Chapter 6

The 4:1 Unun

Sec 6.1 Introduction

From an analysis standpoint, the 4:1 unun can be said to have received the most attention in the literature. It began with Ruthroff's introduction and complete analysis of this device in his classic paper published in 1959.[9] Ruthroff's paper then became the industry standard for this class of devices known as *transmission line transformers*. These are devices that transmit the energy from the input to the output by an efficient transmission line mode, and not by flux linkages (as in conventional transformers).

However fifteen years earlier, Guanella had introduced, in his classic 1944 paper,[3] the first broadband baluns by combining coiled transmission lines in a series-parallel arrangement, yielding ratios of $1:n^2$ where n = 1, 2, 3, and so on. Recently, it was shown that Guanella's technique also lends itself to ununs as well.[2] In fact in this chapter, you will see that his technique of summing voltages of equal delays promises to yield high-power designs capable of operating on the VHF and UHF bands.

The 4:1 unun also exemplifies (more than any other transformer) the many choices that can be made in its design. These 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. The 4:1 unun is the most prevalent of all the ununs. It finds extensive use in solid-state circuits and in many antenna applications involving the matching of ground-fed antennas—where impedances of 12 to 13 ohms must be matched to 50-ohm coaxial cable. This chapter provides information on many 4:1 unun designs.

Sec 6.2 The Ruthroff 4:1 Unun

Figure 6-1 illustrates two versions of Ruthroff's approach to 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 may also be used.

Ruthroff's design uses a single transmission line connected in, what I call, the "bootstrap" configuration. That is, terminal 2 is connected to terminal 3,

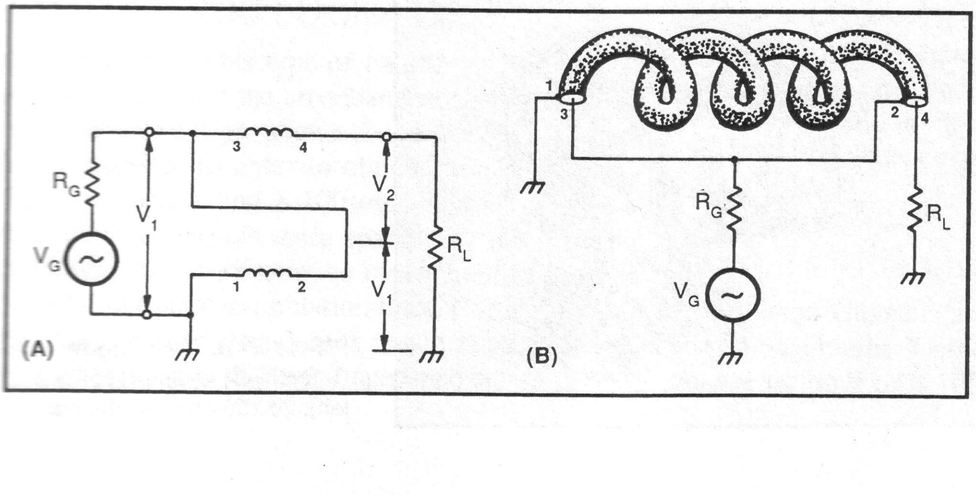

Figure 6-1. The Ruthroff 4:1 unun (R_L=4R_G): (A) coiled bifilar winding; (B) coiled coaxial cable.

