Ferrites in HF-applications

TRANSMISSION-LINE TRANSFORMERS

Examples
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General

This chapter is the fifth in a series of articles on ferrite materials in HF-applications. The first article is an introduction to this field with an overview of some widely applied materials and most important properties. The second article is on materials back-ground and most important HF-application formulas. The third article is on HF inductors and transformers. The fourth article is an introductory to transmission-line transformers.
It is advisable to read the articles in the above order especially since each next chapter is building on information and formula's already explained earlier and referencing to this.

Guanella and Ruthroff 1 : 4 unun

Guanella
A schematic diagram of a Guanella 1 : 4 unun may be found in figure 17. Two transmission-lines are connected in parallel at the input, while the outputs are connected in series and in series with the load R_b.

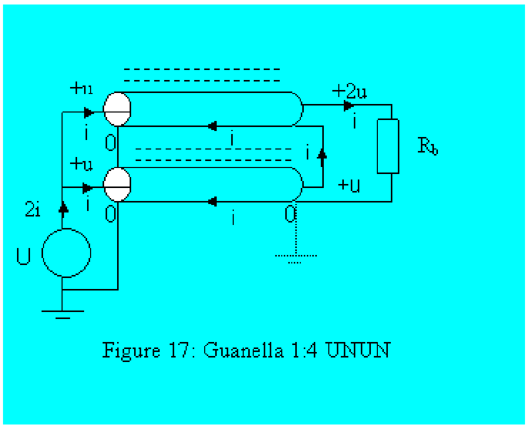

Figure 17: Guanella 1:4 UNUN

Transformer analysis
The voltages and currents have been drawn in figure 17 according to the principles 31 - 33. Each following analysis will start off with this 'exercise' as this first step already completes half of the analysis.

At the generator side, transmission-lines are connected in parallel, so each is connected to a voltage 'u'. At the load side, the center conductor of the bottom transmission line is connected to the outer conductor of the upper line, effectively putting the outputs of the transformer in series, so the output voltages will add. With the inputs connected in parallel and each transmission-line is carrying a voltage 'u', the load is connected across a voltage '2.u', making this construction a 1 : 2 voltage transformer.
At the input the transmission-lines each are carrying a current 'i'; the generator therefore carries a current '2 . i'.

With voltages and currents in position in figure 17, all impedances will be referenced to the load in the next step.
A voltage of '2.u' is found across the load with a current of 'i' flowing. Load resistance is characterized by:
$R_b = 2.u / i$.

The generator carriers a voltage 'u', with a current '2.i' flowing. This will make the generator 'see' an impedance:

$$Z_{in} = \frac{(u / 2i)}{(2u / i)} * R_b = R_b / 4$$

This indeed is a 1 : 4 impedance transformer.
Each of the transmission-lines is carrying a current 'i' with a voltage 'u' across. Optimal characteristic impedance for these lines follows from:

$$Z_C = \frac{(u / i)}{(2u / i)} * R_b = R_b / 2$$

When this transformer is to operate in a 50 Ohm environment (Z_{in}), optimal load resistance will be 4 x 50 = 200 Ohm while transmission-lines should have a characteristic impedance of 100 Ohm, for which RG 62 comes close at 93 Ohm. This type of cable still might be found in older data networks.

Sleeve impedance
No voltage is found across the outside of the bottom transmission-line, so no (parasitic, return) current will flow.

At the upper transmission-line, the outside is at ground potential at the generator and at a potential of 'u' at the load. The outside of this line therefore is effective connected across the generator (same potential). This parallel reactance we like to be of 'negligible' influence, for which we derived this to be at least 2,5 x the system impedance, so we calculate:

$Z_{sleeve} = 2{,}5 \text{ x } Z_{in} = 2{,}5 \text{ x } R_b / 4 = 0{,}625\ R_b$

In our 50 Ohm example, Z_{sleeve} will be 125 Ohm at the lowest design frequency, for this example 1,5 MHz. When selecting a 36 mm. toroide of 4A11 (43) ferrite material we calculate the number of turns (see previous chapters):

$n = \sqrt{}(125 / \omega \,.\, m_C \,.\, F) = 3{,}3\ (3)$

Note that we calculated the upper transmission-line (length!); the bottom line will have the identical length (equal delay Guanella principle).

