W2FMI presents this epilogue to his series on transmission line transformers. He also presents us with a challenge for the future.

A Subsequent Look At 4:1 Baluns

BY JERRY SEVICK*, W2FMI

The June 1993 issue of *CQ* contained an article[1] of mine on baluns entitled "A Balun Essay." It presented six designs with the following ratios: 1:1, 1.5:1, 2:1, 4:1, 6:1, and 9:1. All were of the "current" type which have lately found favor in the amateur literature. The article also included a little history and theory of these devices. If you read the article, you would have found that I was also quite critical of recent articles which appeared in the amateur journals proposing new 1:1 designs using coaxial cables either wound around ferrite cores or threaded through ferrite beads.

More recently *CQ* published another balun article of mine entitled "Baluns for Antenna Tuners."[2] It introduced a new look at the 4:1 Ruthroff[3] (voltage) balun under a balanced-to-ground condition, which is the usual case with balanced antenna systems. It also presented an improved design of McCoy's balun,[4] which uses powdered-iron toroids with a permeability of 10 and has been successfully utilized in antenna tuners for many years. Powdered-iron cores with permeabilities greater than 10 were also investigated. Permeabilities of 20 to 35 looked somewhat promising but needed accurate insertion loss measurements in order to prove their usefulness. Their bulk-resistivities of less than 1000 times that of the No. 2 mixture, which has the permeability of 10, cast some shadow of a doubt.

This article is really an extension of my recent publication on baluns for antenna tuners. It not only presents new designs using Ruthroff's approach, but also gives some history and an evaluation of what has appeared in the amateur radio literature on 4:1 balun designs. It is then followed with a section on suggested applications for the various 4:1 designs, and finally, a brief overview of this technology known as transmission line transformers.

A Little History and Design

Looking back at my old issues of amateur radio handbooks (and I have some missing), I found that the first presentation on broadband 4:1 baluns was in the 1955 edition. The section was called Coil Baluns. The schematic diagram, which is shown in fig. 1(A), was taken from Guanella's classic 1944 paper[5] which introduced the concept of a broadband balun. What surprised me was that this section appeared to use many of the important words contained in Guanella's paper. It mentioned that the choking action of the coiled transmission lines should be great enough to isolate the input from the output at the lowest frequency of interest. It also included the requirement on the characteristic impedance of the coiled transmission lines; namely, that the characteristic impedances should be equal to $R_L/2$, where R_L is the load.

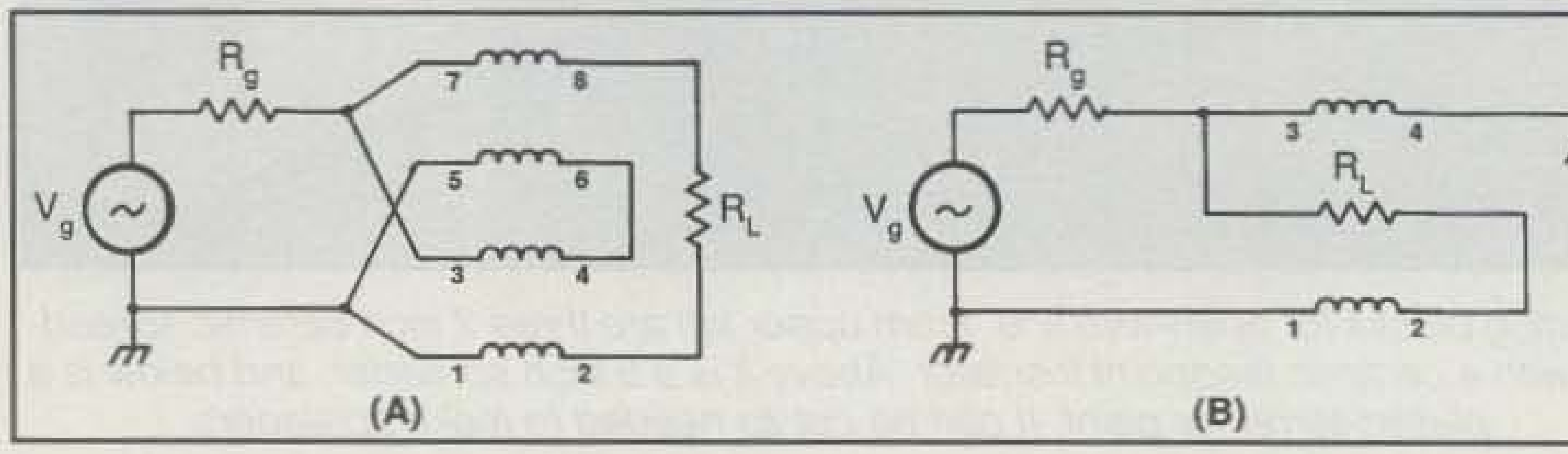

Fig. 1– High frequency models of the two 4:1 baluns: (A) Guanella (current) balun; (B) Ruthroff (voltage) balun.

The section included two other statements which are not correct in today's design practices. One recommended that the length of the winding in each coil be equal to about a quarter wavelength. The other stated that the principal application is in going from a 300 ohm balanced line to a 75 ohm coaxial line. With ferrite cores, the length of windings is now considerably shorter than a quarter wavelength, and the applications include a host of different impedance levels.

Recent issues of the handbooks now include the 4:1 broadband coil balun (with the same write-up as in the 1955 edition) and one with the windings on ferrite cores. They are now called 4:1 air-core current baluns and "just plain" 4:1 current baluns (ferrite cores being assumed). But what is now lacking in the description of the 4:1 current balun is the importance of the characteristic impedance of the windings and the value of the permeability of the ferrite cores. They state that 8 to 10 turns (of No. 14 Formvar-coated, close-spaced wire, I guess) on a toroidal core or 10 to 15 turns on a rod are typical values for the HF range. Ferrite cores with permeabilities from 850 to 2500 are also suggested. Also, nothing is mentioned regarding the dimensions of the cores.

In essence, there is very little information available today in our handbooks on how to understand and construct the "popular" current balun. Even the choices of ferrites to be used are found wanting. Accurate loss measurements[6] have shown ferrites with permeabilities of 850 to 2500 to be lossy in balun (and unun) applications. Only when the permeabilities of ferrites are 300 or less will baluns exhibit the very high efficiencies of which they are capable. For more information on the theory and construction of current baluns, I refer the reader to my June 1993 article in *CQ*.[1]

Even though the 4:1 "voltage" balun has actually had a shorter history than the current balun, considerably more construction detail (including an actual photograph) has been available in the ama-

