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Magnetic Materials for Broadband Transmission Line Transformers

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The author's series of articles on broadband transmission line transformers (TLTs) concludes with these notes on magnetic materials and the properties that are important for best performance

Ferrite and iron powder magnetic materials were developed to support a wide range of components, including inductors, EMI suppressors, conventional transformers and transmission line transformers (TLTs). This article deals with transmission line transformers, presenting the observations and conclusions of the author, reached after extensive experimental research into the behavior and performance of these devices in broadband applications.

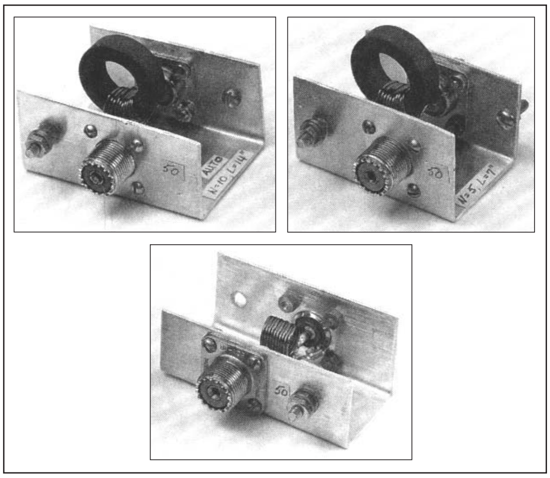

Figure 1 · The three transformers used in comparing the performance of the autotransformer and the transmission line transformer. At the top left is an autotransformer; at the top right is the transmission line transformer, while at the bottom is a transmission line transformer without a ferrite core. All transformers had a total of 10 turns.

Background

In 1944 George Guanella [1] published the first paper on the broadband transmission line transformer. His technique was to connect transmission lines in parallel on the low side and in series on the high side. His transformation ratios were 1:n^2 where n is 1:4. His goal was to develop a balun (balanced-to-unbalanced transformer) to match the internal impedance of a push-pull vacuum tube amplifier with impedance of 960 ohms to the unbalance load of 60 ohms of a coaxial cable. Since Guanella did not have the magnetic materials of today, his air wound transmission lines could not satisfy his goal. Even with the current materials it would still be a very difficult task.

Fifteen years later Clyde Ruthroff [2] published his classic paper on the TLT. He not only produced a 1:4 balun but also a 1:4 unun (unbalanced-to-unbalanced transformer), each using a single transmission line. For the unun the bottom of the transmission line was connected directly to the input, thus raising it by the input voltage. Coiling the transmission lines isolates the input and output, allowing for low frequency operation. The output consists of a direct voltage in series with a delayed voltage. This technique has been described as a "bootstrap." His balun was achieved by connecting the transmission line as a phase inverter. The load then was connected directly to the input voltage and to the end of the transmission line. Ruthroff's 1:4 unun was a successful design for amplifiers using transistors, which have low impedance and ferrite cores, which were then available.

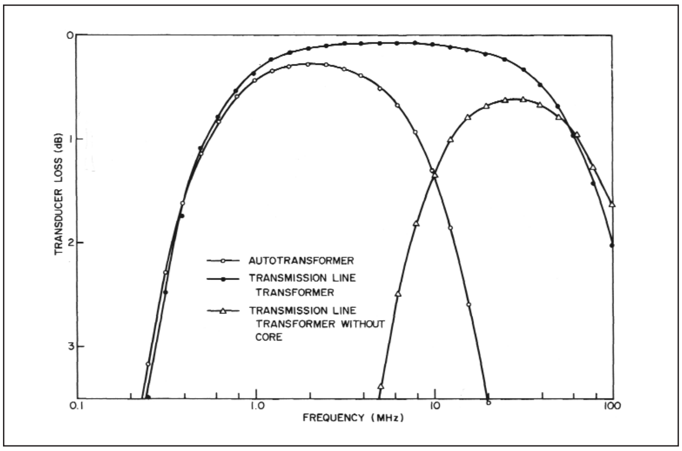

Figure 2 · Measurements taken on the three transformers in Figure 1 when matched at 12.5:50 ohms. Note that the transmission line transformer is superior to the autotransformer both in efficiency and bandwidth. Also notice the limited bandwidth without a core.

