Design and Realization of Broadband Transmission Line Matching Transformers

by Jerry Sevick

Background

The broadband transmission line matching network first appeared after World War II. Since its inception, this class of matching devices has been referred to as transmission line transformers, broadband transformers, and equal-delay networks. Some subsets of this class are known as baluns, ununs, hybrids, and combiners.

Although these devices have been widely used in solid-state circuitry or in matching transmission lines to antennas, there has been little information available that deals with the aspect of design and application of practical hardware. As is well-known, many companies are reluctant to publish their design and development work for fear of “giving away” their hard-earned technology to competitors. As a result, this class of devices is far from reaching its application potential.

This EPT briefly describes three specific areas of interest concerning broadband transmission line matching networks:

1) Education
2) Specifications
3) New designs

This EPT also presents several designs with impedance transformations of 2:1 and 2.25:1 ratios. These devices only represent a small fraction of the designs possible with this class of matching transformer. Furthermore, some design information may be introduced here for the first time.

Introduction

The first presentation on broadband matching transformers using transmission lines was given by Guanella in 1944 [B1]. He coiled transmission lines forming a choke such that only transmission line currents were allowed to flow, no matter where a ground was connected to the load. A single coiled transmission line resulted in a 1:1 balun. Prior to this, 1:1 RF baluns were achieved by the use of quarter and half-wave transmission lines, and, as a result, had narrow bandwidths. Guanella then demonstrated broadband baluns with impedance transformation ratios of $1{:}n^2$, where n is the number of transmission lines connected in a parallel-series arrangement.

The second, and other significant paper addressing the use of transmission lines, was written by Ruthroff in 1959 [B2]. He introduced 4:1 broadband baluns and ununs (unbalanced-to-unbalanced transformers) using a single transmission line connected as a *phase-inverter*, or as a *boot-strap*. His broadband 4:1 unun has especially found widespread use in small-signal and large-signal power applications.

Many investigators followed the approaches of Guanella and Ruthroff, which were different. They not only confirmed the techniques of Guanella and Ruthroff for obtaining broadband baluns and ununs, but extended the performances of their transformers by using transmission lines with step-function and exponential changes in their characteristic impedances [B3, B4]. But many important areas remain unresolved in this special class of very broadband and efficient matching networks.

TRANSFORMERS

An Education in Broadband Matching Transformers

In practice, many designers and users of broadband impedance matching networks still perceive these devices as conventional transformers. Therefore, terms like *core size, saturation, leakage inductance*, and *less than optimum coupling* are important considerations for them. This highly suggests that they either have not been exposed to, or have not accepted, the models of Guanella and Ruthroff, which treat these devices as a configuration of chokes and transmission lines.

A contributing factor to this misconception is due, in large measure, to the titles used by the investigators who have published in this field. Invariably, the word *transformer* is included in their titles. The most popular of which are *broadband transformers* and *transmission line transformers*. Since engineering handbooks and textbooks typically have not included this special class of matching devices, there are very few trained designers available to exploit their advantages over conventional transformers. In an attempt to fulfill the need in this area, a book containing the theory and practice of these new devices has been recently published [B5].

Specifications on Matching Transformer Devices

Probably the most difficult (and controversial) specification to establish for these devices is the power rating. The loss mechanism is completely different from that of the conventional transformer, which is current-dependent (hysteresis, wire, and eddy-current losses). With these broadband devices, which mainly use ferrite cores or beads, the losses are voltage-dependent (a dielectric-type loss). Therefore, higher-impedance devices or devices subjected to mismatched loads of higher-impedances, have larger voltage gradients along their transmission lines, and hence, more loss.

Furthermore, this dielectric loss, which does not damage the ferrite, is related to the permeability. Only low-permeability ferrite (less than 300) has been found to offer the extremely high efficiencies (98%-99%) of which these devices are capable [B5]. Therefore, there are trade-offs with these devices in efficiency for low-frequency response and for high voltage-standing wave ratio (VSWR).

There is virtually no information from handbooks or manufacturers on the use and specification of ferrites in these broadband devices. <u>All</u> of the available information is only applicable for its use in conventional transformers and inductors or microwave devices.

