performance of components available to circuit designers. However, these materials should not be used in high-power circuits or antenna systems unless they are adequately characterized regarding power-handling capability and saturation effects. This is necessary so that interaction of the material with your system can be thoroughly understood. Put another way, sufficient core material must be used to keep the flux density well below the saturation level. Data on harmonic distortion measurements, taken at high power on a popular commercial ferrite core balun, are presented in part 2 of this article.

Ferrite baluns and transformers are usually wound with copper wire coated with thin enamel insulation. Pairs of wires are placed close together or twisted to make transmission lines, which are wound tightly onto the core. The conductors must be close, because the surge impedance of the wire pairs must be correctly related to the impedances to be matched. For this reason, thin insulation is often used. Inadequate insulation may result in arcing between wires or to the core when operated at high power.[1,2] Those who have blown a balun in the heat of competition are all too familiar with these problems.

transmission-line transformers

Basically a transmission-line transformer consists of two or more parallel lengths of transmission line connected in parallel at one terminal and connected in series at the other (**fig. 1**). For example, if two lengths of coaxial line are connected in parallel at the input and 1 volt is applied, 1 volt appears at the output end of each of the two lines. If the output ends are connected in series so that the two voltages add, the output is 2 volts, thus creating a 1:2 voltage increase (1:4 impedance transformation). **Fig. 1** also can be used to describe a 4:1 impedance reduction; for example, from 50 ohms to 12.5 ohms.

Sufficient rf impedance must be provided between the input and output ends of the transformer of **fig. 1** to prevent the connections at one end of the lines from shorting the other end of the lines. The impedance is usually provided by wrapping the transmission lines around magnetic cores.

the Collins balun

By far the best balun I've ever used is the Collins balun which, to my knowledge, was first described in a book published by the Collins Radio Company entitled *Fundamentals of Single Sideband*.[6] The Collins balun derives its name from this reference. I believe the earliest reference to an Amateur application was in an article by K2HLT in *G.E. Ham Notes* in 1960.[7] The Collins balun is rarely mentioned in Amateur literature, which is surprising in view of its superb performance. However, Bill Orr, W6SAI, describes one in his *Radio Handbook*.[8]

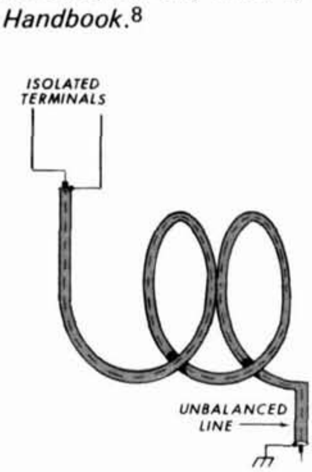

fig. 2. Simple coiled length of coaxial line isolates output terminals from ground.

Perhaps the reason the Collins balun hasn't gained popularity with Amateurs is that it's quite bulky when made with RG-8/U. The balun is extremely simple. No exotic materials are used in its construction; only coaxial cable and insulated wire. I've used these baluns for years with various antennas and never had a failure. One has been on my three-element 10-15 meter quad for eight years with no sign of deterioration. There are only two disadvantages to the Collins design: 1) when made with RG-8/U, the balun is bulky — too large for installation on a clean-design antenna system; and 2) the balun is useful only at 50 ohms. This article shows how to eliminate these disadvantages.

balun theory

Baluns convert energy from unbalanced coaxial line to balanced two-wire line by isolating the two balanced terminals from ground. As in the transmission-line transformer, this is often accomplished by coiling transmission lines around magnetic material so the impedance to ground from both output terminals is high compared with the characteristic impedance of the input coaxial line. By using this technique, shown in **fig. 2**, the two balanced terminals are "floated" with respect to ground by the isolation provided by the coiled-line impedance. However, a simple coiled length of transmission line is often not adequate because it doesn't contribute to the balance of the system.[9] For a balun to make this contribution, the impedance ground from both terminals must be nearly matched.

