## RF Transformer Design

We have seen earlier how matching networks can be constructed from lumped elements (L, pi, and T networks), tapped C and L networks, and from transmission line sections. All of these approaches are effective at matching source to load impedances. Resonators have also been used for filtering and matching purposes.

At high frequencies, transformers can also be used for matching. They can provide much wider bandwidths than tuned matching circuits. They are used because:

1. high permeability magnetic materials exist that are very low loss over wide frequency ranges.

2. They can also be small in volume due to the high frequencies involved, but

3. are of limited usefulness on-chip for analog RF ICs.

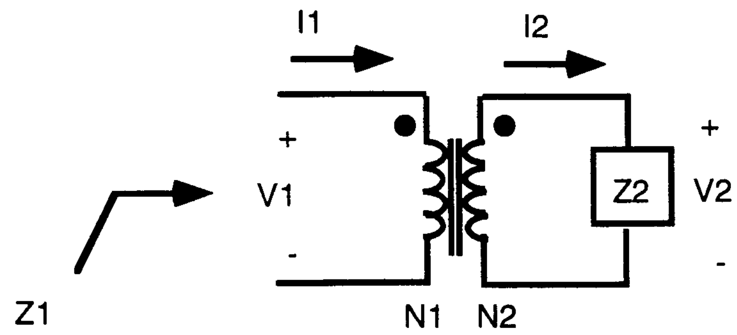
Typically, they are of use over frequencies that range from 1 MHz up to about 500 MHz. At higher frequencies, it is hard to get good low loss magnetic materials.

In this document, 2 types of RF transformers will be discussed:

1. Magnetic flux-linked (wideband) transformers

2. Transmission line transformers (very wideband)

## Ideal Transformer




1. Current into dot causes current to flow out of dot.

2. For ideal transformer, complete magnetic coupling is assumed. L1 and L2 are assumed to be infinite. Ferromagnetic core material is required.

3. $V2 = V1\ (N2/N1)$

$I2 = I1\ (N1/N2)$

Since $Z2 = V2/I2$ and $Z1 = V1/I1$

$$\boxed{\mathbf{Z1 = Z2\ (N1/N2)^2}}$$

***An ideal transformer produces an impedance ratio = (turns ratio)$^2$***

4. Also, $L1/L2 = (N1/N2)^2$. The ratio of self inductance of the windings is finite.

## Nonidealities of RF transformers

1. Finite primary inductance.

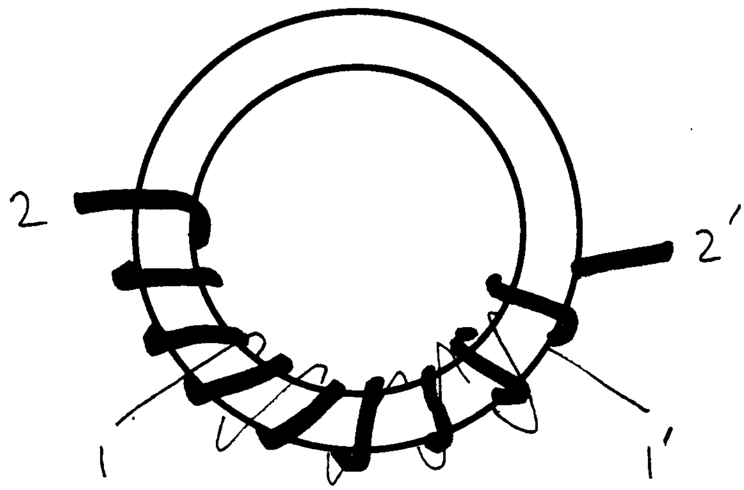
a. L1 can't be arbitrarily large. This restriction will limit the low frequency cutoff. As the number of turns becomes larger, the capacitance between turns on the core leads to self resonances. The transformer behavior will become nonideal near resonance. This will cause a high frequency limit to performance.

b. The low frequency cutoff will be limited by the inductance. The rule of thumb for wideband transformer design is to keep the inductive reactance of the low impedance side about 4 times larger than Z1.

$$\boxed{\omega L_1 \geq 4\ Z_1}$$

High permeability ferrite core materials help to increase this inductance per turn. But, the highest $\mu$ ferrites become rather lossy at higher frequencies.