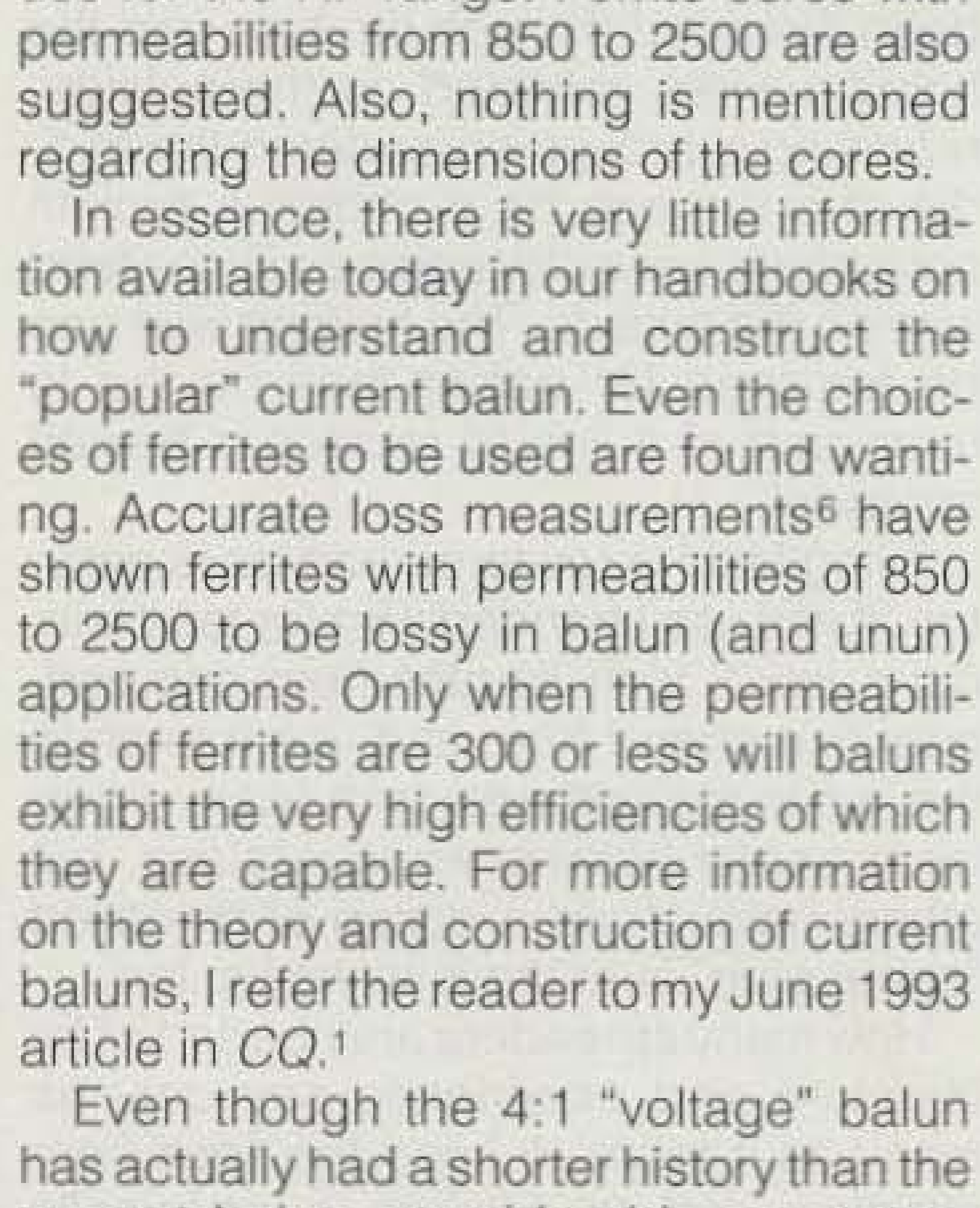

Fig. 2– Pictorial representation of the 4:1 Ruthroff (voltage) balun.

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teur radio handbooks. As far as I can tell, the first presentation took place between 1965 and 1968. In looking through succeeding issues (including the 1993 issue), I find the write-up has not changed much (if any) over the years.

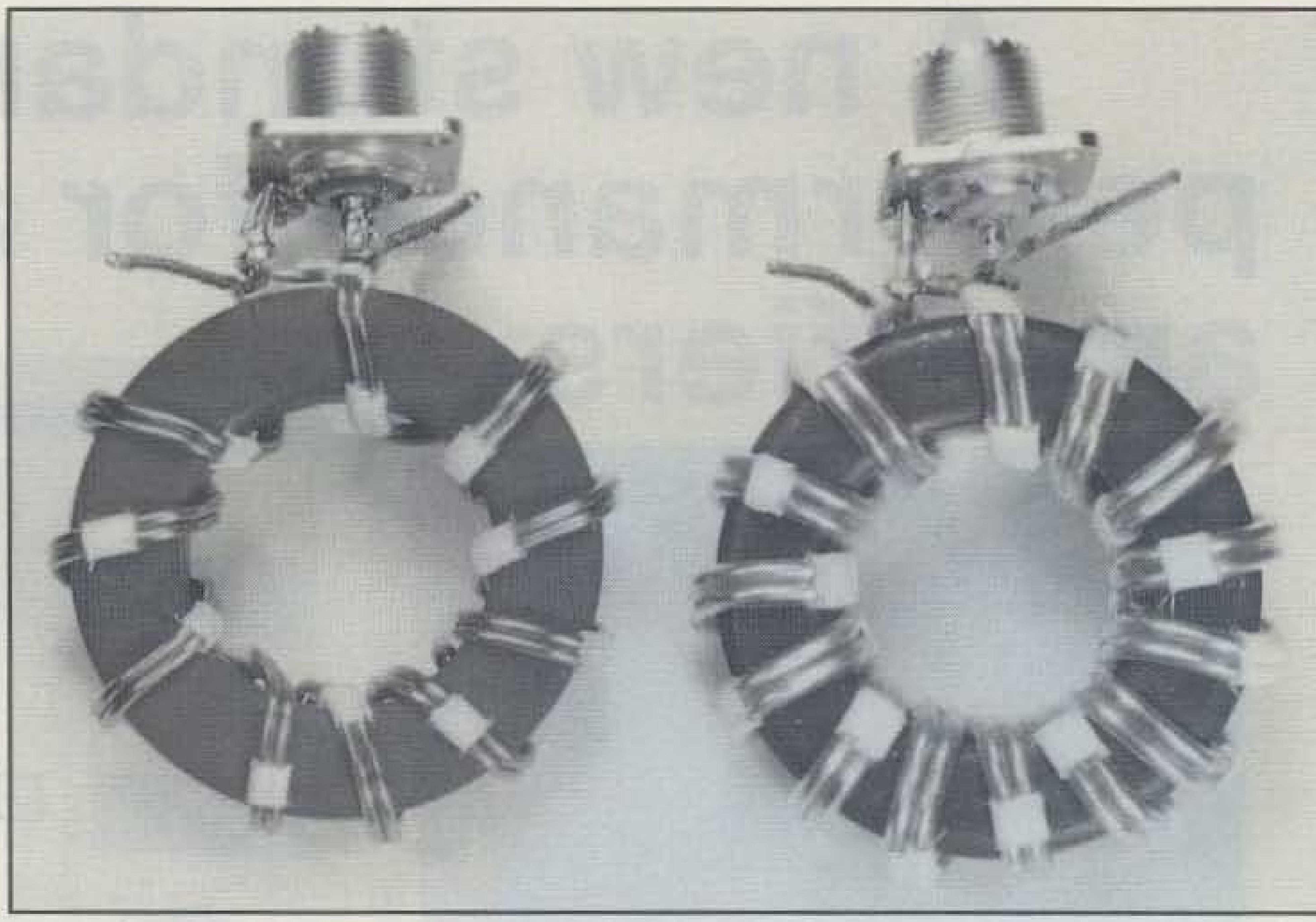


Photo A– Two designs of the 4:1 Ruthroff (voltage) balun. The one on the left is taken from the amateur radio handbook. The one on the right is my improved version.

Fig. 1(B) shows the schematic diagram of the 4:1 Ruthroff (voltage) balun.[3] Fig. 2 shows a pictorial representation of the balun. Photo A (on the left) shows my construction of a design close to the one shown in the handbook's photographs. It has 10 bifilar turns of No. 14 Formvar-coated wire (close-spaced, I assume) on a 2.4 inch OD ferrite toroid with a permeability of 40. Fig. 3 shows a plot of the input impedance versus frequency when the 200 ohm load is center-tapped-to-ground (which is close to the actual case when matching into balanced antenna systems). As you can see, when compared to a design that has the proper characteristic impedance of the winding and sufficient choking, the response is very poor. Although this balun has been rated at 1000 watts of RF power from 1.8 through 60 MHz, I would suggest it not be used below 6 MHz for fear of excessive flux in the core (especially when the magnitude of the load is greater than 200 ohms). Also, above 14 MHz the transformation becomes considerably greater than 4:1.

My design, on the right in photo A, has 14 bifilar turns of No. 14 tinned copper wire on a 2.4 inch OD ferrite toroid with a permeability of 125 or 250. The wires are threaded through No. 13 Teflon tubing with a wall thickness of 20 mils. As you can see by its excellent high frequency response in fig. 3, the characteristic impedance of the bifilar winding must be very close to the ideal value of 100 ohms. Photo B shows two different views of my design mounted in a 4"L × 3"W × 2.25"H Bud CU 234 aluminum box. The balun, which is placed equidistant between the top and bottom and the sides of the enclosure, is securely mounted when soldering its leads to the two feed-through insulators and the SO-239 chassis connector.

