new class of
coaxial-line transformers

Coreless 4:1 and 1:1 balun transformers are described with a systematic design procedure for making your own — Part 2 of a two-part series

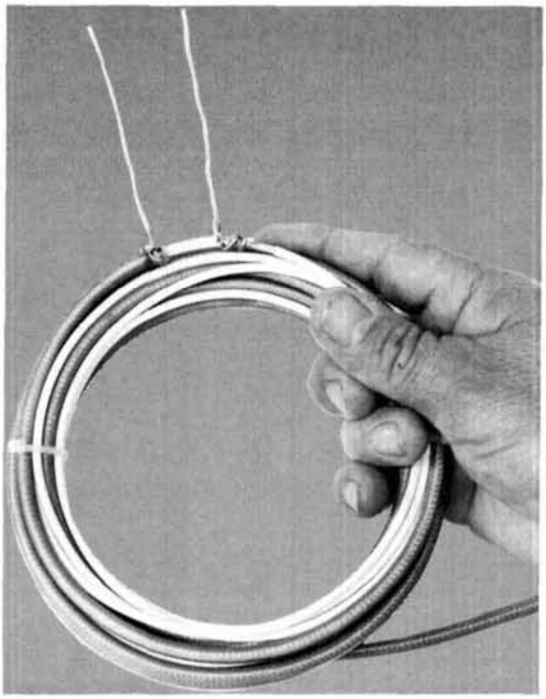
Part 1 of this article reviewed the theory of *transmission-line transformers* and *baluns*, as well as problems with magnetic cores such as arcing, distortion, and harmonics. A simple balun that doesn't depend on magnetic materials was described. A new class of *coaxial transmission-line transformers* based on the same principles as the coreless balun was introduced. Also described were two specific transformer designs with experimental performance data.

In this article I will describe additional 4:1 and 1:1 balun transformers, including one for vhf. Impedance, VSWR, and balance data on these specific designs and on commercially available balun transformers are compared. I have included data on baluns working into various loads, with information on how to build and modify balun transformers. A systematic design procedure, evolved during the development of these transformers, is summarized.

how to make coreless baluns

While the *balanced-to-balanced 4:1 transformers* described in Part 1 are interesting, more useful configurations are 50-ohm unbalanced to 12.5-ohm balanced, and 50-ohm unbalanced to 200-ohm balanced, *balun transformers*. These were made in two stages using coreless baluns together with the balanced-to-balanced coreless transformers of **figs. 5** and **6** described in Part 1.

The first step in making these balun transformers was to arrive at an optimum 50-ohm 1:1 balun design. I tried many lengths of coax and many configurations before choosing the design shown in **fig. 1**. A length of RG141/U* Teflon coaxial transmission line longer than 127 cm (50 inches) was used. A dummy length of line 127 cm (50 inches) long was soldered to the outer conductor of the Teflon coax 127 cm (50 inches) from the end as shown in **fig. 1**.



How to add a simple compensating winding to the W1JR balun to provide superior balance. Thanks to W6ZO for building the balun and suggesting the easy modification. Low reactance adjustable load shown is connected with 1.27-cm (0.5-inch) copper strap for match and balance measurements.

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*Available from Radiokit, Box 429, Hollis, New Hampshire 03049. RG-142B/U (Belden 83242-100) may also be used.

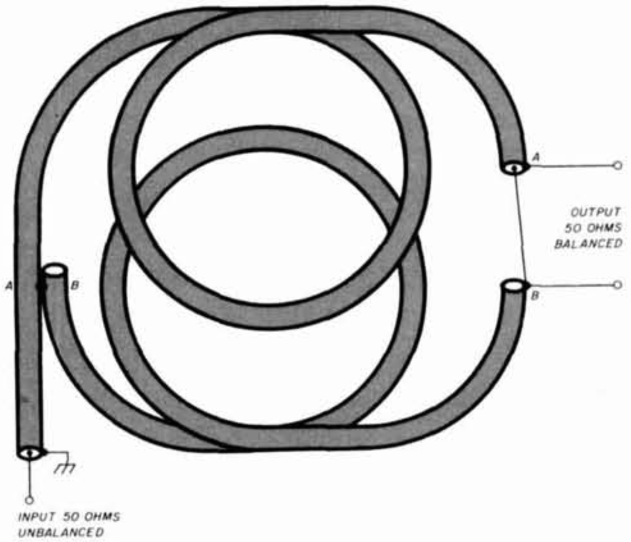


fig. 1. 50-ohm unbalanced to 50-ohm balanced coaxial balun. From the common point (system ground) to the output terminals, coax line A and compensating line B are each 127 cm (50 inches). The lines were wound into a seven-turn random-wound coil of 11.5 cm (4.5 inch) nominal diameter. For clarity, only three turns are shown. Performance data are shown in table 1.

The resulting 254 cm (100 inches) of line was then random wound into a nominal 11.5-cm (4.5-inch) diameter seven-turn coil. **Fig. 1**, for clarity, shows only three turns of coaxial line. The dummy length of line used for the compensating winding was made with RG-58A/U. The advantage of using small coax is that the balun is compact and results in a convenient configuration for mounting on beam antennas. Performance is shown in **table 1**. Note the excellent balance data. Balance was determined by measuring the rf voltage with respect to the common point (ground) at each of the output terminals when terminated with a floating matched load. The difference between the readings taken at each frequency was divided by the sum of the readings expressed as a percentage . The rf voltage was measured with an HP model 410C rf voltmeter.

Rather than use coax for the compensating winding, to save money and space I decided to try a length of hookup wire. I tried some surplus no. 12 (2.1-mm) Teflon insulated wire. Hookup wire instead of coax for the compensating winding results in an excellent design. The balun is shown in the photo. A balun made this way was compared with one made entirely of coax. The two designs used for this comparison were optimized for the low bands. Data taken on these designs are shown in **table 2**. This table compares the use of Teflon coated no. 12 (2.1-mm) wire with coax for the compensating winding. VSWR performance of the Teflon wire version was at least equal to that of the all-coax balun, and the balance was actually better.

The balun design optimized for the 80 through 10 meter bands (**table 1**) was made with 127-cm (50-inch) lines. The balun designs optimized for the 160 through 20 meter bands (**table 2**) were made with 254-cm (100-inch) lines.