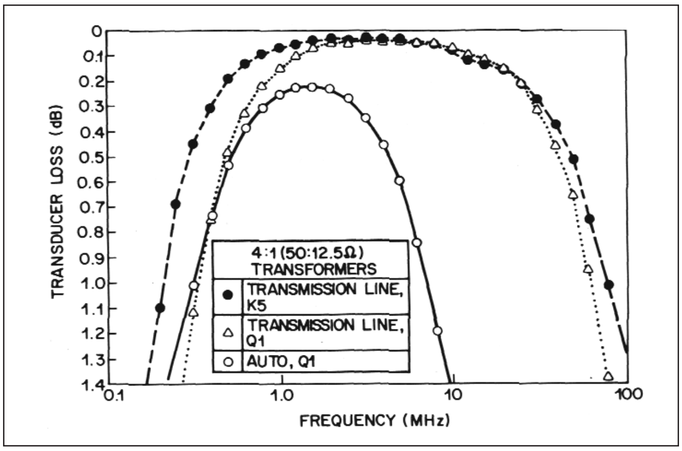

Figure 3 · Loss and bandwidth performance of 4:1 transformers operating at the 50:12.5 ohm level. Note the shift in frequency range when materials of different permeability are used.

These amplifiers were used in the emerging digital systems of the time, namely high speed PCM (pulse code modulation).

It can be said that the broadband TLT favors low impedance matching as will be shown. Higher impedances cannot use higher permeabilities because they tend to have higher losses. On the other hand lower impedances not only benefit from lower reactive requirements but also by use of higher permeabilities. The next section will show the general relationship between permeability and loss.

Magnetic Materials

An investigation on the short vertical antennae in the 40-meter amateur radio band [3] led to an interesting conclusion. A 6-foot high, "top-hat" loaded vertical over a lossless image plane (100 radials) presented an impedance at resonance of only 3 ohms. After much searching it was found that two 1:4 Ruthroth-style ununs, connected in series, provided a match to a 50 ohm cable. The resulting 1:16 impedance ratio efficiently transformed the 3 ohms of the short vertical radial to 50 ohms.

The first experiment performed for understanding these broadbrand devices was the comparison of a TLT with an autotransformer, and with a TLT without a magnetic core. Figure 1 shows the three transformers. Since all have the same number of turns, the transformers on the top look the same while the one with the missing core is obvious. Figure 2 shows the results of this experiment. As can be seen, the autotransformer performs very poorly compared to the TLT, and the core is very important for low frequency response. The rest of this paper will review results obtained for various magnetic materials.

Figure 3 shows the comparison of K5 and Q1 ferrite cores operating at a 50:12.5 ohm using Ruthroff's 1:4 design. These are in turn compared to an autotransformer using the Q1 core. As can be seen, the autotransformer is vastly inferior and the TLTs have similar efficiencies at this impedance level. Also the K5 transformer has a better low frequency response because of the higher permeability of this material.

Figure 4 includes a comparison of the two cores used in Figure 3, but at the higher impedance level of a 200:50 ohm ratio. A similar transformer using a Q2 core is also shown in the figure. The Q2 core shows that at a higher impedance level a higher bulk resistivity is required for optimum efficiency. Results for a fourth transformer using a powdered iron core (E material) are also included. Since this material has much lower permeability than the ferrite materials, its low frequency response suffers accordingly.