New Design Concepts

There still remain two areas where the understanding and design of broadband ununs and baluns could prove to be very valuable. This is particularly true for designs that could handle appreciable power. The areas are the following:

- Designs for the UHF band and above
- Designs with impedance transformation ratios other than $1{:}n^2$ where n is 1, 2, 3,..etc. These are called fractional-ratio designs.

The approach by Guanella of essentially summing in-phase voltages on the high-impedance side of the networks offers the best opportunity in both areas. With transmission lines threaded through ferrite beads or immersed in a ferrite medium, the high-frequency response is very likely limited by the parasitics of the interconnections. With techniques exploiting good microwave design, successful operation of these devices should at least be obtained in the UHF band. With thin-film technology, the high-frequency limit could very well be extended further.

As in practically all of the conventional broadband transmission line network designs, the two different approaches by Guanella and Ruthroff still form the basis for the new designs with fractional ratios.

In the Guanella case, instead of only summing in-phase voltages (at the high-impedance side) of single transmission lines connected in a parallel-series arrangement, his technique is carried a step further. Combinations of matching networks with impedance ratios of $1{:}n^2$ are now connected in parallel-series. These designs usually involve connecting the high-impedance side of one network in parallel with the low-impedance side of the other [B6, B7].

In the Ruthroff case, his technique of lifting a single transmission line (at the high-impedance side) by a direct voltage from the low-impedance side (called a "boot-strap") to form a 4:1 unun is also carried a step further. By using higher-order windings (trifilar, quadrifilar, etc.) and with appropriate taps on the windings, broadband ununs with ratios very close to 1.33:1, 1.5:1, 2:1, and 3:1 become readily available. By connecting these ununs in series with various Guanella baluns with ratios of $1{:}n^2$, a continuum of ratios from 1.33:1 to 16:1 are now possible with ununs and baluns.

Techniques and Approaches

Many important applications can be found for efficient and broadband matching networks with impedance transformation ratios other than $1{:}n^2$ where n is 1, 2, 3, etc. These are called fractional ratios.

In the field of antennas, baluns are needed to match 50-ohm coaxial cable to the following:

1) 100-120 ohm Quads
2) 300 ohm folded-dipoles
3) 600 ohm rhombics and Vs
4) 8-35 ohm Yagis.

The need is even greater for ununs (unbalanced-to-unbalanced transformers) with fractional-ratios. Again, for antennas, the need exists for matching 50-ohm cable to the following:

1) Ground-fed antennas like verticals, slopers, inverted Ls
2) 75-ohm cable
3) A junction of two 50-ohm cables

Most important of all, the solid-state circuit designer could use much more freedom-of-design since only 4:1 ratios were previously available.

Although this EPT only presents 2:1 and 2.25:1 designs, the principles shown can be readily extended to a host of designs with other fractional ratios [B5]. As will be described, fractional ratio designs are really extensions of Ruthroff's "bootstrap" approach [B2] or that of Guanella's parallel-series approach [B1]. Appropriate comments regarding their comparisons are also given.

The "Bootstrap" Approach

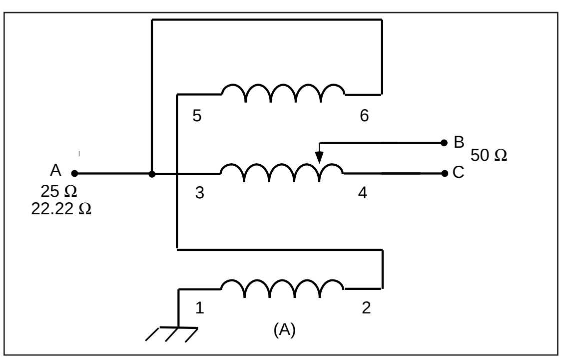


Figure 1A*—Schematic diagram of an unun matching 50-ohm cable to an unbalanced load of 25 ohms or 22.2 ohms*

Figure 1(A) shows the schematic diagram of an unun designed to match 50-ohm cable to an unbalanced load of 25 ohms (2:1 ratio with connections A-B) or 22.22 ohms (2.25:1 ratio with connections A-C). A design is shown in Figure 2. It has 6 trifilar turns of No.14 H Thermaleze wire on a 1.5-inch OD ferrite core with a permeability of 250. The tap (connection B) is at one turn from terminal 4. The positioning of the wires is such that the design is optimized to match 50 ohms to 25 or 22.22 ohms. With either ratio, the response is essentially flat from 1 mHz to 60 mHz. A conservative power rating is 1 kW of continuous power and 2 kW of peak power.