Maximum core load
We calculate maximum voltage across the sleeve reactance for this core ($A = 1{,}18\ .10^{-4\ m2}$ and $B_{sat} = 0{,}33$ T) for linear behavior at 1,5 MHz. according to:

$U_{L\ (induction)} < 0{,}89\ .B_{sat}\ .f\ .n\ .A = 0{,}89\ .0{,}33\ .1{,}5\ .10^6\ .3\ .1{,}18\ .10^{-4} = 156$ V.

As we expect core dissipation to set the application limit, we calculate maximum voltage across the sleeve reactance for maximum 4 Watts of core loss:

$U_{L(dissipation)} = \text{Ö}P_{max} \cdot (Q/6 + 1/Q) \cdot X_L = 52$ V.

As expected this lower value will set the application limit, in a 50 Ohm system to be reached at 53 Watt. Depending on modulation we may go up to 3,2 x this voltage (SSB, see enhancement factors in the second chapter) but this value should be checked against maximum voltage for linear application ($U_{L(induction)}$). More turns and / or more ferrite (volume) will also allow higher voltages.

One or two cores?
This Guanella 1 : 4 transformer may be constructed on one ferrite toroide, when winding in the same direction. In the above example, the transformer could be made by placing six turns on the core and cutting half way. At this position lines are to be connected in parallel (effectively creating a parallel tap on the line) while at the other side the lines are connected in series.

Different characteristic impedance?

The characteristic impedance of the transmission-line is especially important at the high-frequency limit of the transformer. We calculated transmission-line impedance to be 100 Ohm in our 50 to 200 Ohm example. Since 50 Ohm line is more common we may want to construct the transformer with this type of line. As an example a transformer with this line impedance was exhibiting SWR = 2 at 100 MHz. Measuring the same transformer when terminated into 100 Ohm, as required for a 25 to 100 ratio, SWR = 1,1 at 200 MHz.
In this last measurement set-up two effects are active at the same time. One effect points at the importance of the characteristic impedance of the transmission-line in the transformer, the other points at the effect of the relative line length as related to mismatching impedance.

To further investigate the effect of mismatching we calculated behavior over frequency of a Guanella 1 : 4 impedance transformer with $m = R_b / Z_0$ (or reversed!) as a parameter. The transformer has been constructed on a 36 mm. toroide with two times three turns of transmission-line each with an electrical length of 50 cm. Figure 18 depicts high frequency cut-off related to mismatch parameter 'm' for two SWR cut-off definitions. Calculations have been verified with measurements afterwards and appear to be reliable.

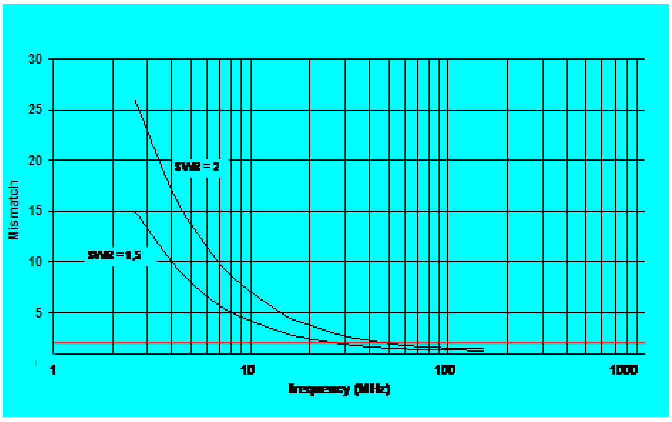

Figure 18: High-frequency cut-off of a 1 : 4 Guanella 1 : 4 transformer

In figure 18 high frequency cut-off is going down rapidly with rising mismatch. At a mismatching of 2 (red line) high frequency cut-off is down to 25 MHz. at the SWR = 1,5 definition and to 45 MHz. at SWR = 2.
When total line length was 70 cm. instead, frequencies in this graph should be multiplied by 50 / 70 (0,71) making this transformer even more sensitive to mismatching.

