

A Simplified Analysis of the Broadband Transmission Line Transformer

By Jerry Sevick
Bell Laboratories (Retired) and Consultant

This article presents the fundamental concepts and describes the impedance-matching capabilities of broadband transmission line transformers

This paper presents an easily understood analysis of the transmission line transformer (TLT). It also includes some history and the author's suggestion for the future of these

devices. It is hoped that future device development and application will be encouraged.

The Transmission Line Transformer

The TLT transmits the energy from input to output by a transmission line mode and not by flux-linkages as in the conventional transformer. As a result the TLT has much wider bandwidth and higher efficiencies than its conventional counterpart. With proper core materials and impedance levels of 100 ohms or less, bandwidths of about 100 MHz and efficiencies approaching 99% are possible today when matching 50 ohms up to 100 ohms and 50 ohms down to about 3 ohms. Future research and development, especially with impedance ratios less than 4:1, should make TLTs operate at much wider bandwidths.

The TLT and conventional transformer have two models used in their analysis. The low frequency models are similar, usually containing an inductive impedance in parallel with the input impedance. The high frequency model of the conventional transformer consists of a distributed capacitance in parallel with the leakage inductance. The TLT in turn contains a configuration of transmission lines in the high frequency model. Therefore, the conventional transformer model only requires a background in circuit theory, while the TLT requires both circuit and transmission line theory.

The TLT first appeared upon the scene in 1944 in a classic paper by George Guanella in the *Brown Boverie Review*. The title of his paper was "Novel Matching Systems for High Frequencies" [1]. The second classic paper was written by Clyde Ruthroff at Bell Labs and was published fifteen years later in the *Proceedings of the IRE*. His paper was named "Some Broadband Transformers" [2] and introduced the 1:4 unbalanced-to-unbalanced transformer (unun).

Guanella's basic designs were balanced-to-unbalanced (balun) transformers. They consisted of transmission lines connected in a parallel/series arrangement. They are the basis for the later "equal-delay" TLTs. Ruthroff on the other hand, applied the input voltage to part of the output, which has been known as a "Bootstrap Effect." His transformers usually added a delayed voltage to a direct voltage therefore a cancellation effect took place limiting the high frequency response.

Guanella's goal was to develop a balun to match the balanced internal impedance of a push-pull vacuum-tube amplifier of 960 ohms to the unbalanced impedance of a coaxial cable of 60 ohms, a 16:1 ratio. Since Guanella did not have access to the modern nickel-zinc ferrites of today, his goal was never realized. Even today it would be a formidable task. Ruthroff on the other hand, designed ununs to match the low impedance of transistors up to 50 ohm coaxial cable.

Since the TLT can also operate as a very efficient isolation transformer it is now possible to convert a balun to an unun or vice versa. Therefore, the classification on these devices can be simplified, resulting in only four basic classifications: 1) TLTs with 1:1 ratios, 2) TLTs

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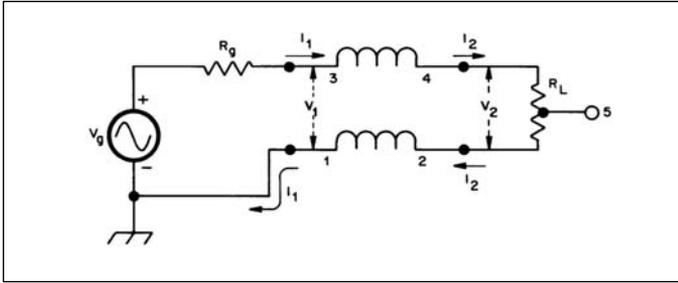


Figure 1 · Guanella's basic building block, a transmission line segment with input and output isolated by the inductive reactance of the windings.