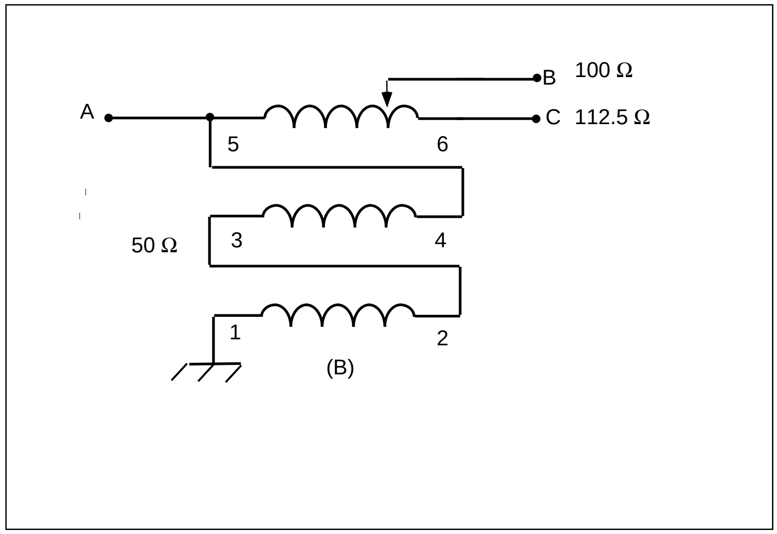
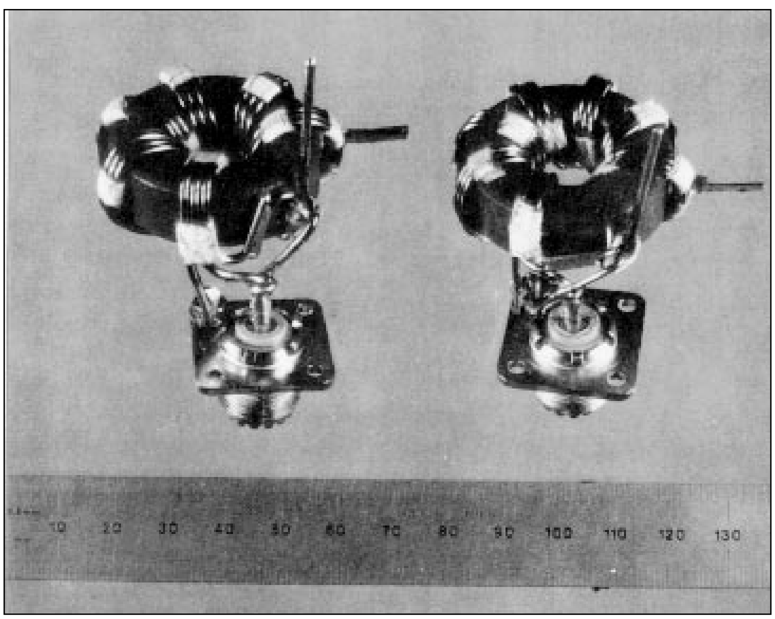


Figure 1B—*Schematic diagram for an unun matching 50-ohm cable to an unbalanced load of 100 ohms (A-B) or 112.5 ohms (A-C)*

Figure 1 shows the schematic diagram of an unun designed to match 50-ohm cable to an unbalanced load of 100 ohms (2:1 ratio with connections A-B) or 112.5 ohm (2.25:1 ratio with connections A-C). A design is shown on the right in Figure 2. It has 7 trifilar turns on a 1.5-inch OD core with a permeability of 250. Winding 5-6 is No.14 H Thermaleze®wire and the other two are No.16 H Thermaleze®wire. The tap (connection B) is at one turn from terminal 6. The performance of this unun is essentially the same as the lower-impedance one shown on the left in Figure 2.