Wind the transformer turns over each other as shown in the sketch below.




If you really need higher frequency bandwidth than the RF "ideal" transformer can provide, then you need to use a **transmission line transformer.**

## Transmission Line Transformers[1][2]

These transformers consist of transmission lines wound on a magnetic core. At high frequencies, the lines themselves act independently of the core. At low frequencies, the core magnetic flux links the windings and they behave like conventional transformers. Because they operate in two modes, the bandwidth is greatly extended.

The transmission lines can consist of:

- twisted pairs of wires with enamel or plastic insulation
  - enameled #24 wire gives a $50\Omega$ impedance
  - plastic insulated #24 wire gives about $100\Omega$
- coax cables
- parallel wires separated by air or plastic (for higher Zo)
- for lower impedances, twisted line pairs can be twisted together and connected in parallel.

Core material: ferrite has the higher permeability and is preferred. Toroidal shapes are generally used, although rods or beads can also be used in special cases.

These transformers can be used to convert from

- balanced to unbalanced (a "balun" transformer)
- unbalanced to unbalanced (an "unun" transformer)

Impedance transformations can also be obtained, generally fixed to ratios of 1, 4, 9, 16.

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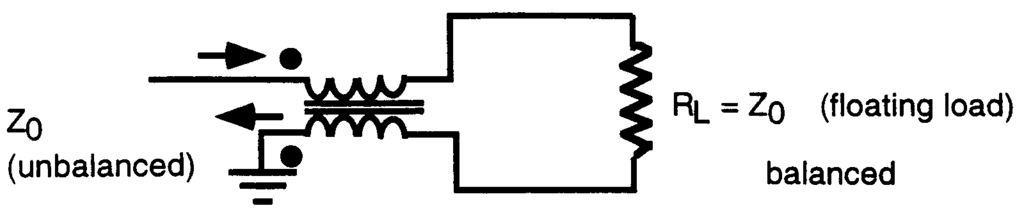
[1] J. Sevick, *Transmission Line Transformers*, Noble Publ., 1996.
[2] H. Krauss, C. Bostian, F. Raab, Solid State Radio Engineering, pp. 371-382, Wiley, 1980.

## Guanella 1:1 Balun

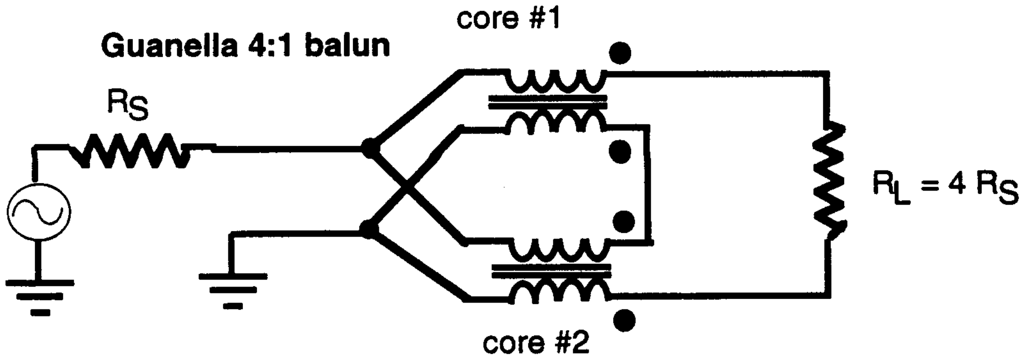



1. Currents must flow in opposite directions through winding that forms the transmission line. Equal currents will flow in and out at the dots.

