A Tutorial on Transmission Line Transformers

by

Chris Trask / N7ZWY
Sonoran Radio Research
P.O. Box 25240
Tempe, AZ 85285-5240
Email: christrask@earthlink.net
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Introduction

The concept of transmission line transformers (TLTs) has been a distinct element of RF circuit design at least since 1944 when Guanella disclosed an impedance transformer of novel design which consisted of a pair of interconnected transmission lines [1]. TLTs have been found to possess far wider bandwidth and much greater transmission efficiencies by arranging the windings of the TLT to have uniform transmission line properties. In general, these devices are widely used for matching networks for antennas and amplifiers in the HF and VHF bands [2], and their low losses (a fraction of a dB) makes them especially useful in high power circuits [3].

Typical structures for TLTs consist of parallel wires [4], coaxial cable, or bifilar twisted wire pairs [5, 6], with the latter being most popular as the characteristic impedance can easily be determined by the wire diameter, the insulation thickness, and, to some extent, the twisting pitch [6, 7]. In the case of using coaxial cable transmission line having the correct characteristic impedance for the TLT, the theoretical high frequency bandwidth limit is reached when the cable length comes into the order of a half wavelength ($\lambda/2$), with the overall achievable bandwidth being about a decade [5].

By introducing magnetic materials such as powdered iron or ferrite [8, 9] to the TLT, both the low frequency limit and the high frequency limit are improved [5], and when low-loss high permeability ferrites are used alongside good quality semi-rigid coaxial cable, bandwidths of four decades or more are achievable. [10].

Misconceptions

There are a number of misconceptions regarding the design and application of TLTs, amongst which are:

> "*...it is impossible to build a 4:1 ratio current balun that uses two 1:1 baluns on a single core* [11]."

> "*It's well established (that) any balun made up of series / parallel transmission lines requires different voltages from the start to finish of each transmission line* [12]."

> "*It is quite impossible to build a current balun of any ratio other than 1:1 using multiple transmission line transformers on a single core unless flux leakage between transmission lines is terrible* [13]."

> "*It (is) impossible to build anything but a 1:1 ratio current balun when multiple transmission line transformers are placed on a single core* [14]."

> "*It is physically impossible to build a transmission line current balun other than 1:1 on a single core when the windings have mutual coupling through the core* [15]."

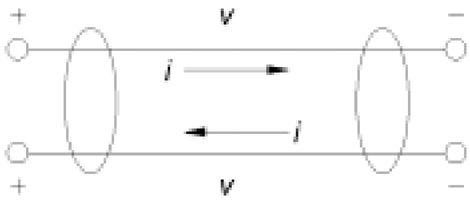

Figure 1 - Transmission Line in Transverse (TEM) Môde

In order to avoid having these and other misconceptions regarding the design and applications of TLTs become widespread, I'll provide here a fairly extensive tutorial on the subject, beginning with the fundamental concepts, then practical design considerations, followed by a brief synthesis procedure which will include some examples.

Fundamental Concepts

The TLT operates by transmitting energy by way of the transverse (or TEM, meaning ***T****ransverse* ***E****lectro****M****agnetic* [16], also known as ***T****ransverse* ***E****lectric and* ***M****agnetic* [17]) transmission line môde, rather than on the more familiar coupling of flux as with a conventional transformer [3], and Fig. 1 illustrates this concept in generalised form, where the two lines represent the two conductors of a transmission line, regardless of whether it is made of parallel wires, twisted wires, coaxial cable, or any other means. Here, the currents in the two conductors are equal in magnitude and opposite in phase, while the voltages across the length of the two conductors are equal in both magnitude and phase. In the TLT, the windings serve to eliminate, or at least substantially reduce common-môde currents from the input to the output [5].

As was previously mentioned, the theoretical high frequency bandwidth for a TLT made with coaxial cable having the correct characteristic impedance is reached when the cable length comes into the order of a half wavelength ($\lambda/2$) with the overall achievable bandwidth being about a decade [7].