Left: a design for matching 50 ohms to 25 ohms or 22.22 ohms; Right: a design for matching 50 ohms to 100 or 112.5 ohms. The connectors are on the low-impedance sides.

Figure 2—*Bottom views of two ununs using the schematic diagrams of Figure 1*

Another unun that should find use in matching 50 ohms to lower or higher impedances with a transformation ratio less than 4:1 is the quadrifilar design [B5, B8]. Without tapping, its natural ratio is 1.78:1. Since this design now sums three delayed voltages with one direct voltage (at the high-impedance side), its high-frequency response exceeds that of the trifilar design (which exceeded that of the Ruthroff bifilar design).

Furthermore, since the four turns are now mutually-aiding in forming the choking reactance at the low-frequency end, the transmission lines are shorter, which also contributes to its higher frequency performance. This unun, in series with a Guanella 4:1 or 1:1 balun, can provide an efficient and broadband match of 50-ohm cable to Quad antennas of 100-120 ohms or to Yagi beam antennas of 25-30 ohms.

Figure 3 shows a schematic diagram of a 2.25:1 balun designed to match 50-ohm cable to a balanced load of 112.5 ohms. Figure 4 is a design mounted in a 2.25” H x 2” W x 4” L minibox. The 1.78:1 unun on the left (in Figure 3) has 5 quadrifilar turns on a 1.5-inch OD core with a permeability of 250. Winding 5-6 is No.14 H Thermaleze®[1] wire and the other three are No.16 H Thermaleze® wire.

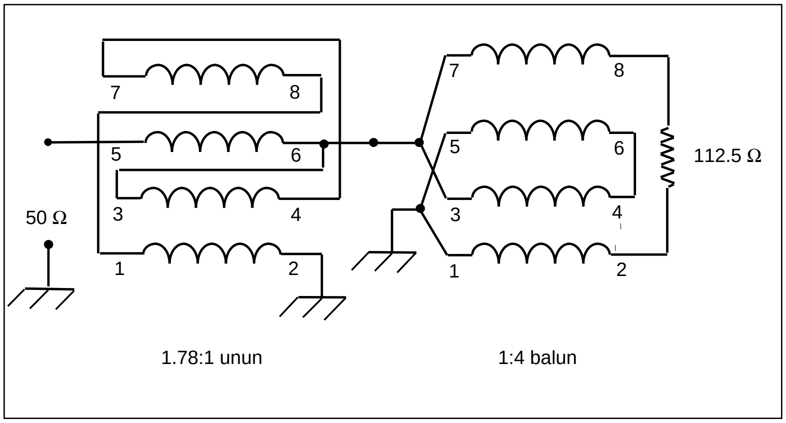


Figure 3*—Schematic diagram of a 2.25:1 balun designed to match 50-ohm cable to a balanced load of 112.5 ohms*

The 4:1 Guanella balun on the right (in Figure 3) has 8 bifilar turns of No.14 H Thermaleze® wire on each core (with a permeability of 250). On one core, one of the wires is covered with two layers of Scotch®[2] No.92 polyimide tape resulting in a characteristic impedance of about 60 ohms. The windings on the other core (without the Scotch® No. 92 tape) have a characteristic impedance of about 45 ohms. Since the two transmission lines have characteristic impedances a little above and below the optimum value of 55 ohms, a compensating effect takes place resulting in an improvement in the high-frequency response [B3, B4].