2. This provides a 1:1 impedance ratio. Optimum line impedance is Z0.

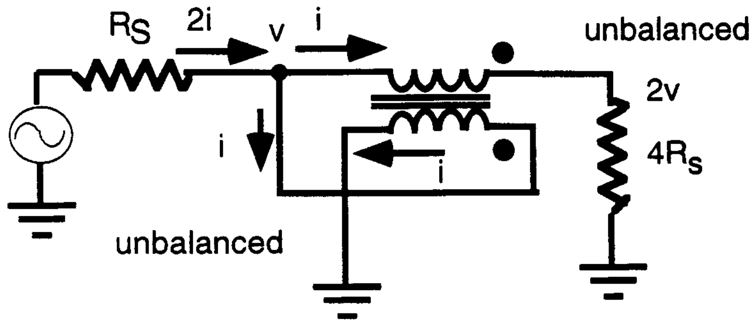
3. The inductance of the transformer provides common-mode isolation for low frequencies. See below for a discussion of how much inductance is needed.

**4:1 balun.** Two baluns can be connected in parallel at the input and in series at the output to give a 4:1 impedance transformation ratio and a unbalanced to balanced transformation.




Each transmission line sees 1/2 of the load $R_L$. Therefore, the optimum Zo = $R_L/2$.

**Ruthroff 4:1 un-un**

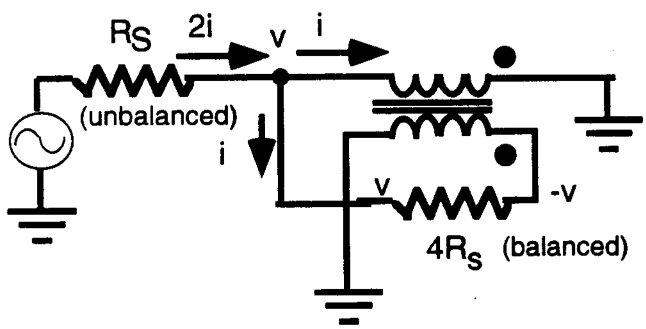



The circuit above provides a 4:1 transformation between two unbalanced impedances. It works by bootstrapping the voltage from v at the left to 2v at the right. The transformer windings are connected in series. The current at the input is 2i, split two ways. So the output current is just i. So, we get twice the voltage and half the current at the output.

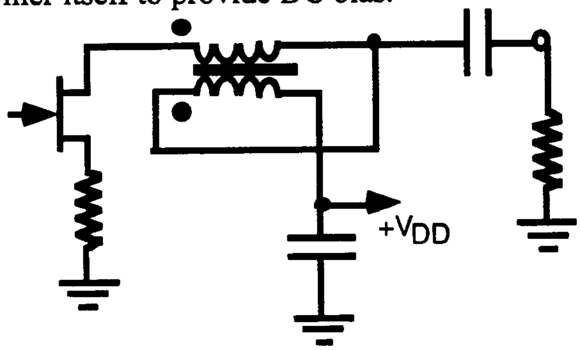
The optimum transmission line impedance is $Zo = R_L/2$.

The Ruthroff un-un can be modified to operate as a balun as well as shown below.

**Ruthroff 4:1 balun**




Finally, we can see that all of these baluns and ununs have a DC path through them. This helps with biasing. We can often eliminate the need for an RF choke by using the transformer itself to provide DC bias.



**How many turns should be used?**

High Frequency limitations. Fig. 1.4 shows that the 1:4 Ruthroff unun is very sensitive to transmission line length. The shorter the length the better. Thus, the minimum number of turns should be used for lowest loss at high frequency. The Guanella balun is less sensitive since two lines are combined with equal lengths, minimizing the phase shift.

