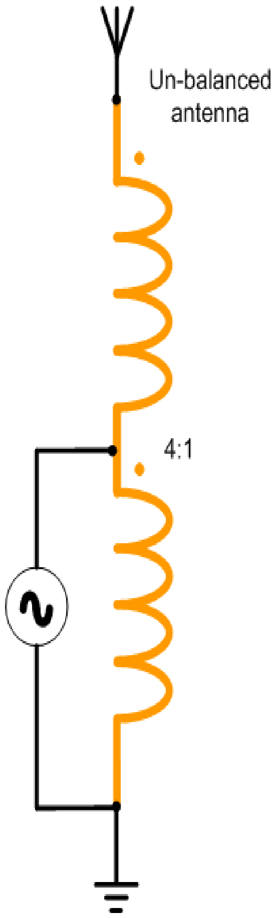
The design of Ruthroff broadband voltage transformers – M. Ehrenfried – G8JNJ

Introduction

I started investigating balun construction as a result of various observations I made whilst building HF antennas. These problems were particularly evident when the transformer was installed at the base of a short vertical, in order to facilitate the use of a remote, coax fed tuner. I wanted to achieve a wide (1 - 55MHz) bandwidth and whilst optimising the antennas found that I had great difficulty in getting many broadband transformers to work well, especially published designs using low permeability type 2 or type 6 iron powder cores.

Problems included, limited bandwidth, poor impedance transformation ratios, high through loss and large impedance swings due to self resonance, especially when connected to reactive loads such as antennas. Many of these problems seem to be directly associated with the widespread use of low permeability of the core materials, which I do not believe are suited for this purpose.

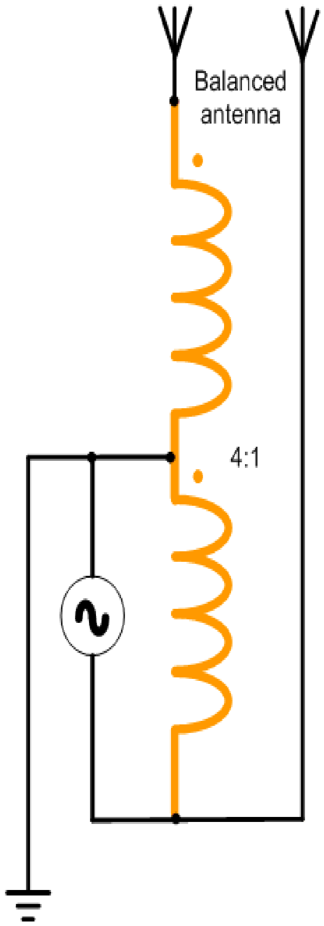
Whilst researching the subject I also discovered several other factors which play a major part in implementing a successful design. Some of these are not totally in agreement with previously published articles on the subject and I invite feedback on any of the subjects raised in this document.



These notes primarily relate to the construction of 4:1 Unbalanced to Unbalanced, Ruthroff voltage transformers (UnUn), where one end of the windings are connected to ground and the centre connection is used as the 50 ohm feed point.

This configuration has a reduced upper frequency limit in comparison to the same transformer when being used to feed a balanced load. The reason for this will be explained later.

However many of the basic principles outlined will equally apply when the design is used for other impedance ratios, or as a Balanced to Unbalanced (BalUn) transformer.



I have documented my findings and summarised the influences on overall performance.

In order to illustrate some of the problems I have observed, I constructed and measured the performance of three transformers wound on T200A-2 core material.

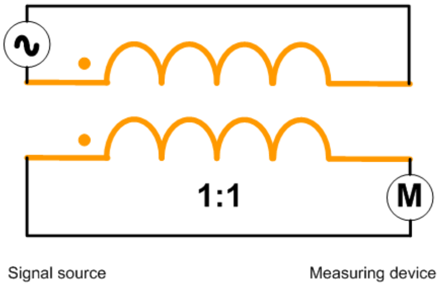
The sequence of graphs relate to the following transformers:-

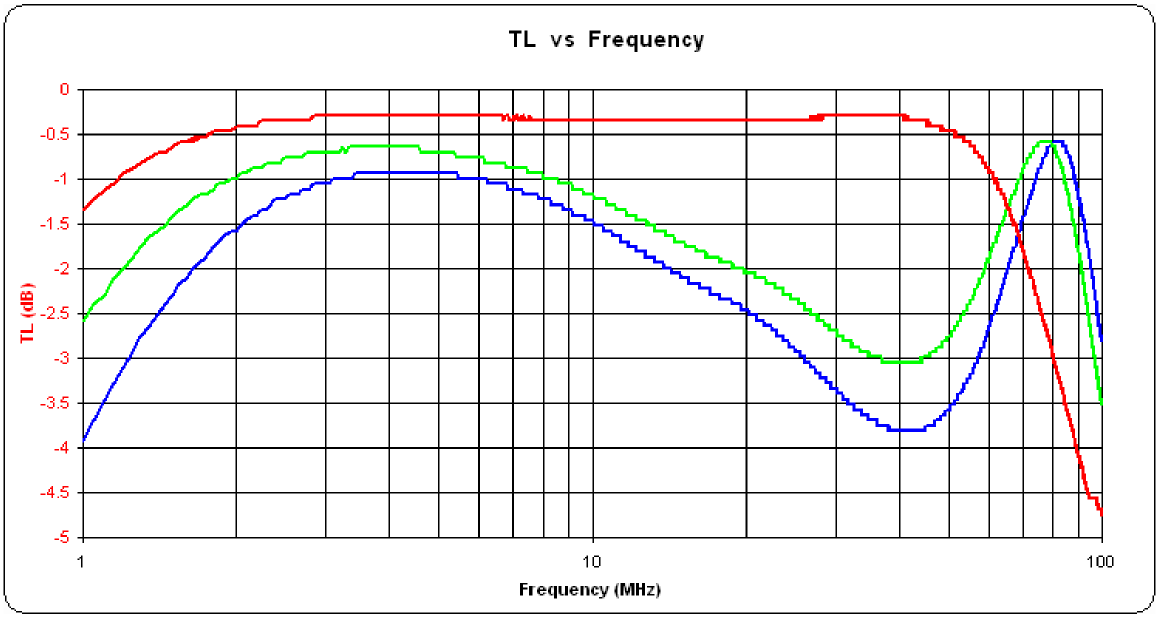
Red trace -1mm enamelled wire close spaced bifilar wound. (In this example the core is wound with PTFE tape to prevent the damage to the wire insulation layer). I played around with this particular design in order to optimise the performance and get a good flat response. Note that the windings are not evenly spaced around the ring core. I will comment on this later.

Blue trace - Twin speaker cable, typical of many published designs.

Green trace - Twin speaker cable, but with closely spaced windings. I did this is order to demonstrate how variations in construction can affect the performance.

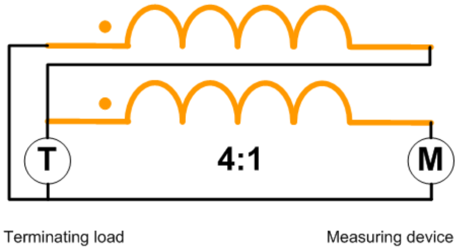
The first graph shows the through loss of each design configured as a 1:1 broadband transformer. Note that this is not a transmission line transformer, but two sets of closely coupled windings. The purpose of this is to demonstrate how different winding styles can alter the coupling coefficient.