Low Frequency Bandwidth Limit

The low frequency bandwidth limit of a TLT made with coaxial cable is determined by way of the magnetising inductance of the outer surface of the outer conductor, which results in the low frequency model illustrated in Fig. 2 [2, 18]. Here, the transmission line proper is represented by the ideal 1:1 transformer. The resistance R_0 represents the losses of the transmission line, and the inductance L_{ac} represents the magnetizing inductance of the outer surface of the outer conductor. Note that there is no parallel inductance for the inner conductor, which is due to the fact that the series inductances of the inner conductor and the inner surface of the outer conductor are part of the transmission line proper [18].

An approximation to the magnetizing inductance can be made by considering the outer surface of the coaxial cable to be the same as that of a straight wire (or linear conductor) which, at higher frequencies where the skin effect causes the current to be concentrated on the outer surface, would have the self-inductance of [19]:

$$L_{ac} = 2l\left[ln\left(\frac{2l}{r}\right) - 1\right]\text{nH} \qquad (1)$$

where l is the length of the coaxial cable in

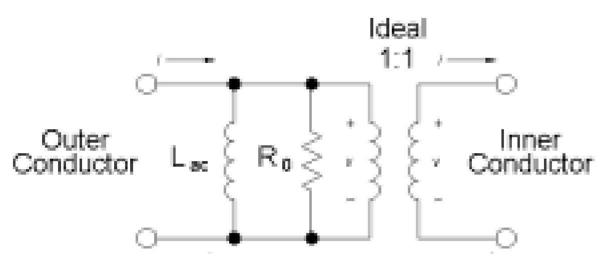

Figure 2 - Low Frequency Model of 1:1 Transmission Line Transformer Using Coaxial Cable

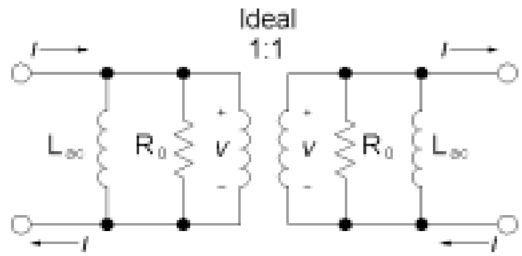

Figure 3 - Low Frequency Model of 1:1 Transmission Line Transformer Using Twisted or Parallel Wires

cm and r is the radius of the outer surface of the outer conductor in cm. This inductance is, as stated, for a straight conductor, therefore it will generally increase when the coaxial cable is formed into various shapes such as a helix, making the inductance L_{ac} of (1) a lower limit in the design process.

A similar low frequency model for TLTs using twisted or parallel wires is shown in Fig. 3 [22]. Here, the model is symmetrical as both conductors are exposed to any magnetic material and therefore contribute to the losses and low frequency characteristics of the TLT.

This is a matter that is understood by way of sufficient practical experience more than anything else. As a general rule, the length of the transmission line is generally kept to no more than an eighth of a wavelength ($\lambda/8$) at the highest frequency for the application.

For best performance, the characteristic impedance of the transmission lines used in the TLT should be equal to the geometric mean of the input and output impedances:

$$Z_{TL} = \sqrt{Z_{in} \times Z_{out}} \qquad (2)$$

although nonoptimal transmission line characteristic impedances may be used provided that the increased losses, degraded return loss, and reduced bandwidth are acceptable, which is sometimes a necessary tradeoff when using commercial coaxial transmission line.

From (1) and (2) we can now estimate the low frequency bandwidth limit by:

$$f_L = \frac{Z_{TL}}{2\pi L_{ac}} \qquad (3)$$

Magnetic Materials

The introduction of magnetic materials such as powdered iron or ferrite improves the low-frequency bandwidth limit of TLTs made with coaxial cable by increasing the magnetically induced inductance of the conductors by approximately:

$$L'_{ac} = L_{ac}\sqrt{\mu_r} \qquad (4)$$

where L'_{ac} is the apparent magnetization inductance of the coaxial transmission line and μ_r is the relative permeability of the ferrite material.