Accordingly, in the Collins balun, a dummy length of coax is wound as a continuation of the isolating winding, so that the coil consists of the original length of coiled coax of **fig. 2** plus an equivalent length of dummy line, as shown in **fig. 3**.

The dummy-line center conductor is unused and is left floating, or both ends may be shorted to the outer conductor if desired. The dummy length of line causes the impedance to ground, from each of the two output terminals, to be nearly equal. The isolation impedance (common-mode impedance) is held higher than the coax-line characteristic impedance over a wide frequency range by the distributed capacitance and inductance of the combined coil. The coil must have sufficient inductance so the impedance, at the lowest operating frequency, is higher than the line surge impedance. As the frequency is increased, the impedance increases through parallel self-resonance, then decreases as the frequency is further increased.

Because the self-resonant circuit consisting of the distributed capacitance and inductance of the combined coil is loaded by the low characteristic impedance of the line, the impedance versus frequency curve is broad. Balun performance therefore is not critical with respect to frequency. Data taken on measurements of the common-mode impedance on a typical Collins balun are presented in Part 2.

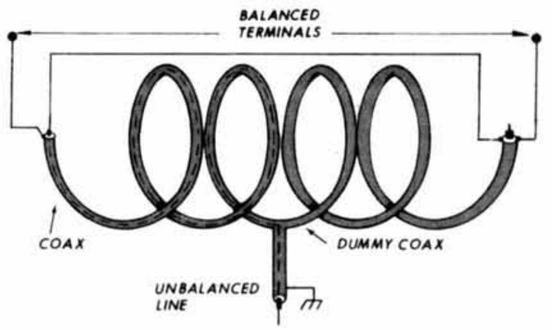

fig. 3. Broadband coil balun is evolved from the coiled coaxial line of fig. 1.

The symmetry provided by the dummy line makes balun performance less dependent on common-mode impedance and is therefore often essential in baluns and balanced systems.[9] The isolation, balance, and impedance match of this class of balun are superb over the hf Amateur bands. Specific designs, performance data, and a systematic design procedure are presented in Part 2.

new class of transformers

Faced with the need to match a very low-impedance antenna system, I decided to try to develop a 4:1 transmission-line transformer based on the principles of the well-proven Collins balun. The transformer was successfully developed; in fact, a new class of wideband transformers evolved from this work.

One of the nice things about an avocation — as compared with a vocation — is that you're not on a time schedule. I found that the performance of the 4:1 transformer was so good that the idea of other transformer designs based on the same principles looked interesting. I shelved the phased-array project long enough to enjoy the freedom to explore the possibilities of these transformers. The result was a series of broadband balanced and unbalanced transformer designs that are extremely simple, made entirely of coax, and, most important, don't depend on ferrite or powdered-iron materials.

design concept

Because the Collins balun so successfully isolates the balanced output terminals from the unbalanced coaxial line input, it seemed reasonable that a similar broadly resonant configuration would provide the isolation necessary to the series and parallel lines of **fig. 1**. From previous experience I'd found that it's unnecessary to wind the Collins balun on a cylindrical form as shown in **fig. 3**. It's sufficient to random-wind the turns without a coil form, as shown in the photo. I decided to try winding the two lines of **fig. 1A** into a continuous winding similar to the Collins balun of **fig. 3**.

My first try was with a nine-turn coil random wound on a nominal 25-cm (10-inch) diameter shown in **fig. 4** (Only three turns are shown in the drawing for clarity.) Two 254-cm (100-inch) lengths of 50-ohm line were used. The transformer was tested by inserting a 12.5-ohm low-inductance load at the output and measuring the input impedance with a Hewlett Packard Vector Impedance Bridge. While the transformer made the 12.5-ohm resistor appear to be a 50-ohm resistor over a wide range, the useful range was centered in the broadcast band. As the frequency was increased through 3.5 MHz, the input impedance magnitude increased rapidly, and the impedance phase angle was greater than 30 degrees. However, the useful frequency range was 4:1. Encouraged, I removed half the turns, expecting equivalent results more nearly centered over the ham bands. Results were disappointing. A good match was achieved only over a narrow frequency range.