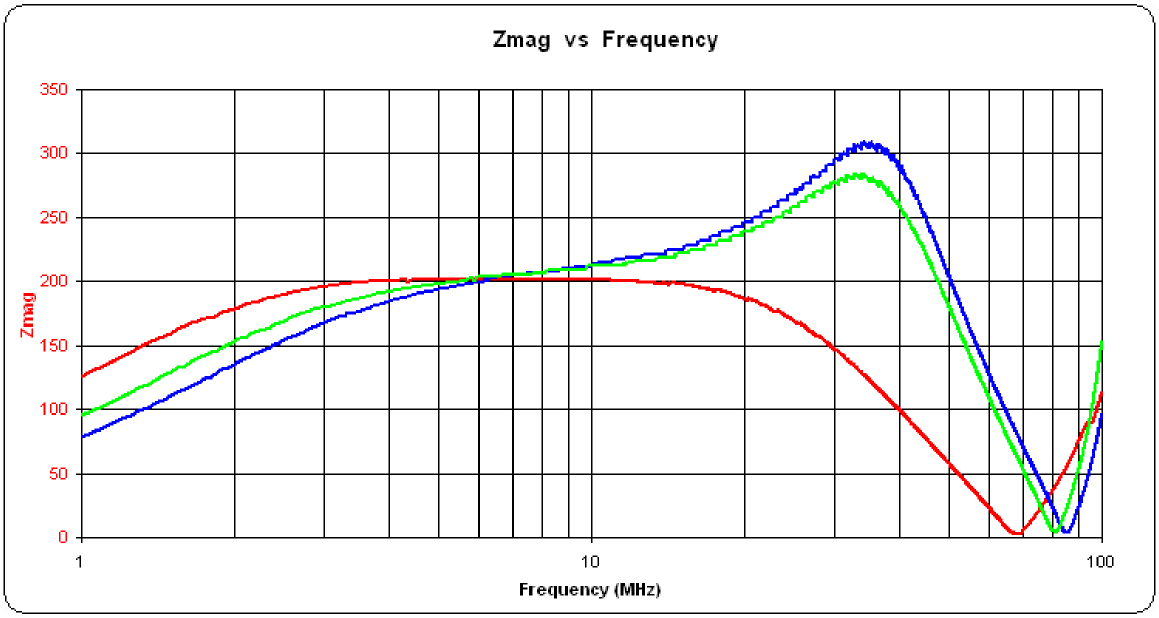




Red trace -1mm enamelled wire close spaced bifilar wound
Blue trace - Twin speaker cable
Green trace - Twin speaker cable close spaced

The next graph shows the same windings but connected as a 4:1 Ruthroff transformer, with a target secondary impedance of 200 ohms.





Red trace -1mm enamelled wire close spaced bifilar wound
Blue trace - Twin speaker cable
Green trace - Twin speaker cable close spaced

Notice how the low permeability of the core limits the performance at low frequencies, and the resulting length of winding limits the performance at high frequencies. There is a peak at around 40MHz where the electrical length of the transmission line is ¼ wavelength and a trough at around 80MHz where the electrical length of the transmission line is ½ wavelength.

From this it is apparent that type 2 material does not have a high enough permeability for use as an HF transformer (type 6 is even worse) with this number of winding turns.

As a stated earlier, I found that I could influence the performance of the transformers by winding adjacent turns closer together, which led me to investigate further.

First let's review how a Ruthroff transmission line transformer works. In the Unun configuration, one wire of the transmission line is connected across the signal source.

The end of the first wire is also connected to the start of the second wire pair which forms the transmission line.

The load is connected across the start of the first wire, and the end of the second wire.

The second wire has a voltage induced into it which is equivalent to that across the first wire.

This adds in phase with the source voltage to create a voltage across the load, which is twice the input voltage. Because product of the input current and voltage has to equal the product of the output current and voltage (minus any losses). This equates to an output impedance of four times the input impedance.

The main problem is that the first wire is connected directly across the source, so it needs to have a high enough reactance to prevent the input signal from being shorted to earth.

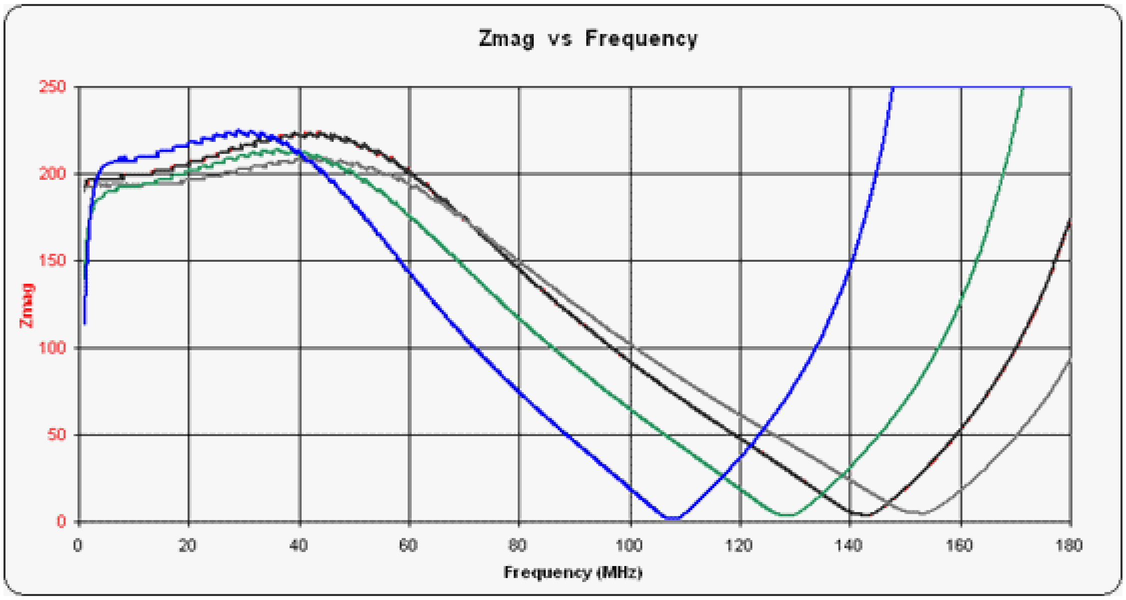
The second problem is that a phase shift occurs along the second wire, resulting in a phase reversal when the wire is ½ wavelength long; at this point the output voltage becomes zero. So in practice this limits the upper operating frequency to a point at which the wire is ¼ wavelength long (corresponding to a 90 degree phase shift). Beyond this frequency the fall off in performance becomes much more rapid.

Note that any common mode current will manifest itself as a common mode impedance shunting the input, reducing performance. So this parameter is very important in the implementation of a successful design.

It is possible to wind a Ruthroff transformer by using coax in place of a bifilar winding. In this case common mode currents will flow on the outer of the coax screen. The inside of the coax outer screen, and the inner conductor form a balanced transmission line. As is the case with a Ruthroff transformer wound with a twin wire TL, maintaining a high common mode impedance is equally important, as we will see later.

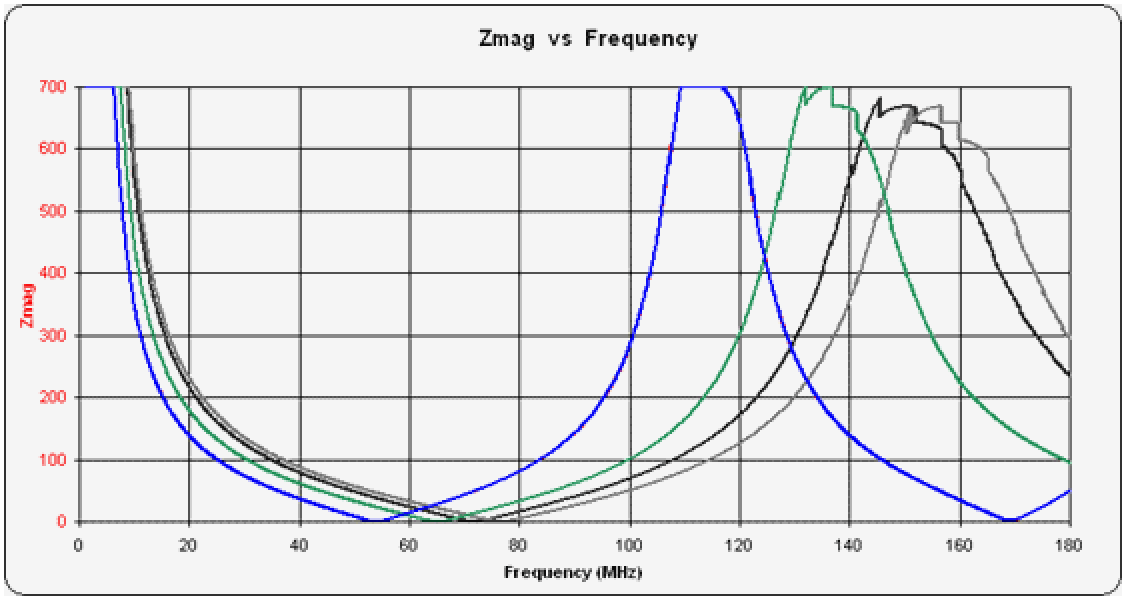
High Frequency performance

The next set of graphs show the secondary impedance of 4:1 Ruthroff transformers wound on different cores when terminated with a 50 ohm load on the primary. In all cases the windings had been optimised for performance over the 2 to 52MHz frequency range. The differing permeability's of the materials required slightly different numbers of turns and therefore different cable lengths.



Notice the notches in the response curves at around 110 to 150MHz.