For TLTs made with twisted or parallel wires, the introduction of magnetic materials is viewed as increasing the length of the transmission line by approximately:

$$l' = l\sqrt{\mu_r} \qquad (5)$$

where l' is the apparent length of the transmission line.

At lower frequencies the response of the TLT is dominated by the effect of the magnetising inductance for all windings [2, 5]. Additionally, the transverse transmission line môde works as long as the current on the outside surface of the outer conductor of the coaxial cable is negligible [5], and the considerable magnetic losses of the magnetic material dissipates these outside surface currents, thereby improving the high frequency bandwidth limit.

Several transmission lines of a trans-

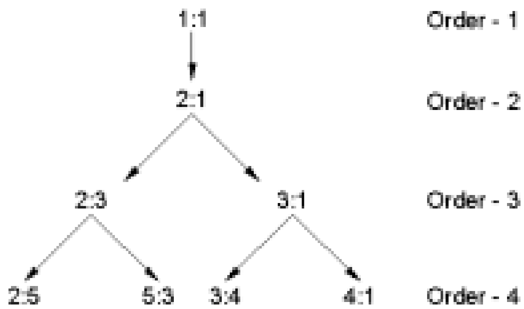

Figure 4 - Voltage Transformation Ratios of the First Four Orders of TLTs (from Rotholz [6])

former may be wound on a single magnetic core, as was demonstrated by Ruthroff [6, 20], provided that the voltages and currents of each transmission line in the transformer are identical.

In practice, the magnetic material is selected so that the ferroresonance frequency of the magnetic material is well above the low frequency bandwidth limit of the transmission line by itself. As an example, the ferroresonance frequency of Fair-Rite type 43 material is approximately 50MHz with the initial permeability (μ_i) peaking around 2MHz, so we would choose a coaxial cable length such that it's low frequency bandwidth limit is around 10MHz to 20MHz, just to be safe.

Transmission Line Transformer Order and Synthesis

The number of transmission lines which comprise a TLT is termed the *order* of the TLT. An order-*m* TLT is a two-terminal pair device

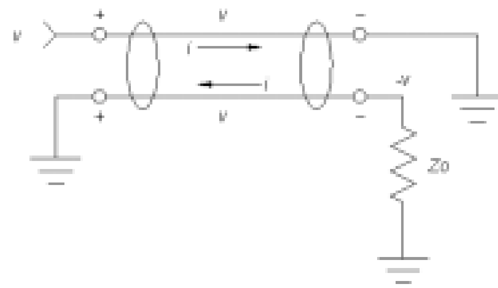

Figure 6 - Order-1 Transmission Line Transformer Used as a 1:1 Phase Inverter

which consists of *m* connected lines. A TLT of order (*m* + 1) is obtained by connecting an additional transmission line to the terminals of an order-*m* TLT, in parallel at one end and in series at the other end [6]. The voltage transformation ratios of the first four orders of TLTs are shown in Fig. 4.

A TLT of order-1 is a single transmission line [6], and applications of order-1 TLTs are shown in Fig. 5 as a device commonly referred to amongst radio amateurs as a choke balun, where the floating load Z_{out} receives the equal and opposite currents from the output terminals of the TLT. Since the voltages along the length of both sides of the TLT must be equal, the voltage along the length of the TLT is half the input voltage, therefore causing the output terminal voltages to be +v/2 and -v/2. This convenient form of balun will work equally well with symmetrical (balanced) loads.

The order-1 TLT is also shown in Fig. 6 as a 1:1 phase inverter, and again in Fig. 7 as a 1:1 current balun, which has output cur-