It should be mentioned that if the balun is mainly to be used on the lower portion of the HF band (including 160 meters), then the 250 permeability ferrite is recommended. Even though the difference in low frequency response between permeabilities of 125 and 250 doesn't show up in fig. 3, the 250 permeability would give an extra degree of safety margin (from flux in the core) at the low frequency end. The trade-off is in giving up a little in efficiency (about 1 percent) for an increase in the safety margin (a factor of 2) at the low end.

Incidentally, the handbooks also state that the balun can be used between a balanced 300 ohm point and a 75 ohm unbalanced line. Since I suspected this statement as well, I again measured the input impedances versus frequency of both baluns when terminated in a 300 ohm center tapped to ground load. Fig. 4 shows the deterioration, which especially takes place at the high end. Even a balun well designed for a 50:200 ohm impedance level is not recommended for the 75:300 ohm level. Because the length of the transmission line becomes significant beyond 10 MHz, standing waves then change the impedance ratio due to the mismatch with the balun's transmission line. My design also shows more safety margin at the low end. I am sur-

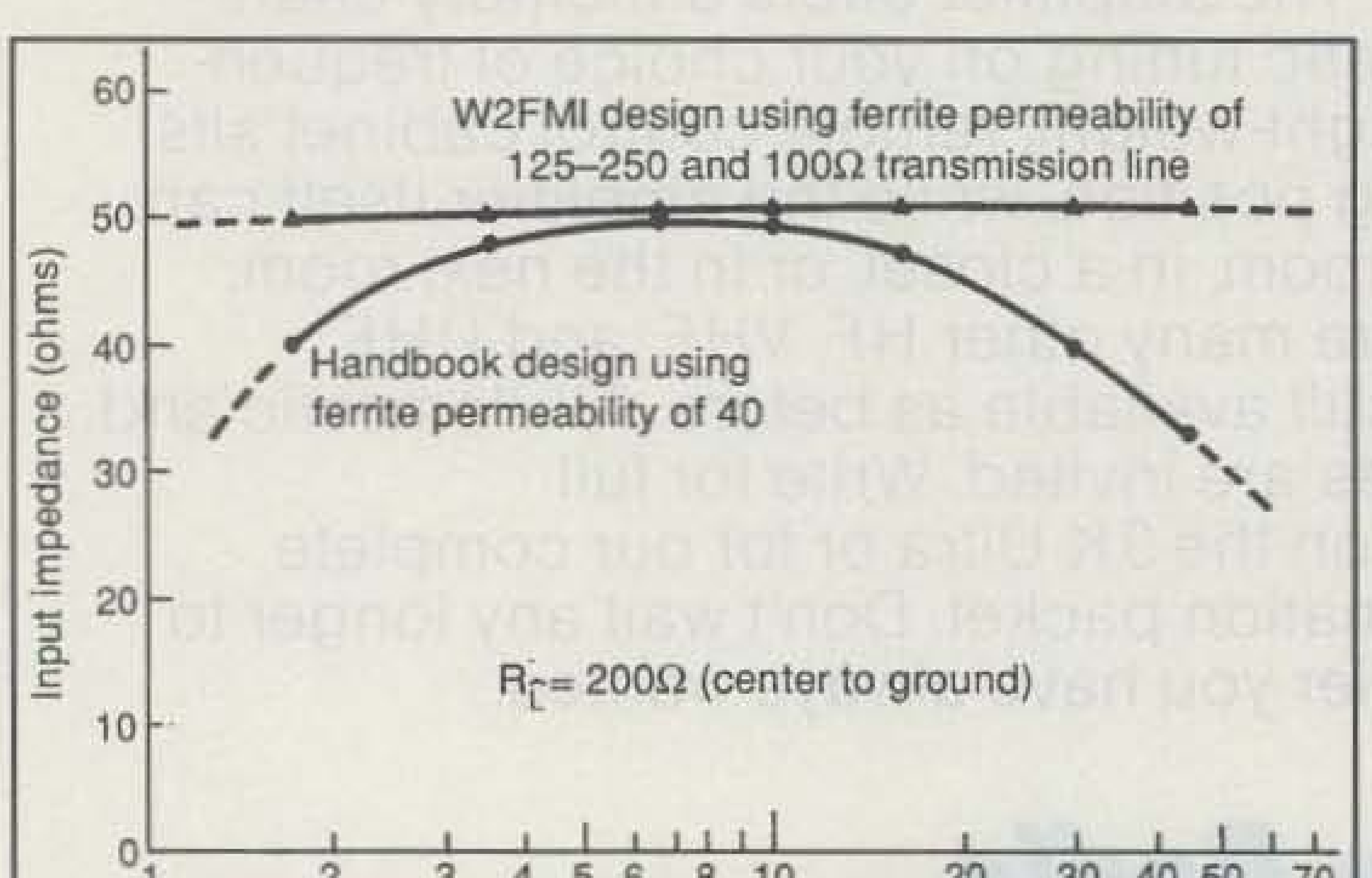


Fig. 3– The input impedance versus frequency for a 4:1 Ruthroff (voltage) balun design from the amateur radio handbook and one optimized for the 50:200 ohm level. The load is grounded at its center.

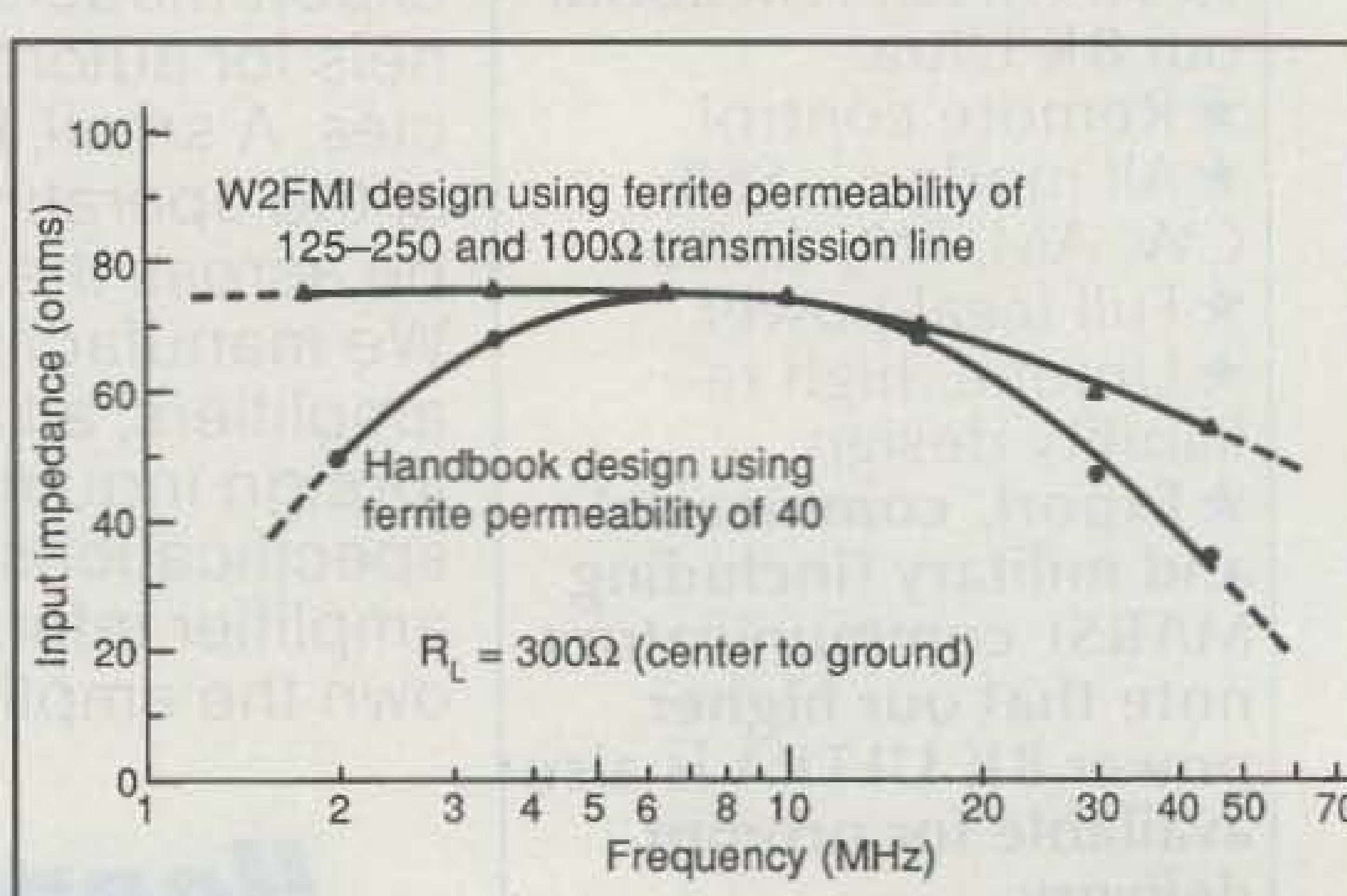


Fig. 4– The input impedance versus frequency for the two 4:1 Ruthroff baluns of fig. 3, but with a 300 ohm load. Note the deterioration of the W2FMI design which was optimized for the 50:200 ohm level.