Ruthroff

Since the line output is completely decoupled from the input (basic rule 33), we may connect any of the output terminals to any other point in the circuit or to ground, as depicted by the dashed ground symbol in figure 17. Note the lower terminal of the upper transmission-line to be at a potential 'u', which is equal to the generator potential. Therefore we may directly connect this terminal to the generator and leave out the bottom transmission-line. This situation is depicted in figure 19, the Ruthroff 1 : 4 unun.

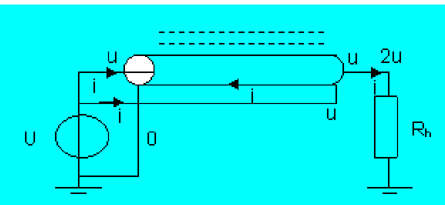

Figure 19: Ruthroff 1:4 unun as derived from the Guanella unun

After applying basic rules 31 - 33, voltages and currents may be placed in the figure. As with the Guanella, the generator with a voltage 'u' is supplying a current '2.i', the transmission-line is carrying a voltage 'u' with a current 'i' while the load is carrying a current 'i' with a voltage '2.u' across. The Ruthroff will therefore exhibit the same characteristics as a 1 : 4 Guanella impedance transformer, including the requirements as to the transmission-line.
For a 50 - 200 Ohm application, the transmission-line should have a characteristic impedance of 100 Ohm. When constructing this transformer on a 36 mm. 4A11 (43) ferrite core, we again need three turns at a lower operational frequency of 1,5 MHz. Maximum load is identical to the Guanella with the same possibilities to extend this.

Also with this transformer a few tests have been performed to determine sensitivity to the transmission-line characteristic impedance. For these tests the transformer has been constructed using three turns 93 Ohm transmission - line on a 36 mm. 4A11 toroide.
With our SWR = 1,5 definition, frequency range is 0,5 - 120 MHz. The same transformer has been constructed on the same toroide, this time using 50 Ohm transmission-line. This time the frequency range was 0,5 - 100 MHz.

We noticed before that the Ruthroff concepts adds direct voltages to delayed ones. This makes this transformer more sensitive to the transmission-line length. For this reason designers sometimes prefer the somewhat 'larger' Guanella to the Ruthroff principle.

Guanella and Ruthroff 1:4 balun

Guanella
The Guanella balun in figure 20 is very much like the figure 17 design. Since all outputs are decoupled from the input any of the output terminals may be connected to ground, also the center connection. In this latter situation the unun of figure 17 is transformed into a the balun of figure 20.

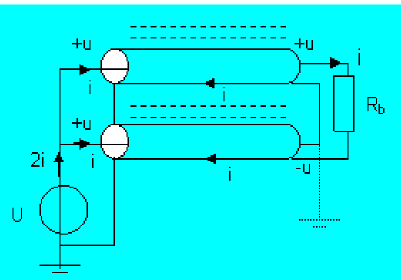

Figure 20: Guanella 1:4 Balun

After we placed all currents and voltages into the figure according to the basic rules 31 - 33, an almost identical situation arises and all impedances are the same as derived before. One of the differences is the voltage at the lower output terminal of the bottom transmission-line, that is now at a voltage of '-u', while the voltage on the upper terminal of the top line is at 'u' voltage. Therefore it is now the outside of the lower terminal that is carrying the voltage 'u', where we should ensure a low parasitic current in stead of the outside of the upper line.

When constructing this transformer for an impedance ratio of 50 - 200 Ohm, we again should be using a 36 mm. toroide of 4A11 (43) ferrite material and when designing for a lower operating frequency of 1,5 MHz., we should again apply three turns of transmission-line with 100 Ohm of characteristic impedance. Of cause both lines will be of equal length (equal delay). Again both lines may be on the same toroide as above.

Ruthroff
In figure 20 we find a voltage of 'u' at the top of the load, that is equal to the generator voltage. Therefore we may connect this side of the load directly to the generator and leave out the upper transmission-line. The circuit of figure 20 then resolves into figure 21, the Ruthroff 1 : 4 balun.