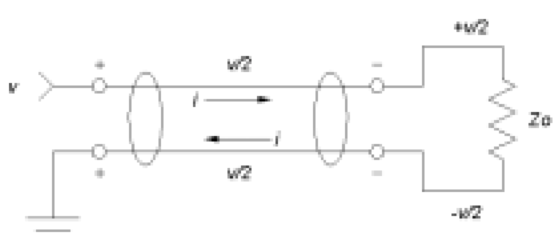

Figure 5 - Order-1 Transmission Line Transformer Used as a 1:1 Choke Balun

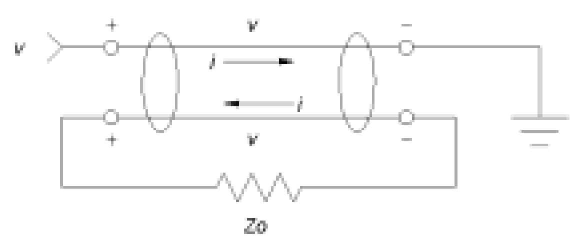

Figure 7 - Order-1 Transmission Line Transformer Used as a 1:1 Current Balun

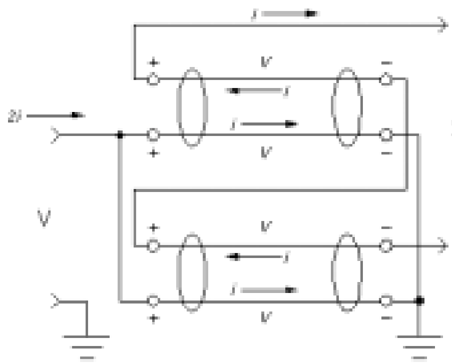

Figure 8 - Order-2 Transmission Line Transformer Used as a 2:1 Current (1:4 Impedance) Balun

rents that are equal in magnitude and opposite in phase regardless of the potentials at the output terminals with regard to the ground connection on the unbalanaced (input) side [21].

TLTs of *r* :1 voltage ratio are the simplest configuration; they consist of *r* transmission lines, all of them connected in series at one end and in parallel at the other [6]. Fig. 8 and Fig. 9 shown the connections for TLTs having voltage (and current) ratios of 1:2 (1:4 impedance) and 1:3 (1:9 impedance), respectively. In Fig. 8 it is obvious from the voltages and currents that the output voltage is twice

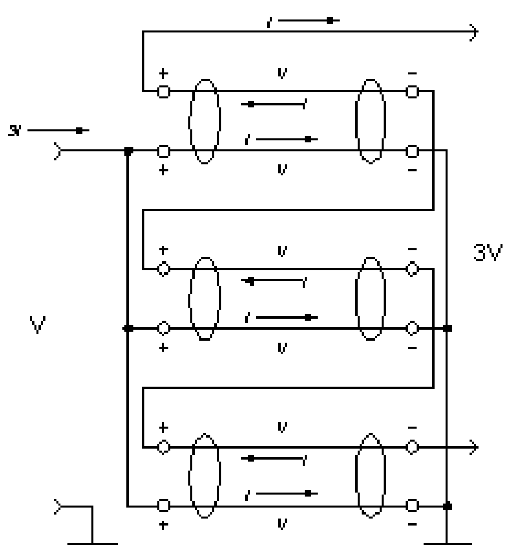

Figure 9 - Order-3 Transmission Line Transformer Used as a 3:1 Current (1:9 Impedance) Balun

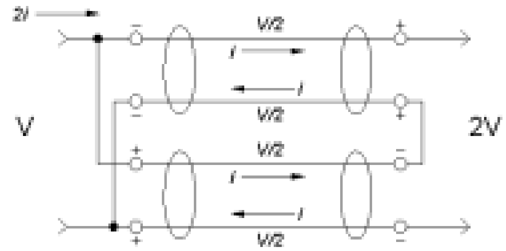

Figure 10 - The Guanella 1:4 Impedance Ratio Transmission Line Transformer (single core realisation)

the input voltage, and the input current is twice the output current, thus the impedance ratio is 1:4 (1:r^2). A similar analysis can be followed for Fig. 9. Since the voltages and currents for all sections of the 1:r voltage ratio are identical, this class of order-*r* TLT can be constructed on a single core.

The synthesis procedure for an arbitrary integer voltage ratio is fairly simple. An $H : L$ ($H > L$) voltage ratio TLT is decomposed into an (H - L):L ratio TLT and a transmission line which is connected in series with the (H - L) side and in parallel with the L side. The procedure is repeated until a 1:1 order-1 TLT is reached [6].