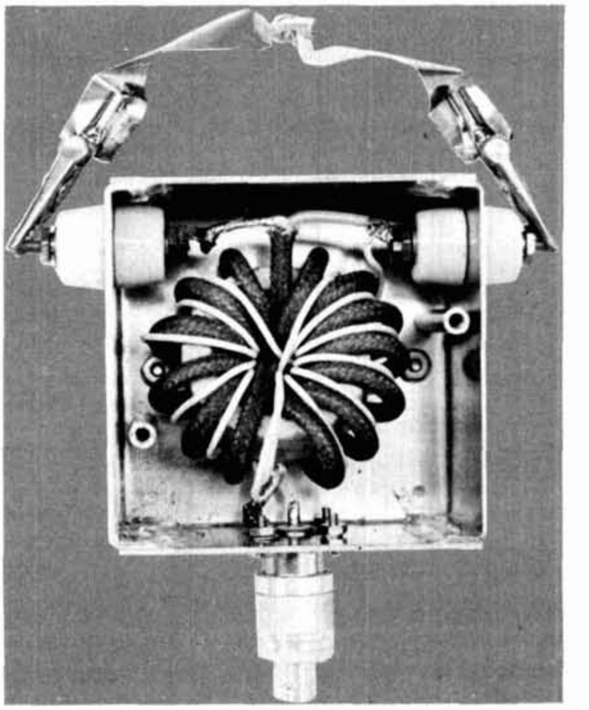
vhf balun

A vhf version of the coreless 1:1 balun is shown in **fig. 2**. The balun has a nominal diameter of 5.8 cm (2.25 inches). The length of coax from the output to the common point is 45.7 cm (18 inches). An equal length of coax line is used for the dummy. The lengths of RG-58A/U were wound into a five-turn coil. **Table 3** shows the performance of this balun.

two-stage balun transformers

After the 50 to 12.5 ohm and 50 to 200 ohm balanced-to-balanced transformers (Part 1) and the 50-ohm unbalanced to 50-ohm balanced balun (see **fig. 1**) were optimized, I combined them into two-stage 50 to 12.5 ohm and 50 to 200 ohm unbalanced-to-balanced configurations. These two-stage transformers are shown in **figs. 3** and **4**. **Tables 4** and **5** show performance data.

The first stage converts from 50-ohm unbalanced



Compact broadband 1:1 balun. The only materials used are a short length of RG-141/U and insulated hookup wire. The balun provides excellent match, balance, and several kW reserve power-handling capability.

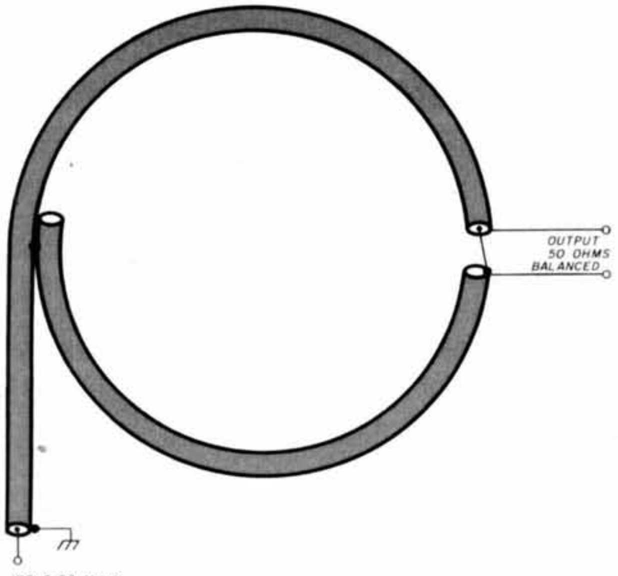


fig. 2. Vhf version of the coreless balun. Length of each line from the common point to the output terminals is 45.7 cm (18 inches). The lengths of RG-58A/U were wound into a five-turn coil of about 5.8 cm (2.25 inches) diameter. For clarity, only one turn is shown. The center conductor of the compensating coax line winding may be left floating or shorted to the outer conductor at both ends. Performance data are shown in table 3.

to 50-ohm balanced; the second stage converts from 50-ohm balanced to 12.5-ohm or 200-ohm balanced loads. Note that the bandwidth of these two-stage balun transformers is somewhat less than that of the individual stages.

When the two stages are coiled together into one compact bundle of coax, the way in which connections are made between the two stages is important. Note the lead crossover between the first and second stage (**fig. 4**). Performance was significantly better when the leads between stages were cross-connected because of the magnitude and direction of rf current flow over the coaxial-line outer conductors. The leads between the two stages must be short. The length of grounding wire, **AB**, was not critical.

a 50/12.5-ohm unbalanced-to-unbalanced transformer

A transformer particularly useful for matching low-impedance unbalanced loads, such as a mobile whip or short ground plane antenna, is shown in **fig. 5**. Note that this configuration differs from the designs described earlier because the line lengths aren't random wound into a common coil and, therefore, aren't coupled together. Because of the unbalance-to-unbalance connection, both ends of the outer conductors of line **CD** are grounded. Thus, line **CD**, if coiled with and therefore coupled to coil **AB**, would act like a shorted turn, reducing the common-mode impedance of coil **AB**. Both ends of line **CD** are at the same potential so no isolation impedance is required. Thus the line may be positioned in any convenient way that doesn't couple to coil **AB**. The line is shown folded in the drawing to minimize coupling. The line may be twisted and taped to the incoming 50-ohm line. Line **CD** must be the same length as line **AB** so that the two rf paths are equal, thus preserving the phase relationship. Lines **AB** and **CD** are each 127 cm (50 inches) long and are made of two paralleled lengths of RG-58A/U.

Performance data on the 50/12.5-ohm unbalance/unbalance transformer is shown in **table 6**. The VSWR data show the harmful effect of the shorted turn when **CD** is coiled and coupled to **AB**. The VSWR curve could be centered to improve the match at the low end by adding length to lines **AB** and **CD** by the design techniques described later.

efficiency and power

The power-handling capability and efficiency of these new transformers made with RG-58/U coaxial cable were analyzed in Part 1. The 4:1 baluns shown in **figs. 5** and **6** of Part 1 and **fig. 5** of Part 2 can handle 1 kW at 30 MHz. This is twice the rating of RG-

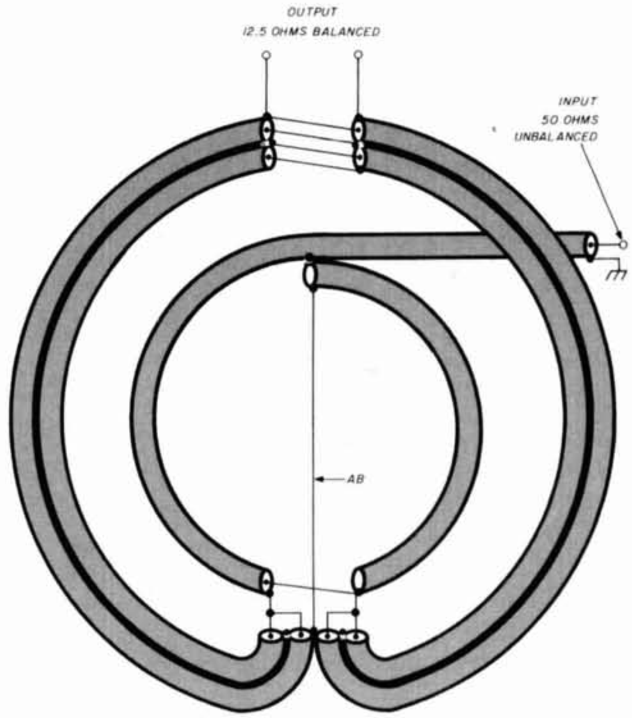


fig. 3. This 50-ohm unbalanced to 12.5-ohm balanced balun transformer is a two-stage design combining the transformer of fig. 5 (Part 1) with the balun of fig. 1. Performance data are shown in table 4.