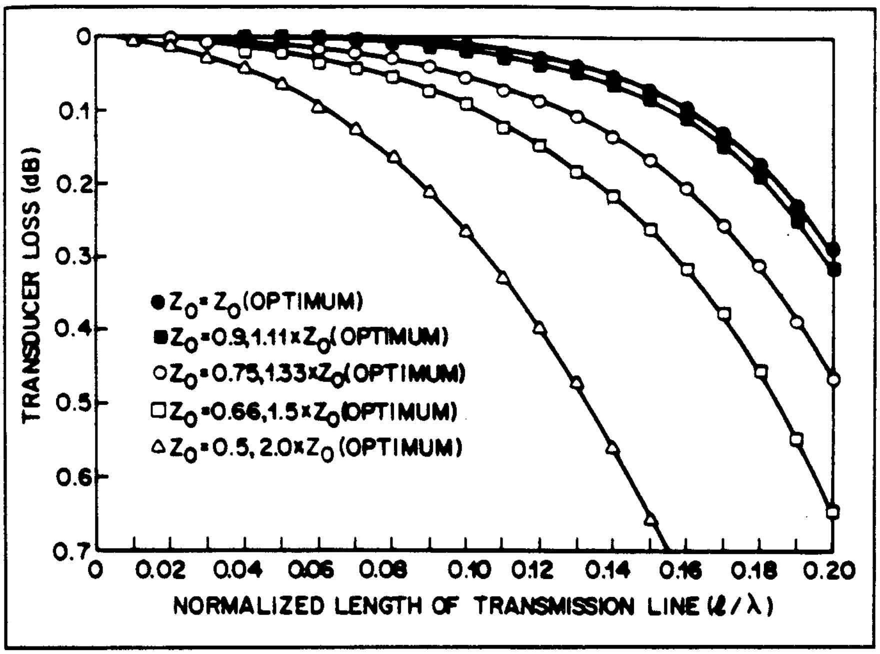



**Fig 1-4—Loss as a function of normalized transmission line length in a Ruthroff 1:4 unun for various values of characteristic impedance, $Z_0$.**

But, the low frequency response will require some specific inductive reactance relative to the load impedance being used since it is operating as a conventional flux-linked transformer at low frequencies. So, the type of ferrite and the number of turns of the lines around the core are determined by the low frequency behavior.

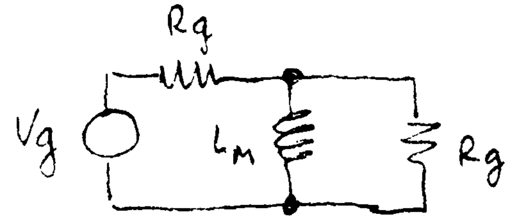
For a toroid, the core magnetizing inductance is given by:

$$L_M = 0.4\pi\, N_P^2\, \mu\mu_0 (A_e/l_e)$$

where $N_P$ = number of primary turns (normally same as secondary turns for the transmission line transformer)

$\mu$ = relative permeability
$\mu_0 = 4\pi \times 10^{-7}$ Henry/meter
$A_e$ = effective cross sectional area of core
$l_e$ = average magnetic path length in the core

At low frequencies, the equivalent circuit of the transformer becomes:




It can be shown that

$$P_{av}/P_{out} = (R_g^{\,2} + 4X_M^{\,2})/4X_M^{\,2}$$

where $X_M = \omega L_M$

Therefore, large $X_M$ leads to smaller losses. If we consider a 10% loss to be tolerable, $X_M \sim 3R_g/2$.

Then you can combine the equations above to solve for the approximate minimum number of turns required for 10% loss at a given frequency for a given core material.

$$N_P = 388\,(R_g l_e/f\mu A_e)^{1/2}$$

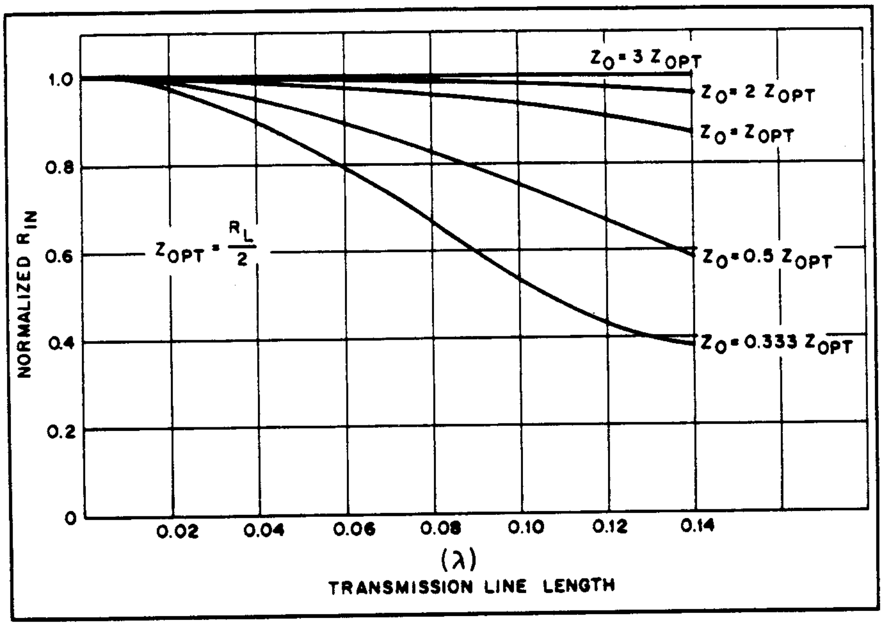
From this equation, we can observe two things:

