This month W2FMI picks up his discussion of ununs with a description of the 4:1 unun and an overview of the work done by Guanella and Ruthroff.

The 4:1 Unun

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A careful study of the transmission line transformer reveals that the works of two men continue to dominate the field. They are Guanella[1] and Ruthroff.[2] Interestingly enough, they used two different approaches in designing their 1:1 and 4:1 baluns. Although the record doesn't show that Guanella considered an application for the unun (unbalanced-to-unbalanced transformer), his technique of connecting transmission lines in a parallel-series arrangement has extended the high-frequency capability of these devices.[3]

One might argue that recent amateur publications[4-7] on current, choke, and voltage baluns have added significant information to the field. But the literature shows[3,8] that the current or choke baluns are really Guanella's designs and the voltage baluns, Ruthroff's. To make it more confusing, someone (probably a radio amateur) took Ruthroff's three-conductor 1:1 balun design and put the third wire in parallel with the other two (trifilar), resulting in an inferior (so-called) voltage balun. This is the design that mainly has been used for the comparisons with the "new" coaxial cable 1:1 baluns.[4-7] Ruthroff originally proposed that the third wire (which extends the low-frequency response over the two-conductor Guanella 1:1 balun) be wound on a separate part of the toroid.

In looking further into the field, one finds that there are a lot of choices to make regarding the design of these very broadband and efficient transmission line transformers. They include: (1) Ruthroff's or Guanella's designs; (2) wire or coaxial cable transmission lines; (3) coiled or beaded lines; (4) rods or toroids; (5) low-power or high-power designs; (6) HF, VHF, or UHF designs; and (7) the trade-offs in efficiency for low-frequency response or for high VSWR.