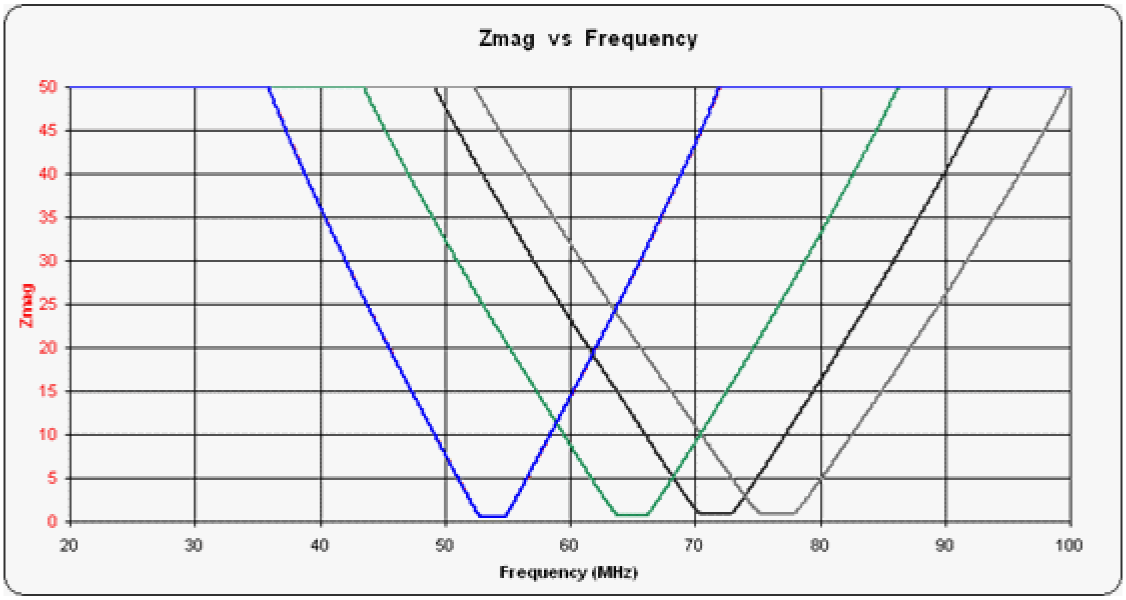
These correspond to a ½ wavelength of cable, when measured as a transmission line. This can be better seen in the next graph which shows the input impedance of the cable used to wind the transformer with the far end un-terminated (open circuit).



So in practice the upper frequency limit of operation of a 4:1 Ruthroff transformer is defined by the electrical wavelength of the wire used for the winding, which has to be less than ¼ wavelength at the highest required operating frequency. This to the point at which a 90 degree phase reversal occurring along one of the windings when it is electrically ¼ wavelength long.

This highlights the major difference between the Ruthroff transformer used as an Unun or as a Balun. When configured as a Balun the ‘earth’ point is at the centre of the transformer. The load can be considered to be split with its centre point also at ‘earth’ potential (even if it is a ‘virtual earth’). Because of this the phase shift occurs across both wires so there is no phase cancellation when the electrical length of transmission line becomes ½ wavelength.

The next graph is a selected portion of the previous graph showing the transformer in an Unun configuration. I've chosen this to demonstrate the frequencies at with the various windings are electrically a ¼ wavelength long.



This has a serious consequence if you wish to wind a Ruthroff 4:1 transformer for operation over a wide frequency range of say 1.9 to 52MHz. The upper frequency limit sets the maximum length of winding and therefore the maximum number of turns which can be accommodated on a given size of ring core.

In order to obtain good performance at the low frequency end either a higher permeability material has to be used or the core size has to be reduced.

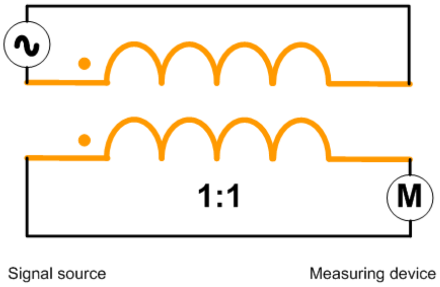
Increasing the inductance by using a greater depth of ring core, such as twice height versions (type A), do not improve this situation, because the reduction in turns is offset by the increased length of wire required to complete each turn. In fact the wire length remains almost constant for a given value of inductance.

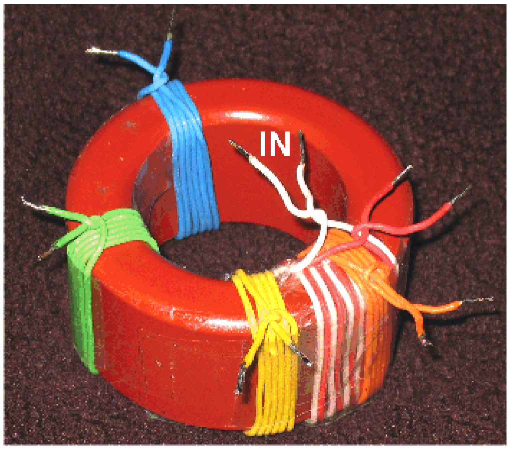
Many popular broadband transformers use ring core sizes of around 2" diameter, this equates to a maximum number of turns which can be used in order to ensure adequate performance at the HF end of the required frequency range. For an upper frequency limit of 50MHz this is about 8 to 10 turns, and for 30MHz it is about 20 turns. Type 2 and 6 Iron powder cores generally do not have a high enough permeability to give good low frequency performance with this number of turns.

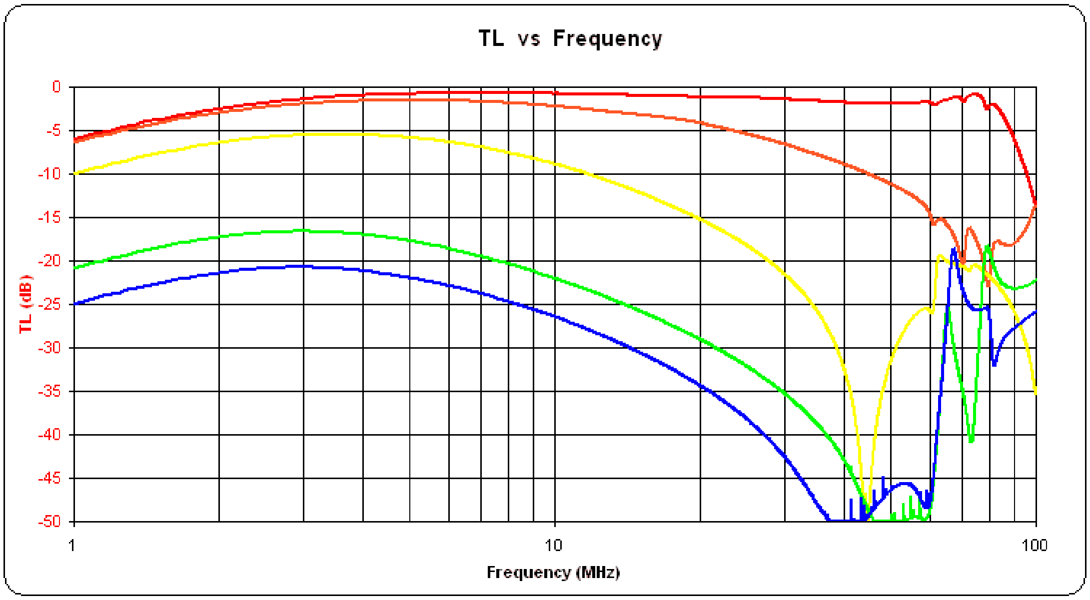
Unfortunately another side effect of adding turns, apart from the reduction in the usable frequency range, is that it leads to rather unpredictable self resonances occurring. Particularly when used to feed reactive loads such as antennas.

Low frequency performance

In order to investigate the influence of the core on low frequency performance I tried measuring the coupling between coils mounted at different positions on a T200A-2 Iron powder core. The signal was fed into the white set of windings and the output measured on each of the other sets of coloured windings.