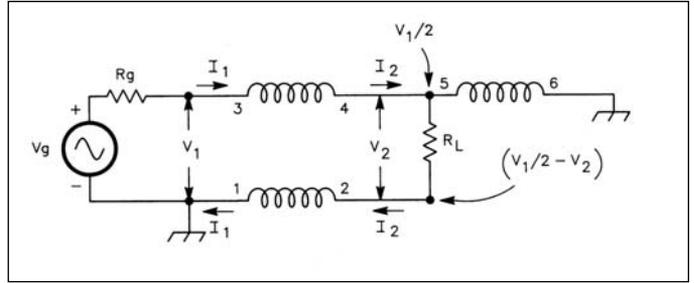


Figure 2 · Ruthroff's 1:1 balun design, which includes an isolated transmission line section, along with a third winding acting as a voltage divider.

with 1:4 ratios, 3) TLTs with less than 1:4 ratios and finally TLTs with ratios greater than 1:4. These will be covered in the next sections.

TLTs with 1:1 Ratios

Figure 1 shows Guanella's basic building block. With terminal 5 grounded, the device operates as a balun, matching the unbalanced source to the balance load R_L . In this case, the low-frequency performance is determined by the reactance of winding 3-4. In practice, this reactance should be 10 times greater than $R_L/2$ (or 5 times greater than R_L). If terminal 4 is grounded, the building block performs as a phase-inverter. Thus, terminal 2 becomes negative. In this case the reactance of inductor 3-4 should be 10 times greater than R_L . If terminal 2 is grounded, the result is a simple delay line. In this case no reactance is necessary. Instead of coil windings, ferrite-loaded straight transmission lines can also be used, although the required inductance may be impractical to obtain at lower frequencies.

Figure 2 shows Ruthroff's version of the 1:1 balun. Windings 3-4 and 5-6 act as a voltage divider. Windings 3-4 and 1-2 act as Guanella's basic building block. In this case the reactance of 5-6 should be 10 times greater than R_L . When the reactance of 5-6 is much greater than R_L , its high impedance is swamped by the lower impedance of R_L and the device acts exactly the same as a Guanella building block.

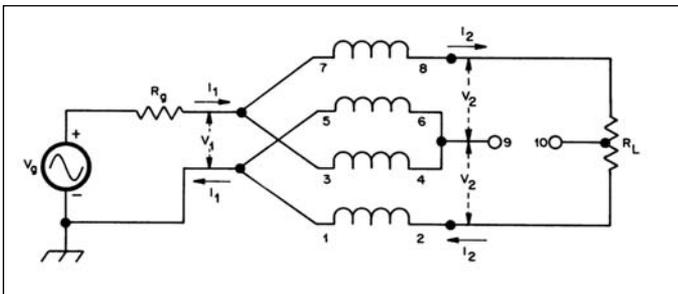


Figure 3 · Schematic of Guanella's 1:4 balun, showing the inputs in parallel and outputs in series.

TLTs with a Ratio of 1:4

Figure 3 shows Guanella's version of a 1:4 balun. The two transmission lines are connected in parallel at the low impedance side and in series at the high end. For an ideal match, the characteristic impedance of the two transmission lines should be $R_L/2$. Thus, if the transmission lines are terminated in their characteristic impedance, Z_0 , the high-frequency limit is that of a regular transmission line. Further, by grounding terminal 8, the device can act as a phase-inverter and by grounding terminal 2 it performs as a 1:4 unun.

Figure 4 shows the low frequency model of Guanella's 1:4 transformer. As a 1:1 balun the reactance of winding 3-4 in series of winding 5-6, wound on two separate cores, should be greater than 10 times the input impedance. When terminal 2 is grounded, the reactance winding 1-2 is eliminated and therefore should be considered when using Guanella's 1:4 transformer acting as an unun.

Figure 5 shows the schematics of Ruthroff's 1:4 TLTs. (A) is his 1:4 unun, with terminal 2 connected to the input