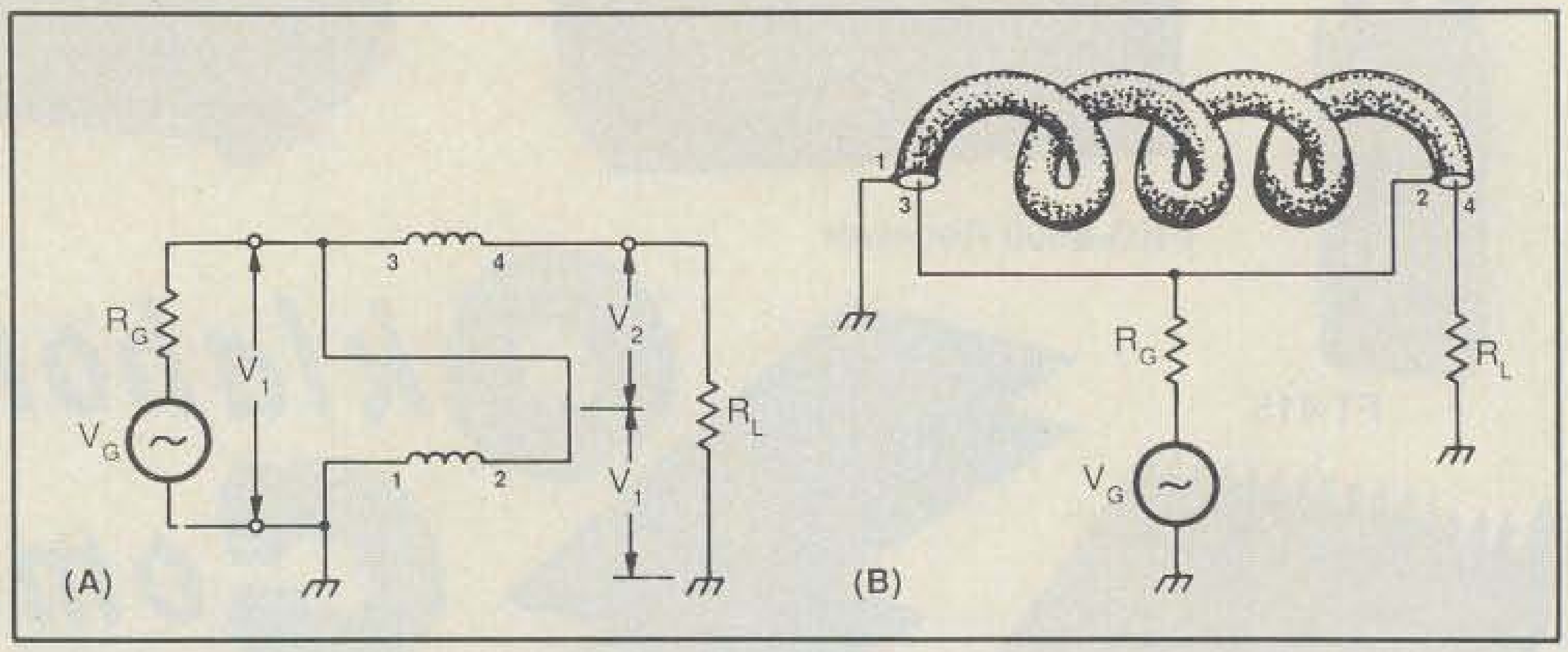

Fig. 1– Ruthroff 4:1 unun ($R_L = 4R_G$): (A) coiled bifilar winding. (B) coiled coaxial cable.

The 4:1 unun, which first appeared in Ruthroff's classic 1959 paper,[2] exemplifies (more than any other transformer) the many choices that can be made in its design. It is also the most prevalent of all the ununs. This article attempts to show the reader many of them.†

The Ruthroff 4:1 Unun

Fig. 1 shows two versions of Ruthroff's approach[2] in obtaining a 4:1 unbalanced-to-unbalanced transformer (unun). As can be seen, one uses a coiled wire transmission line while the other uses a coiled coaxial cable. Depending upon the frequency, beaded transmission lines can also be used.

Ruthroff's design uses a single transmission connected in what I call the "bootstrap" configuration. That is, terminal 2 is connected to terminal 3, lifting the transmission line (at the high-impedance side) by the voltage V_1. If the reactance of the coiled winding or beaded line is much greater than R_G, then only flux-cancelling transmission line currents are allowed to flow. It can also be seen that the output voltage is the sum of a direct voltage V_1 and a delayed voltage V_2 which traversed a single transmission line. This delay in V_2 eventually limits the high-frequency response. For example, if the electrical length of the line is a half-wave, the output is zero. Ruthroff also found that the optimum value of the characteristic impedance of the transmission line (for maximum high-frequency response) is $R_L/2$.

Therefore, the electrical length and characteristic impedance of the transmission line play major roles in Ruthroff's design. Since his work was mainly concerned with small-signal applications, he was able to obtain broad bands of a few tens of kiloHertz to over a thousand megaHertz. This was possible since he used a few turns (5 to 10) of fine wire (No. 37 and 38) on high-permeability toroids as small as 0.08 inches in OD. Thus, the phase-delay with these very short transmission lines was very small. However, in large-signal (power) applications, it is a different matter. For operation in the HF band (including 160 meters), transmission lines vary between one to three feet in length (depending upon impedance level). Consequently, phase-delay can play a major role, as will be seen in the following examples.

50:12.5 ohm ununs. Photo A shows two examples of efficient and broadband 4:1 ununs matching 50 ohms to 12.5 ohms. The rod version (on the left) has 14 bifilar turns of No. 14 H Thermaleze wire on a low-permeability (125) ferrite rod 0.375 inches in diameter and 3.5 inches long. The connections are shown in fig. 1(A). The cable connector is on the low-impedance side.

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

The response is flat from 1.5 MHz to 30 MHz. In a matched condition, it can easily handle the full legal limit of amateur radio power. Since a tightly wound rod unun yields a characteristic impedance very close to 25 ohms (the optimum value), this is quite likely the easiest one to construct that covers the above bandwidth.