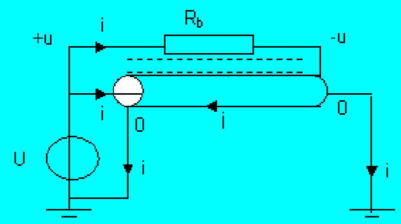

Figure 21: Ruthroff 1:4 balun

Identical to the Ruthroff unun, this circuit will function for short length of the transmission-line (low delay). The pattern of voltages and currents according to the basic rules 31 - 33 is identical to the Guanella, so all impedance calculations apply including the characteristic impedance of the transmission-line and the minimum impedance of the sleeve impedance (toroide size, ferrite type, number of turns) at the lowest frequency of operation.

Guanella and Ruthroff 1 : 9 unun

Guanella

The Guanella 1 : 9 is build-up in an identical way as the Guanella 1 : 4 unun, using the same basic elements. Inputs are in parallel and all outputs in series, putting a voltage of three times the input voltage across the load. This makes for an impedance ratio of 1 : 9 as may be appreciated from figure 22. Note the un-even number of lines will exclude a balancing output terminal to ground.

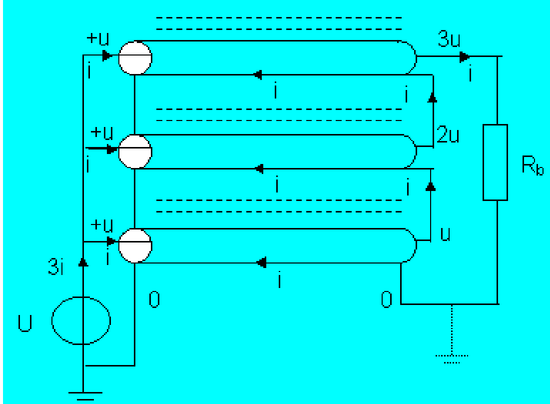

Figure 22. Guanella 1:9 UNUN

Analysis

Applying the basic principles of 31 - 33 will complete the picture of voltages and currents in the figure. From this it follows that a voltage of '3.u' is across the load with a current 'i' flowing. At the generator is a voltage 'u' with a current of '3.i' flowing. The generator therefore 'sees' an impedance of:

$$Z_{in} = \frac{(u / 3i)}{(3u / i)} * R_b = R_b / 9$$

Each of the transmission-lines is carrying a voltage 'u' with a current 'i' flowing, requiring a characteristic impedance of:

$$Z_c = \frac{(u / i)}{(3u / i)} * R_b = R_b / 3$$

Transmission-lines

When we like to design a transformer for an impedance range 50 - 450 Ohm, the characteristic impedance of the transmission-lines should be 450 / 3 = 150 Ohm. This is a value normally not available in coaxial lines. Twisting a pair of plastic isolated, mounting wires (0,5 mm. single strand) makes up for a characteristic impedance in the range of 100 - 150 Ohm, that usually will do. Experiment with wire diameter for the required application power and isolation for minimum loss (avoid pvc isolation as this is very lossy at HF frequencies).

Sleeve impedance

As we derived before, total parallel reactance at the input should be higher than 2,5 x Z_{in} = 2,5 x R_b /9 = 0,28 R_b.

In figure 22 we notice no voltage across the length of the lower transmission-line, a voltage of 'u' across the middle line and a voltage of '2.u' across the upper line, translating into two times the impedance for the upper line

to the middle line for equal currents. These impedance are found in parallel at the input, so we may write:
2 x Z_{sleeve} in parallel to $Z_{sleeve} = 0{,}28\ R_b$, from which we derive $Z_{sleeve} = 0{,}42\ R_b$ en 2 $Z_{sleeve} = 0{,}84\ R_b$.

When designing a transformer for an impedance range 50 - 450 Ohm, the upper sleeve reactance at the lowest operating frequency therefore should be 0,84 x 450 = 378 Ohm. When constructing this on a 36 mm. toroide of 4A11 (43) ferrite material, for a lower operating frequency of 1,5 MHz., the number of turns follows from:

$n = \sqrt{(378 / \omega \,.\, m_C \,.\, F)} = 5{,}7\ (6)$

Although the sleeve impedance of the middle line could be halved, the line should be of equal length according to the Guanella principle of equal delay. This will improve the lower operating frequency.