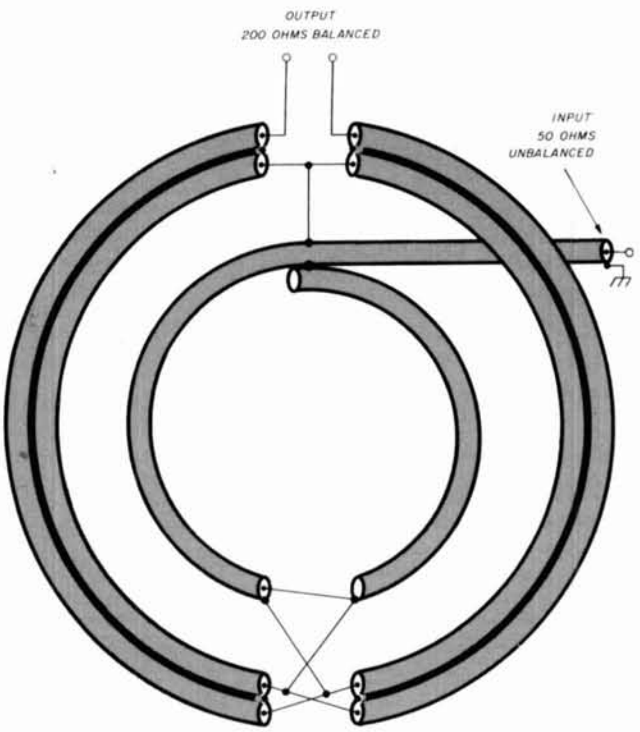


fig. 4. This 50-ohm unbalanced to 200-ohm balanced balun transformer is a two-stage design combining the transformer of fig. 6 (Part 1) with the balun of fig. 1. Performance data including balance are shown in table 5.

58A/U cable because the line pairs are connected in series or parallel.

In the case of the coreless 1:1 baluns, all of the power is transmitted through a single coax. Therefore, for high-power applications, the 1:1 baluns must be made with RG-8/U or RG-141/U transmission line. RG-141/U is the same size as RG-58A/U but it's about four times as expensive. The dielectric used in this coax is Teflon; therefore, the baluns can handle about 5 kW at 30 MHz. Using RG-141/U or RG-142B/U results in a rugged balun of reasonable size. From my experience, these compact baluns made with Teflon coax are virtually indestructible in Amateur use.

Efficiency of the Teflon coax balun shown in the photo was tested by the method described in Part 1. Efficiency was better than 95 per cent over the useful bandwidth shown in **table 2**.

table 1. Performance of the 50-ohm balun shown in fig. 1. Balance expressed as a percentage is shown. This design was optimized for 80 through 10 meters.

F_0 (MHz)	Z (ohms)	θ degrees	VSWR	balance (per cent)
3.5	48	16	1.33	2.8
4.0	49	14	1.28	2.1
7.0	50	10	1.19	1.3
14.0	50	8	1.15	2.5
21.0	51	8	1.15	4.2
28.0	52	9	1.18	1.3
30.0	53	9	1.18	1.3

comparison with commercial products

Just how good are these balun transformers regarding match and balance? The best way to answer this question is to compare them with popular, commercially available products. The devices described here were compared with a commercial ferrite rod core 1:1 balun and a commercial toroid-wound 1:4 balun transformer. Performance comparisons are summarized in **tables 7** and **8**. **Table 7** shows the comparison between the commercial 1:1 ferrite-core balun and the corless balun of **fig. 1**. **Table 8** compares the performance of the commercial 1:4 toroid balun transformer with the two-stage 50/200 ohm balun transformer shown in **fig. 4**. On the average, the VSWR and balance are

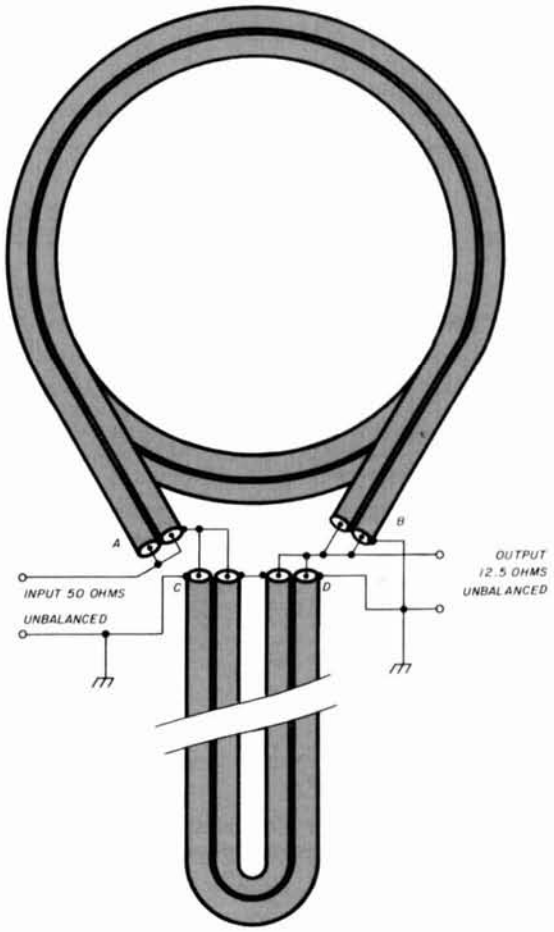


fig. 5. This 50/12.5-ohm unbalanced-to-unbalanced transformer consists of two 127-cm (50-inch) parallel pairs of RG-58A/U coaxial cable connected in series at the input and in parallel at the output. Line CD must be the same length as line AB and should not be coupled to AB. Data comparing the coupled and uncoupled cases are shown in table 6.

table 2. Comparison of two baluns optimized for the low bands. Balun A was made entirely of coax as shown in fig. 1 but with 254-cm (100-inch) lines. Balun B is identical except for the dummy compensation line, which was made with an equivalent length of insulated no. 12 (2.1-mm) wire. These baluns are optimized for the low bands, so performance is good on 160 meters and poor on 10 meters.

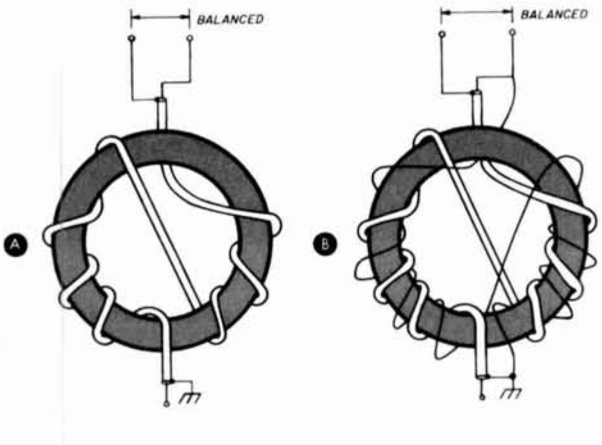
	balun A				balun B			
F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)
1.8	53	10	1.20	3.8	51	6	1.11	1.90
2.0	53	9	1.18	4.7	51	5	1.09	1.40
3.5	53	4	1.10	4.5	51	2	1.04	.68
4.0	53	3	1.08	4.5	51	1	1.03	.67
7.0	53	0	1.06	5.1	49	1	1.05	2.00
14.0	53	1	1.02	6.1	46	5	1.13	4.00

better for the devices described here than for the commercial balun transformers tested. I evaluated only two commercial balun products, which were selected at random.

balun performance with varying loads

All the test data were taken with terminations for which the balun transformers were designed. In the real world, balun transformers are connected to antennas. Antennas are rarely ideally matched; as operating frequency is changed across the band, both resistive and reactive components of the antenna impedance change. It is therefore important to understand the influence of the balun when terminated with other than the characteristic impedance of the line and balun.