The toroidal version (on the right in photo A) has 6 turns of homemade, low-impedance coaxial cable on a 1.5 inch OD ferrite toroid with a permeability of 250. The connections are shown in fig. 1(B). The cable connector is on the low-impedance side. The inner conductor is No. 14 H Thermaleze wire and is covered with Teflon® tubing. The outer braid is from a small coaxial cable (or from ⅛ inch tubular braid). It is also tightly wrapped with Scotch No. 92 tape in order to obtain the desired characteristic impedance. In matching 50 ohms to 12.5 ohms, the response is flat from 1.5 MHz to 50 MHz. Since the current is evenly distributed on the inner conductor, this small unun has an exceptionally high power capability—at least 5 KW of continuous power and 10 KW of peak power (in a matched condition).

Photo A– Two versions of the Ruthroff 4:1 (50:12.5 ohm) unun: coiled wire rod (on the left); coiled coaxial cable toroid (on the right).

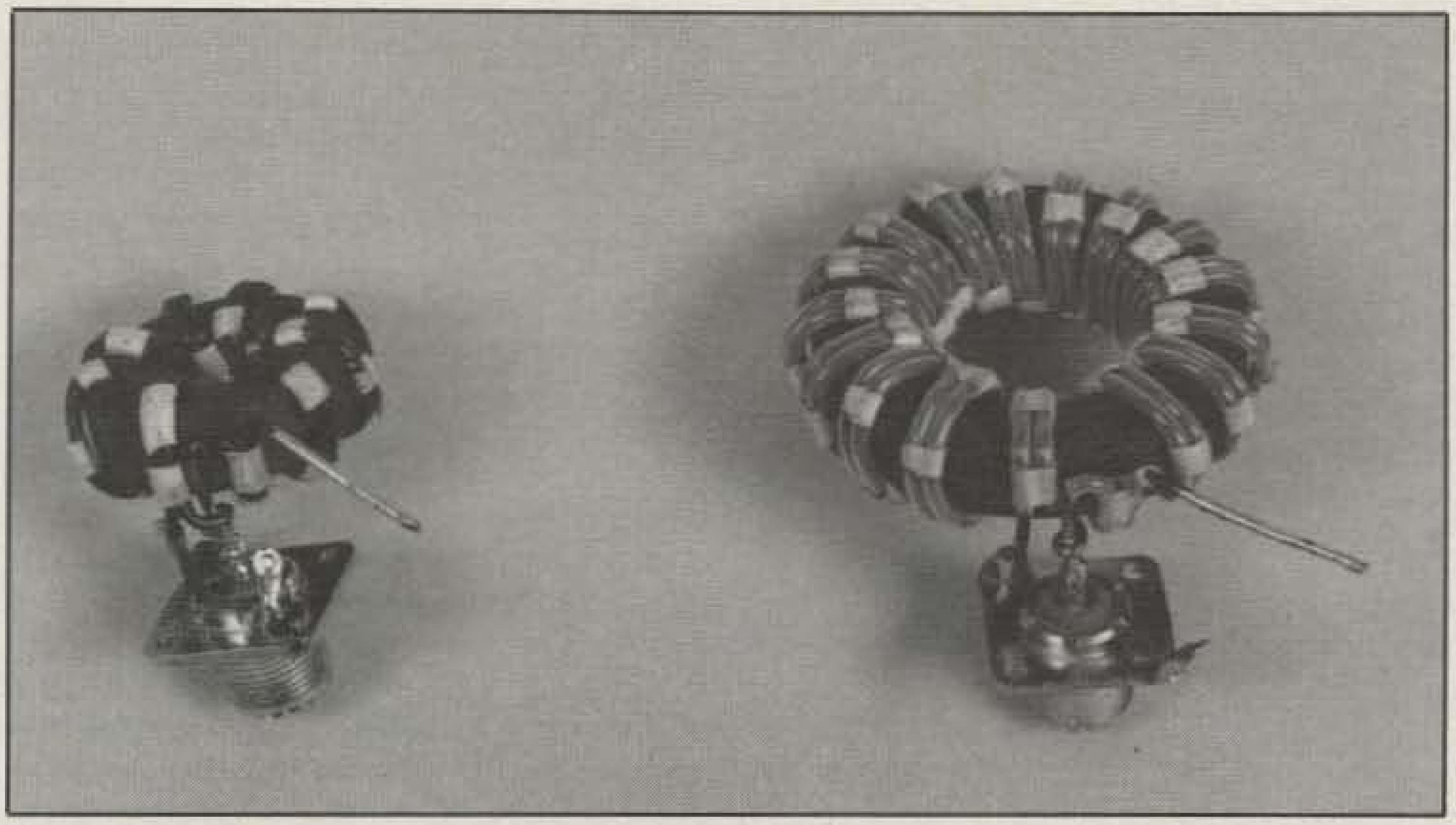

Photo B– Two higher impedance Ruthroff 4:1 ununs: 100:25 ohm (on the left); 200:50 ohm (on the right).

100:25 ohm unun. In some combiner applications, an unun matching 100 ohms to 25 ohms is required. The smaller toroidal version on the left in photo B shows a Ruthroff design that can satisfy many of these requirements. It has 8 bifilar turns of No. 14 H Thermaleze wire on a 1.5 inch OD ferrite toroid with a permeability of 250. One wire is also covered with one layer of Scotch No. 92 tape, giving a characteristic impedance close to the desired value of 50 ohms. In matching 100 ohms to 25 ohms, the response is essentially flat from 1.5 MHz to 30 MHz. This unun can easily handle the full legal limit of amateur radio power.

200:50 ohm unun. This is the area where the Ruthroff approach cannot yield the broadband response of the lower impedance designs shown above. Since more turns are required in order to obtain the necessary choking reactance, and a 100 ohm characteristic impedance which requires more spacing between the wires is used, the cores have to be considerably larger. This results in longer transmission lines. Thus, the high-frequency response is now limited by the greater phase-delay of this high-impedance unun.