When looking somewhat more in detail to figure 22, it appears the lower two transmission-line to represent a copy of the Guanella 1 : 4 unun transformer. We where allowed to construct this at a single toroide as described above. This also applies to Guanella 1 : 9, provided we apply the number of turns as dictated by the upper line (on a separate core). Since the number of turns is doubled for this application, we better select the small diameter Teflon RG188 in stead of RG58 when constructing on a 36 mm. 4A11 (43) type of ferrite toroide.
The transformer construction now consists of two cores, one with 12 turns cut halfway with one side in series and the other in parallel plus a second core with 6 turns with one side connected in parallel tot the parallel side of the first transformer, the other side in series with the series-side.

Maximum load
As usual we calculate maximum load for this transformer. The upper core is strained most since it is carrying a voltage of '2.u'. Calculating maximum voltage across this inductor for linear application with 6 turns on a 36 mm., 4A11 (43) type of ferrite material at a lower operating frequency of 1,5 MHz.

$U_{L(inductie)} = 0{,}89\ .B_{sat}\ .f\ .n\ .A = 0{,}89\ .0{,}33\ .1{,}5\ 10^6\ .\ 6.1{,}18\ .10^{-4} = 312$ V.

Since this represents a voltage of '2.u', total input voltage is halved at 166 V.

Next we calculate maximum voltage for maximum core dissipation, which we found to be 4 Watt for this core size

$U_{L(dissipation)} = \sqrt{P_{max} \cdot (Q/6 + 1/Q) \cdot X_L} = 103$ V.

Again half this voltage is at the input, allowing maximum 52 Volt at the generator which translates to 54 Watt of continuous power in a 50 Ohm system. Higher power will be allowed at different modulation schemes as may be calculated form the 'enhancement' table, even up to a couple of hundred Watt. In the latter situation, the maximum voltage for linear use should be checked again.

Application area.
The above type of transfer ratio usually will be applied at low impedance ranges, e.g. to transform to and from the in- and output stages of power amplifiers. The transformer will then operate in a 5,6 - 50 Ohm environment, where the requirements to the sleeve impedance will be lowered by the same amount.

Ruthroff

Identical to earlier designs, also the Guanella 1 : 9 transformer may be transformed into a Ruthroff variation. Since the outside of the middle transmission-line is at a voltage of 'u', this may be directly connected to the generator to yield figure 23, the Ruthroff 1 : 9 unun.

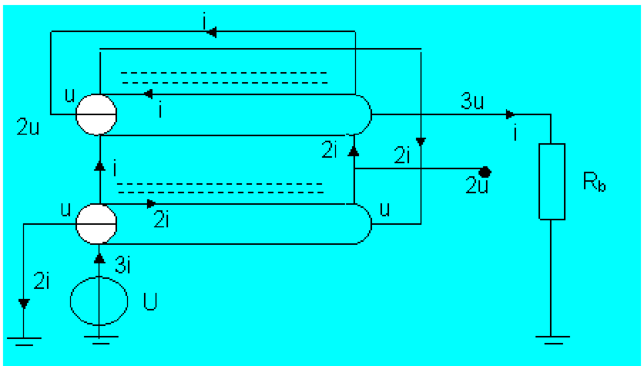

Figure 23. Ruthroff 1 : 9 unun

Analysis
As usual we start off by putting all voltages and currents into the figure according to basic principles of 31 - 33. This time the exercise is somewhat more complicated, depending on the starting position. For this analysis it is best to start form the (single) current through the load and the upper transmission-line. With all currents and voltages in position we calculates impedances as related to the load:

$$Z_{in} = \frac{(u / 3i)}{(3u / i)} * R_b = R_b / 9$$

For the upper transmission-line we find the familiar relation:

$$Z_{boven} = \frac{(u / i)}{(3u / i)} * R_b = R_b / 3.$$ For a 50 op 450 W transformer, the characteristic impedance is 150 W

The impedance of the lower transmission-line however has been changed:

$$Z_{onder} = \frac{(u / 2i)}{(3u / i)} * R_b = R_b / 6.$$ In the above example: 75 W!