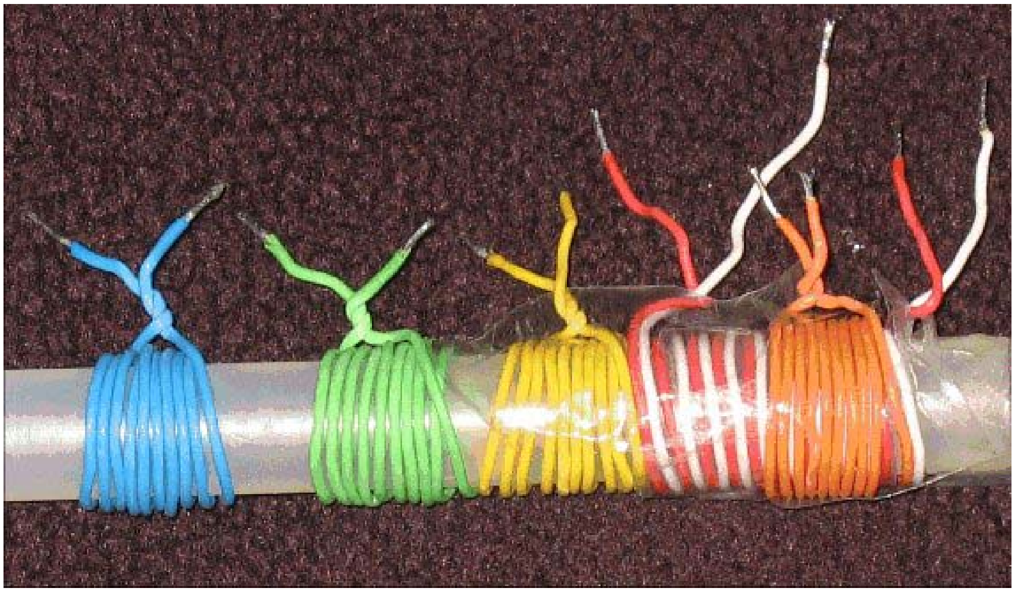


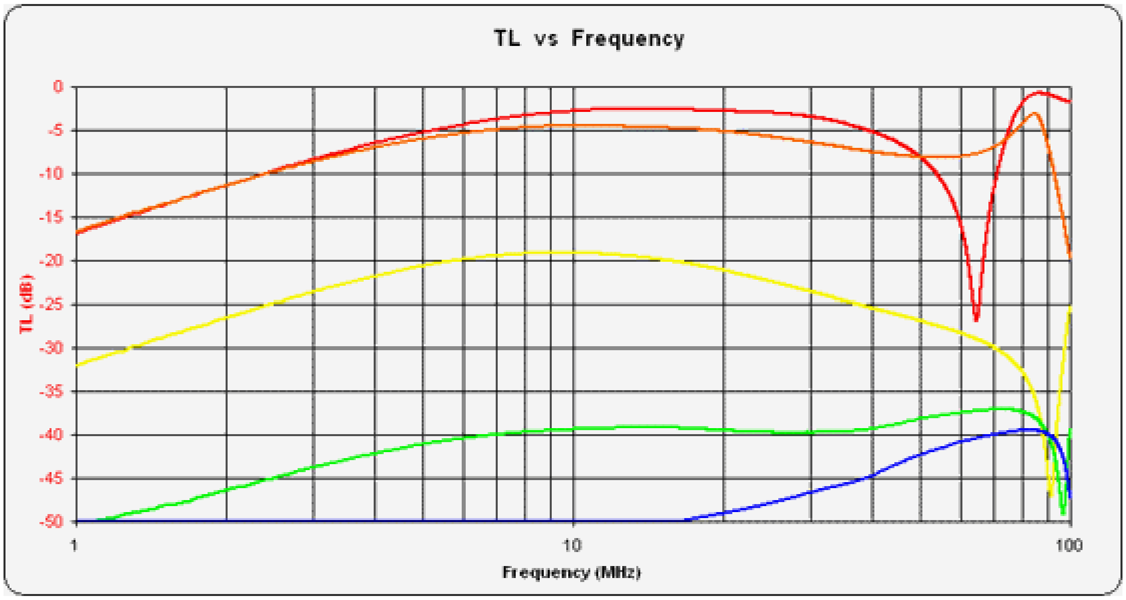


Red trace – winding bifilar with the input winding
Orange trace – winding laid over the input winding
Yellow trace – winding adjacent to input winding
Green trace – winding ¼ way around core
Blue trace – winding ½ way around core

As can be seen from the graph the red and white bifilar windings produced the best performance. There is a progressively higher level of loss as the windings are moved further apart on the core. The larger the core diameter, the higher the loss. I have seen a few examples of transformers wound with separate coils on opposite sides of a ring core. I think this graph dramatically illustrates why this is not a good idea.

The low permeability of the T200A-2 core limits its performance and it is worthwhile comparing these results against similar sized coils wound on a plastic rod using similar spacing.



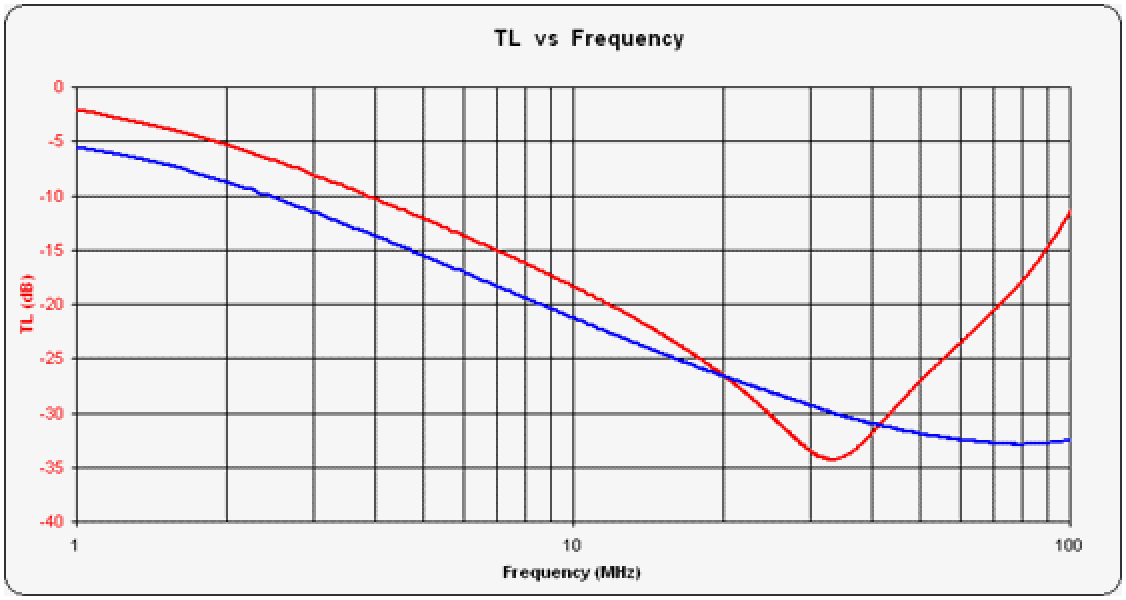


Red trace – winding bifilar with the input winding
Orange trace – winding laid over the input winding
Yellow trace – winding adjacent to input winding
Green trace – winding ¼ way along rod
Blue trace – winding ½ way along rod

By comparing the two sets of graphs it is possible to see how the core influences the low frequency performance.

These measurements also indicated that there is little flux coupling through the core material, beyond the actual windings. In order to further demonstrate this point, here is a plot of the coupling between two coils wound on opposite sides of much higher permeability cores. In this case two different types of ferrite material.

The small amount of coupling which is present due to the core is only likely to be noticed at the low frequency end of the frequency range. I return to this subject later.



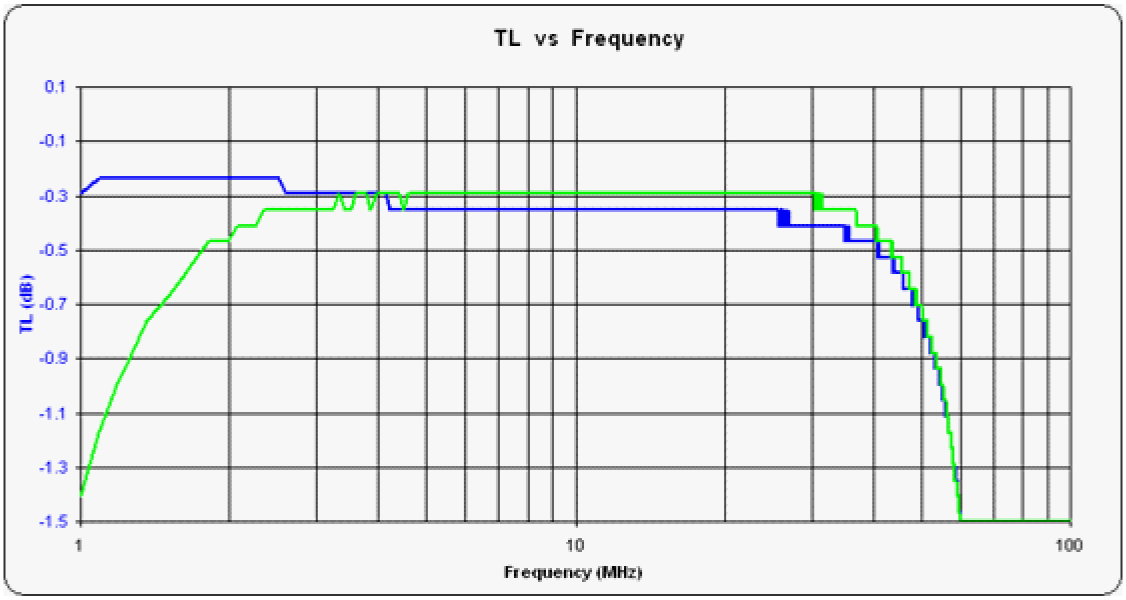
Blue trace - FT 240-61
Red trace - FT180-43

It struck me that using a ring core for transformer construction was not as important as many people may have suggested. The main argument being that transformer wound on a ring core is less susceptible to core saturation than one wound on a rod made of the same material.