The larger transformer on the right in photo B is my optimized version of a Ruthroff 200:50 ohm unun. It has 16 bifilar turns of No. 14 H Thermaleze wire on a low-permeability (250) 2.4 inch OD ferrite toroid. Each wire is covered with Teflon tubing, resulting in a characteristic impedance of 97 ohms. Because of the long transmission line (36 inches), the impedance transformation ratio (in matching 200 ohms to 50 ohms) varies from 4 to 4.44 from 1.5 MHz to 30 MHz. A conservative power rating (under a matched condition) is 2 KW of continuous power and 4 KW of peak power. Since this higher impedance unun has a larger voltage drop along the length of its windings, its loss (a dielectric-type[3]) is a little greater than the lower impedance ununs described before. In a matched condition, it is about 97 percent, while the others are 98 to 99 percent.

The Guanella 4:1 Unun

Even though Guanella's investigation[1] was directed toward developing a broadband balun to match the balanced output of a 100 watt push-pull, vacuum-tube amplifier to the unbalanced load of a coaxial cable, his technique of connecting transmission lines in a parallel-series arrangement has only recently been recognized as the design for the widest possible bandwidth in an unbalanced-to-unbalanced application.[3] Some have labelled his approach the "equal-delay network."[9] The major difference in Guanella's approach (from Ruthroff's) is that by summing the equal-delay voltages of coiled (or beaded) transmission lines, he minimizes the dependence of the high-frequency response on the lengths of the transmission lines. As was mentioned before, Ruthroff's method of summing a direct voltage with a delayed voltage which traversed a single transmission line has a limited application, especially with high-power, high-impedance ununs (like 200:50 and 300:75 ohms).

