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Design of Broadband Ununs With Impedance Ratios Less than 1:4

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Broadband transformers with impedance ratios less than 1:4 are required for solid-state power amplifiers as well as signal dividing and combining circuits from HF to microwaves

The first appearance of the broadband transmission line transformer occurred in 1944, in a paper published by George Guanella [1] in the *Braun-Boveri Review*. In that paper, he expounded the principles of this broadband impedance matching device and is considered the inventor. His goal was to design a broadband balun (balanced-to-unbalanced) for the HF band, matching the balanced impedance of 960 ohms in a vacuum tube amplifier to the unbalanced impedance of a 60 ohm coaxial cable; a 16:1 ratio. Since he did not have the magnetic materials of today he was unable to reach his goal. Even today it is a formidable task.

Figure 1 shows Guanella's approach for a 1:4 transmission line transformer, which is generally considered to be a balun. With terminal 2 grounded it becomes an unbalanced-to-unbalanced (unun) transformer. As seen in the figure, his technique uses two transmission lines, connected in parallel on the input and in series on the output side, the transmission lines are coiled such that their common-mode "choking" action provides input-to-output isolation for the desired low frequency performance. Since each transmission line sees one-half of the load R_L its optimum characteristic impedance Z_0 should be $R_L/2$. Since Guanella adds voltages that have equal delays through the transmission lines, his technique is can be considered to be a member of the "equal-delay transformer" family. The method can be expanded by connecting three transmission lines in series parallel to obtain a ratio of 1:9, four lines to obtain a 1:16 ratio, etc.

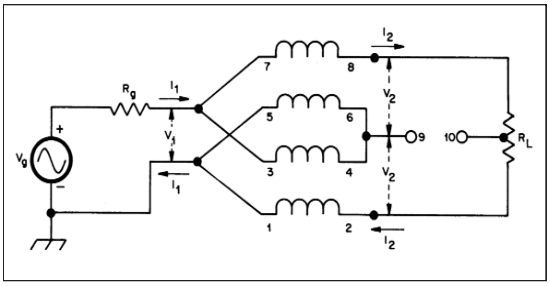

Figure 1 · Schematic of Guanella's 1:4 balun, showing the inputs in parallel and outputs in series. By grounding terminal 2, this transformer acts as a broadband 1:4 unun.

In 1959 Ruthroff [2] presented his classic paper in the *Proceedings of the IRE*. In it he employed two different versions of the balun and unun (Figure 2). Figure 2A is his unun and Figure 2B is his balun. As can been seen his unun has a direct connection from the input to the output. Since the transmission lines are coiled forming chokes the transmission lines are literally raised by a voltage equal to the input, resulting in a voltage twice the input and hence a 1:4 ratio. The characteristic impedance Z_0 of the transmission line should be equal to one-half the load impedance R_L. This technique has been described as a "bootstrap." Clearly, it is a simpler circuit than Guanella's but does not have the same high frequency response because it adds a delayed voltage to a direct one. The delay is excessive when the lines reach a significant fraction of a wavelength. In many cases, however, the transmission lines will be short enough provide sufficient bandwidth for the desired application.