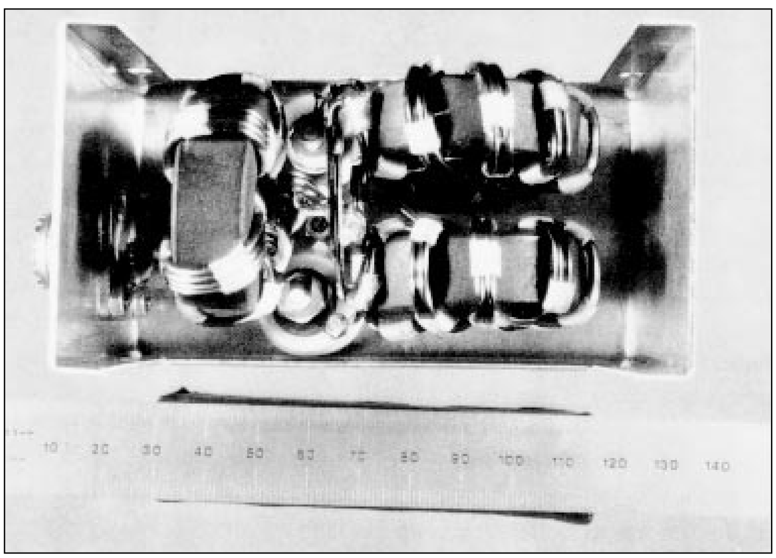


Figure 4*—A balun, using the schematic diagram of Figure 3, mounted in a 2.25" H x 2"W x 4"L minibox. (The top toroid is the quadrifilar 1.78:1 unun. The bottom two toroids are the Guanella 1:4 balun.)*

When matching 50 ohms to a balanced load of 112.5 ohms, this compound balun has a flat response from 1 mHz to at least 50 mHz. It is conservatively rated at 1 kW of continuous power and 2 kW of peak power.

By using a 2.25:1 or 2:1 step-down unun (Figure A) in series with a 22.22 of 25-ohm 1:1 Guanella balun, excellent baluns are now available to match 50-ohm cable to Yagi beam antennas with impedances of 20 ohms to 30 ohms. Both units can be wound on the same core [B5].

[1]Thermalez® is a registered trademark of Phelps Dodge Copper Products Corp., aka Phelps Dodge Industries, 2600 North Central Avenue, Phoenix, AZ 85004-3014
[2]Scotch® is a registered trademark of 3M, St. Paul, MN 55144

The Parallel-Series Approach

Since little design information is available on fractional-ratio baluns and ununs using Guanella's parallel-series approach [B6, B7], this section includes more analysis than the previous one.

Figure 5 shows a configuration for obtaining a ratio of 2.25:1. It consists of a 1:1 Guanella balun (on the top) connected in series on the left side with a 4:1 Guanella balun, and in parallel on the right side. Because the 4:1 balun has its high-impedance side on the right side, it only adds a current of $I_1/2$ to the load. This results in an output current of $3/2I_1$ and a transformation ratio of 2.25:1. In matching 50 ohms to 22.22 ohms, the optimum characteristic impedance of the three transmission lines (twin-lead coaxial cable or stripline) is found to be 33.33 ohms. In matching 50 ohms to 112.5 ohms, it is 75 ohms.

The voltages and currents shown are for a matched condition when the characteristic impedances of the windings are at the optimum value of 33.33 ohms, or when the lengths of the transmission lines are much shorter than the wavelength.

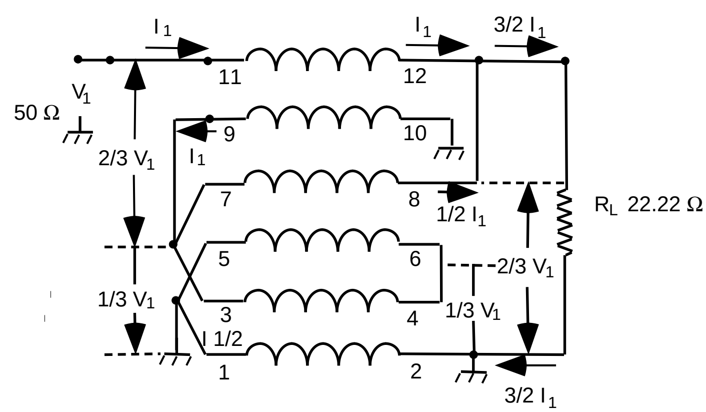
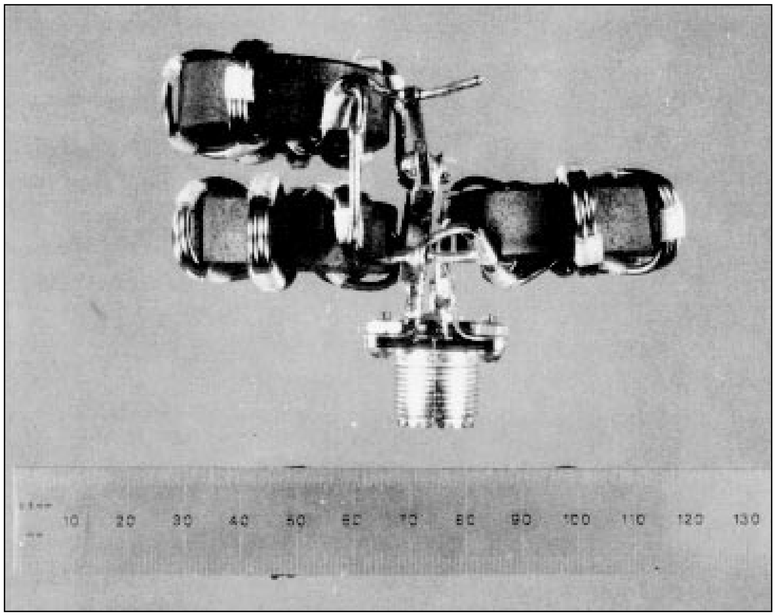