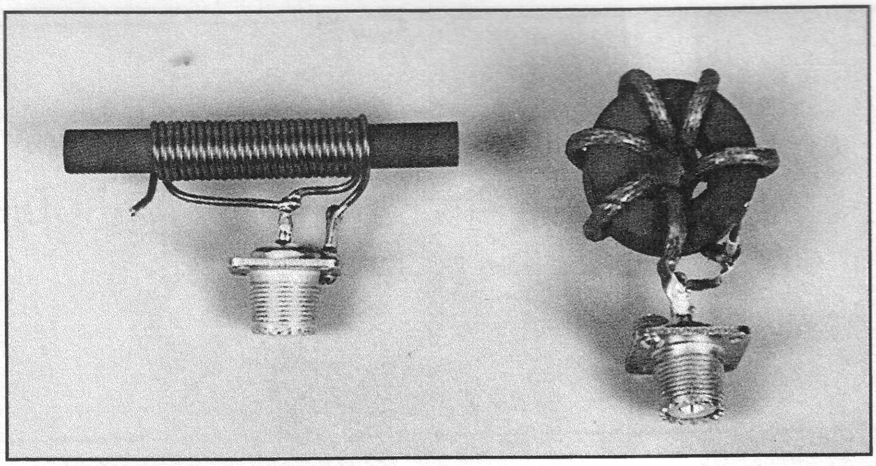

Photo 6-A. Two versions of the Ruthroff 4:1 (50:12.5 ohm) unun: coiled wire rod (on the left); coiled coaxial cable toroid (on the right).

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-canceling transmission line currents are allowed to flow. It is also apparent that the output voltage is the sum of a direct voltage, V_1, and a delayed voltage, V_2, which traverses 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. Because his work was mainly concerned with small-signal applications, Ruthroff was able to obtain broad bands of a few tens of kilohertz to over a thousand megahertz. This was possible because he used a few turns (5 to 10) of fine wire (Nos. 37 and 38) on high-permeability toroids as small as 0.08 inches in OD. As a result, the phase-delay with these very short transmission lines was very small. However, large-signal (power) applications present an entirely different picture. 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.

Sec 6.2.1 50:12.5-ohm Ununs

Photo 6-A shows two examples of efficient, broadband 4:1 ununs matching 50 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 **Figure 6-1A**. The cable connector is on the low-impedance side. The response is flat from 1.5 to 30 MHz. In a matched condition, this unun can easily handle the full legal limit of amateur radio power. Because 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 6-A**) has

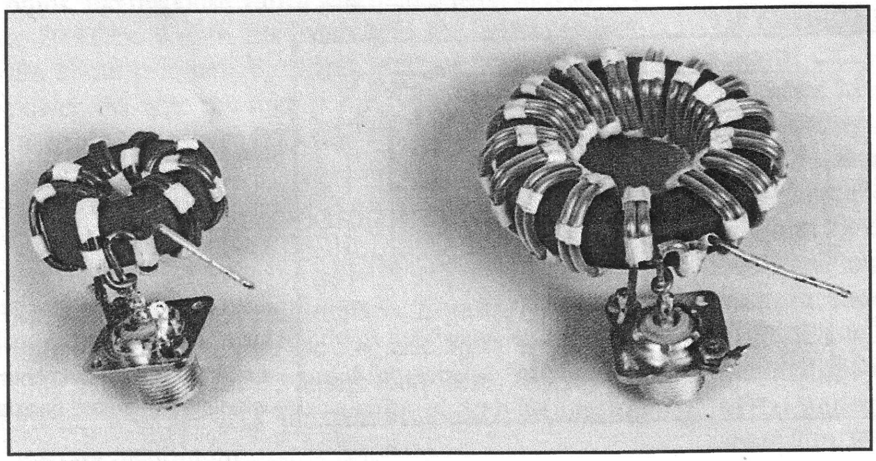

Photo 6-B. Two higher-impedance Ruthroff 4:1 ununs: 100:25 ohm (on the left); 200:50 ohm (on the right).

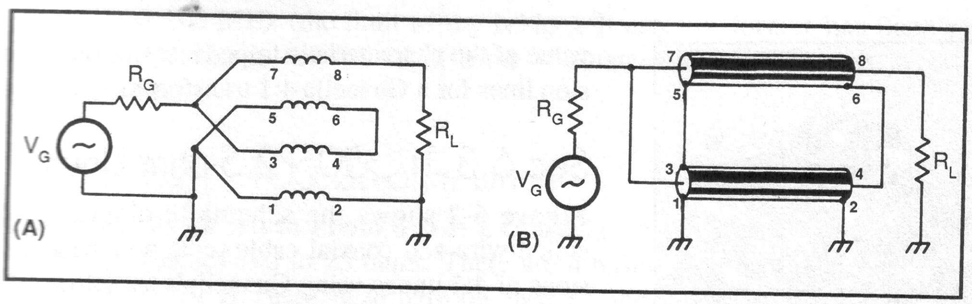

Figure 6-2. The Guanella 4:1 unun (R_L=4R_G): (A) coiled bifilar windings; (B) coiled or beaded coaxial cables.