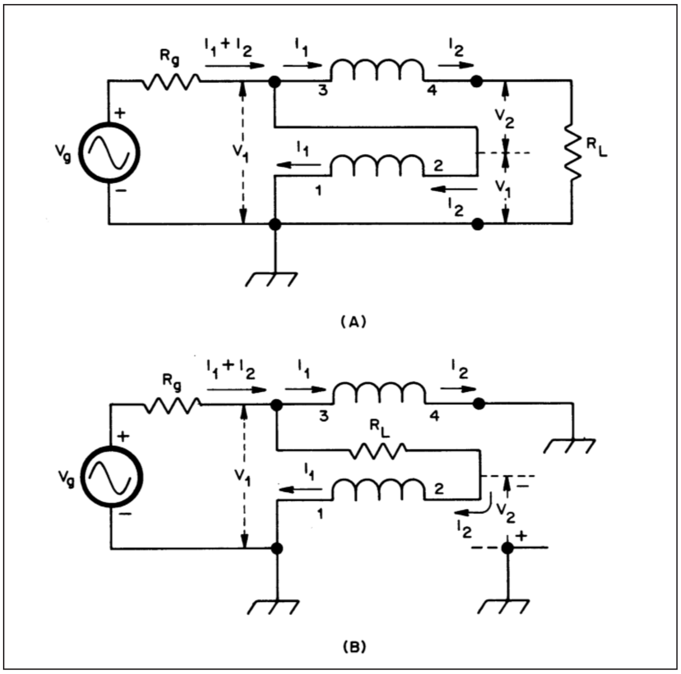

Figure 2 · Ruthroff's 1:4 transformer as an unun (A) and as a balun (B).

Guanella's Technique for Ratios of Less Than 1:4

Figure 3 shows Guanella's 1:1 balun combined with his 1:4 balun. The voltages on the left side of the transformers are in series and the currents in parallel on the output. In this case, the left side has the higher impedance. If the generator impedance was 100 ohms, the output impedance (R_L) should be 44.44 ohms and the characteristic impedances of all three transmission lines should be 67 ohms for a matched condition. If the generator impedance is 50 ohms then R_L and the characteristic impedances of the lines are reduced proportionately to 22.22 and 33 ohms respectively. In a matched condition, this transformer should have a high frequency response similar to a single transmission line. By grounding the indicated terminals, it becomes a broadband unun.

Operation of this combination of transformers can be described as follows: At the right side, the 1:1 and 1:4 transformers are connected in parallel to R_L. Thus, the voltage across the load, V_L appears at both transformers. At the left side, the same voltage appears at the 1:1 transformer, but the 1:4 transformer reduces the voltage by one-half, or $V_L/2$. These voltages are connected in series, so the input voltage (V_g) is $1.5V_L$, which corresponds to an impedance transformation of $R_g/R_L = 2.25$.

In Figure 4, Guanella's 1:9 transformer is used instead of his 1:4. In this case, the voltages at the left side are V_L in series with $V_L/3$, so V_g is $1.33V_L$ and $R_g/R_L = 1.78$. If the generator is 100 ohms then the 1:1 transformer above "sees" 75 ohms and the 1:9 transformer sees 25 ohms. The characteristic impedance of all four transmission lines should be 75 ohms in a matched condition. If the generator impedance is 50 ohms then R_L and the characteristic impedances of the transmission lines should be reduced by a factor of two.

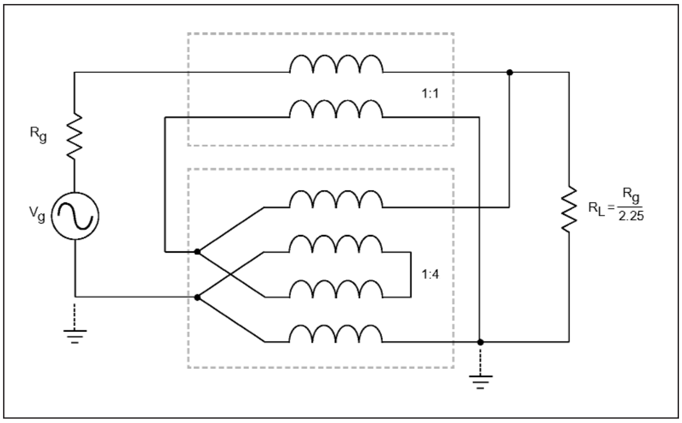

Figure 3 · An equal-delay unun with an impedance ratio of 2.25:1, using Guanella's technique.

By using a 1:16 Guanella transformer below the 1:1 unit, this configuration provides a ratio of 1:1.56. Again if the generator is 100 ohms the 1:1 transformer sees 80 ohms and the bottom one 20 ohms. If the generator is 50 ohms then all characteristics impedances are 40 ohms. The 1:1.56 ratio is important because it supports applications such as transforming between the common system impedance of 50 and 75 ohms.