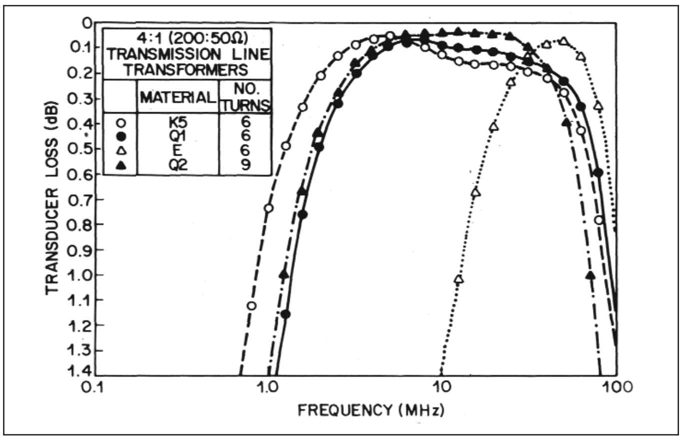

Figure 4 · Loss vs frequency of four 4:1 transformers at the 200:50 ohm level.

Material	Supplier	Permeability (μ_i)	Bulk Resistivity (W-cm)
Q1 (NiZn)	Allen-Bradley (formerly Indiana General)	125	10^8
Q2 (NiZn)	Allen-Bradley	40	10^9
H (NiZn)	Allen-Bradley	850	10^4–10^5
E (Powdered Iron)	Arnold Engineering	10	10^{-2}
C2050 (NiZn)	Ceramic Magnetics	100	3×10^7
C2025 (NiZn)	Ceramic Magnetics	175	5×10^6
CN20 (NiZn)	Ceramic Magnetics	800	10^6
CMD5005 (NiZn)	Ceramic Magnetics	1400	7×10^9
61 (NiZn)	Fair-Rite	125	10^8
43 (NiZn)	Fair-Rite	850	10^5
77 (MnZn)	Fair-Rite	2000	10^2
3C8 (MnZn)	Ferroxcube	2700	10^2–10^3
K5 (NiZn)	MH&W Intl. (TDK)	290	2×10^6
KR6 (NiZn)	MH&W Intl. (TDK)	2000	10^5–10^6

Table 1 · Cores, suppliers and specifications for the experiments described in this paper. (*The list is not comprehensive and includes some materials not examined by the author. Readers should note that other materials are also available for TLT applications—editor.*)

Figure 5 shows the results of 4 transformers using nickel zinc cores, but with different permeabilities. It is interesting to note that the core CMD5005 has the same efficiency but with a much higher permeability. Table 1 shows that this ferrite also has a very high bulk resistivity, which contributes to its performance at the 200:50 ohm level.

Figure 6 shows three other ferrite cores, which can be seen performing quite poorly at the 200:50 ohm level. Of particular note is the 3C8 curve. This is a manganese zinc core, which has a high permeability and a low bulk resistivity, as shown in Table 1.

Concluding Remarks

After consideration of the information displayed in Table 1 and in Figures 3 through 6, we can reach the following conclusions:

1) Since very little flux occurs in the cores in the passband, the losses are basically due to the potential difference along the lengths of the transmission lines. The losses are due to the voltages and are therefore dielectric in nature. As was seen, the highest bulk resistivity yields the highest efficiency.

2) The other parameter that is important with transmission line transformers is the permeability. High permeability of core materials results in shorter transmission lines. This directly benefits Ruthroff's bootstrap approach, which adds a delayed voltage to a direct voltage. Further, with shorter transmission lines, their characteristic impedance is somewhat less critical. If a toroid is used for the core, the magnetizing inductance L_M (in henrys) is:

$$L_M = 0.4\pi N^2 \mu_0 \left(\frac{A_e(\text{cm}^2)}{L_e(\text{cm})}\right)\times 10^{-8}$$

where N is the number of turns, μ_0 is the permeability of the core, A_e is the effective cross-sectional area of the core, and L_e is the average magnetic path length in the core.