Furthermore, Guanella's approach is also important in designing high- and low-impedance baluns and ununs with impedance transformation ratios other than 4:1. Connecting three transmission lines in parallel-series results in a 9:1 ratio, four in a 16:1. Also by connecting a fractional-ratio unun in series with his baluns, or by using various combinations of parallel-series transmission lines,[9,10] ununs and baluns

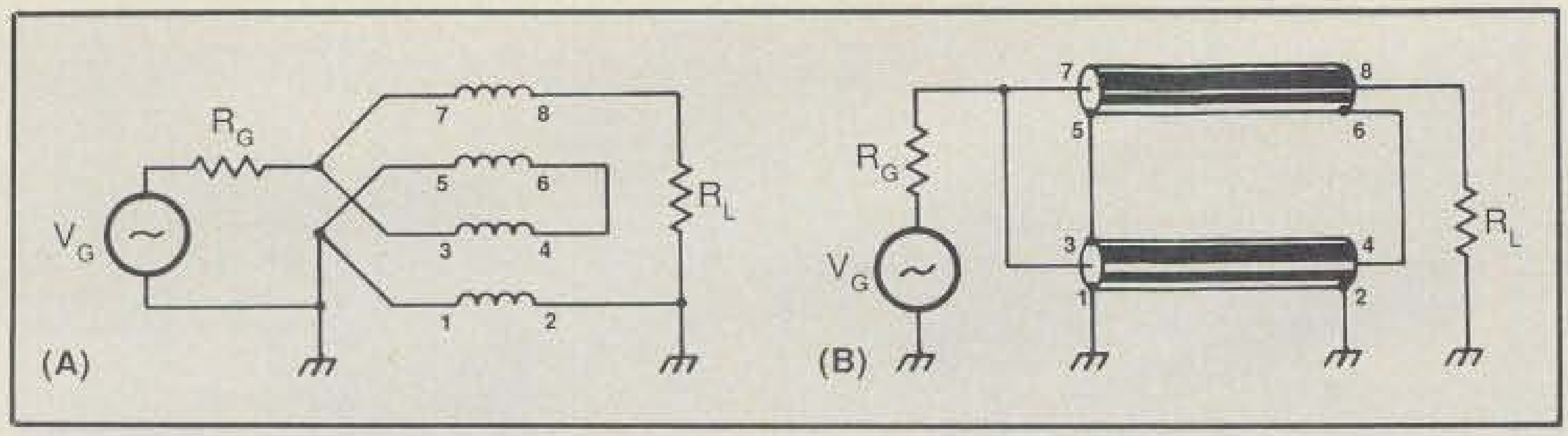

Fig. 2– The Guanella 4:1 unun ($R_L = 4R_G$): (A) coiled bifilar windings; (B) coiled or beaded coaxial cables.

are now available with a continuum of ratios from 1.36:1 to 16:1. Moreover, these ratios now make it possible to match 50 ohm cable to impedances as low as 3.125 ohms and as high as 800 ohms. A major factor in the success of these designs rests in the understanding of the low-frequency models of these various transformers.[3] This section treats the 4:1 unun using Guanella's approach. As in the Ruthroff case, the optimum value of the characteristic impedances of the transmission lines for a Guanella 4:1 transformer is also $R_L/2$.

50:12.5 ohm unun. Fig. 2 shows the schematic diagrams of the coiled-wire and coaxial cable (coiled or beaded) versions of 4:1 ununs using Guanella's technique of connecting transmission lines in parallel-series arrangements. As can be seen in fig. 2, the lower transmission lines are grounded at both ends and therefore have no potential drop along their lengths. Thus, the coiling or beading has no effect. The core only acts as a mechanical support and the beads can be removed. In essence, the bottom transmission plays the important role of a delay line. Also, the low-frequency response of this form of an unun is solely determined by the reactance of the top coiled or beaded transmission line.[3]

The top unun in photo C shows a rod version of Guanella's 4:1 unun. There are 13.5 bifilar turns of No. 14 H Thermaleze wire on low-permeabilty (125) ferrite rods 0.375 inches in diameter and 3.5 inches long. For ease of connection, one winding is clockwise and the other is counter-clockwise. The cable connector is on the high-impedance side. In matching 50 ohms to 12.5 ohms, the response is flat from 1.5 MHz to over 50 MHz! This unun is capable, in a matched condition, of handling the full legal limit of amateur radio power. Furthermore, with the 50 ohm generator on the right, in fig. 2(A), and a 12.5 ohm floating load on the left (perhaps a Yagi beam), this transformer makes an excellent step-down balun.