I tested the coreless balun of **fig. 1** and a commercial 1:1 balun at 3.5 and 14 MHz with loads varying from 16 to 150 ohms. These measurements are summarized in **table 9**. Impedance magnitude, phase angle, and calculated VSWR of the loads are listed. Measurements taken through the balun of **fig. 1** and the commerical balun are also recorded. Both resistive and reacitve components of the impedance looking through the baluns varied widely from the data taken on the loads alone. In general, however, the resulting VSWR was not significantly altered.



UNCOMPENSATED

COMPENSATING WINDING ADDED

fig. 6. Compensating winding added to W1JR balun[2] for improved performance. A length of no. 16 (1.3-mm) Teflon insulated wire equal to the coax line, wound and connected as shown, improves balance and VSWR of the uncompensated balun.

table 3. Performance of the vhf balun shown in fig. 2.

F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR
21	60	10	1.29
28	60	5	1.22
30	60	15	1.22
50	53	−1	1.06
56	52	−1	1.05
70	48	3	1.07
80	49	6	1.11
90	50	8	1.15
100	54	12	1.25

balun rf distortion measurements

Saturation effects in magnetic-core materials in balun transformers may contribute to nonlinearity and cause generation of harmonics with attendant TVI problems. However, to my knowledge, this problem has not been addressed in the literature and no measurements have been made to lend experimental validity to these concerns. For this reason a popular commercially available rod magnetic core 1:1 balun was measured for nonlinearity at a power level of 2 kW PEP.

The two-tone test method[1] offers a convenient means for measuring harmonic distortion. It's the method commonly used for determining the linearity of power tubes and solid-state devices. If two rf signals are linearly combined and are equal in amplitude, the resultant envelope varies periodically from zero to maximum. When a two-tone rf signal is passed through a nonlinear device, many new signals are produced, including harmonics and products resulting from harmonics and the original signals. Products that fall near the original signals in frequency are known as odd-order products (3rd, 5th, 7th, 9th, 11th). The measurement of the amplitude of these products with respect to the amplitude of one of the original signals is an excellent method for evaluating the harmonic distortion products generated by a nonlinear device.

The two-tone method was used to measure the harmonic distortion contribution of the commercial ferrite balun. In this experiment, the two rf signal sources were 2000 Hz apart at 2.001 and 2.003 MHz. The signals were combined and amplified to 2 kW PEP and fed through the balun to the load. The distortion products were measured with a modified HP310A Wave Analyzer. Power output at the 50-ohm load was measured with an HP3400A rms Volt-Meter. **Table 10** summarizes the results of the measurements. Note the 3rd-order distortion product increased from 43 to 39 dB below one of the two original signals, a 4-dB deterioration. Under the set of power-amplifier operating conditions chosen, the 5th- and 7th-order products decreased, and the 9th-order distortion product again increased.

table 4. Performance characteristics of the two-stage 50/12.5-ohm transformer of fig. 3 consisting of the balun of fig. 1 combined with the 4:1 transformer of fig. 5 (Part 1).

F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)
3.5	53	22	1.49	3.5
4.0	53	20	1.44	2.7
7.0	56	9	1.21	2.1
14.0	55	−1	1.10	3.3
21.0	47	−1	1.07	0.0
28.0	45	10	1.23	4.3
30.0	47	12	1.25	6.5

It's clear from these measurements that you can't assume that a magnetic-core device, such as a ferrite core balun, is perfectly linear at all power levels. Unless flux density is held below the saturation threshold for the core material used, magnetic-core baluns and transformers can affect the linearity of your equipment and may cause TVI through the generation of harmonics.

W1JR balun improvement

Joe Reisert, W1JR, made an excellent contribution to the state of the art in his article, "Simple and Efficient Broadband Balun," in the September, 1978, issue of *ham radio*.[2] An improvement in the balance of the W1JR balun can be made by the very simple addition of a length of insulated hookup wire wound on the toroid as a continuation of the coax winding.

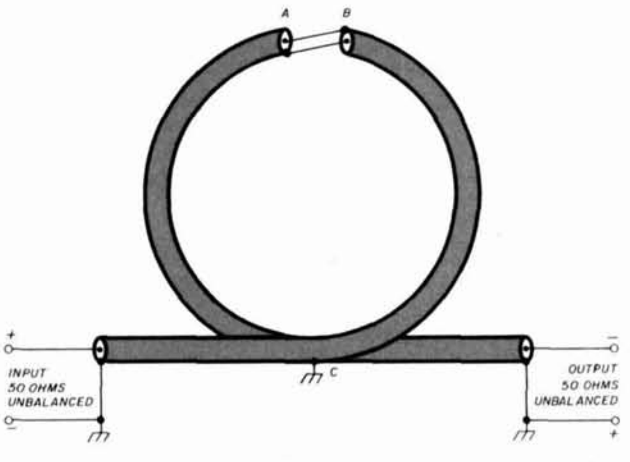


fig. 7. Phase inverter based on the same principles as the coreless balun. This useful coaxial line component changes the phase of an rf signal applied at the 50-ohm input terminal by 180°; the phase reversal is produced by the cross connections between the two coaxial lines at A-B. Connections at A-B are isolated from ground by the self-resonance of the coiled coax lines. Construction, dimensions, and connections are the same as the coreless balun shown in fig. 1. From the common point C (system ground) to the output terminals, coax lines A and B are each 127 cm (50 inches) long. The lines are wound into a seven-turn random wound coil of 11.5 cm (4½ inches) nominal diameter. For clarity, only one turn is shown. Performance data is shown in table 12.

See **fig. 6** and the photo. The length of the compensating winding must, of course, be equal to the coax length. This modification was made at the suggestion of Ray Rinaudo, W6ZO.* It's based on the principles described in Part 1, showing how the length of coiled coaxial line of **fig. 2** (Part 1) is evolved into the compensated balun of **fig. 3** (Part 1).

Data showing VSWR and inherent balance of the compensated and uncompensated baluns are shown in **table 11.**. The balance measurement was made by terminating the balun with 50 ohms, driving at the frequencies shown, and measuring the voltage with respect to ground (enclosure) at each of the output terminals. Note the very significant variations in balance shown for the uncompensated balun, compared with the reasonably good inherent balance shown in the right-hand column. Balance is defined

table 5. Performance characteristics of the two-stage 50/200-ohm transformer of fig. 4 consisting of the balun of fig. 1 combined with the 4:1 transformer of fig. 6 (Part 1).