Fig. 10 illustrates the connections for another form of order-2 TLT having a 1:2 voltage transformation ratio (1:4 impedance ratio) commonly known as the Guanella 4:1 impedance ratio transformer [1, 4, 22], where an additional transmission line has been added to the order-1 1:1 choke balun of Fig. 5. Notice here that the added transmission line is connected in parallel on the left and in series on the right. This device is very popular amongst radio amateurs, and when used with a floating load such as an antenna it may be constructed on a single core as the voltages and currents for the two transmission lines are identical.

Fig. 11 illustrates the connections for an order-3 TLT having a voltage ratio of 3:2 (im-

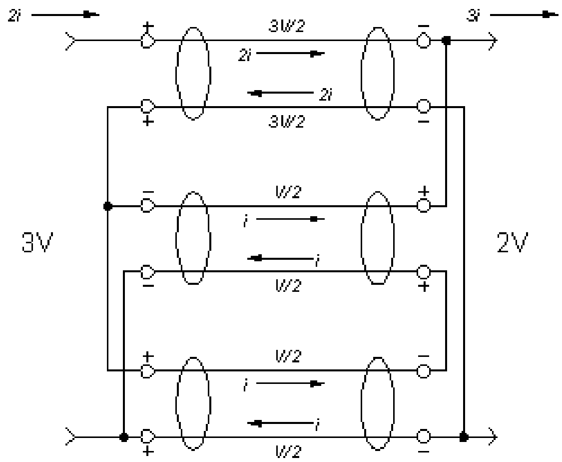

Figure 11 - Order-3 Transmission Line Transformer Having a 3:2 Voltage (2.25:1 Impedance) Ratio

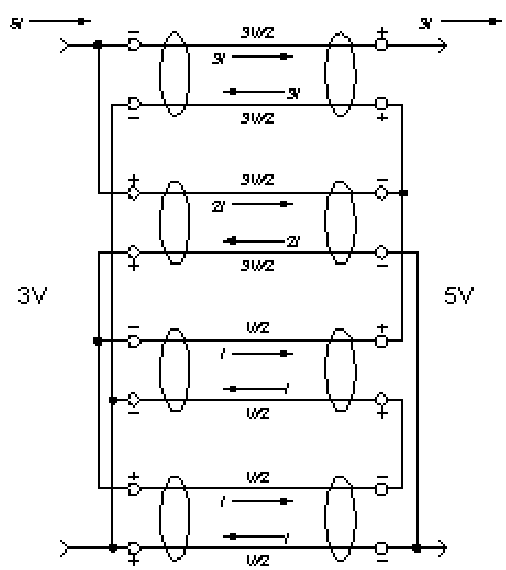

Figure 12 - Order-4 Transmission Line Transformer Having a 3:5 Voltage (1:2.78 Impedance) Ratio

pedance ratio of 2.25:1), where an additional transmission line has been added to the order-2 Guanella 1:2 voltage ratio TLT of Fig. 10. Notice here that the added transmission line is connected in parallel on the right side and in series on the left.

Fig. 12 illustrates the connections for an order-4 TLT having a voltage ratio of 3:5 (impedance ratio of 1:2.78), where an additional transmission line has been added to the order-3 3:2 voltage ratio TLT of Fig. 11. Notice here that the added transmission line is connected in parallel on the left side and in series on the right.

Additional forms of order-2, order-3, and order-4 TLTs are possible, the ones shown here being used as examples. Many rigorous synthesis procedures have been published, such as those by McClure [23, 24], Myer [25], and Gluszczak [26], as well as a synthesis procedure for designing TLTs having fractional transformation ratios [27].

Closing Remarks

The design and application of transmission line transformers using multiple sections of transmission line having identical lengths and characteristics is an establish element of RF design and has been part of the technology for over 60 years, beginning as early as the impedance transformer published by Guanella [1]. TLT realizations using magnetic materials to extend the low and high bandwidth limits can have frequency bandwidths of four decades or more, The technology and synthesis procedures are readily available and easily understood even by those having entry level experience in the profession of RF circuit design.

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