Note this transformer is requiring different transmission-lines for optimal performance.

Sleeve impedance
In figure 23 we notice the outer conductors of both transmission-lines to be in parallel. Since both are carrying the same voltage the transformer may be constructed on the same core. Across this common line we find a voltage 'u', which makes the inductance appear directly across the generator. Since we derived this parallel reactance to be minimum 2,5 x the parallel impedance at the lowest operational frequency, we may calculate:

$$Z_{sleeve} = 2,5 \text{ x } Z_{in} = 2,5 \text{ x } R_b/9 = 0,28\ R_b$$

When designing the transformer for an impedance range of 50 - 450 Ohm, sleeve impedance will be 125 Ohm. We next calculating the number of turns for this transformer when constructed around a 36 mm., 4A11 (43) type of ferrite for a lower operating frequency of 1,5 MHz.

$$n = \sqrt{(125 / \omega \,.\, m_C \,.\, F)} = 3,3\ (3)$$

Maximum load
Calculating maximum voltage across the sleeve inductor for linear application:

$$U_{L(induction)} = 0,89\ .B_{sat}\ .\ f\ .n\ .A = 0,89\ .0,33\ .1,5\ 10^6\ .\ 3.1,18\ .10^{-4} = 156\ V.$$

Next maximum voltage for maximum allowable core dissipation:

$$U_{L(dissipatie)} = \sqrt{P_{max} \cdot (Q/6 + 1/Q) \cdot X_L} = 52\ V.$$

This is equal to the generator voltage, making this transformer applicable to a maximum and continuous system power of 54 Watt in a 50 Ohm environment. For non-continuous loads, higher power may be possible, but voltages should be checked against maximum voltage for linear use limits.

Different transformer ratio
In the above Ruthroff 1 : 9 transformer, a terminal may be found carrying a voltage of '2.u'. This will allow an impedance ratio of 1 : 4. Since both the 1 : 9 and 1 : 4 ratio's appear in the same design, it is possible to apply this transformer in the odd ratio of 9 : 4 (1 : 2,25) as well.

Ruthroff 1:2,25 unun

In figure 24 the Ruthroff 1 : 2,25 transformer may be found, as derived from the Ruthroff 1 : 9 design. The generator is now at the '2.u' position, with the original generator terminal grounded. This transformer has been applied to the Multiband trap antenna.

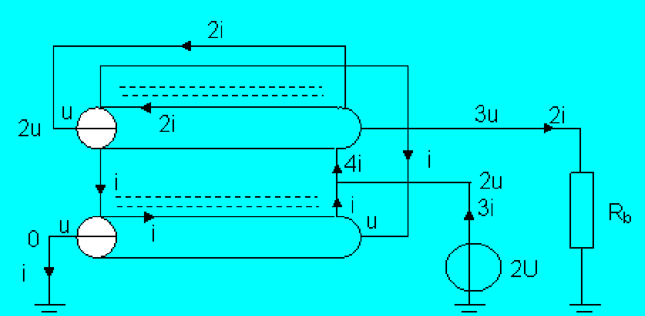

Figure 24. Ruthroff 1:2,25 UNUN

Analysis
Again we apply the basic rules as in 31 - 33, and apply voltages and current to the design, which is again more complicated than before. The load 'sees' a voltage of '3.u' across with a current '2.i' flowing. The generator is at a voltage of '2.u' with a current of '3.i' flowing. This makes the input impedance equal to:

$$Z_{in} = \frac{(2u / 3i)}{} * R_b = 4\ R_b / 9 = 0.44\ R_b$$ (which is a ratio of 2.25!)

(3u / 2i)

Across the lower transmission-line is a voltage 'u' with a current 'i' flowing. Optimal characteristic impedance therefore will be:

$$Z_{C\ lower} = \frac{(u / i)}{(3u / 2i)} * R_b = 2 R_b / 3 = 0.66 R_b$$

In an analogue way we calculate the upper transmission-line carrying a voltage 'u' with a current '2.i' flowing:

$$Z_{boven} = \frac{(u / 2i)}{(2i / 3u)} * R_b = R_b / 3 = 0.33 R_b$$

Again we discover different transmission lines for optimal performance.