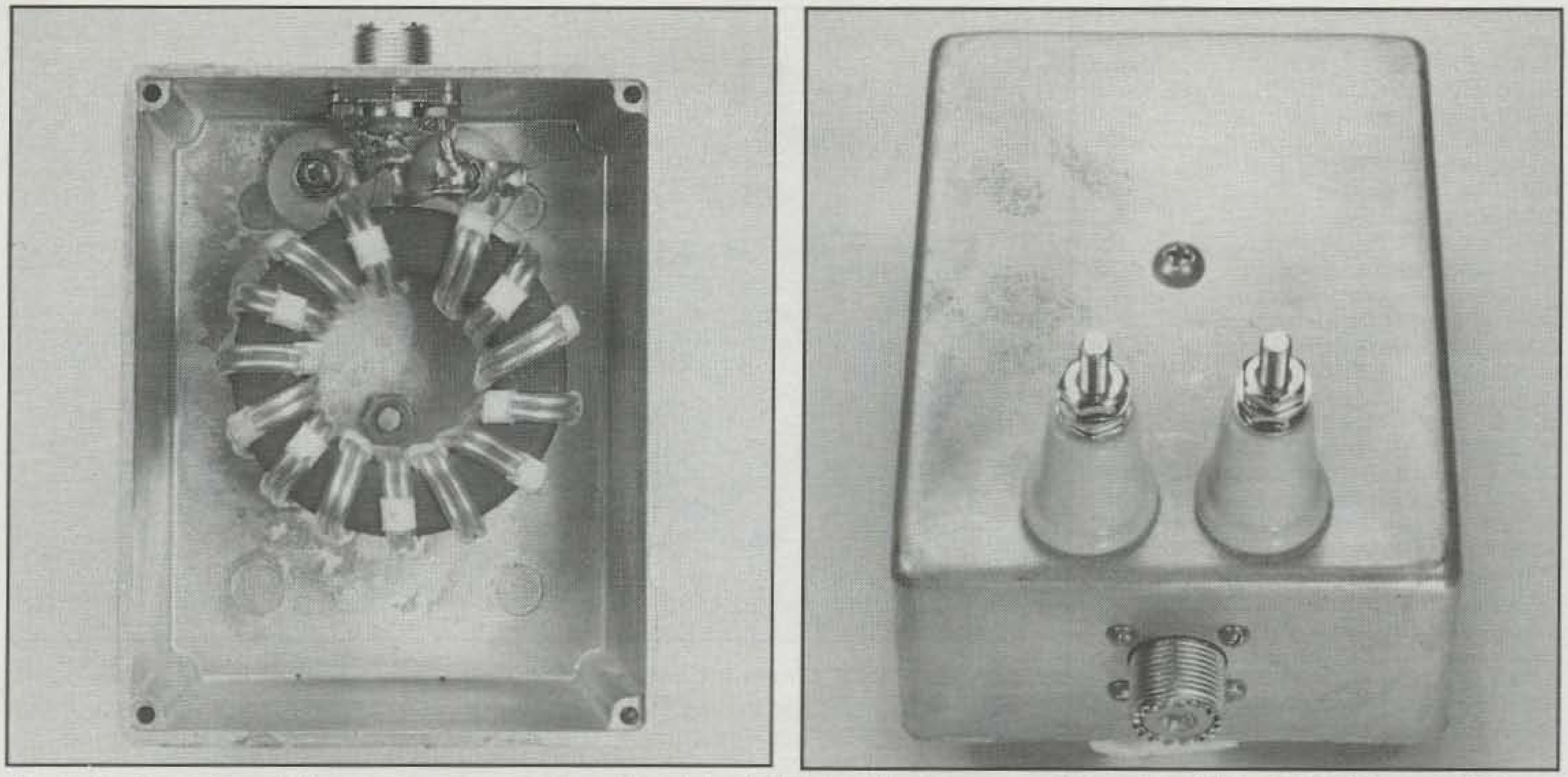


Photo B– Two different views of the optimized version of the 4:1 Ruthroff balun mounted in a 4"L × 3"W × 2.25"H Bud CU 234 aluminum enclosure.

prised that these simple measurements were not made many years ago.

The balun shown in the handbook, however, does have one interesting feature. It uses a very low permeability ferrite (40) which has been shown by very accurate insertion loss measurements[6] to yield efficiencies in baluns (and ununs) of 99 percent at the 50:200 ohm impedance level! This is even a percent or two better than the ferrite with a permeability of 125. Since this ferrite permeability is so low, the major problem is in obtaining sufficient choking reactance at the lowest frequency of interest so that only trans-