The bottom transformer in photo C shows a beaded-coax version of a 50:12.5 ohm step-down unun designed for 2 meter operation. It has 3.5 inches of beaded coax on the top transmission line (fig. 2(B)and no beads on the bottom transmission line (actually, the bottom rod in fig. 2(A) can also be removed with no change in performance). The beads are low-permeabilty (125) ferrite. The inner conductor of the coaxial cable is No. 12 H Thermaleze wire with about 3.5 layers of Scotch No. 92 tape (two 0.5 inch tapes wound edge-wise like a window shade), giving a characteristic impedance close to the optimum value. The outer braid is from a small coaxial cable (or from ⅛ inch tubular braid). This homemade coax is further wrapped tightly with Scotch No. 92 tape in order to preserve its low characteristic impedance. The cable connector is on the low-impedance side. The response of this unun is essentially flat from 10 MHz to 100 MHz (the limit of my bridge). It can also (easily) handle the full legal limit of amateur radio power.

100:25 ohm unun. The unun on the left in photo D is a Guanella version matching 100 ohms to 25 ohms. There are 8 bifilar turns of No. 14 H Thermaleze wire on each 1.5 inch OD low-permeability (250) toroid. One toroid is wound clockwise and the other counter-clockwise. One of the wires (on each toroid) is covered with one layer of Scotch No. 92 tape. The cable connector is on the low-impedance side. The response is flat from 1.5 MHz to well over 30 MHz. This unun can also handle the full legal limit of amateur radio power.

It might be interesting to point out that as a balun (the ground removed from terminal 2), and with a 1.78:1 unun[11] in series (on the left side) with it, this compound arrangement makes an excellent balun for matching 50 ohm coaxial cable directly to quad antennas of 100 to 110 ohm impedances.

200:50 ohm unun. The transformer on the right in photo B is an excellent unun (or balun with terminal 2 removed from ground) in matching 50 ohms to 200 ohms. It has 14 bifilar turns of No. 14 H Thermaleze wire on each low-permeability (250) toroid with a 2.4 inch OD. Each wire is covered with Teflon tubing, giving a characteristic impedance of 98 ohms (which is quite good, since the optimum value is 100). Again, for ease of connection, one winding is clockwise and the other counter-clockwise. When operating as an unun or a balun, when matching 50 ohms to 200 ohms, the response is essentially flat from 1.5 MHz to 30 MHz. A conservative power rating (in a matched condition) is 5 KW of continuous power and 10 KW of peak power. This transformer has been reported to handle peak pulses of 10,000 volts!

Summary

- For ununs with impedance levels of 100:25 ohms and lower, the Ruthroff approach is recommended because of its simplicity.
- For high-impedance levels (such as 200:50 and 300:75 ohms), the Guanella approach is recommended.
- For low-impedance operation in the VHF band, the beaded-coax Guanella approach is recommended.