From these measurements I concluded that very little magnetic flux was carried around the whole of the core, and that even this small amount is only noticeable at the low frequency end of the spectrum.

In order to demonstrate this theory I wound a 4:1 Ruthroff transformer on an Iron Powder core, and measured the through loss into another 4:1 transformer. I then cut a section out of the core and repeated the same measurement.

Here’s a graph showing the difference in loss, both before, and after the modification.



Blue trace – Full core
Green trace – With section removed

Notice how the response curves are practically the same except at the very low frequency end of the graph. The blue trace shows the loss with the core intact, the green trace shows the loss with the section removed, which only makes about 0.2dB difference at 2MHz.

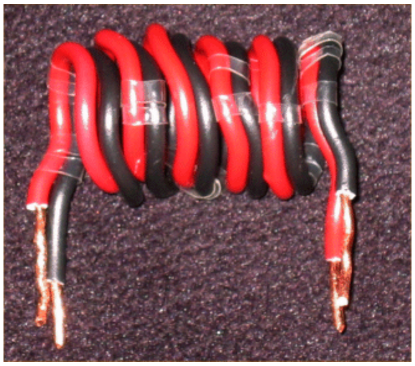
I believe this clearly demonstrates how little difference any flux circulating around the core material actually makes. Obviously this is effect would be more noticeable when using small cores, as a larger proportion of the total core would be within the field of flux that extends around the windings.

There are a couple of other factors relating to low permeability cores, the first is the limited inductance which means that the performance can be improved by winding adjacent turns next to each other, rather than evenly spacing turns around the whole of the core diameter. This has the positive effect of slightly increasing the common mode impedance.

Another problem with using a low permeability ring core is that the shape of the winding further reduces the inductance of close spaced windings.

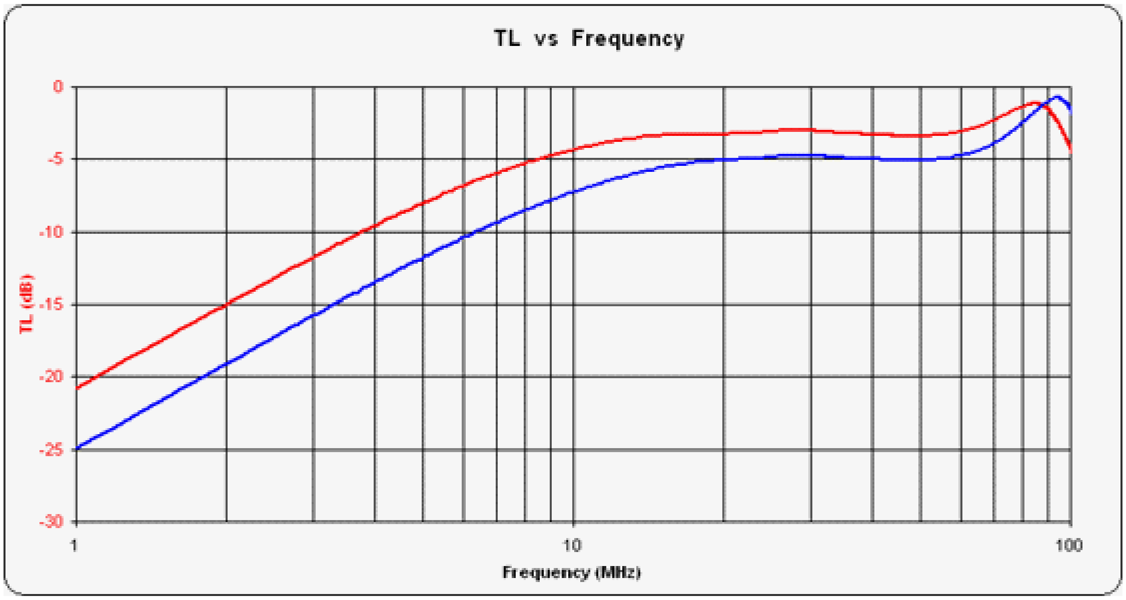
When wound on a ring core the windings on the outside of the core are further apart from each other, than those on the inside of the core.

In order to demonstrate this I measured a 1:1 transformer, made from a bifilar pair of wires with and air core under two conditions.



The red trace was with the coil conventionally wound.

The blue trace was with the coil unwound to follow the shape of a ring core. The loss associated with each style of winding is shown below

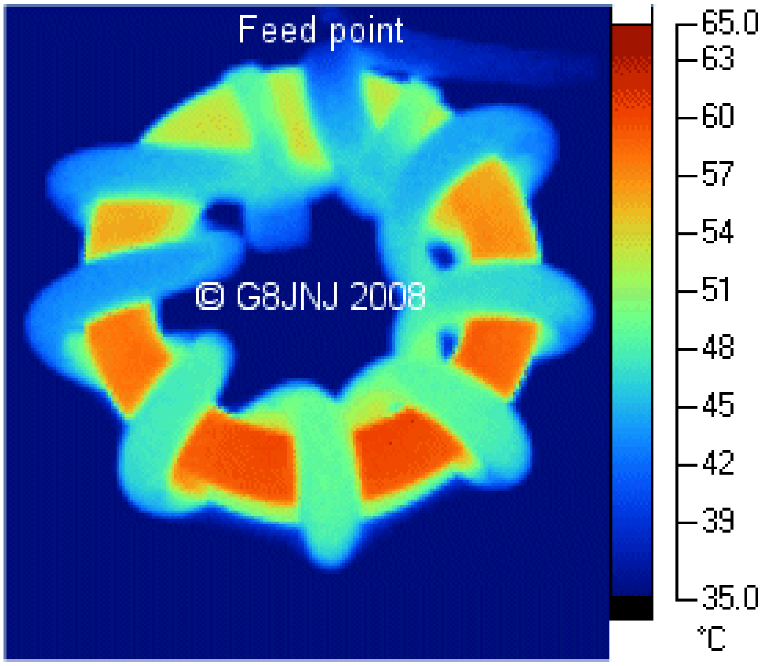


Red trace – close wound
Blue trace – curved winding

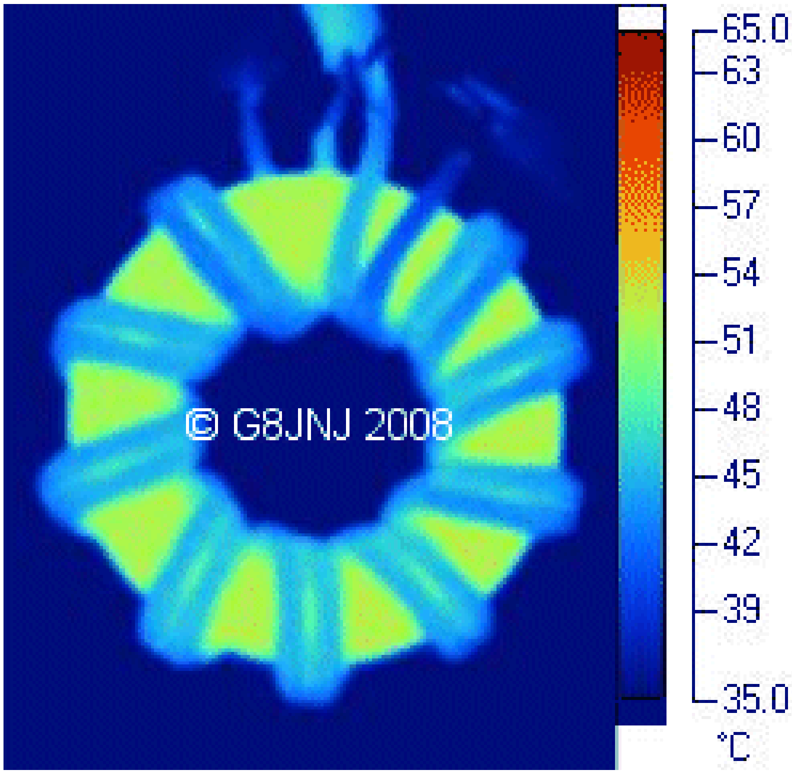
As can be seen the effect is more noticeable at the low frequency end where the reduction in coupling between turns has increased the loss by 5dB.