F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)
3.5	60	25	1.63	1.3
4.0	60	25	1.63	0.6
7.0	60	3	1.21	0.6
14.0	48	0	1.04	0.6
21.0	51	10	1.19	0.0
28.0	60	2	1.20	3.3
30.0	60	−1	1.20	3.3

*Also proposed by K4KJ and discussed in the February, 1980, issue of *ham radio*, page 28.

table 6. Performance of 50/12.5-ohm unbalanced-to-unbalanced transformer of fig. 5. The two right-hand columns compare VSWR of coupled and uncoupled configurations as explained in the text. VSWR on the 80-meter band can be improved by increasing the length of the coax lines as explained in the design procedure.

F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR (uncoupled)	VSWR (coupled)
3.5	49	20	1.4	1.6
4.0	50	19	1.4	1.6
7.0	54	14	1.3	1.5
14.0	58	11	1.3	1.5
21.0	61	6	1.2	1.6
28.0	55	4	1.1	1.4
30.0	53	4	1.1	1.4

as the difference between the rf voltage readings at each of the two output terminals to ground (enclosure) divided by the sum of the two readings, expressed as a percentage.

Fig. 7 shows how to build a useful component for reversing the phase of an rf signal in a coaxial line. This phase inverter is useful for coaxial-fed W8JK antennas and other close-spaced phased arrays. The phase reversal takes place at the cross connection of two coax lines at terminals **A** and **B**. Terminals **A** and **B** are isolated from ground by the self-resonance principles described last month (**fig. 3**) and in **fig. 12**. Terminals **A** and **B** are not shorted by the grounded common connection between the coax outer conductors at **C** because of the high impedance over the outer conductors of the coiled coax lines. Of course, 180-degree phase shift can be accomplished in coax with a half-wavelength line; phase shift by this method, however, depends on frequency. The simple device shown in **fig. 7** inverts phase by 180 degrees independent of frequency; it inverts rf phase by exactly 180 degrees, with respect to equivalent length of coaxial cable, over a very broad band of frequencies. Measured broadband VSWR performance of the phase inverter is shown in **table 12**.

Phase inverters optimized for other frequency ranges may be designed according to the systematic design procedure for balun transformers detailed at the conclusion of this article.

summary of results

Of the various coreless rf devices made during the project, eleven are described in Parts 1 and 2 of this article. For convenience, they are summarized in Table 13, which correlates the construction of each device with measured performance data.

The transformers described in this article were, for the most part, designed with a combination of intuition and practical experience with coax baluns. However, as the project evolved, I gathered information that can be organized into a systematic design procedure. For example, N6AIG suggested a method of analysis starting with diagramming all of the possible ways to connect the ends of two or more coaxial cables.

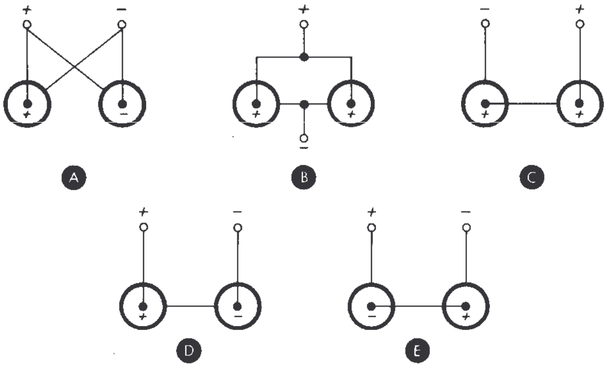


fig. 8. Various connections for pairs of coaxial lines. Polarity is arbitrarily assigned to the terminals, and the resulting polarity of the center conductors with respect to the outer conductors is indicated.

The diagram of **fig. 8** shows most of the connections possible with a pair of lines, and **fig. 9** shows some of the combinations for four lines. Similar diagrams can, of course, be drawn for any number of lines. Polarities are then assigned to the network terminals.

Next, assign polarities to each of the coax center conductors with respect to the outer conductors. Ex-

table 7. Performance of the 50-ohm coreless balun shown in fig. 1 compared with a commercial ferrite-core balun. VSWR was calculated from the impedance magnitude and phase data and is referred to 50 ohms.

	coreless balun				ferrite-core commercial balun			
F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)
3.5	48	16	1.33	2.8	49	11	1.21	11.8
4.0	49	14	1.28	2.1	49	9	1.17	12.0
7.0	50	10	1.19	1.3	50	9	1.17	11.6
14.0	50	8	1.15	2.5	55	11	1.24	7.9
21.0	51	8	1.15	4.2	63	12	1.37	1.4
28.0	52	9	1.18	1.3	72	5	1.46	3.9
30.0	53	9	1.18	1.3	75	8	1.54	1.6

table 8. Performance characteristics of a popular commercial 1:4 toroid balun transformer compared with the two-stage 50/200-ohm balun transformer of fig. 4.

	coreless balun transformer				commercial toroid balun transformer			
F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)
3.5	60	25	1.63	1.3	53	6	1.12	1.8
7.0	60	3	1.21	0.6	53	8	1.16	2.5
14.0	48	0	1.04	0.6	54	16	1.34	12.0
21.0	51	10	1.19	0.0	57	27	1.66	18.0
30.0	60	−1	1.20	3.3	69	44	2.53	21.0

amples of these assignments are shown in **figs. 8** and **9**.

Now make a table similar to **table 14**. This table will be an aid in analyzing each of the possible end-connection combinations. Construct the table by choosing the input and output connections you want for your application, taking into account balance/unbalance and impedance. Show these connections in columns 1 and 2.

Next, determine whether there is a polarity match. The input connection must be compatible with the output connection. This is determined by inspecting the polarities assigned to the inner conductors. For example, **A** cannot be matched with **B** in **fig. 8** because **A** has one + and one − center conductor polarity, whereas **B** has two + polarities. **A** and **D** are compatible because both have + and − polarities. Indicate whether there is a polarity match in column 3.

Whether the connection is balanced or unbalanced can be determined by inspection; this information is entered in columns 4 and 5. For example, **A** is balanced and **B** is unbalanced. An unbalanced connection can be converted to a balanced connection by the addition of one or more compensating lines. For example, unbalanced connection **F** or **fig. 8** may be converted to a balanced configuration by connecting the outside conductor of a dummy length of coax to the positive terminal. Wind the coax as a continuation of the line connected to the negative terminal.

Part 1 explained how the compensating winding creates balanced terminals by showing how the isolated terminals of **fig. 2** (Part 1) evolve into the balanced terminals of **fig. 3** (Part 1).

Input and output impedances of transformers made with 50-ohm lines are shown in **table 14**, columns 6 and 7. For example, for connections **A-D** (third line in **table 14**, the input impedance is 25 ohms, because two 50-ohm lines are connected in parallel at the input. The output impedance is 100 ohms, because the two 50-ohm lines connected in series at the output are properly terminated with 100 ohms.