Ruthroff's Technique for Ratios of Less Than 1:4

Figure 5 shows a bootstrap circuit for a 1:2.25 unun. It shows that there are three conductors with one of the conductors in this case terminal 4 connected to the input impedance. This is an extension of Ruthroff's basic "boot-

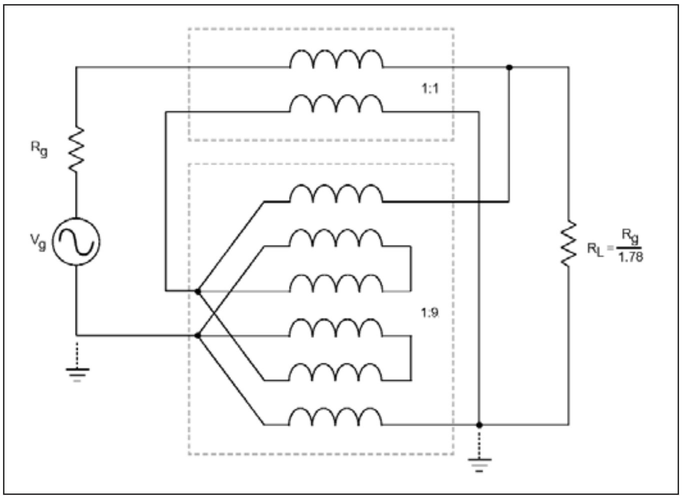

Figure 4 · An equal-delay unun with an impedance ratio of 1.78:1.

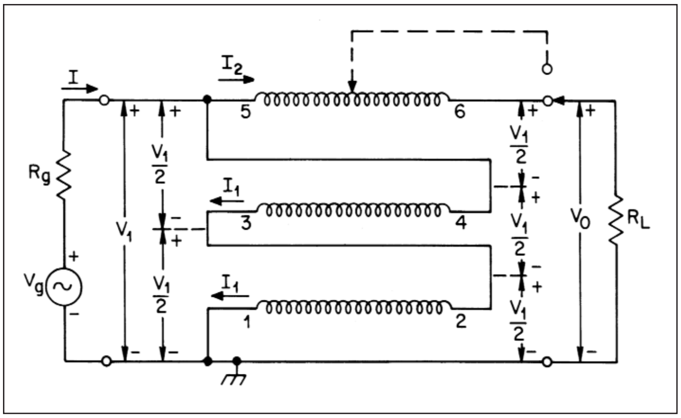

Figure 5 · Trifilar 1:2.25 bootstrap transformer, showing how a tap can be used to obtain variable matching.

strap" technique as can be seen a direct voltage equal to the input voltage is connected to terminal 4 which raises the top transmission line by V_1. Thus the output is equal to $(3/2)V_1$. It has been found experimentally that if the top conductor is tapped at 0.8 of its length from the input that the result is equally broadbanded and produces a 1:2 impedance ratio. This transformer also has advantages over Ruthroff's unun since the low frequency model shows that the three conductors are in series-aiding, resulting in shorter transmission lines, also the delayed voltage is only equal to half the direct voltage. Rather large structures have shown to provide broad bandwidth of the order 100 MHz [3]. By interposing winding 5/6 between the other two conductors this transformer can be optimized at the 50 ohm level, otherwise it has better performance operating at the 100 ohm level.

Using four conductors with the input connected to the output of the third conductor this provides even a greater bandwidth with a ratio of 1:1.78. By the application of five conductors shown in Figure 6, an even greater bandwidth can be provided with the important ratio of 1:1.56. The Figure shows two versions, the one on the left is more useful for matching 50 ohms to 75 ohms, while the one on the right with the transposed winding is better suited to match 50 ohms to about 33 ohms.