line impedance

Note that the load at the transformer output of **fig. 4** terminates two coax lines connected in parallel. If the lines have 50 ohms characteristic impedance the load must be 25 ohms for the lines to be properly terminated. At the input the two lines are connected in series, so the input impedance will be 100 ohms. Thus the transformer of **fig. 4** will match a 25-ohm balanced load to a 100-ohm balanced line, but per-

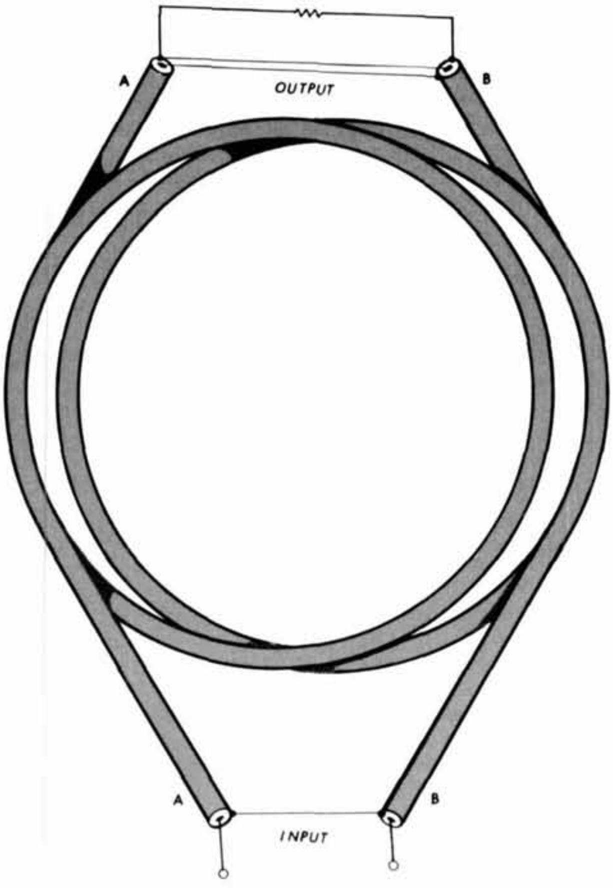

fig. 4. Two lengths of coax (A and B) wound into a multiturn coil similar to the Collins balun of fig. 3. Only three turns are shown for clarity. Note that the input ends of the lines are connected in series and the output ends are connected in parallel. Made with 50-ohm coax, this transformer will match a 100-ohm balanced line to a 25-ohm balanced load.

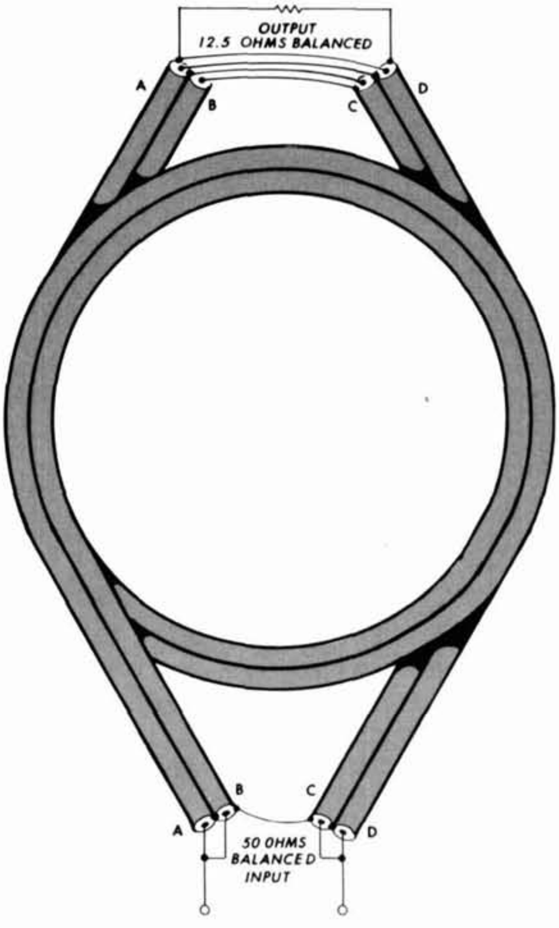

fig. 5. A 4:1 rf transformer (shown in the photo) consisting of two parallel 127-cm (50-inch) lengths of RG-58A/U random wound into a 7 turn, 11.5 cm (4.5 inch) nominal diameter coil. Each of the two paralleled 50-ohm lines (AB-CD) is connected in series at the input and in parallel at the output. The excellent performance is shown in table 1.