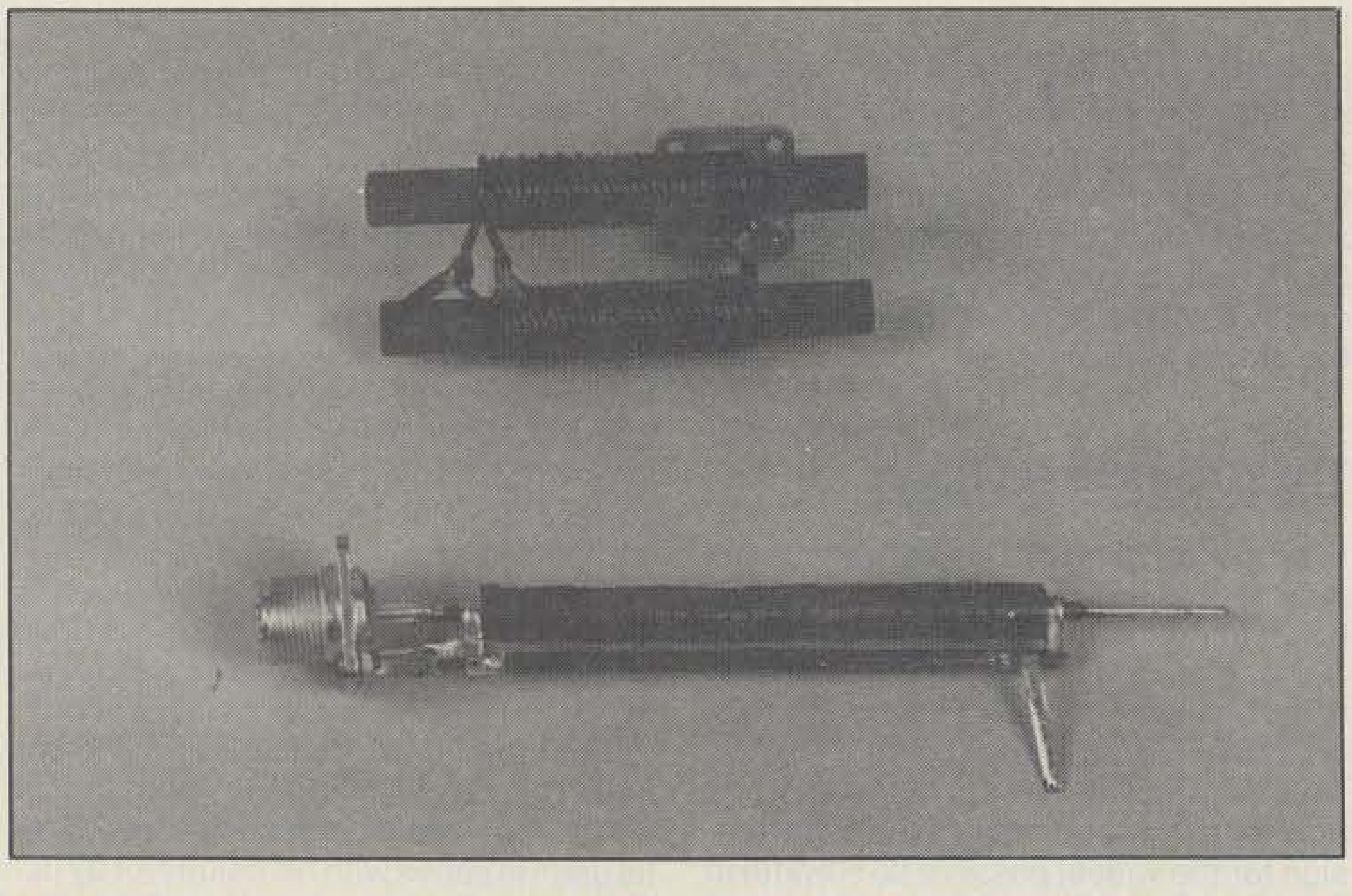

Photo C– Two Guanella 4:1 (50:12.5 ohm) ununs: rod version (on the top), 1.5 MHz to 50 MHz; beaded version (on the bottom), 10 MHz to over 100 MHz.