Another interesting aspect of low permeability cores is the concentration of flux towards the centre of the windings. This causes localised heating of the core material which can be clearly seen with a thermal imager.

The following picture of a 4:1 transformer wound with coax and being fed with 100 watts of RF for about 5 minutes, shows this effect quite dramatically, as there is a 10 degree temperature differential across the core.



This does not occur with higher permeability materials and the heating is evenly distributed around the whole diameter of the core.



Other Factors

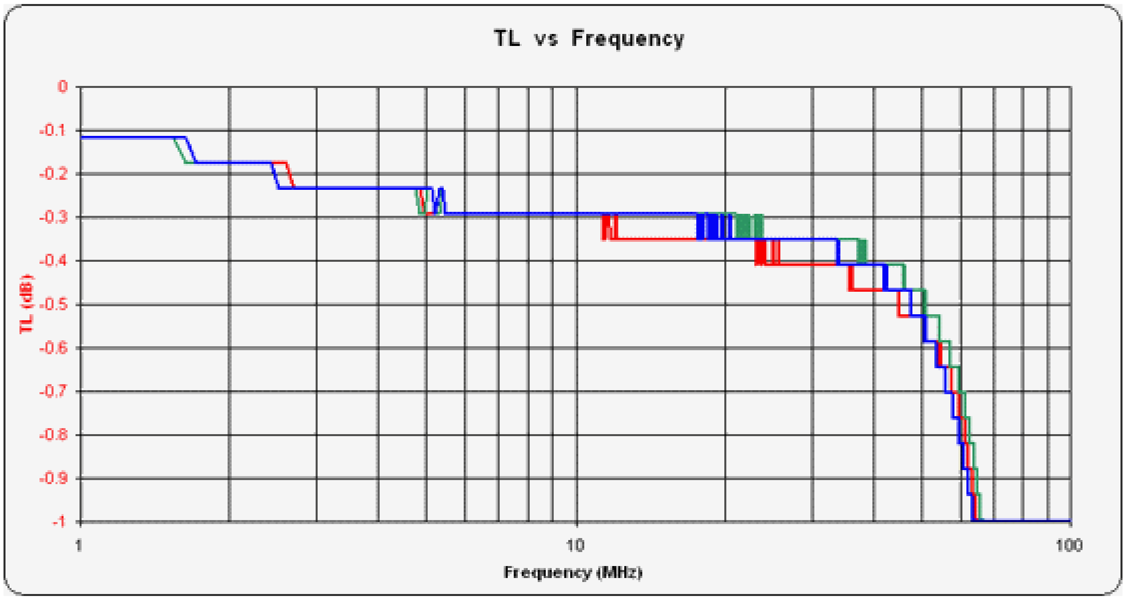
In addition to the coupling between wire pairs, the loss occurring along the transmission line forming the windings has also to be considered.

One way of minimising this loss at high frequencies is to decrease any stray leakage from the transmission line. This can be achieved by using twisted bifilar or trifilar windings as shown here... Or, as I have indicated previously good results can also be obtained by winding the transformer with coax.

Ruthroff suggests that the characteristic impedance of the transmission line should be chosen to suit the required impedance transformation ratio. So for a 4:1 transformer the impedance should be 100 ohms.

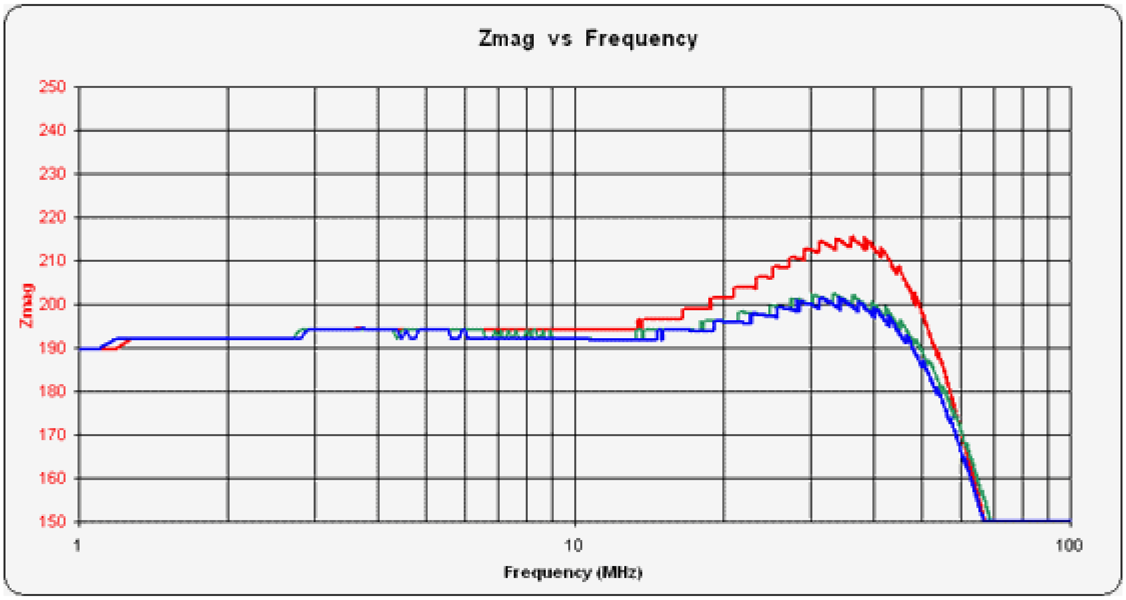
However none of my experiments have shown it to be essential to use a transmission line having exactly the correct characteristic impedance. To further illustrate this fact I made three different Ruthroff 4:1 transformers using different impedance coax, all of which were wound on FT180-43 ferrite cores.

The next graph shows the loss measured through a 4:1 transformer wound on a FT200-61 core.



Blue trace - 50 ohm coax
Green trace - 75 ohm coax
Red trace - 95 ohm coax.

The next graph shows the output impedance measured with the input terminated in a 50 ohm load.



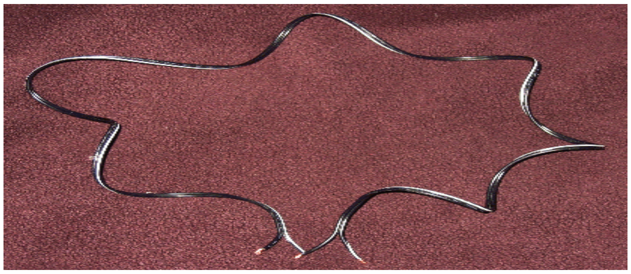
Blue trace - 50 ohm coax
Green trace - 75 ohm coax
Red trace - 95 ohm coax

Apart from the slight impedance peak at the frequency where the coax line is ¼ wavelength long, there is very little difference between the traces.

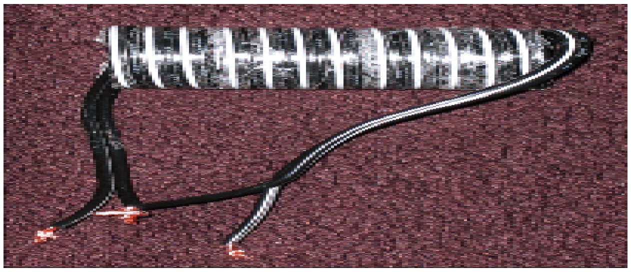
I find that winding the transformer with coax, particularly types with PTFE dielectric insulation, gives more predictable results, less loss, faster construction and has better insulation resistance than designs using twin core figure of 8 speaker cable or cores removed from mains wiring. However for high power levels it is better to use Thermaleze insulated copper wire, with an additional layer of PTFE insulating sleeve.

The transformer does not have to be wound around a ring core. In order to illustrate this I made up a version using a length of figure of 8 speaker cable and some ferrite sleeve cores. This clearly demonstrates the evolution from a narrow band ¼ wave transmission line transformer to a broadband transmission line transformer by the addition of ferrite sleeves. These increase the reactance of the wire connected across the source and also suppress common mode currents which may be flowing along both wires.

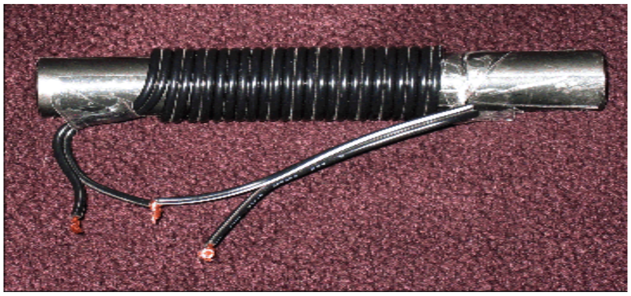
First a transformer made from figure of 8 twin speaker cable (measured as having a transmission line Zo of 126 ohms), electrically ¼ wavelength long at 40MHz.