1. Higher Rg leads to more turns. Thus, it is harder to build a wideband balun that steps up to high impedances.

2. Smaller diameter cores will reduce $l_e/A_e$ and reduce the transmission line length. Therefore, small cores will give better bandwidth.

How sensitive is the unun or balun to the transmission line impedance?

In these figures, the normalized input (low impedance side) resistance and reactance are plotted vs. length with the characteristic impedance of the transmission line $Z_0$ as a parameter. $Z_{OPT}$ = 2 Rg for the 4:1 balun or unun.



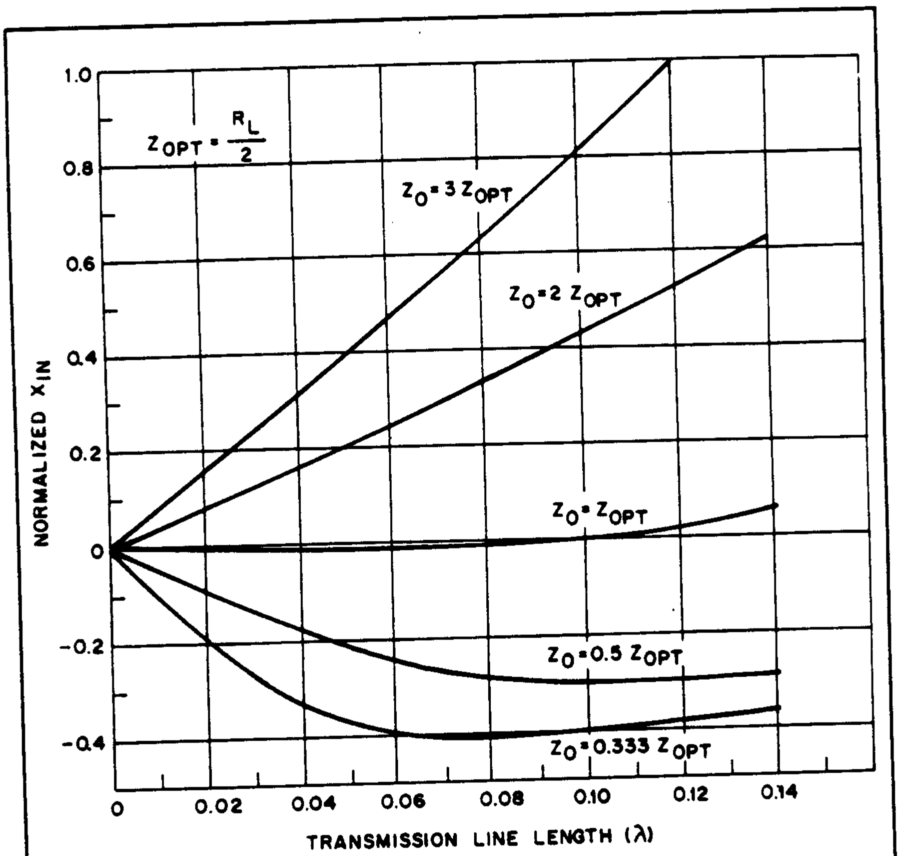




**Fig 1-6—The normalized imaginary part of the input impedance of a Ruthroff 1:4 unun as a function of $Z_0$ and the length of the transmission line.**