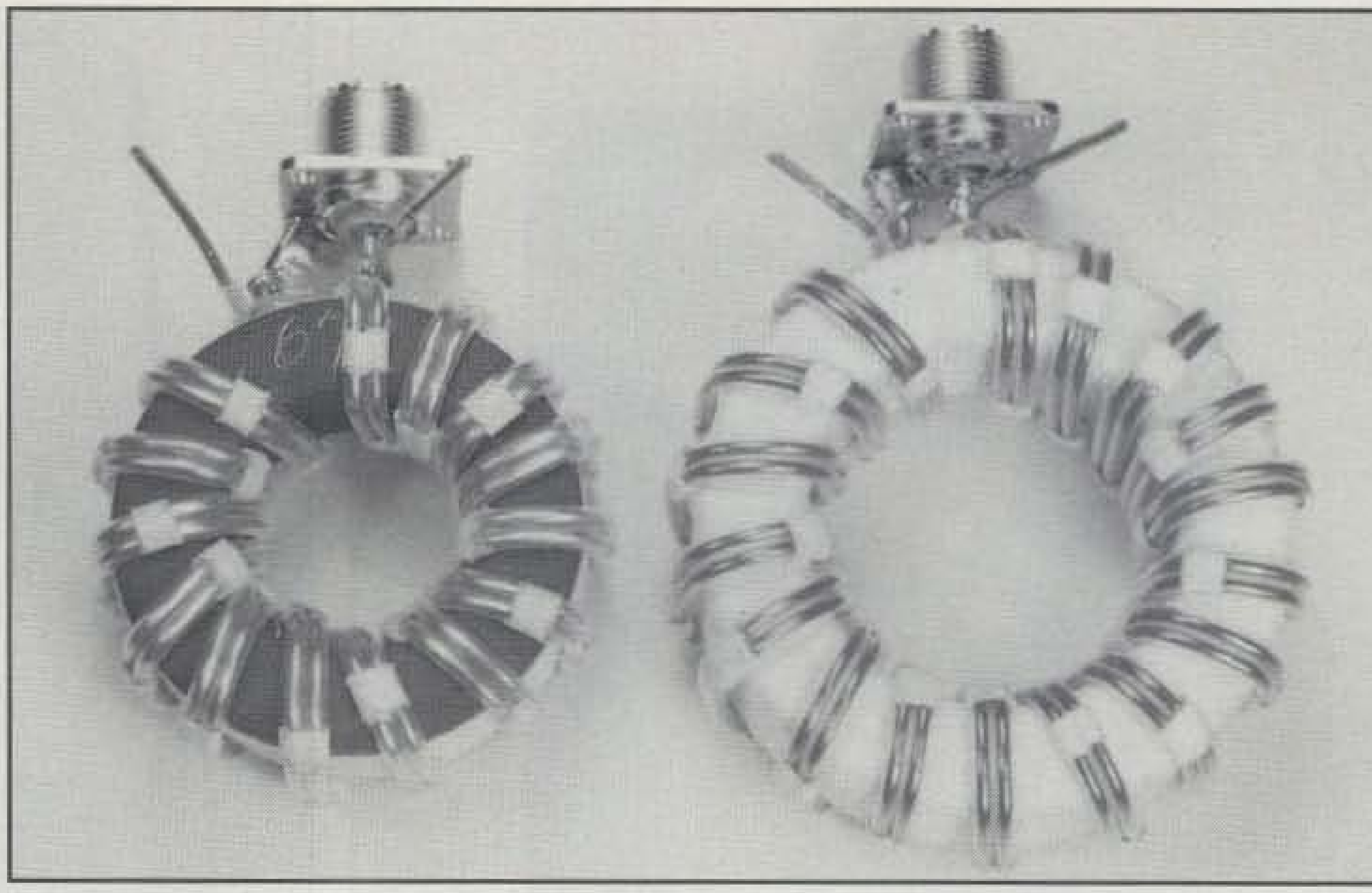


Photo C– Two 4:1 Ruthroff (voltage) baluns capable of handling 10 kW of peak power and 5 kW of average power. The one on the left uses two ferrite cores (stacked) with permeabilities of 40. The one on the right uses a large (3 inch OD) powdered-iron core with a permeability of 10.

mission line currents are allowed to flow.

The design chosen (in order to exploit this very high efficiency) is shown on the left in photo C. It uses 14 bifilar turns of the same wire, as with my previous balun shown on the right in photo A, on two 2.4 inch OD cores (bound together with No. 27 glass tape) with permeabilities of 40. Photo D shows three views of this low-loss 4:1 Ruthroff (voltage) balun. The unmounted view shows how the two cores are bound together by glass tape. The other views attempt to give an example for mounting the balun. The balun is supported by two acrylic end pieces which are, in turn, held fast to the enclosure by a long bolt. The balun is placed equidistant between the top and bottom and the sides of a 5"L × 3.5"W × 2.25"H aluminum enclosure. A few washers at the point where the bolt comes through the enclosure help to position the balun between the top and bottom.

When matching 50 ohms (unbalanced) to 200 ohms (balanced), the response of this balun is practically the same as mine shown in fig. 3 using a single core. From 1.7 MHz to 30 MHz it can certainly handle the full legal limit of amateur radio power with an efficiency close to 99 percent. But if the operation of this balun is restricted to the HF band only (that is, 3 to 30 MHz), then it could be conservatively rated at 10 kW of peak power and 5 kW average power. It would be an ideal balun for a log-periodic beam antenna.

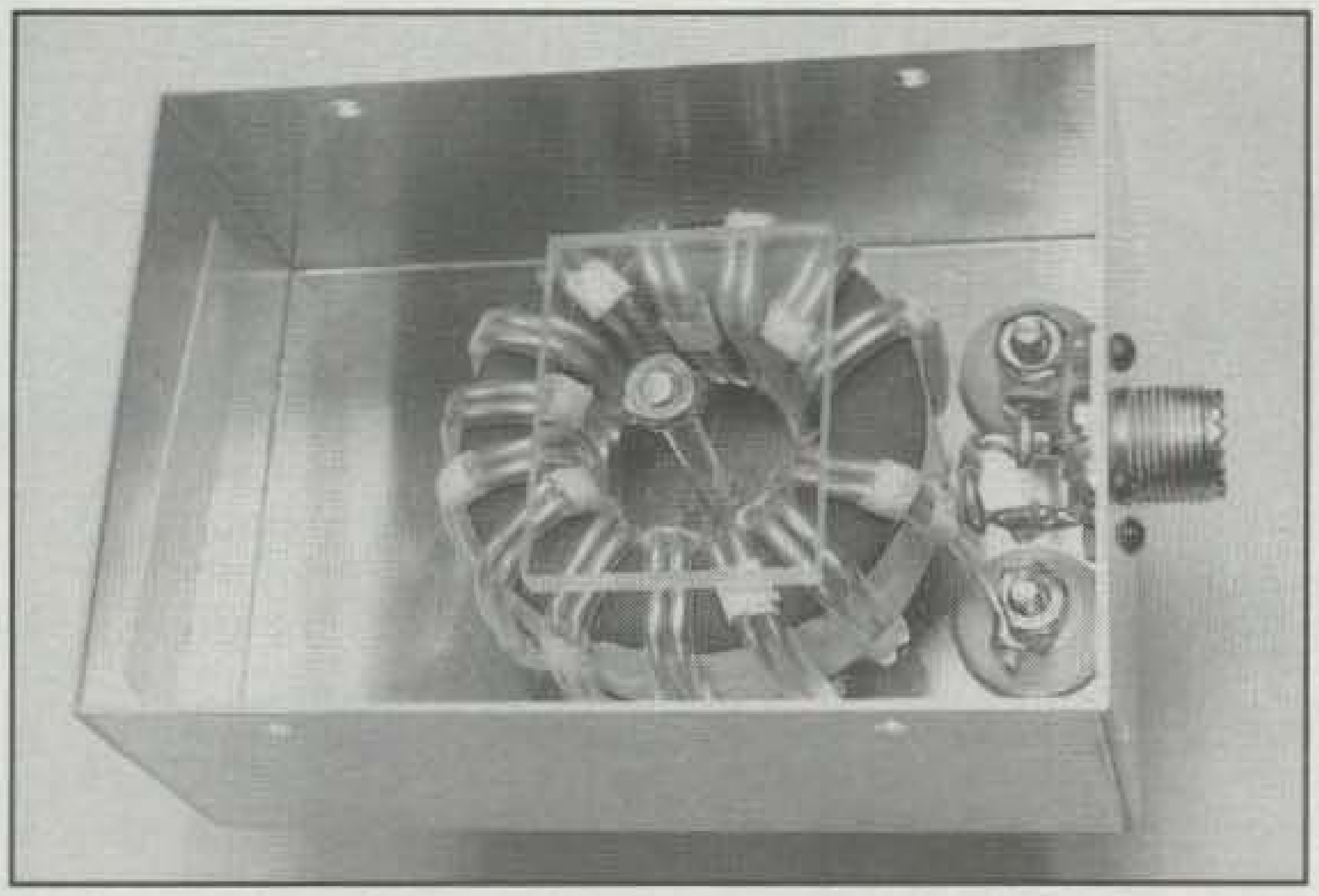
On the right in Photo C is shown a very high power 4:1 balun using a powdered-iron core with a permeability of 10. In its passband it also demonstrated efficiencies approaching 99 percent.[6] It has 17 bifilar turns, of the same wire as above, on a 3 inch OD, 1 inch high powdered-iron toroid. It was primarily designed for use in antenna tuners where hostile conditions (very high impedances) can exist. Since its permeability is one fourth that of the ferrite of the very high power balun (on the left in Photo C) and the effective path length is larger, the increase in the number of turns from 14 to 17 does not give it quite as much choking reactance, hence the same low frequency response.