***Figure 5**—Configuration for obtaining a ratio of 2.25:1*

As shown in Figure 5, the circuit performs as an unun. If terminal 10 is connected to terminal 2 and the ground is removed at terminal 2, the circuit then performs as a step-down balun. With the circuit having the generator on the right side and the load on the left and with the ground removed from terminal 1-5, it operates as a step-up balun. Very little difference in performance will be found whether the circuit is connected as a balun or an unun.

A host of different ratios can be obtained with other configurations. For example, replacing the 4:1 balun with a 9:1 balun yields a 1.78:1 ratio; with a 16:1 balun, the ratio becomes 1.56:1. Also replacing the 1:1 balun (on the top in Figure 5) with a 4:1 balun with its high-impedance on the left side, results in a 6.25:1 ratio.

In order to verify the high-frequency model of Figure 5, several designs were constructed and measured. Figure 6 shows a 2.25:1 unun/balun design using bifilar windings with characteristic impedances of 45 ohms. Each 1.5-inch OD core (with a permeability of 250) has 7 bifilar turns of No.14 H Thermaleze® wire. The response, as an unun or balun, was found to be flat from 1 mHz to over 100 mHz when matching 31 ohms (on the right in Figure 5) to 70 ohms (on the left in Figure 5). This was found to be the optimum impedance level, thus verifying the model. This design is also conservatively rated at 1 kW of continuous power and 2 kW of peak power.

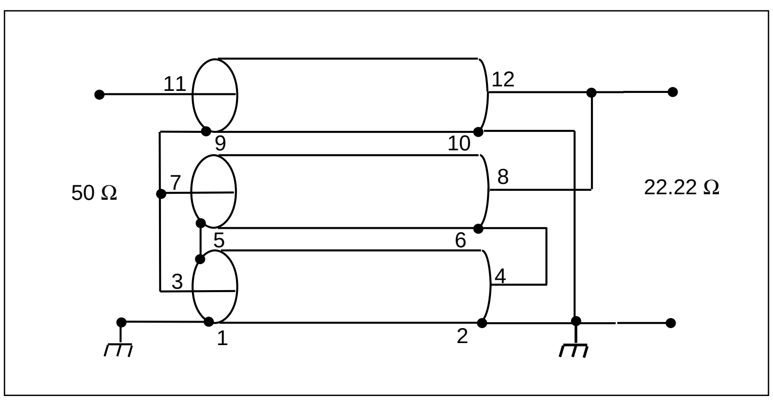


With the windings having characteristic impedances of 45 ohms, the maximum high-frequency response did occur at the predicted impedance level of 70:31 ohms

Figure 6—*A Prototype Design to Verify the Model of Figure 5*

Furthermore, if one winding on each toroid were covered with Teflon®[3] tubing resulting in a characteristic impedance of 75 ohms, this unun/balun design would have the same very broadband response when matching 50 ohms to 112.5 ohms.