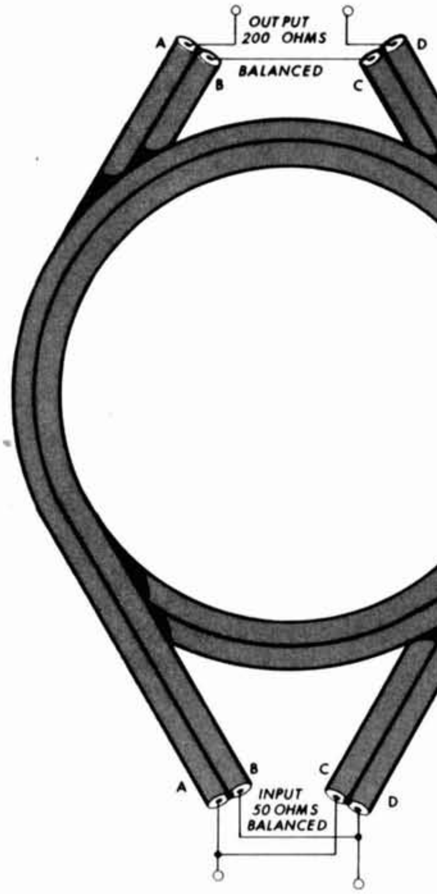

fig. 6. A 50- to 200-ohm balanced-to-balanced transformer made from two 127-cm (50-inch) 100-ohm lines each consisting of two 50-ohm lines in series. The 100-ohm lines are connected in parallel at the input and series at the output. Performance data are shown in table 2.

formance will be poor when trying to match a 12.5-ohm load to a 50-ohm line.

50/12.5-ohm transformer

To match a 50-ohm line to a 12.5-ohm load, 25-ohm transmission line must be used so that the 50-ohm source will be correctly terminated by two 25-ohm lines in series. Similarly, the two 25-ohm lines in parallel at the output will be correctly terminated by a 12.5-ohm load. I decided to make 25-ohm lines by connecting pairs of 50-ohm line in parallel. A transformer similar to that in **fig. 3** was wound with two lengths of transmission line, each made with a pair of 50-ohm RG-58A/U lines in parallel (25-ohm line).

After much cutting, winding, soldering, and data taking, the optimum design of **fig. 5** evolved. The design looks somewhat more complex than the simple configuration of **fig. 4** because each length of transmission line consists of two 50-ohm lines in parallel; however, in other respects the configuration is exactly the same as that of **fig. 4**. Note that the two 125-cm (50-inch) 25-ohm lines are connected in parallel at the output and are properly terminated by the 12.5-ohm load. This transformer design was useful over a wide frequency range. The VSWR is low over the high-frequency Amateur bands. The excellent data are shown in **table 1**.

construction

While it's not necessary to cut the lengths of coax to exactly 127 cm (50 inches), this length wound into a seven-turn, 11.5-cm (4.5-inch) nominal diameter coil is optimum to cover the high-frequency bands. The detail of coil winding is unimportant. You can bind the lines tightly with tape or leave them loose. You can hold the coil in your hands and separate the turns several cm (2 inches) before the magnitude or phase of the match are greatly affected.