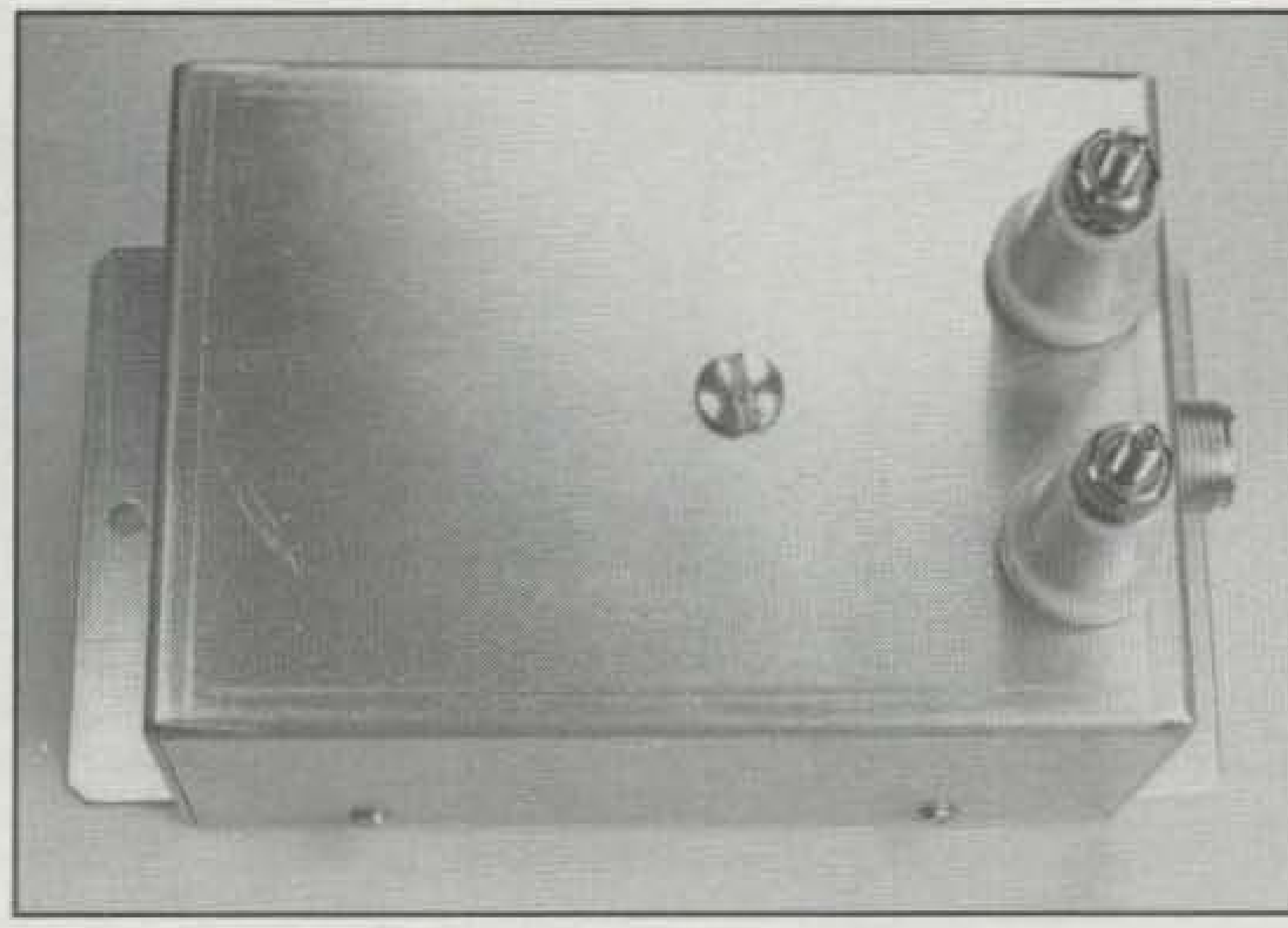
This powdered-iron balun, which is more completely described in a recent *CQ* issue,[2] can handle the full legal limit of amateur radio power from 3 to 30 MHz. Because of its comparable very high efficiency,[6] it could very well be rated at 10 kW of peak power and 5 kW of average power from 6 MHz to 30 MHz. It does have an advantage over its ferrite counterpart in that it is less prone to damage due to flux in the core. Furthermore, powdered-iron is a more linear material.

Finally, photo E shows three different views of a low power 4:1 Ruthroff (voltage) balun designed to easily handle the output power of any HF transceiver. It has 10 bifilar turns of No. 18 hook-up wire on a 1.5 inch OD ferrite toroid with a permeability of 250. The enclosure is a 2.75"L × 2.125"W × 1.625"H CU-3000-A minibox.

4:1 Balun Applications

As was shown in fig. 1, there are two different designs for the 4:1 balun. One uses Guanella's approach[5] of connecting two transmission lines in series at one end and in parallel at the other. It has recently been called in the amateur radio literature a "current" balun. The other uses





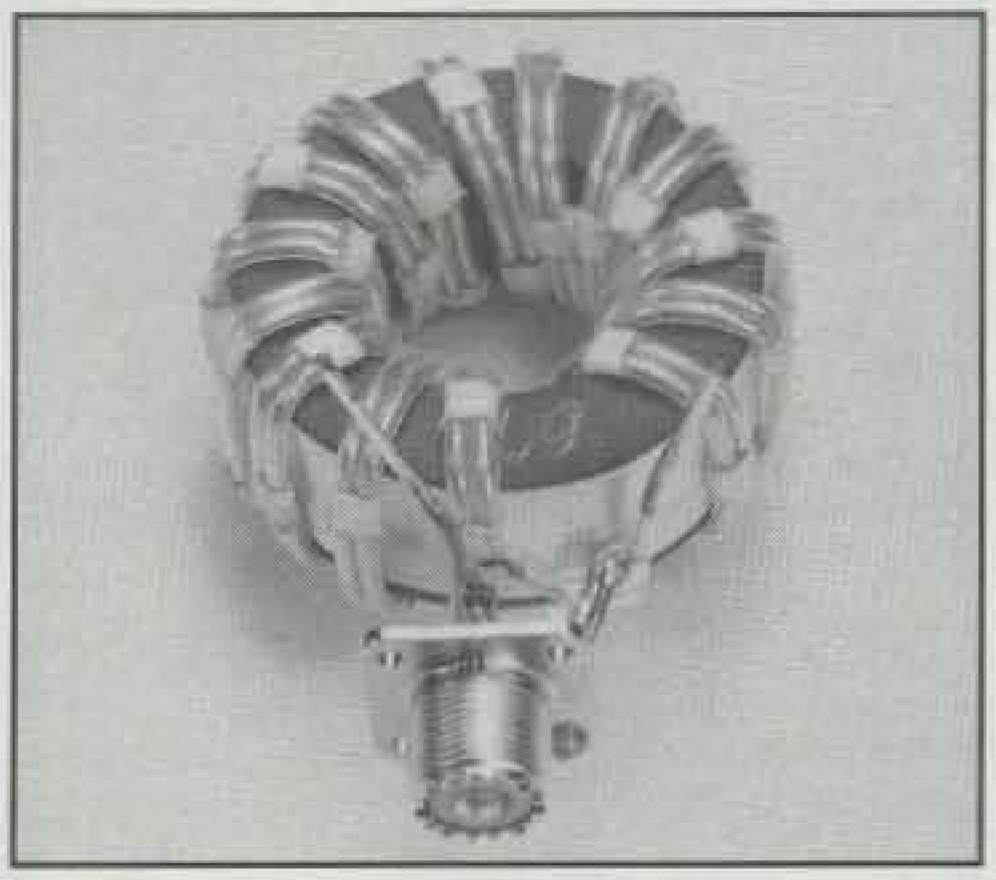
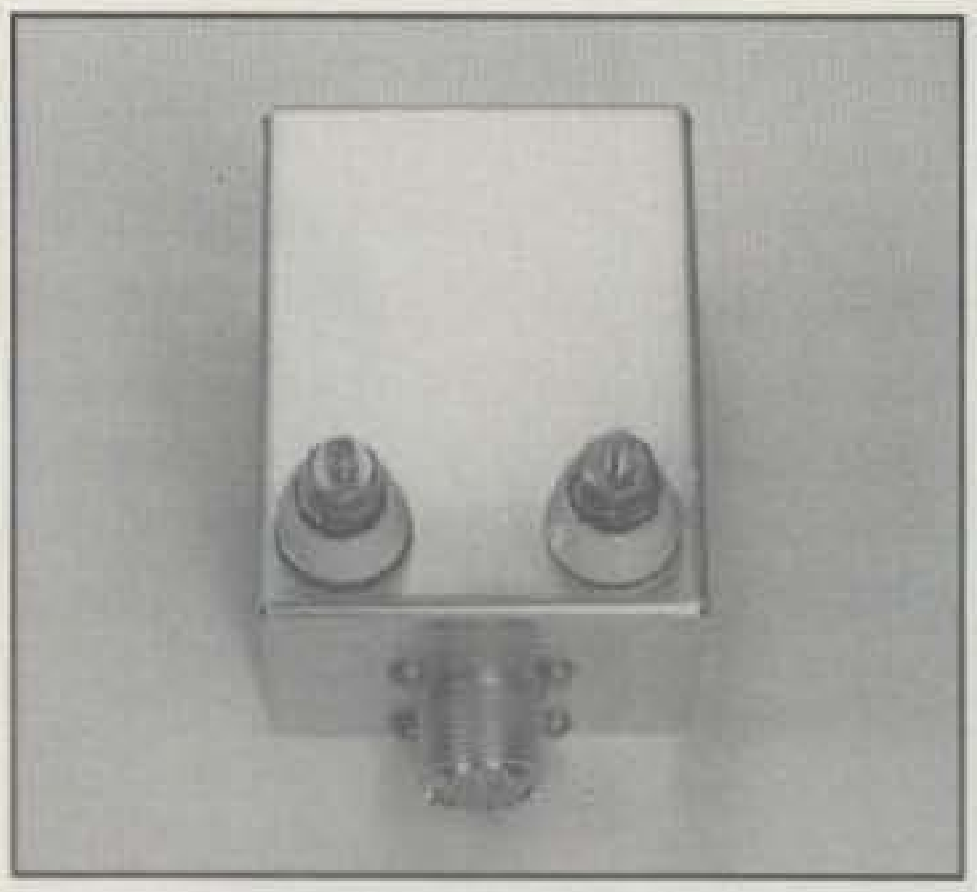