Figure 7 is the circuit diagram of a coaxial-cable version of the 2.25:1 unun/balun. Figure 8 shows a beaded-coax design for the VHF band (and above) matching 50 ohms to 22.22 ohms. It has 4 inches of low-permeability (125) beads on 33-ohm coaxial cables. The inner conductors of the coaxial cables are No.14 H Thermaleze® wire and are covered with a 10-mil-wall Teflon® tubing. The outer-braids are from small coaxial cables (or 1/8th-inch tubular braid). The outer braid is also tightly wrapped with Scotch® No.92 tape in order to obtain the low, optimum characteristic impedance of 33 ohms.



Schematic Diagram of a 2.25:1 Beaded-Coax Unun Designed to Match 50 ohms to 22.22 ohms in the VHF Band and Above

Figure 7—The coaxial cables have characteristic impedances of 33 ohms.

Simple measurements show the response to be flat from 10 mHz to well over 100 mHz, when matching 52 ohms to 23 ohms, by using beads with a permeability of 250 (instead of 125) or 8 inches of 125 permeability beads. This balun would make an excellent match of 50-ohm coaxial cable to Yagi beam antennas operating from 10 mHz to well beyond 100 mHz. A very conservative rating of this design is 1 kW of continuous power and 2 kW of peak power.

[3] Teflon® is a registered trademark of the Dupont Corporation, 1007 Market St., Wilmington, DE 19898.

There are 4 inches of beads on each 33-ohm coaxial cable. The connector is on the low-impedance side.

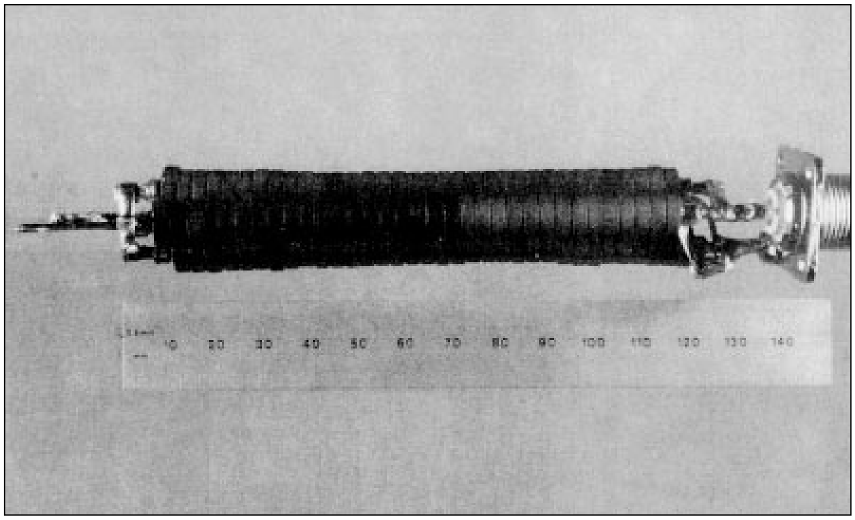


***Figure 8**—A Design Using the Schematic Diagram of Figure 7*

Definitions

balun. a passive device having distributed electrical constants used to couple a balanced system or device to an unbalanced system or device. *Note:* The term is derived from balance-to-unbalance transformer.

bootstrap approach. a single-core, fractional-ratio unun with higher-order windings and a bootstrap connection. A part of the voltage on the low-impedance input side appears directly across part of the output load. The transmission lines are essentially *lifted up* by this voltage.

equal-delay networks. Guanella's parallel-series approach of summing voltages at the high-impedance side of equal delays.

fractional ratios. ratios other than 1:n^2 where n is 1, 2, 3,..etc.

Guanella 1:1 balun. a 1:1 balun formed by a two-conductor transmission line (twin-lead, coaxial cable or stripline) coiled around a core, or threaded through beads.

Guanella 4:1 balun. a 4:1 balun formed by connecting two transmission lines in parallel on the low-impedance side and in series on the high-impedance side.

higher order windings. trifilar, quadrifilar, quintufilar,...etc.

optimum characteristic impedance. when the value of the characteristic impedance is equal to the portion of the load effectively terminating it.

parallel series approach. a configuration of transmission lines connected in parallel-series resulting in fractional-ratios. This is an extension of Guanella's technique of connecting single transmission lines in a parallel-series arrangement.

quad antenna. a wire antenna with an electrical length of one wavelength that is formed into a square geometry.