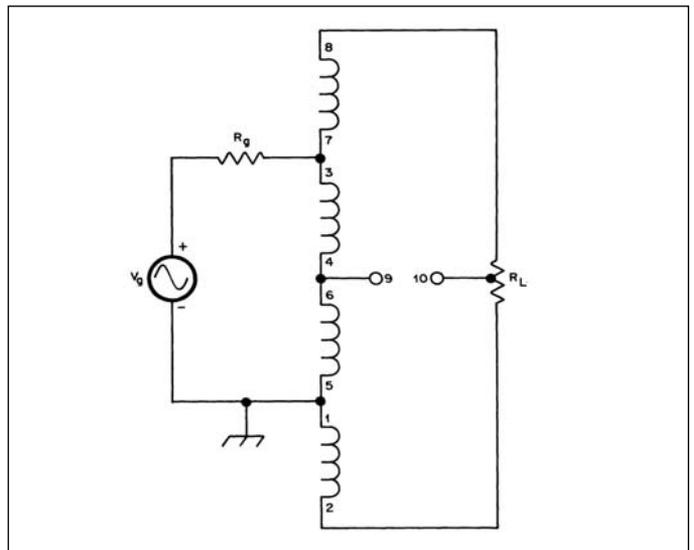


Figure 4 · Low-frequency model of Guanella's 1:4 balun.

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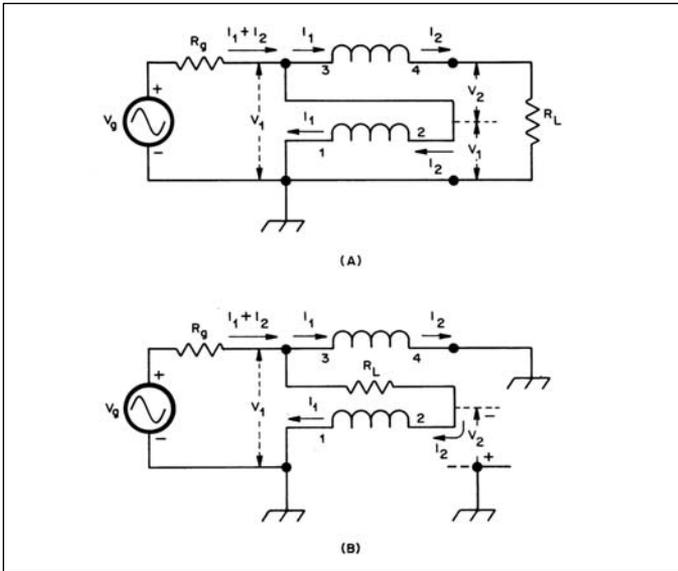


Figure 5 · Ruthroff's 1:4 transformer, (A) as an unun and (B) as a balun.

terminal 3, thus raising this transmission line by the input voltage V_1 . This is called the "Bootstrap Effect." The output voltage V_2 is delayed as it travels the transmission line. Because of this, Ruthroff's 1:4 design does not have the high frequency response of Guanella's, but if the transmission lines are short compared to the wave length, Ruthroff's design is practical. Figure 5(B) shows Ruthroff's 1:4 balun, first acting as a phase inverter, followed by R_L between terminals 3 and 2 to become a 1:4 balun. This configuration also adds a direct voltage to a delayed voltage, limiting its high frequency performance.

Figure 6 shows the low frequency models of Ruthroff's 1:4 TLTs. (A) is the unun model and (B) the balun model.

TLTs with Ratios Less than 1:4

Figure 7 shows the high frequency model of a trifilar "Bootstrap" model of an unun yielding a ratio of 1:2.25. Since the low frequency model for this device would show

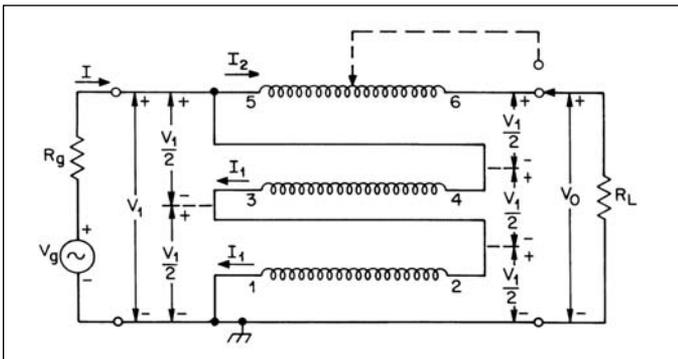


Figure 7 · Trifilar 1:2.25 Bootstrap TLT, showing how a tap can be used to obtain variable matching.