We can see from the above equation that by increasing the permeability ten-fold, the number of turns

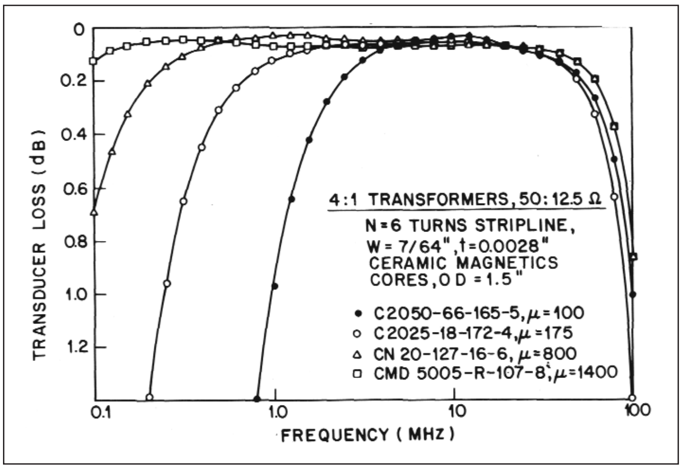

Figure 5 · Loss vs frequency for four core materials from Ceramic Magnetics with optimized windings for the 50:12.5 ohm level.

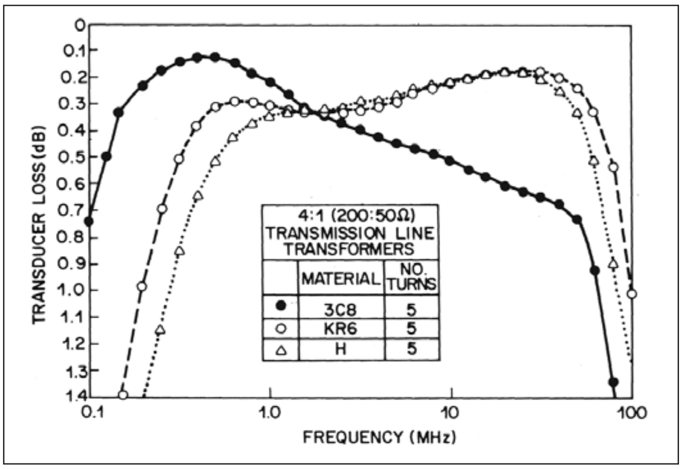

Figure 6 · Measurements of 3C8, KR6 and H materials at the 200:50 ohm level.

is reduced by about one-third. Thus, for a Ruthroff transformer, which adds a delayed voltage to a direct voltage, the high frequency response is about three times greater.

3) When looking at the table and the figures, two properties of the core material stand out: permeability and bulk resistivity. In fact, a figure of merit can be defined in this case, which is permeability times bulk resistivity.

Also, as seen from the figures, powdered iron and manganese zinc (MnZn) ferrite are not recommended for the broadest bandwidth. Again, from the experimental results it is seen that the nickel zinc (NiZn) ferrite CMD5005 has the highest figure of merit. In recent discussions with the supplier it was learned that the typical value for the permeability is 1,500 and the bulk resistivity is 10^{10} ohm-centimeters.

References

1. G. Guanella, "Novel Matching Systems for High Frequencies," *Brown-Boveri Review*, Vol. 31, Sep. 1944, pp. 327-329.

2. W. K. Ruthroff, "Some Broad-Band Transformers," *Proc. IRE*, vol. 47, Aug 1959, pp. 1337-1342.

3. J. Sevick, *Transmission Line Transformers*, Noble Publishing, Fourth Edition, 2001.

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Editor's Notes

In addition to the dominant performance factors of permeability and bulk resistivity, there are other characteristics of ferrite materials that affect loss and optimum frequency of operation. Among these parameters are hysteresis and other dynamic responses to magnetizing forces, temperature stability, and permeability vs. frequency. Ferrites generally have a flat μ_i curve up to a cutoff frequency. Just below this cutoff frequency, the permeability often increases, then begins a roll-off with increasing frequency. This behavior reduces the effective inductance with increasing frequency, which can, in some cases, affect high frequency response.

Also, ferrites typically have a distinct frequency where maximum Q is obtained. This characteristic results in a "sweet spot" of lowest loss in many transformers, even when loss is generally low over a wider bandwidth. For maximum performance, a designer will choose the material that is a best fit with the frequency range of the application.

We recommend that readers contact ferrite manufacturers for additional information. These companies represent the best available source of technical information on magnetic materials.