The transformation ratio (column 8) is simply determined from columns 6 and 7. If the transformer in this case had been made with 75-ohm line, the input impedance would be 37.5 ohms, and the output

table 9. This table compares the performance of the corless balun of fig. 1 with that of a typical 1:1 commercial ferrite core balun with varying loads. VSWR is calculated with respect to 50 ohms from the impedance magnitude and phase-angle data.

	load			coreless balun			commercial ferrite balun		
F_0 (MHz)	R (ohms)	θ (degrees)	VSWR	R (ohms)	θ (degrees)	VSWR	R (ohms)	θ (degrees)	VSWR
3.5	16.0	7	3.1	22.0	34	2.9	17	25	3.2
3.5	20.0	4	2.5	25.0	28	2.4	22	20	2.5
3.5	25.0	3	2.0	28.5	25	2.1	26	18	2.1
3.5	33.0	2	1.5	37.0	21	1.6	35	15	1.6
3.5	50.0	1	1.0	54.0	20	1.3	51	13	1.3
3.5	75.0	0	1.5	77.0	20	1.8	75	14	1.6
3.5	100.0	0	2.0	98.0	25	2.0	97	25	2.3
3.5	125.0	−1	2.5	127.0	24	2.9	122	18	2.6
3.5	150.0	−1	3.0	140.0	31	3.4	144	20	3.1
14.0	16.5	22	3.3	53.0	60	3.7	33	60	4.1
14.0	21.0	20	2.6	54.0	48	2.6	36	51	3.0
14.0	25.0	18	2.2	54.0	34	1.9	38	46	2.6
14.0	32.0	14	1.7	57.0	30	1.8	43	35	2.0
14.0	51.0	7	1.1	56.0	2	1.1	61	15	1.4
14.0	75.0	5	1.5	62.0	−20	1.5	80	0	1.6
14.0	100.0	3	2.0	62.0	−36	2.0	100	−13	2.1
14.0	125.0	1	2.5	65.0	−46	2.6	117	−21	2.6
14.0	150.0	1	3.0	66.0	−50	2.9	126	−26	2.9

table 10. Summary of the distortion contribution of a typical commercial ferrite core balun at 2 kW PEP. The linearity of a high-power linear amplifier was measured with and without the balun connected between the amplifier and the load.

	odd order products				
	3rd	**5th**	**7th**	**9th**	**11th**
distortion products, amplifier without balun (dB)	43	43	52	63	60
distortion products, amplifier with balun (dB)	39	48	56	60	60

impedance would be 150 ohms. Incidentally, the transformer of this example (**A-D, table 14**) is the same configuration as that shown in **fig. 4** of Part 1 except that input and output connections are reversed. All the possible connections are not listed in **table 14**, as indicated by the dashed lines. Completing the list of possible combinations is left as a challenge to the reader.

The next step is to determine how the lines are to be coiled and to determine the coupling between the coils. Draw a schematic diagram similar to **fig. 1** of Part 1. A sample drawing of the example **A-D** in **table 14** is shown in **fig. 10**. For analysis, assign an arbitrary input rf voltage of 100 volts. In this case, the input is balanced, so a balanced input voltage of ± 50 volts is assigned. A total of 100 volts is applied to each line, so the output voltage is 200 volts (± 100 volts with respect to ground). Note that 50 volts appears along the outside conductor across the length of each of the lines.

Determine the magnitude and polarity of the voltage along the outer conductors by tracing the applied voltage. Current will tend to flow over the outside of the outer conductors in the direction shown by the arrows. Sufficient impedance must be provided to prevent shorting the applied voltage. Another example of this technique for analysis is shown in the schematic of the unbalanced-to-unbalanced 50/200-ohm transformer of **fig. 11**.

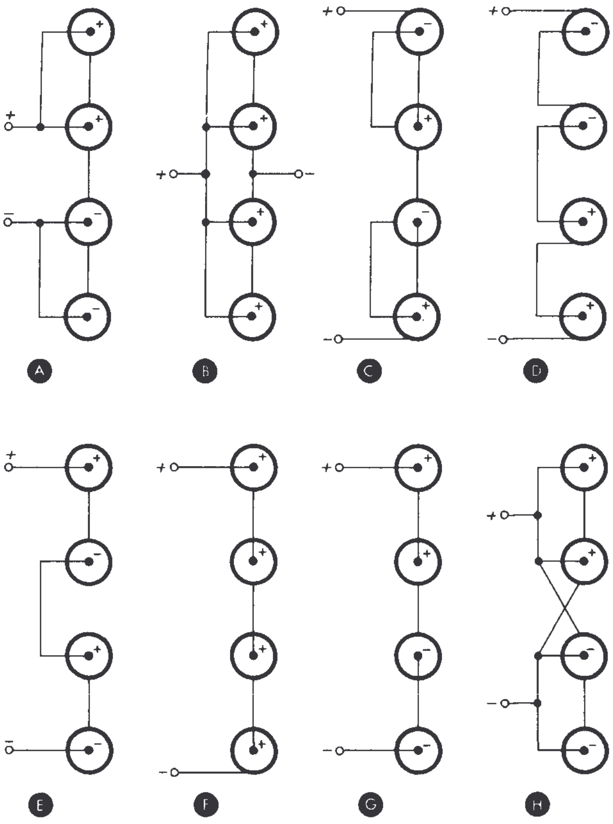


fig. 9. Some of the many possible connections for four coaxial lines. Polarity of the network terminals as well as the polarity of the coax center conductors is shown.

The required common-mode impedance is provided by coiling the coaxial lines. The lines of **fig. 10** may be coiled together (closely coupled), because the voltage across the two lines is the same. The direction of current flow dictates that the lines must be coiled together as shown in **fig. 4** of Part 1. If the lines are coiled in opposite directions so that the current flow, as indicated by the arrows, is in the same direction, the coils will have positive mutual coupling and maximum common-mode impedance (input/output isolation). This is the reason the lines are coiled together into a continuous winding as shown, for example, in **fig. 4** of Part 1.

table 11. Comparison of W1JR Balun[2] with and without compensating winding. Additional winding of insulated hookup wire on the toroid shown in the photograph and the drawing (fig. 6B) substantially improves balance as shown below. Because of lead length, load VSWR is high at 14 MHz and above. See load data below.

	load			W1JR balun,[2] uncompensated				W1JR balun,[2] compensated			
F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR	Z (ohms)	θ (degrees)	VSWR	balance (per cent)	Z (ohms)	θ (degrees)	VSWR	balance (per cent)
1.8	49	1	1.03	48	1	1.05	99.0	49	7	1.13	1.5
3.5	49	2	1.04	49	4	1.08	93.0	50	6	1.11	1.5
4.0	49	3	1.06	49	4	1.08	92.0	50	7	1.13	1.5
7.0	49	5	1.09	51	8	1.15	71.0	52	8	1.16	0.0
14.0	49	10	1.19	63	11	1.35	3.7	61	8	1.28	0.0
21.0	50	15	1.30	76	4	1.35	38.0	68	0	1.36	7.1
28.0	52	19	1.41	79	− 12	1.66	47.0	51	− 11	1.21	15.0
30.0	52	21	1.46	67	− 17	1.53	48.0	36	− 1	1.39	39.0

Depending on the choice of the many input/output configurations partially listed in **figs. 8** and **9**, the coaxial lines may or may not have current flow similar to that in example **A-D**. In some configurations, the direction of current flow on two lines is the same, in which case the lines must be wound together in the same direction. In other configurations, the voltage drops are not the same, so the coils should not be tightly coupled. The configuration shown in **fig. 11** is an example. In a number of unbalanced-to-unbalanced configurations, the voltage drop in one or more of the lines is zero (zero current flow). These lines should not be coupled with lines having voltage drop, because lines with zero voltage drop act like shorted turns. The unbalanced-to-unbalanced transformer of **fig. 5** is an example of this.