However, the length of the short between the coax-line outer conductors at the input end of the balun is critical. Performance is degraded at the high-frequency end of the useful range unless the coaxial outer conductors are soldered together into a common joint as shown in the photo and **fig. 5**. Performance deteriorates if the shorting lead is as long as 2.5 cm (1 inch). The cross-connected leads at the output should be short. In the version shown, the length of the center conductors exposed beyond the outer conductors is about 2 cm (0.75 inch). Construction is shown schematically in **fig. 5** and in more detail in the photo.

measurements

Impedance measurements were made with the Hewlett-Packard rf vector impedance meter model 4815A shown in the photo. The vector impedance meter reads directly in impedance magnitude and phase angle. Data in this article are presented using the abbreviation Z for magnitude of the impedance and θ for the corresponding phase angle. Balance measurements, described in Part 2, were made with the HP rf voltmeter model 4-10C also shown. The terminating resistor is critical to the evaluation of these balun transformers. The VSWR looking into the transformer is, of course, no better than the quality

table 1. Frequency, impedance magnitude, phase angle and calculated VSWR for the balanced-to-balanced 4:1 transformer of fig. 5.

F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR
1.8	50	13	1.26
3.5	51	8	1.15
4	51	6	1.11
7	49	3	1.06
14	54	5	1.12
21	55	1	1.10
28	53	−1	1.06
30	53	−1	1.06

of the load. Shown in the photo is a bundle of eight parallel-connected, 100-ohm, 1/4-watt resistors soldered directly to the 50/12.5-ohm broadband transformer for minimum inductance.

performance

Referring to **table 1**, note that the VSWR between 3.5-30 MHz is less than 1.15. Even on 160 meters, the VSWR is only 1.26. Data were recorded only in the ham bands; however, with each configuration, I swept the impedance bridge over the full range looking for spurious resonances. In the designs presented here, none were found within the frequency range of the data shown.

Data are presented in tabular form. Displaying experimental results in this convenient form required calculation of VSWR from the impedance-magnitude and phase-angle data. These calculations are long and tedious, so a Hewlett Packard HP65 programmable calculator was used. N6AIG suggested the idea and wrote the program. The program is very useful and is included in the appendix. The program calculates VSWR based on an impedance of 50 ohms and can be modified easily for any impedance.

50/200 ohm transformers

After the 50/12.5 ohm transformer was optimized, it seemed reasonable to expect that a 50/200 ohm (1:4 impedance stepup) transformer could be made using the same principles. In this case, 100-ohm lines were used so they would match 50 ohms when connected in parallel at the input and would be properly terminated by 200 ohms at the output. The 100-ohm lines were made with two pairs of RG-59A/U cable; each pair was connected in series. The outer conductors of each pair were connected together at both ends. Each pair is 127 cm (50 inches) long. The lengths of coax were wound into a compact package of seven turns at a nominal diameter of 11.5 cm (4.5 inches). The package looks very similar to the 50/12.5 ohm transformer shown in the photo. The transformer is shown schematically in **fig. 6**. Performance data recorded for this transformer are listed in **table 2**.

To show the effect of increasing the length of the lines and increasing the number of turns, another similar 50/200 ohm transformer was built. Data taken on this transformer are also shown in **table 2**. The modified transformer was optimized for the low bands. It is similar to the configuration of **fig. 6**. However, the coax lines are twice as long, 254 cm (100 inches), and have twice as many turns on the same nominal diameter. Note that the increased length makes the transformer useful on 160 meters and substantially improves VSWR on 80 and 40 meters. The low-band transformer performance is good through 10 MHz; however, the VSWR climbs to 1.37 at 14 MHz.

table 2. Data taken on the 50-ohm balanced to 200-ohm balanced transformer. (A) lists data for the transformer made with 127-cm (50-inch) lines as shown in fig. 6. (B) lists data for another version optimized for the low bands. This transformer has the same configuration as that of fig. 6; however, the two 100-ohm lines are made with pairs of 254-cm (100-inch) lengths of RG-58A/U.

F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR
A. Data for transformer of fig. 6			
3.5	56	20	1.45
4	57	18	1.41
7	52	7	1.14
14	51	1	1.03
21	47	5	1.11
28	46	15	1.32
30	46	16	1.34
B. Data for low-band version			
1.8	55	10	1.22
3.5	55	2	1.11
4	55	0	1.10
7	51	−4	1.08
10	46	−2	1.09
14	46	−17	1.37

The common-mode impedance of the transformers described in this article is sufficiently high so that the transformers can be driven from either a balanced or an unbalanced coax transmission line. Two-stage balun transformers with improved isolation are described in Part 2.