Photo D– Three views of the very high power 4:1 Ruthroff balun using two low permeability (40) ferrite cores. The aluminum enclosure has the dimensions 5"L × 3.5"W × 2.25"H.

Ruthroff's approach[3] of using a single transmission line in a "phase-inverter" configuration.[1] His approach is called a "voltage" balun. Since we presently have two baluns which appear to perform the same function and one takes two transmission lines (and cores) and the other only one, questions arise as to which balun should be used and why. The following are suggestions for some of the more common uses.

a) Antenna Tuners. Baluns are primarily used in antenna tuners to convert the balanced input to an open-wire or twinlead transmission line to an unbalanced impedance which can easily be handled by L-C networks. Antenna tuners provide the most hostile environments for baluns. With poor antenna designs,[2] the impedances seen by the balun can be very high, and hence harmful due to excessive flux in the core or voltage-drops along the length of the transmission lines. Since powdered-iron is much hardier than ferrite (and more linear as well), I would recommend it in a 4:1 voltage balun for use in antenna tuners. Until more insertion-



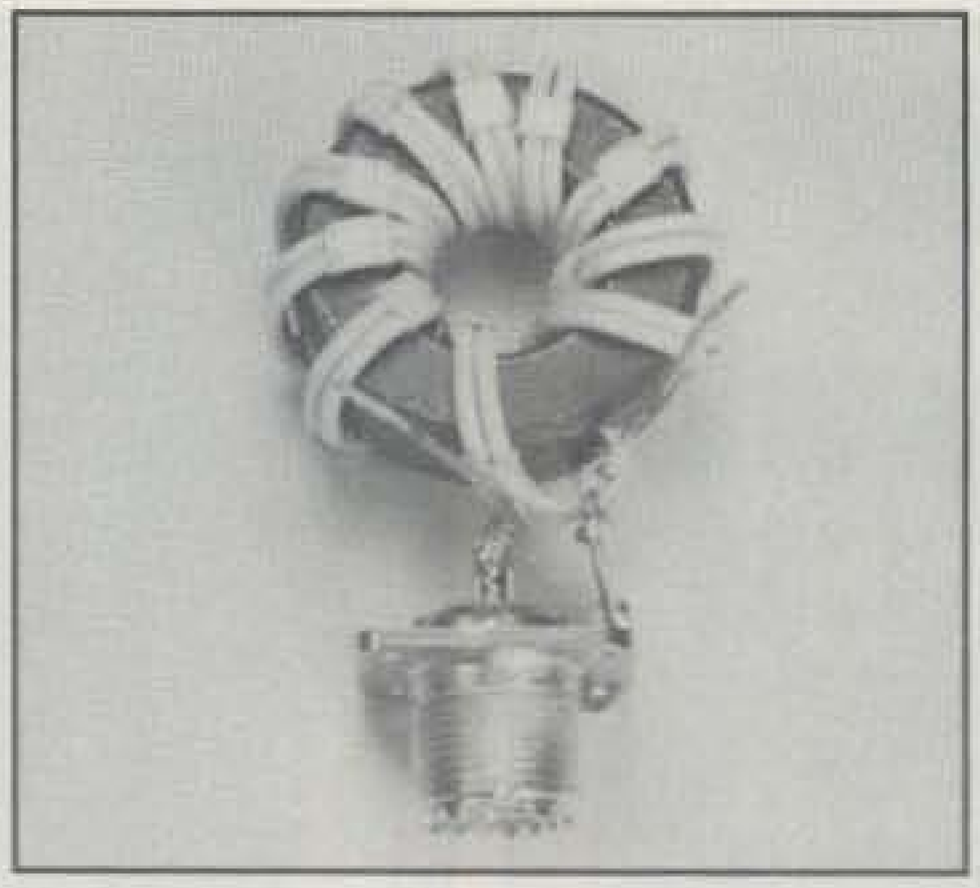


Photo E– Three different views of the low power 4:1 Ruthroff balun designed to handle the output of any HF transceiver. The enclosure is a 2.75"L × 2.125"W ×1.625"H CU-3000-A minibox.

loss information is available on powered-irons with permeabilities in the range of 20 to 35, I suggest using my design, shown on the right in photo C (which uses a permeability of 10).

b) Folded Dipoles. If a folded half-wave dipole, using 300 ohm TV ribbon, is erected at a height of about 0.17 wavelengths above ground, its resonant input impedance is close to 200 ohms. Experiments[2] have shown that a 4:1 voltage balun performs as well as a current balun under normal conditions (that is, the coax feedline comes away at right angles from the dipole). Therefore, depending upon the power level and frequency range, this article has supplied four new useful designs.*

c) Off-Center-Fed Dipoles. When a dipole is fed off center, there is no ground-plane (or zero-potential-plane) bisecting the drive point. In other words, the load is not grounded at its center. Thus, the "current" balun is recommended since it accommodates itself to a ground at any place along the load. But the penalty for this flexibility is that it requires two windings (and cores) like the one used in the Ruthroff (voltage) balun. They are then connected in a series-parallel arrangement as shown in fig. 1(A). This is the classic Guanella approach. In some cases when dipoles are unintentionally unbalanced or have their feed lines at poor angles from the antenna, current baluns are also recommended.

For more information on current baluns, reference is made to my June 1993 *CQ* and Fall 1992 *Communications Quarterly* articles.[1,7]

d) Log-Periodic Beam Antennas. If the frequency range is limited to the HF band (that is, 3 to 30 MHz), then I would recommend the voltage balun shown on the right in photo A using a single ferrite core with a permeability of 125. It can easily handle the full legal limit of amateur radio power in this application where the input impedance can be said to be "well-behaved." For much higher power applications I would recommend the double-stacked core arrangement using two low permeability cores of 40. This is shown in photos C and D.

e) 300:75 ohm Applications. As was shown in this article, well-designed 200:50 ohm baluns are not really made to adequately handle the 300:75 ohm impedance level. It can provide a good 4:1 impedance ratio on the lower portion of the frequency range where the transmission line(s) are very short compared to the wavelength. But at the high end of its response the transmission line(s) is mismatched and standing waves cause an increase in the impedance ratio. The ratio also takes on a capacitive reactance component. However, 300:75 ohm baluns can successfully be designed with coiled transmission lines of No. 16 wire covered with Teflon tubing and further separated by a hollow Teflon tubing. This would yield the 150 ohm characteristic impedance, which is the optimum value. Furthermore, this balun could be connected in series with a 1:1.5 unun, resulting in a very efficient and broadband 6:1 balun.[1]

f) The G5RV Antenna. In giving talks at local radio clubs, I find that the topic of baluns for G5RV antennas always arises. Some think a 4:1 balun is necessary, and others, a 1:1 balun. If one studies this very popular multiband antenna, one finds that the magnitude of the impedances seen at the input to the 34 foot open-wire line is close to 100 ohms on most bands. On 20 meters it is a center-fed, three half-wave dipole with a transmission line acting as a 1:1 transformer. Therefore, on this band the resonant impedance seen at the input to the feedline should be very close to 100 ohms. As a result, the most logical balun appears to be one with a 2:1 ratio. It would be interesting to try out this balun[1] and see how many of the bands can successfully be operated without an antenna tuner. Incidentally, Varney[8] (G5RV) himself recommended that his antenna design only be matched with an antenna tuner. An adequate 2:1 balun design was not available then.