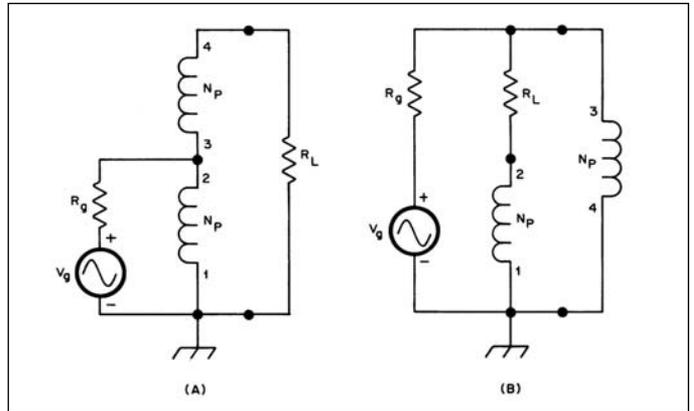


Figure 6 · Low frequency models for the Ruthroff 1:4 unun (A) and balun (B).

three inductors in series on the same core, the low frequency end is greatly aided. Also, as this device adds two direct voltages in series with one delayed voltage the high frequency performance is much better than Ruthroff's 1:4 unun. This device has produced exceptional bandwidth and efficiencies. This TLT can be tapped on the "top" winding to obtain other impedance ratios. For example, if the tap is set for $V_0 = 1.414(V_1)$ the ratio is exactly 1:2.

Figure 8 shows two high frequency models using ratios of 1:1.56. (A) is designed to match 50 ohms to 78 ohms while (B) is optimized to match 32 ohms to 50 ohms. This device has 5 transmission lines in series to help the low frequency performance, and because it adds a delayed voltage of only $V_1/5$ it can have a better high frequency response than its trifilar counterpart.

TLTs with Ratios Greater than 1:4

Figure 9 shows Guanella's models of his 1:9 TLT. (A) shows the high frequency model and (B) its low frequency counterpart. Since each line has an equal delay, this TLT has high frequency performance the same as a simple transmission line. As seen in the diagram each transmission sees 1/3 of the load R_L . In matching 50 ohms to

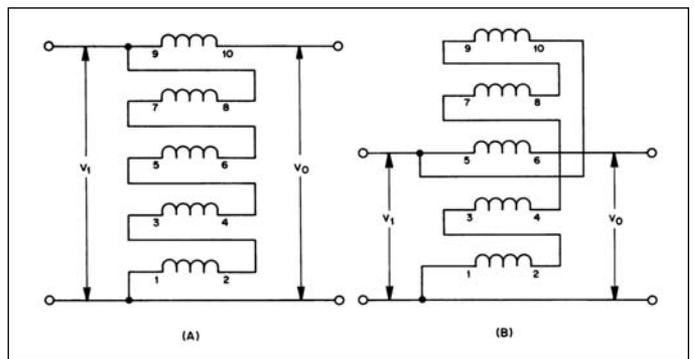


Figure 8 · 5-winding 1:1.56 Bootstrap TLT connections: (A) higher impedance; (B) lower impedance.