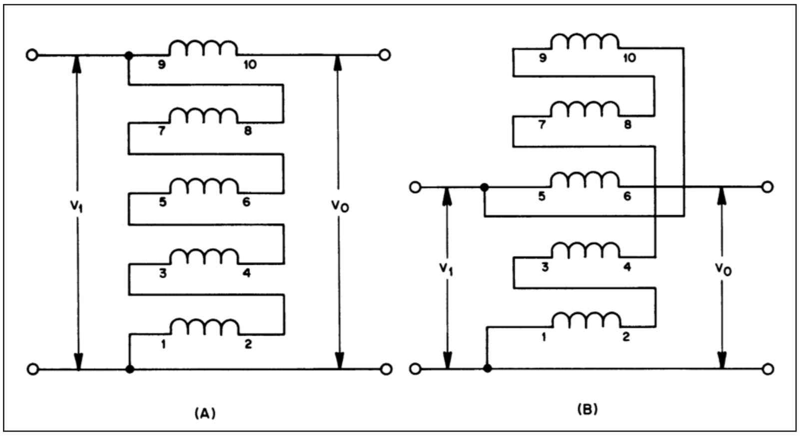

Figure 6 · 5-winding 1:1.56 Bootstrap transformer connections: (A) higher impedance, and (B) lower impedance.

Concluding Remarks

In reviewing the history and theory of the transmission line transformers it can be seen that it they are ideal for matching the lower impedance of today's solid-state amplifiers. With proper understanding and use of current fabrication technologies, i.e. thin film, thick film and molecular beam epitaxy (MBE), and with the equal delay principles of Guanella, ununs (as well as baluns) with ratios of less than 1:4 should be popular. For example, in 2-way combiner/splitter components, the 1:2 transmission line transformer should be used. It is surprising that fairly recent publications have shown the use of autotransformers to match 25 ohms to 50 ohms! The transmission line transformer is by far a broader bandwidth and lower loss matching device.

As we have seen, the equal delay transformer basically has the same high frequency performance as a single transmission line. The low frequency response is more complicated since coiled transmission lines must be wound on separate cores. This is where the bootstrap approach has the advantage, since all the windings are wound on the same core and therefore are in series-aiding configuration. For very high frequency responses the straight beaded transmission line has the advantage since it does not have a self-resonance. Here is where the equal delay transformer has the advantage since it does not a have a direct connection from input to output like that of the bootstrap transformer. The parasitic inductance of the direct connection can limit the high frequency response in the bootstrap device. Experiments should be performed on the equal-delay unun to see if a practical 1:2 ratio can be obtained.

Also it can be shown that the ununs described in this paper can be constructed with coaxial cables transmission lines. In the equal-delay case the application is quite obvious. The use of coaxial cable in the bootstrap case is not so obvious, and is illustrated in Figure 7. Here we have Ruthroff's application using two coaxial cables resulting in a 1:2.25 ratio. The third conductor in this case is the parallel connection of the two outer braids of the coaxial cables. In this case the top transmission line generally sees 1/3 of the load and in the bottom transmission line 2/3. For a 50 ohm load the top transmission line impedance should be 17 ohms and the bottom transmission line 33 ohms. It has also been found that the inner conductor of the top coaxial conductor in Figure 7 can also be tapped

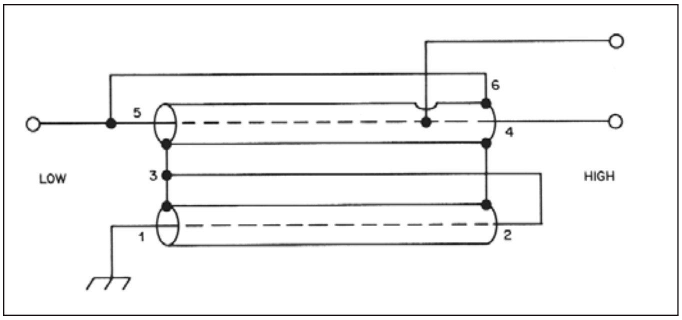

Figure 7 · Connection diagram for Ruthroff's bootstrap application, using two coaxial cables to obtain the impedance ratio of 1:2.25 or 1:2 with a tap winding.

yielding a broadband ratio of 1:2. Many examples of transmission line transformers using coaxial cables are found in the literature [3]. And finally it should be mentioned that equal-delay transformers should be investigated with tapped windings and with windings sharing the same magnetic medium.

References

1. G. Guanella, "Novel Matching Systems for High Frequencies," *Braun-Boveri Review*, Vol. 31, Sep 1994, pp. 327-329.

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

3. J. Sevick, *Transmission Line Transformers*, Noble Publishing Corp., 4th Edition 2001.

Author Information

Jerry Sevick is retired from Bell Laboratories and remains an occasional consultant and lecturer.