A Brief Overview

Until very recently the radio amateur only had two types of baluns available in the literature and on the market. They were the so-called 1:1 and 4:1 "voltage" baluns. As was shown in my June 1993 *CQ* article, the comparisons by others with new 1:1 designs using coaxial cable (called "current" baluns) were made with an inferior trifilar-wound balun instead of Ruthoff's design which appeared in his 1959 paper and became the industry's standard. Ruthoff's third conductor on his 1:1 balun was on a separate part of the toroid, thus giving it practically the same characteristics as the Guanella ("current") balun. These recent articles on new designs not only gave a new language to our baluns, but also questionable statements regarding their performances. It would be interesting if the authors of these articles compared their baluns with well-designed Ruthroff or Guanella baluns using 50 ohm bifilar windings on low-loss ferrite toroids (less than 300 permeability). I am quite sure their claims would be greatly diminished.

As was noted in this article, the 4:1 voltage balun appeared in the amateur radio journals about 25 years ago (the same time as the "inferior" 1:1 voltage balun). Considerable design information appeared in the handbooks then regarding the construction and performance of this balun. Furthermore, this information also stayed the same over these many years. But as was shown in this article, the design was found lacking. However, with some rather simple changes, such as doubling the cross-sectional area of the core, increasing the number of turns from 10 to 14, and using extra insulation on the wires to increase the characteristic impedance of the coiled transmission line from about 50 ohms to 100 ohms (the objective), a much better design emerged. In fact, for balanced antenna systems, this new design might well be described as "peerless."

Lately a 4:1 Guanella (current) balun appeared in our handbooks. This more flexible balun uses two transmission lines wound on separate cores and connected in series on one end and in parallel on the other end. Literally no design information is given on its construction. What is given are recommendations for the permeability of the ferrite cores. Values from 850 to 2500 are proposed. However, using these high permeabilities would result in lossy baluns.

I also found it interesting in my work on these devices that the classic papers of Guanella[4] and Ruthroff[3] are still the cornerstones of this technology known as Transmission Line Transformers. To be sure, some of us have extended the works of these two by using better measuring equipment, using more complicated configurations, and finding new applications. But from the publications in the amateur radio journals and discussions on the air and at club meetings, most radio amateurs still perceive these devices as conventional transformers. They don't look at these devices as Guanella and Ruthroff did—as chokes and transmission lines. As a result, there has been a lack of good design information in our literature.

This lack of good design information is not only endemic to the amateur radio literature. It also applies to the professional literature as well. Very little progress has been made in this field since Ruthroff's classic 1959 paper. From my vantage point, I see that the transmission line transformer technology has been literally frozen in time! However, there are many new and useful designs possible with this technology. They include higher power levels, applications in the VHF and UHF bands and above, and new baluns and ununs with ratios other than $1:n^2$ where $n = 1, 2, 3$, etc.

I see two reasons for the lack of emergence in this technology. They are:

1. This subject is not adequately covered in any college textbook, and it certainly has not been of interest to academics who rightfully view their role as basic research and not applications. Therefore, there are very few (if any) graduates with any skill in this technology. This is in contrast to the areas of transmission line, waveguide, and antenna theory.

2. The professional societies don't receive enough application papers. Although much of the research and development work performed in industry is highly innovative, important to the advancement of the technology, and certainly publishable in scientific journals, corporations are often reluctant to allow publication for fear of "aiding" their competition. It has been stated[9] that in the last fifteen years, the submission of application papers to the technical journals of the IEEE has taken an inexorable slide. A recent survey by one of the technical societies showed that 85 percent of the submissions now come from universities!

In closing, I would like to say that unless a request is received for a balun design that is of general interest and is feasible, this article could well be the last in my series on practical articles on baluns and ununs in *CQ*. The same can be said about my in-depth series on baluns in *Communications Quarterly*. I want to thank the editors of both journals for giving me the space to express my views and to present my latest designs of these broadband and highly efficient matching devices.

After reading articles in these two series, some might think that I was overly critical and didn't agree with any of the designs presented in the amateur radio literature (which is quite true). But I was also overly critical for another reason. In being so, I was hoping to provoke, in return, critical comment on my work. In this way we can help our amateur friends by advancing the understanding and applications of these very useful transformers. Who knows? We could even help our professional friends.

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**Kits and finished units are available from Amidon Associates, Inc., 2216 East Gladwick Street, Dominguez Hills, CA 90220.*

gave me better results. Clover, Version 6.0, was used in the "Normal" bias mode.

Results

After a few months I got lists and lists of figures, and the temptation was great to do all sorts of fancy statistical tests on the figures. I decided to keep it simple, and the final results are shown in fig. 1, where the rates of transfer in the two different modes are given for every test. The results of some of the tests are not given, and the reason for this is that the board could not be activated in the alternative mode. I gave one simple statistic in fig. 1: The mean value of the transfer rate in every mode for all the tests shown in the figure. I am not sure if this is valid, as the conditions varied from test to test, but is perhaps the simplest way to compare the two modes. The theoretical maximum values for Amtor, Pactor ("Long Path"), and Clover ("Normal" bias) are also shown in fig. 1. Maximum value for Pactor ("Short Path") is 16.0.

Remarks About Some Of The Results In Fig. 1

a) I can't explain the low value for Pactor in test number 8. As I had no valid reasons to disregard the test, I had to include it in the results.

b) A glimpse of the potential of Clover came through in test number 21 when a transfer rate of 34.3 bytes/second was obtained.

c) A comparison amongst tests 10, 11, 12, and 13 are very interesting. Tests 10 and 11 were done on a Saturday about noon, and as you can see Clover was substantially better than Pactor. Tests 12 and 13 were done on the next day, also about noon, and as you can see on this day Pactor was better than Clover. In fact, the Clover rates were lower than the previous day. I can't explain this, but this is part of the fascination of HF propagation.

Conclusions

I must mention I am not biased towards any of the modes, so the following conclusions are just based on the results of the tests. Anyway, the reader can draw their own conclusions from fig. 1.

a) In three of the 24 tests under the described conditions Pactor was better than Clover. In all the other cases Clover was better.

b) In six of the tests Clover was more than a factor 2 better than Pactor. In all other tests in which Clover was better, the advantage of Clover varies between 2% and 98%.

c) In all tests in both modes, except two in the case of Pactor, the transfer rate easily exceeded the maximum rate of Amtor.

Test no.	Clover	Pactor
1	13.1	8.3
2	8.8	8.6
3	8.5	5.9
4	11.9	10.9
5	14.3	11.8
6	10.3	10.7
7	11.2	8.8
8	17	2.5
9	16	11.8
10	25.1	11.5
11	19.5	12.2
12	9.8	11
13	8.3	10.5
14	17.4	8.8
15	15.7	7.4
16	12.9	10.1
17	17.1	10.2
18	11.6	9.1
19	11.1	9.6
20	19.4	8.5
21	34.3	11.2
22	28.7	10.6
23	14.4	10.7
24	15.3	11.5

Table I – Values used in fig. 1.

d) In 13 of the tests Clover equals or exceeds the maximum "Long Path" rate of Pactor. In nine of the tests Clover equals or exceeds the maximum "Short Path" rate of Pactor.

e) The mean values of the transfer rates of all the tests given in fig. 1, e.g. Clover = 15.5 bytes/second and Pactor = 9.7 bytes/second, show that in this experiment and under these variable conditions, Clover was on the average 59.8% better than Pactor.

f) It will be most interesting if these types of tests are repeated in other parts of the world, especially over DX-distances under weak conditions. Perhaps then Packet, Amtor, Pactor, and Clover can all be included.

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