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 **Figure 6-1B**. 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 1/8-inch tubular braid) tightly wrapped with Scotch No. 92 tape in order to obtain the desired characteristic impedance. In matching 50 to 12.5 ohms, the response is flat from 1.5 to 50 MHz. Because 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).

Sec 6.2.2 100:25-ohm Unun

In some combiner applications, an unun matching 100 to 25 ohms is required. The smaller toroidal version, pictured on the left in **Photo 6-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 a single layer of Scotch No. 92 tape, providing a characteristic impedance close to the desired value of 50 ohms. In matching 100 to 25 ohms, the response is essentially flat from 1.5 to 30 MHz. This unun can easily handle the full legal limit of amateur radio power.

Sec 6.2.3 200:50-ohm Unun

When dealing with this type of balun, the Ruthroff approach cannot yield the broadband response of the lower-impedance designs shown above. Because more turns are required in order to obtain the necessary choking reactance, and a 100-ohm characteristic impedance that requires more spacing between the wires is used, the cores must be considerably larger. This results in longer transmission lines. Consequently, the high-frequency response is now limited by the greater phase delay of this high-impedance unun.

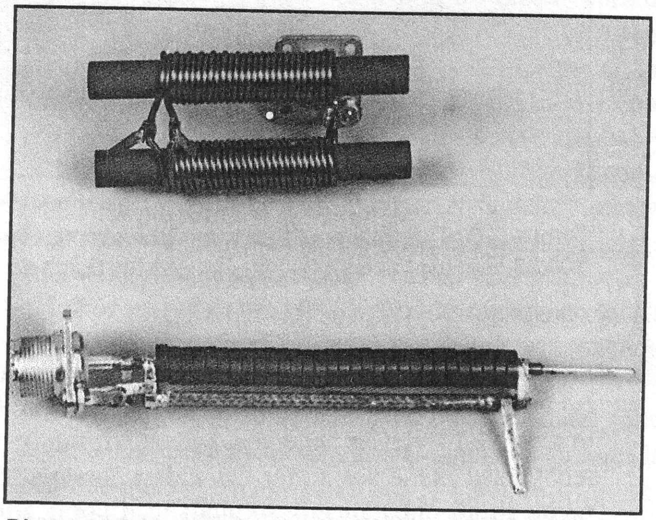

Photo 6-C. Two Guanella 4:1 (50:12.5 ohm) ununs: rod version (on the top), 1.5 to 50 MHz; beaded version (on the bottom), 10 MHz to over 100 MHz.

The larger transformer, shown on the right in **Photo 6-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 to 30 MHz. A conservative power rating (under a matched condition) is 2 kW of continuous power and 4 kW of peak power. Because this higher-impedance unun has a larger voltage drop along the length of its windings, its loss (a dielectric-type[2]) is a little greater than the lower-impedance ununs described earlier. In a matched condition, the efficiency is about 97 percent, while the others experience efficiencies of 98 to 99 percent.

Sec 6.3 The Guanella 4:1 Unun

Even though Guanella's investigation[3] was directed toward developing a broadband balun to match the balanced output of a 100-watt, push-pull, vacuum-

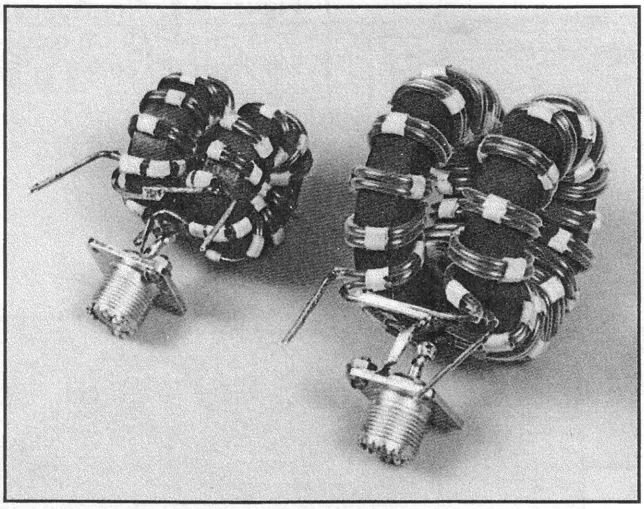

Photo 6-D. Two higher-impedance Guanella 4:1 ununs: 100:25 ohm (on the left); 200:50 ohm (on the right).