Ruthroff 4:1 balun. a 4:1 unun formed by a single transmission line in a bootstrap connection; i.e., the input voltage on the low-impedance side is connected directly to the bottom of the transmission line on the high-impedance side. The transmission line is essentially *lifted up* by the input voltage.

transmission line transformer. a configuration of chokes and transmission lines whereby the energy is transmitted to the output circuit by an efficient transmission line mode.

unun. a passive device having distributed electrical constants used to couple an unbalanced system or device to an unbalanced system or device. *Note:* The term is derived from **unbalance-to-unbalance transformer**.

VSWR (voltage-standing wave ratio). the ratio of the magnitude of the transverse electric field in a plane of maximum strength to the magnitude of the equivalent point in an adjacent plane of minimum field strength.

Yagi antenna. a linear end-fire array consisting of a driven element, one or more reflector elements, and one or more director elements.

Summary

1. By keeping the transmission lines as short as possible (consistent with the low-frequency requirement), the "bootstrap" approach of Ruthroff's, using higher-order windings, yields the simplest ununs to construct. They require fewer cores and offer a larger variety of ratios (because of tapping) than Guanella's parallel-series approach. Low-power ununs, which have shorter transmission lines, have higher frequency responses.

2. Because the parallel-series approach adds in-phase voltages, it offers the highest frequency capability. It is the design of choice for fractional-ratio baluns and ununs in the upper-half of the VHF band and above. The upper-frequency limit is determined, in large measure, by the parasitics of the interconnections.

3. With the use of low-permeability ferrites (less than 300), these ununs and baluns can achieve exceptionally high efficiencies. In matching 50 ohms to impedances of about 100 ohms and less, losses in the passband can be as low as 0.02 to 0.04 dB. Therefore, the power ratings (which have not been established by any professional group) of the designs in this paper could very well be five to ten times higher. Furthermore, the losses with these devices are voltage-dependent (a dielectric-type loss) and, therefore, not damaging to the ferrites.

4. Since very little theoretical and practical information has been available on fractional-ratio ununs and baluns, more work has to be done in order for them to reach their potential uses. One of the major problems has been the unavailability of the components for these devices. Transmission lines with characteristic impedances ranging between 6 ohms and 200 ohms were practically impossible to obtain. But information now exists on how they can be readily constructed [B5]. Also, ferrite cores with the proper permeabilities and geometries have presented the same problem. Recently, this problem has also been solved. Complete kits are now available to construct all of the designs shown (or suggested) in this paper.[1]

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[1]These kits are available from Amidon Associates, Inc., 2216 East Gladwick Street, Dominquez Hills, CA 90220, USA.

Biography

Jerry Sevick earned a B.S. in education from Wayne State University in Michigan, and a Ph.D. in applied physics from Harvard University. He taught physics at Wayne State from 1952 to 1956. In 1956, Dr. Sevick joined AT&T Bell Laboratories where he supervised groups working in high-frequency transistor and integrated-circuit development, reliability, applications engineering and high-speed PCM. Later, he served as Director of Technical Relations there.

During his career, it was his interest in amateur radio that launched Dr. Sevick into experiments with short vertical antennas and broadband matching transformers. He is noted for a classic series on short vertical antennas that appeared in QST, the amateur radio journal of the American Radio Relay League. His April, 1978 QST article on short ground-radial systems now serves as the world's standard for earth conductivity measurements.

Through Dr. Sevick's experience in designing transformers to match coaxial cable to short ground-mounted vertical antennas, he concentrated on the transmission line transformer as a possible vehicle. Dr. Sevick then undertook the characterization and design of transformers for low-impedance applications, which also led him to other studies resulting in his book *Transmission Line Transformers*, published by The Amateur Radio Relay League, Inc. Dr. Sevick is presently completing a series on baluns in *Communications Quarterly*, as well as a series on ununs in *CQ*.

Having retired from AT&T in 1985, Dr. Sevick remains active in his field. He is currently a Technical Advisor for the American Radio Relay League and a member of IEEE, Sigma Xi, Sigma Pi Sigma and Phi Delta Kappa.

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