The outer conductor of coax **CD** (**fig. 5**) has the same potential at both ends. It should not, therefore, be coupled to the coiled length **AB**. The effect of trying to couple incompatible coils together is shown in the two right-hand columns of data in **table 6**.

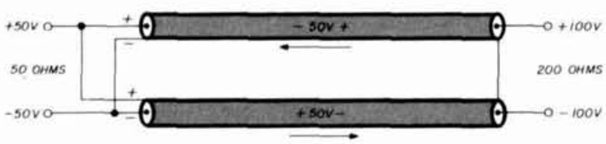


fig. 10. Schematic of the example A-D table 13 and fig. 4 of Part 1. A balanced input voltage of 100 volts (±50 volts) is assigned for analysis. 50 volts appears across the outer conductor along the length of each line, causing current to flow in the direction of the arrows. Enough impedance must be provided along the outside of the lines to prevent shorting the applied voltage.

Fig. 9 shows some of the many possible input and output connections for a group of four coax lines. Terminal and coax center-conductor polarities are indicated in the same format as in **fig. 8**. A number of the four-line connections are shown in **table 15** to serve as examples. Transformers consisting of any number of lines may be analyzed in this way. The highest transformation ratio depends on the number of coax lines. **Table 14** shows that two lines can achieve a transformation of four, and **table 15** shows that four lines can achieve transformation ratios up to sixteen. The highest transformation ratio available is equal to the square of the number of lines.[3] The length of all lines should be the same, to preserve phase relationships.

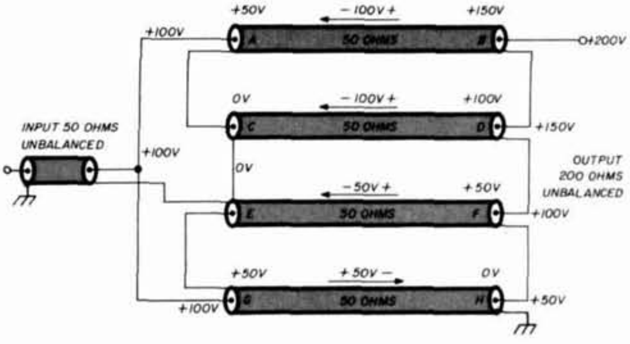


fig. 11. Another example similar to fig. 10 showing how to analyze a transformer configuration for direction and magnitude of voltage drops over the outside conductors of the coax lines. Lines AB and CD should be wound together in parallel and in the same direction for positive mutual coupling, like coiled line AB in fig. 5. Lines EF and GH should be wound together in opposite directions for the same reason.

The final step in the design procedure is to determine the optimum length of coax line and the number of turns in the coil. If the coil has too few turns, performance will be poor at low frequencies; if it has too many turns, performance will be poor at high frequencies. As an example, in the balun described in **fig. 1**, each RG-58A/U line is 127 cm (50 inches) long. The lines were random wound into a 11.5-cm (4.5-inch) nominal diameter coil. VSWR performance over the useful frequency range is shown in **table 1**. Note the increase in VSWR at the ends of the frequency range and compare this with **fig. 12**.

Fig. 12 shows the impedance across the output terminals of the balun of **fig. 1** plotted as a function of frequency. When the balun is open circuited; that is, when the center conductor at the output is disconnected from the dummy coaxial line, the self-impedance of the coax coiled outer conductor can be measured. The vector impedance meter was connected from point **A** to point **B** (**fig. 12**), and the impedance magnitude was measured between 1 and 70 MHz. Note that the impedance from **A** to **B** is always greater than 50 ohms, the line surge impedance, over the useful frequency range of the balun (**table 1**).

When designing a balun or transformer to your needs, make the coil self-resonant frequency approximately equal to the average of the upper and lower frequency limits of the band of interest. For example, if you want to design a transformer to cover 3.5-30 MHz, the open-circuited coil self-resonant frequency should be about 16 MHz. If you want your balun/transformer to be optimum for 160, 80, and 40 me-

table 12. Broadband VSWR performance of the 50-ohm to 50-ohm coax phase inverter shown in fig. 7.

F_0 (MHz)	Z (ohms)	θ (degrees)	VSWR
3.5	54	16	1.34
4.0	54	14	1.30
7.0	57	4	1.16
14.0	53	−3	1.08
21.0	48	−2	1.06
28.0	46	4	1.11
30.0	46	7	1.16

Table 13. Tabular summary of the balun transformers built and measured by W6TC.

input/output impedance ohms	ratio	input/output balance	bandwidth MHz	construction	measured data
50/12.5	4:1	balanced/balanced	1.8-30	fig. 5, part 1	table 1, part 1
50/200	1:4	balanced/balanced	3.5-30	fig. 6, part 1	table 2A, part 1
50/200	1:4	balanced/balanced	1.8-14	fig. 6, part 1	table 2B, part 1
50/50	1:1	unbalanced/balanced	3.5-30	fig. 1, part 2	table 1, part 2
50/50	1:1	unbalanced/balanced	1.8-14	fig. 1, part 2	table 2A, part 2
50/50	1:1	unbalanced/balanced	1.8-14	fig. 1, part 2	table 2B, part 2
50/50	1:1	unbalanced/balanced	21-100	fig. 2, part 2	table 3, part 2
50/12.5	4:1	unbalanced/balanced	3.5-30	fig. 3, part 2	table 4, part 2
50/200	1:4	unbalanced/balanced	3.5-30	fig. 4, part 2	table 5, part 2
50/12.5	4:1	unbalanced/unbalanced	7.0-30	fig. 5, part 2	table 6, part 2
50/50	1:1 (inverted)	unbalanced/unbalanced	3.5-30	fig. 7, part 2	table 12, part 2

ters, make the resonant frequency about 4.5 MHz. For two or three adjacent band designs, the frequency isn't critical; ± 10 per cent accuracy is sufficient.

I found that a grid-dip meter can be used to make this measurement. Make certain that the balun/transformer is open circuited at the output, as described above. The coil diameter should be 15-20 times the coax line diameter. Remember that these baluns and transformers make use of a broadly resonant circuit consisting of the distributed inductance and capacitance of the coax line outside surfaces. Accordingly, if the device is mounted on a metal plate or in a metal enclosure, the resonant frequency should be determined while in place. I tried extending the low-frequency limit of one of these transformers by adding lumped capacitance to the coiled coax at the output. (For example, between **A** and **B** in **fig. 12.**) This artificial loading does, in fact, lower the frequency of minimum VSWR; however, bandwidth is severly reduced.

design procedure summary

In summary, a systematic design procedure for coreless transformers and baluns is as follows:

1. Select input and output coaxial line connections (see examples in **figs. 8** and **9**).

2. Assign polarities.

3. Make certain the polarities of the input and output connections match (column 3, **tables 14** and **15**).

4. Check input and output balance by inspection (columns 4 and 5).

5. Check input and output impedance by inspection (column 6 and 7).

6. Determine transformation ratio (column 8).

7. Draw a schematic diagram similar to that in **figs. 10** and **11** for analysis.

8. Assign an input voltage, such as 100 volts.

9. Determine the polarity and magnitude of voltage across the length of the lines.

10. Determine the direction of current flow over the outer conductors of the lines.

11. Determine which lines must be coiled, if they can be coiled together, and the sense of the mutual coupling.

12. Select the length of line, coil diameter, and number of turns using a grid-dip meter to resonate the coil near the average between the upper and lower frequencies of the band of interest.