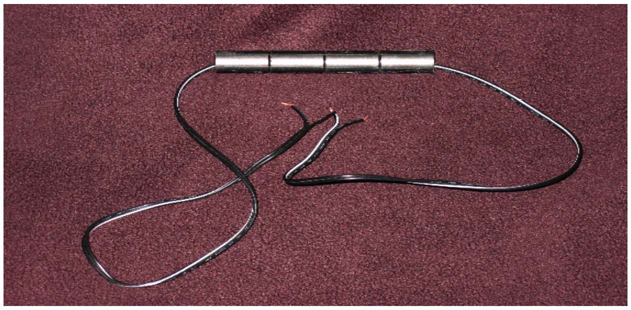
Red trace - length of twin 8 connected as 4:1 Ruthroff



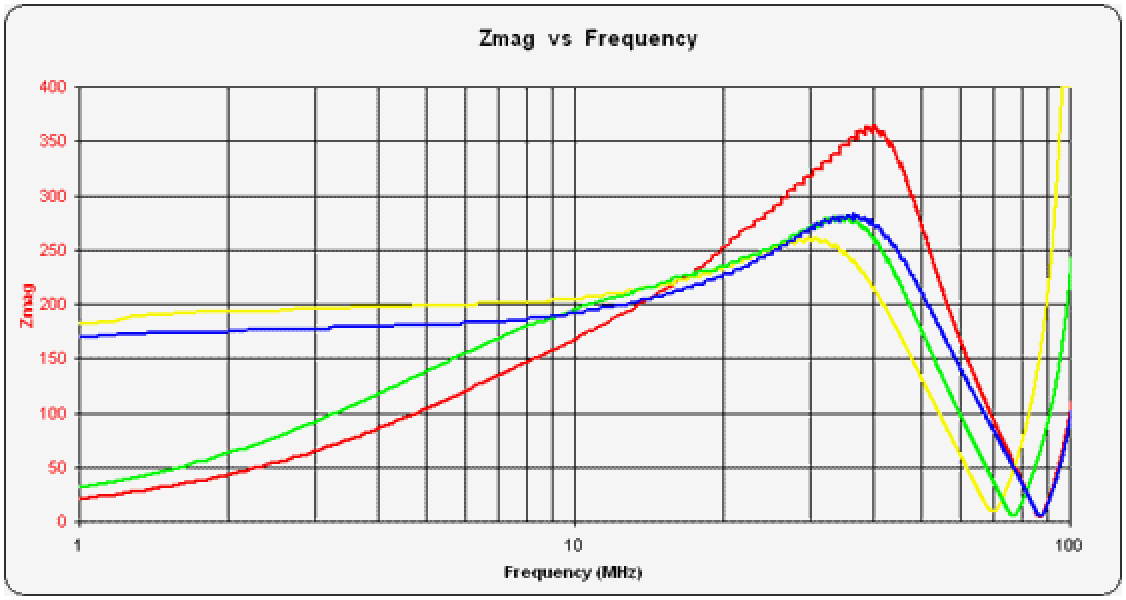
Green trace - length of twin 8 connected as 4:1 Ruthroff coiled on air core



Yellow trace - length of twin 8 connected as 4:1 Ruthroff coiled around ferrite cores



Blue trace - length of twin 8 connected as 4:1 Ruthroff threaded through ferrite cores

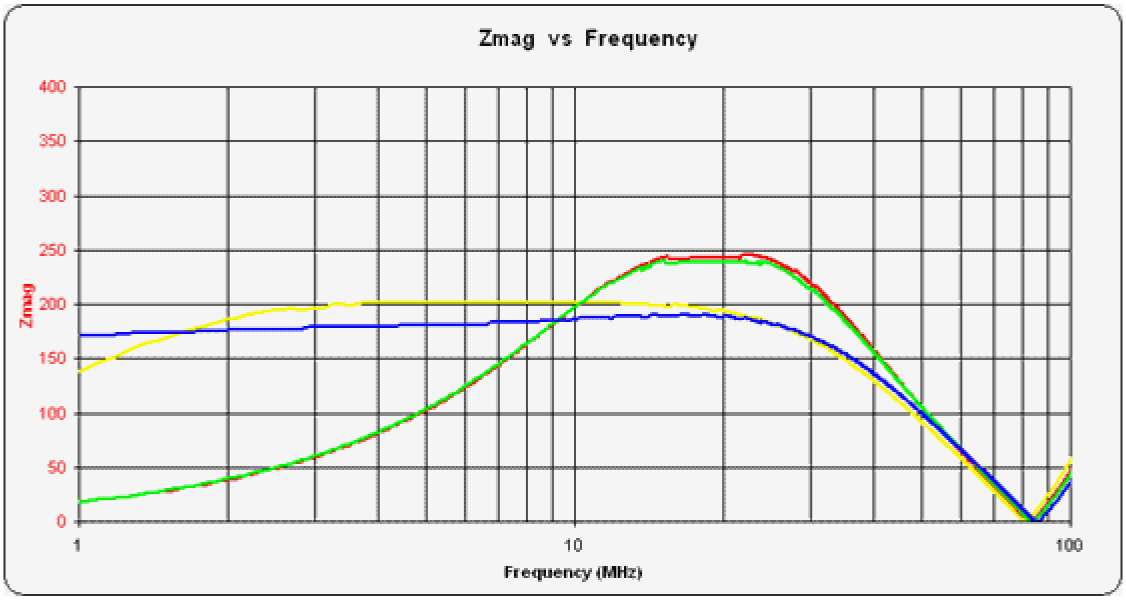


Red trace - length of twin 8 connected as 4:1 Ruthroff
Green trace - length of twin 8 connected as 4:1 Ruthroff coiled on air core
Yellow trace - length of twin 8 connected as 4:1 Ruthroff coiled around ferrite cores
Blue trace - length of twin 8 connected as 4:1 Ruthroff threaded through ferrite cores

This shows much more clearly the transition from being a 1/4 line transformer to broadband transformer, by the increasing the amount of inductance.

Two other factors are noticeable. The first is the peak in secondary impedance at the frequency where the windings are electrically ¼ wavelength long. The second is the slight shift in frequency of the 'notch' at around 80MHz where the windings are electrically ½ wavelength long, as the twin cable is coiled.

Here’s another plot, but this time I have used 50ohm coax. The configurations and colour schemes are the same as before, and I cut the coax to be a ¼ wave long at 40MHz so the graphs should be very similar.

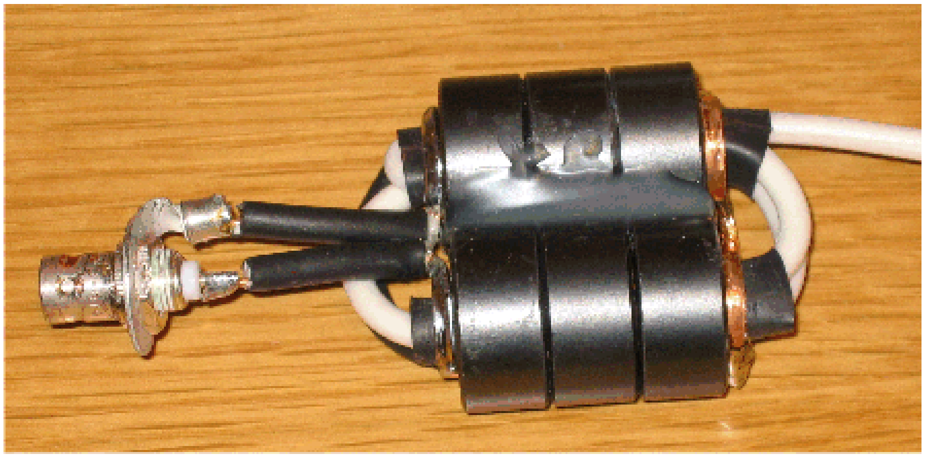


Red trace - length of 50 ohm coax connected as 4:1 Ruthroff
Green trace - length of 50 ohm coax connected as 4:1 Ruthroff coiled on air core
Yellow trace - length of 50 ohm coax connected as 4:1 Ruthroff coiled around ferrite cores
Blue trace - length of 50 ohm coax connected as 4:1 Ruthroff threaded through ferrite cores

However there are some differences. The impedance peak is reduced and is present at a lower frequency. I believe this is due to the velocity factor of the coax. The coiled coax wound on an air former (green trace) does not seem to have sufficient choking impedance. By adding a ferrite core (yellow trace) this can be increased, resulting in a much better response curve. In fact I could transition from the green trace to the yellow trace by gradually sliding the ferrite material into the air space at the centre of the wound coax cable.