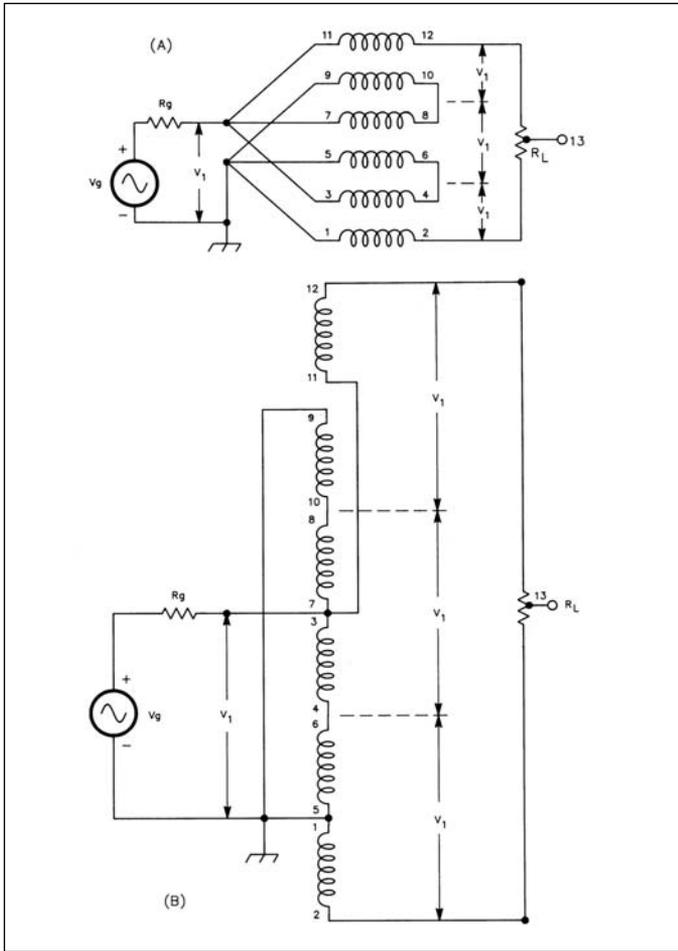


Figure 9 · The Guanella 1:9 TLT, using three two-conductor transmission line windings, each of which may be a coaxial cable.

450 ohms the optimum characteristics impedance Z_0 is 150 ohms. In matching 50 ohms to 5.5 ohms the optimum characteristics impedance is 17 ohms. Since the low impedance version requires much smaller inductances in order to have enough reactance for input-output isolation, its performance at this low impedance level should be vastly greater than the high impedance version. This factor is especially beneficial at lower frequencies.

Figure 10 shows a schematic of a quadrifilar-wound transformer providing ratios as high as 1:9 when connecting terminal A to terminal D and as low as a 1:1.36 ratio when connecting terminal B to terminal F. In the 1:9 ratio three transmission lines are in series which aids the low frequency response, but a single direct voltage is added to a twice delayed voltage yielding a poorer high frequency response than its 1:4 counterpart. When matching 50 ohms on the right to lower impedances on the left this unun is a practical multimatch transformer.

Since these broadband TLTs can also be made very

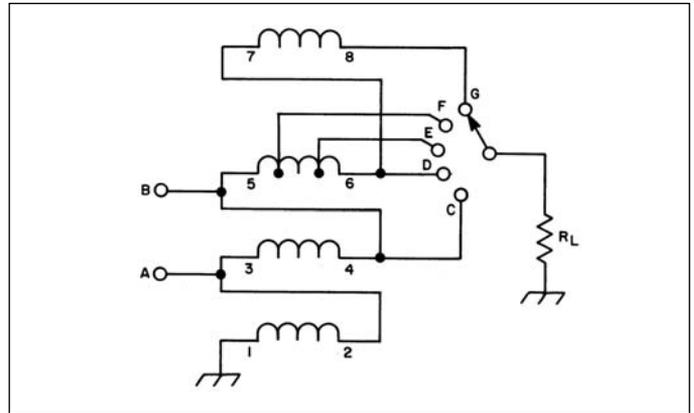


Figure 10 · A four-winding transformer with multiple connections that provide eight impedance ratios.

efficient, they can be connected in series, yielding ratios between 1:9 and 1:4. This compound TLT obviously favors matching 50 ohms to lower impedances.

Closing Remarks

This paper attempts to summarize the simple basics of these broadband TLTs. There are many details regarding the use of magnetic materials, examples of transmission lines, and additional TLT models that have not been included. This would take an entire book or more [3,4]. It is hoped that these notes stimulate an interest in these devices and provide a feeling for their capabilities.

Although the TLT was first intended to be used for matching vacuum tubes its real strength lies in matching to low impedance solid state devices. Further work in the design and application of these lower impedance TLTs needs to be done. Also, continued research on magnetic materials is encouraged. Equal-delayed TLTs acting as ununs appears to be a key technique for the future. Finally it should be pointed out that the TLT is designed to match broadband loads, that is impedances that have no (or small) reactive components.

References

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2. Ruthroff, C.L., "Some Broad-Band Transformers," *Proc IRE*, Vol 47, August 1959, pp. 1337-1342.
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Author Information

Jerry Sevick is retired from AT&T Bell Laboratories, and remains an occasional consultant and lecturer.