13. Make certain that the rf paths through all coax lines are equal, to preserve phase.

table 14. This table is a partial list of the coax connections shown in fig. 8. It is used as an aid in analyzing the connections.

column 1 connection (in)	2 connection (out)	3 polarity (match)	4 balance (in)	5 balance (out)	6 impedance in (ohms)	7 impedance out (ohms)	8 transformation ratio (in/out)
A	B	no					
A	C	no					
A	D	yes	balanced	balanced	25	100	1:4
B	C	yes	unbalanced	unbalanced	25	100	1:4
B	D	no					
—	—	—					
—	—	—					
—	—	—					

table 15. This table shows some of the connections for four coax lines shown in fig. 9. The impedances listed in columns 6 and 7 assume the use of 50-ohm lines.

column

1 connection (in)	2 connection (out)	3 polarity (match)	4 balance (in)	5 balance (out)	6 impedance (in) (ohms)	7 impedance (out) (ohms)	8 transformation (ratio) (in/out)
A	B	no					
B	C	no					
A	D	yes	balanced	balanced	50	200.0	1:4
F	B	yes	unbalanced	unbalanced	200	12.5	16:1
E	C	yes	balanced	balanced	200	50.0	4:1
B	C	no					

advantages of coreless balun transformers

The advantages of this new class of broadband coaxial line transformers over magnetic-core transformers are as follows:

1. They are inexpensive.

2. They are linear; there are no materials in the system that can saturate.

3. They use readily available materials: only coax and hookup wire.

4. They are lightweight and compact.

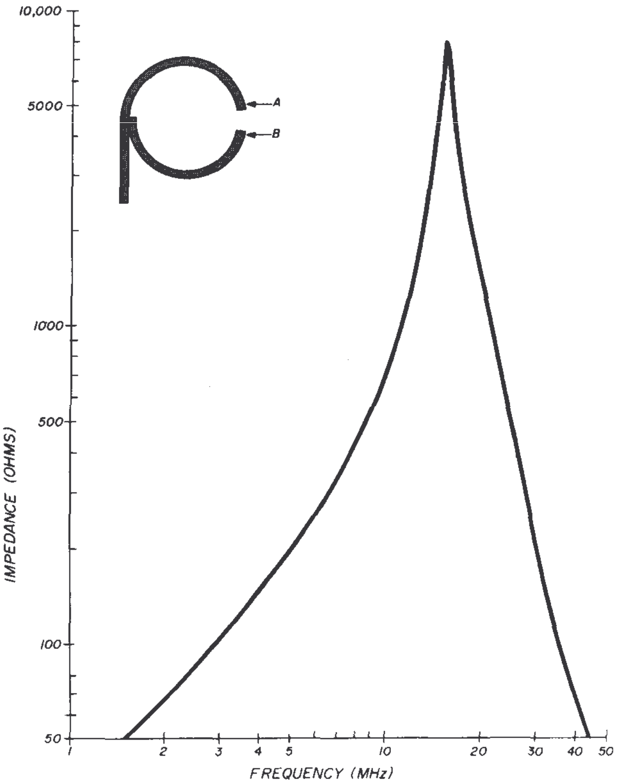


fig. 12. Impedance from point A to point B of open-circuited balun. Impedance at AB is *greater than 50 ohms, the line* surge impedance over the useful frequency range of the balun.

5. They are weatherproof because of the materials; an enclosure is not required.

6. They have low VSWR.

7. They are inherently balanced.

8. They have high power-handling capability limited only by the coaxial line chosen. When made with Teflon coax, they are virtually indestructible in Amateur service.

9. There are no closely spaced or tightly twisted enameled wires and no ferrite or powdered iron core materials that can result in arcing.

conclusion

The purpose of this article is to show how high-performance balun transformers can be built free of the disadvantages of magnetic core materials. I hope I've presented enough data on this new class of devices for you to be able to reproduce one or more of the designs described here, or to design one of your own to meet your requirements. My goal has been to provide enough information for others to be able to reproduce these useful balun transformers, even though they may not have access to fine instruments such as the Hewlett Packard vector impedance bridge, rf voltmeter, or programmable calculator.

acknowledgment

I am indebted to the EIMAC gang (the laboratory staff at EIMAC) and the staff at CTC for counsel, constant encouragement, and after-hours use of their laboratory facilities.

Note: The HP-67 program for calculating VSWR that should have appeared in the appendix of part 1 of W6TC's article (February, 1980, *ham radio*) can be found on page 70 of this issue.

references

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ham radio

considerations regarding microphones and simple speech processing

A look at simple homemade microphones and speech processors

This article describes a microphone stand that can be built easily and that's much more convenient to use than the typical commercial unit. Also described are simple preamplifier and clipper circuits that can be added to a phone station between microphone and transmitter.

improved desk microphone

In spite of all the equipment manufactured for sale to Amateurs, many desirable items still can't be readily purchased. Many times these items are simple to build, and many times the item needed is a simplified version of what's commercially available. In any case, it's seldom that the scratch-built item isn't a big cost saver.

In the case that prompted this article, the audio gain in my low-band rig was marginal. Close talking in a moderate voice into a standard crystal microphone was required for full SSB output. This condition may not be unusual based on my own experience and that of others I've talked to. Additionally, standard microphone stands have always left a lot to be desired, to my way of thinking. First, they're seldom adjustable in height; second, they must be placed off to the side if you want to take notes or fill in your log while talking. One of my friends claims the best he can do is get his nose up to the bottom of the microphone; in my case, I have to bend over to speak into a microphone mounted on a typical commercial stand. The solution to this problem is a boom-type microphone stand.

The mechanical end of this kind of project is wide open with respect to cost and complexity. If you have the shop equipment, the boom stand can be a major project for tools such as a lathe and drill press. It's largely a matter of the materials and tools you have and your personal taste.*

My original stand was made from junk-box parts and some pieces of birch dowel.' It looks a bit "Tinker-Toyish," but it serves the purpose very well. The second design, which is shown in the diagram, requires no unusual tools and works better than the original.

building the microphone stand

The base is made from two or more layers of 6.5-mm (¼-inch) tempered Masonite (**fig. 1**). The base should be at least 153 mm (6 inches) in diameter and may be weighted if a heavy microphone is used. The upright section is a "plumber's delight" made from readily available plumbing fittings. The boom is a piece of Greenfield flexible tubing, which is available at electrical supply houses. This type of tubing is smooth and flexible. To stiffen it, use a piece of aluminum clothes line wire inside of it.

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*Metal is recommended for audio and radio-frequency shielding.