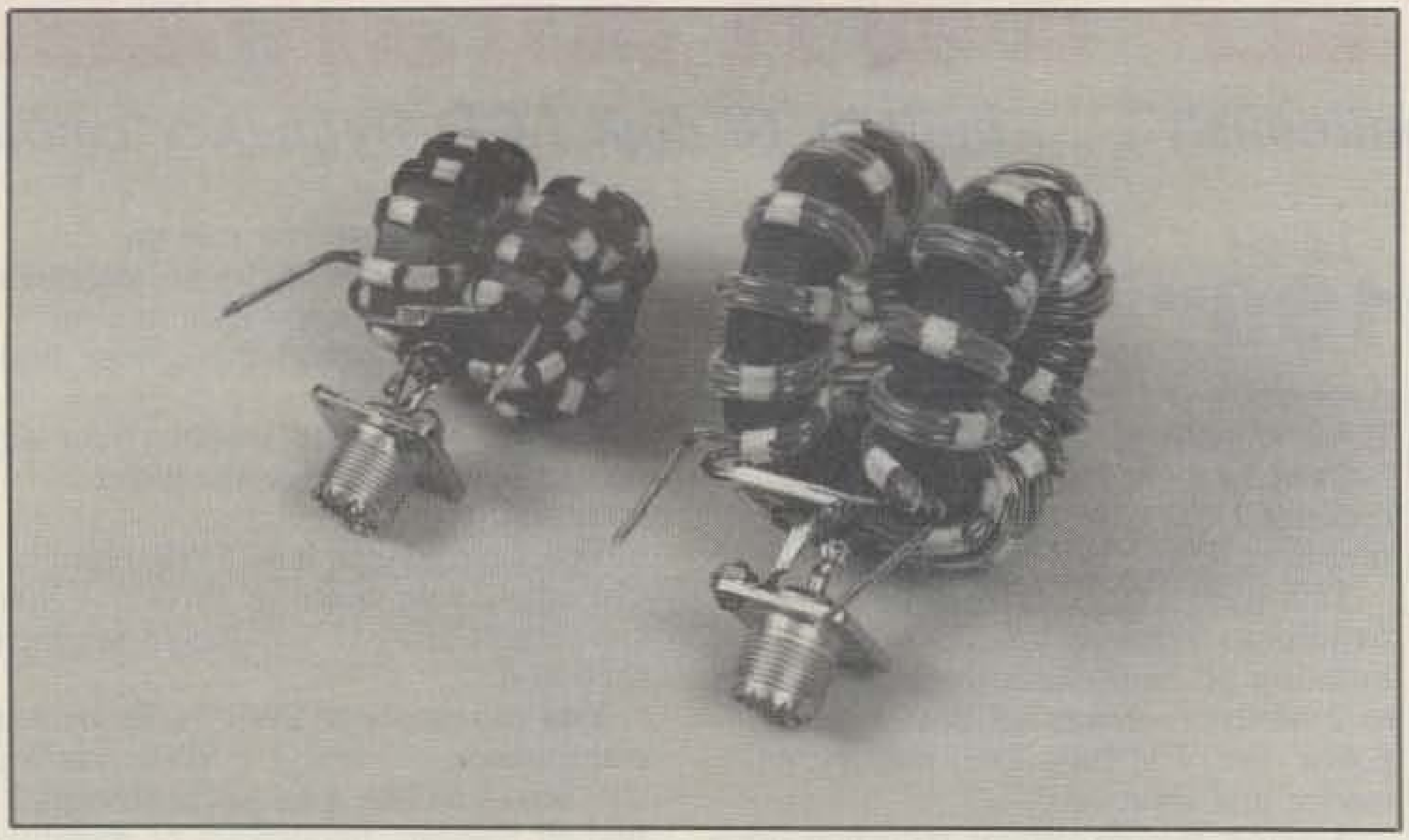

Photo D– Two higher impedance Guanella 4:1 ununs: 100:25 ohm (on the left); 200:50 ohm (on the right).

- For high-impedance operation in the VHF band, the coiled-wire Guanella approach appears to be the best choice and should be investigated. Obviously, the number of turns should be reduced from the examples shown in this article since the reactance of the winding is proportional to the frequency.

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