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.[2] Some have labeled his approach the "equal-delay network".[26] 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 that 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,[26,27] ununs and baluns 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.[2] This section looks at 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 $R_L/2$.

Sec 6.3.1 50:12.5-ohm Ununs

Figure 6-2 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 **Figure 6-2**, 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 line plays the important role of a delay line. In addition, the low-frequency response of this form of unun is solely determined by the reactance of the top coiled or beaded transmission line.

The top unun in **Photo 6-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-permeability (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 counterclockwise. The cable connector is on the high-impedance side. In matching 50 to 12.5 ohms, the response is flat from 1.5 to over 50 MHz! This unun, in a matched condition, is capable of handling the full legal limit of amateur radio power. Furthermore, with the 50-ohm generator on the right (in **Figure 6-2A**) and a 12.5-ohm balanced load on the left (perhaps a Yagi beam), this transformer makes an excellent step-down balun.

The bottom transformer in **Photo 6-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 (**Figure 6-2B**) and no beads on the bottom transmission line. (Actually, the bottom rod in **Figure 6-2A** can also be removed with no change in performance.) The beads are low-permeability (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 edgewise like a window shade), providing a characteristic impedance close to the optimum value. The outer braid is from a small coaxial cable (or from 1/8-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 to 100 MHz (the limit of my bridge). It can also (easily) handle the full legal limit of amateur radio power.

Sec 6.3.2 100:25-ohm Unun

The unun on the left in **Photo 6-D** is a Guanella version that matches 100 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 is wound counterclockwise. 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 is interesting to note that when used as a balun (the ground removed from terminal 2), and placed in series (on the left side) with a 1.78:1 unun (see **Chapter 7**), this compound arrangement provides an excellent balun for matching 50-ohm coaxial cable directly to quad antennas having impedances of 100 to 110 ohms.

Sec 6.3.3 200:50-ohm Unun

The transformer on the right in **Photo 6-D** is an excellent unun (or balun with terminal 2 removed from ground) for matching 50 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, providing a characteristic impedance of 98 ohms (which is quite good because the optimum value is 100). Again, for ease of connection, one winding is clockwise and the other is counterclockwise. When operating as an unun or a balun and matching 50 to 200 ohms, the response is essentially flat from 1.5 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

Since its introduction by Ruthroff in 1959,[9] the 4:1 unun has been the most popular transmission line transformer matching unbalanced impedances to unbalanced impedances. As I mentioned at the beginning of this chapter, there are many choices to consider when designing these broadband and efficient transformers. One of the most important choices involves whether to use the Ruthroff or Guanella approach. In fact, the Guanella design should probably be designated a *balun/unun*. Recently, it has become the design of choice in the higher frequency bands. From the designs presented in this chapter, I offer the following recommendations:

1. For ununs in the HF band with impedance levels of 100:25 ohms and lower, the Ruthroff approach is recommended because of its simplicity.
2. For high impedance levels in the HF band (like 200:50 and 300:75 ohms), the Guanella approach is recommended.
3. For low-impedance operation on the VHF band, the beaded-coax Guanella approach is recommended.
4. For high-impedance operation on the VHF band, the coiled-wire Guanella approach appears to be the preferred choice, and should be investigated first. Obviously, the number of turns should be reduced from the examples shown in this chapter because the reactance of the winding is proportional to the frequency.
5. For high-power use on the HF band, the Ruthroff unun with low-impedance coaxial cable on a toroid (on the right on **Photo 6-A**) is recommended. It is easy to construct and can very likely handle more than 5 kW of continuous power.
6. Also, at high-impedance levels, one might consider using lower permeability ferrites for higher efficiencies. Look at permeabilities of 125 and 40.