By using higher permeability cores threaded onto the cable it is possible to shorten the transmission line considerably, which can be used to compensate for the reduction in upper frequency limit.

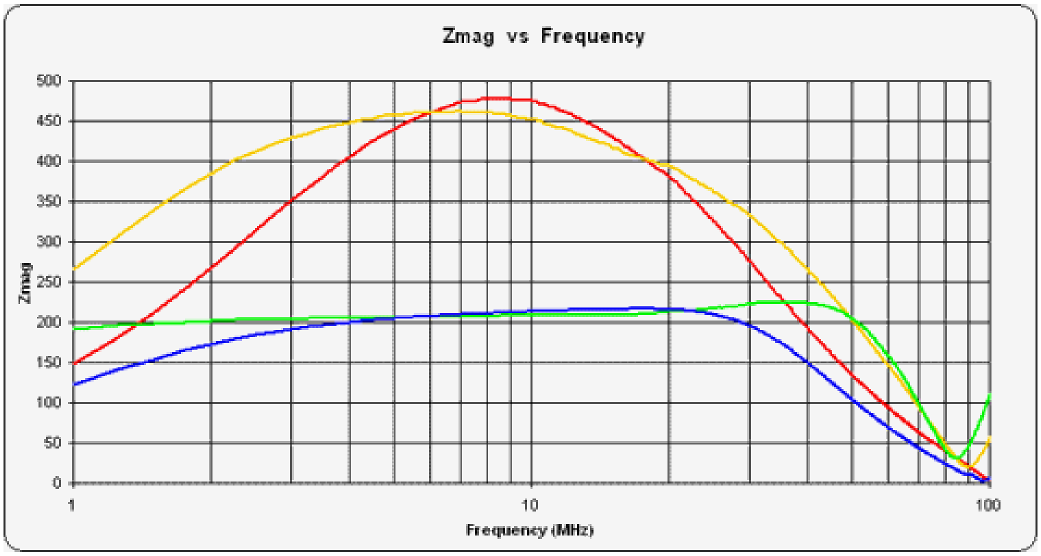
Note how this shortened version is now similar to broadband transformers made with ferrite binocular cores.



Comparison with Ferrite materials

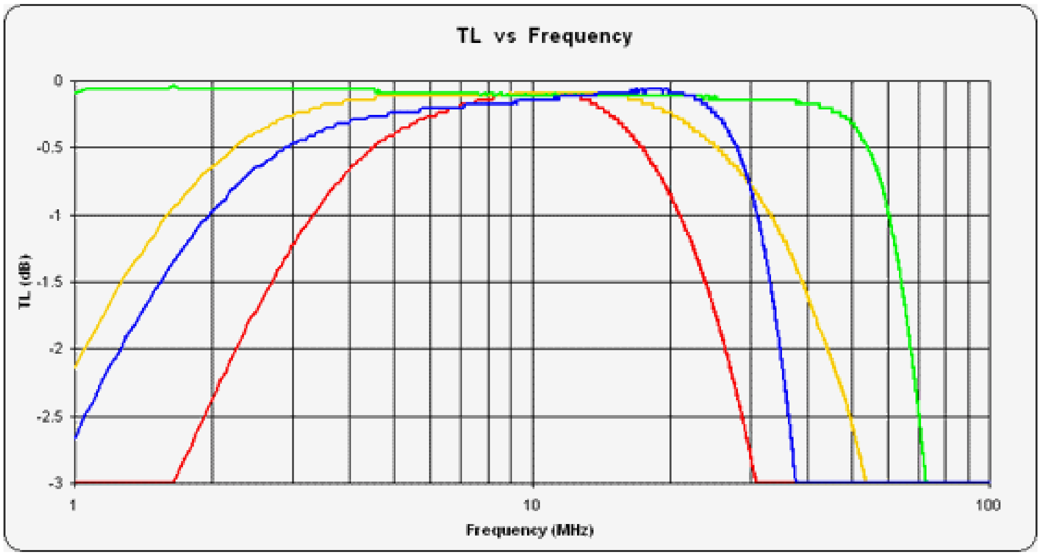
As an additional experiment I made a series of measurements using 4:1 and 9:1 Ruthroff Ununs wound on both Iron Powder and Ferrite cores. In both cases I optimised the windings in order to provide the widest possible bandwidth and lowest loss.

First a graph showing the secondary impedance with the primary terminated in 50 ohms. For the 4:1 the impedance should be 200 ohms and for the 9:1 the impedance should be 450 ohms.



Red trace – T200A- 2 9:1
Orange trace – FT240-61 9:1
Blue trace - T200A- 2 4:1
Green trace - FT240-61 4:1

Next the loss, this was measured by connecting two identical transformers back to back and halving the value to give the loss for one unit.



Red trace – T200A- 2 9:1
Orange trace – FT240-61 9:1
Blue trace - T200A- 2 4:1
Green trace - FT240-61 4:1

From this it can be seen that higher permeability ferrite materials are much more suited in this application. This is particularly evident with the 9:1 Ununs where the Iron Powder core gives a much narrower operating bandwidth. Some companies like to sell 9:1 ratio Ununs wound on Iron Powder cores for use with short vertical antennas because the inclusion of the Unun seems to provide a much lower SWR at the antenna feed point. However I think these graphs demonstrate that any improvement in match may partially be due to adding more system loss rather than providing a more suitable impedance match.

Design parameters

The primary design factor is the required upper frequency limit, as this defines the maximum length of winding which can be used. Once this has been determined, the lower frequency can be set.

The lower frequency limit is set by the permeability of the material. Low permeability type 2 and type 6 Iron powder cores are more suited for high Q resonant circuits than broadband transformers. Ferrites offer higher permeability and lower through loss, but are less popular for high power use because they can suffer irreversible damage due to core heating when subjected to mismatched loads.

A large number of winding turns may, in conjunction with capacitance between windings and core, cause self resonance to occur either within, or near the required frequency range. This is especially problematic with high Q materials.

The design of the windings is particularly important for good high frequency performance and low loss. Loss can be minimised by using windings constructed from twisted bifilar, trifilar or coax instead of insulated wire

The windings must be electrically much shorter than ¼ wavelength (including velocity factor of the cable) at the highest required operating frequency. Some margin (say +20% longer than calculated) should be added to ensure that any manufacturing variation in velocity factor is factored in.

Further experimentation is required to determine the optimum core material for broadband designs, but a minimum permeability figure of about 100 should be used for guidance purposes.

Conclusions

In this document I hope that I have demonstrated some of the problems and design limitations associated with the construction of Ruthroff voltage transformers, particularly those wound on Iron Powder cores.

The widely recommended type 2 and type 6 Iron Powder cores have too low a permeability and do not provide sufficient inductance for a given number of turns for them to provide consistent results when used in the 1 to 30MHz frequency range.

The main problem with this in practice is not the limited bandwidth, poor impedance transformation or high loss, but the unpredictable nature of the self resonances when connected to reactive loads such as antennas.

This can result in very variable results, especially when used at the base of short verticals in order to facilitate the use of a coax fed remote tuner.

My measurements suggest that type 61 or type K ferrite is much more suited for this purpose.

The lower frequency limit is determined by the permeability of the core and number of turns, and the upper frequency limit is determined by the maximum length of wire which can be used for the windings.

The characteristic impedance (when measured as a transmission line) of the wire or coax used to wind the transformer do not seem to dramatically influence the performance. However twisted bifilar or trifilar windings or coax provide better coupling between sets of windings and reduce loss.

There is very little flux circulating through the core outside the main body of the transformer windings. So a large ring core is just as likely to saturate as a rod.

There are four main recommendations:-

1. Use a core material with a high enough permeability to provide sufficient reactance, especially at the low frequency end of the required frequency range. The material should have a high bulk resistivity and low dielectric loss, in order to minimise core heating.

2. The windings need to be as short as possible, ideally less than 1/4 of a wavelength at the highest operating frequency. This equates to approximately 140cm for a 30MHz upper frequency limit (about 20t on a 2" core) and 70cm for a 50MHz upper frequency limit (about 8t on a 2" core) assuming PTFE insulated coax is used with a velocity factor somewhere between 0.6 to 0.7.

3. Use windings which have as low loss as possible. Twisted bifilar or trifilar wires or coax can be used for this purpose. There is very little difference in performance between Ruthroff transformers built using windings with a characteristic impedance of 50, 75, 95 or 120 ohms.

4. Improvements in performance can be obtained by using the smallest possible diameter core for the required power level, as this facilitates better flux coupling through the core reducing the possibility of saturating at low frequencies and minimises the length of wire required for the windings.

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