I determined the efficiency of the 4:1 transformer of **fig. 5**, by carefully measuring the input complex impedance and the complex impedance of the load, driving it with a signal generator and measuring the input and output rf voltages. I used the HP4815A rf Vector Impedance Meter and the HP410C rf Voltmeter shown in the photo. Input power was determined by calculating the power in the real part of the input impedance; the output power was calculated similarly using the complex load impedance data. Efficiency was determined by dividing the output power by the input power. Measurements and calculations were made for each of the bands, from 160 through 10 meters. As you might expect, efficiency was lowest on 10 meters; however, efficiency was greater than 95 per cent on all bands.

power-handling capability

The 4:1 transformers may be made with pairs of RG-58A/U lines connected in series for 100-ohm surge impedance or connected in parallel for 25-ohm surge impedance. Each length of RG-58A/U must therefore handle only 50 per cent of the power delivered by the transformer. Because RG-58A/U is rated for more than 500 watts at 30 MHz, these RG-58A/U transformers will handle 1000 watts of rf. I verified this by connecting two 12.5-ohm transformers back-to-back into a dummy load. At 1 kW, heating was not discernible at 7 MHz. At 30 MHz, the transformers became warm to the touch after about one minute, key down. Part 2 describes how to build baluns capable of several kilowatts overload into severely mismatched loads.

Part 2 of this article, which will appear in March, 1980, *ham radio*, will describe how to build more useful balun transformers and three specific 1:1 baluns, including one for vhf. These designs are capable of conservatively handling high power into widely varying loads. The impedance match (VSWR) and balance of these new transformers and the baluns will be compared with popular commercially available rod and toroid core balun transformers. In addition, harmonic distortion data taken at 2 kW PEP on a typical commercial ferrite core balun will be included.

Balun performance is usually described when working into a "flat" load. In the real world, baluns must work into widely varying loads as frequency is changed across the band. Measured performance of baluns with varying loads will be included and comparative data presented in Part 2. How to design balun transformers to your needs and how to modify a currently popular balun will also be described.

references

1. Doug DeMaw, W1FB, "The Whys and Hows of Bifilar Filament Chokes," *QST*, April, 1979, page 28.
2. Doug DeMaw, W1FB, "The Practical Side of Toroids," *QST*, June, 1979, page 15.
3. Rutheroff, "Some Broad-Band Transformers," *Proceedings of the IRE*, August, 1959, pages 1337-1342.
4. R. Turrin, W2IMU, "Broad-Band Balun Transformers," *QST*, August, 1964, page 11.
5. J. Sevick, W2FMI, "Broad-Band Transmission Line Matching Networks," presented at ELECTRO-76, May 11-14, 1976.
6. *Fundamentals of Single-Sideband*, Third Edition, 15 September, 1960, Collins Radio Company, Cedar Rapids, Iowa, pages 10-11.
7. H. Byler, K2HLT, "All-Band Balun Coil," *G.E. Ham News*, January/February, 1960.
8. W. Orr, W6SAI, *Radio Handbook*, Editors and Engineers, 21st edition, Indianapolis, 1978.
9. W.L. Weeks, *Antenna Engineering*, McGraw Hill, Inc., New York, 1968.

appendix

Program for calculating VSWR for a given load impedance, Z_L using the HP-67 calculator.

$$\text{reflection coefficient, } \Gamma = \frac{Z_L/Z_0 - 1}{Z_L/Z_0 + 1}$$

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

running instructions

step	instruction	input	keys	output
1	(clear memory — enter program)			
2	initialize	—	h RTN R/S	—
3	input magnitude	$\lvert Z_L \rvert$	*R/S*	—
4	*input phase*	*angle°*	R/S	
5	copy VSWR	—	—	VSWR
6	return to step 3		R/S	

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