For the multiband trap antenna as mentioned the transformer was designed for a 50 - 112,5 Ohm range and had been constructed using two transmission-lines RG58 (50 Ohm). Performance of this transformer was within SWR < 1,5 over more than all HF bands (see further on).
For this chapter we constructed the transformer again, this time using the calculated characteristic impedances of 37,5 and 75 Ohm. Bandwidth indeed is larger as may be expected. From this and earlier experiments it is shown characteristic impedance to be an important design parameter but sensitivity to this parameter is low enough to allow some constructional freedom.

Sleeve impedance
In figure 24 we find the outer conductors of both transmission-lines to be in parallel at the output and at the input. Since both lines are carrying the same voltage, the transmission-lines may be constructed on the same core.

Across this common line we find a voltage 'u' , which is half the generator voltage. We derived earlier that the parallel reactance should be 2,5 x the parallel impedance (0,44 R_b) at the lowest operational frequency. We may therefore write:

$$Z_{sleeve} = 0{,}5 \times 2{,}5 \times 0{,}44\ R_b = 0{,}55\ R_b$$

When designing this transformer for an impedance range 50 - 112,5 Ohm, the sleeve inductance should be at least 0,55 x 112,5 Ohm = 61,9 Ohm. When constructing this transformer around a 36 mm. 4A11 (43) type of ferrite at a lowest operational frequency of 1,5 MHz., the number of turns for the sleeve reactance follows from:

$$n = \sqrt{(61{,}9 / \omega\ .\ m_C\ .\ F)} = 2{,}3\ (3)$$

Maximum load
We calculate the maximum allowable voltage across the core inductor for linear application:

$$U_{L(induction)} = 0{,}89\ .B_{sat}\ .\ f\ .n\ .A = 0{,}89\ .0{,}33\ .1{,}5\ 10^6\ .\ 3.1{,}18\ .10^{-4} = 156\ V.$$

which is half the voltage across the generator.

The maximum voltage for maximum core loss of 4 Watt for this size of core is:

$$u_{mantel(dissipatie)} < \sqrt{P_{max} \cdot (Q/6 + 1/Q)}\ .\ X_L = 56\ V.$$

again at half the generator voltage, allowing this transformer to be applied up to 112 volt or 250 Watt of system power in a 50 Ohm system under continuous load. Depending on the modulation scheme, maximum load may be much higher but maximum voltage for linear use should be checked again.

Measurements to a 1:2,25 Ruthroff transformer

Input impedance
A practical 1 : 2,25 transmission-line transformer has been measured in a 50 - 112,5 Ohm environment. For this measurement, the transformer was constructed using a 36 mm. toroide of 4A11 (43) ferrite type, with two times three turns of RG58 transmission-line (not the optimum characteristic impedance). The transformer was terminated into a 112,5 Ohm resistor while input impedance measurements have been performed on a HP Network analyzer. Results may be found in table 8

f (MHz)	R_S (W)	X_S (W)	R_P (W)	X_P (W)	SWR
0,5	45,6	9,97	47,8	218	1,26
1,0	48,4	5,29	49,0	448	1,12
1,8	48,7	3,31	48,9	720	1,07
3,6	48,9	3,12	49,1	769	1,07
7,0	48,9	4,07	49,2	520	1,10
14,2	48,0	6,25	48,8	375	1,14
21,3	46,4	7,60	47,6	291	1,19
29,0	43,7	9,73	45,9	206	1,28
50,0	38,6	11,91	42,3	137	1,45
70.0	34,8	13,60	40,1	103	1,62

Table 8: Measurements to a Ruthroff 1 : 2,25 impedance transformer

At the lower frequencies (up to about 5 MHz) , input impedance mainly consists of the sleeve inductance X_p, roughly equal to 2 x Z_{in} as calculated. Up to 10 MHz. we first see permeability (m') drop with frequency, up to 30 MHz. followed by the increasing value of core loss (m"). Above 40 MHz. the influence of parasitic parallel capacitance is becoming visible, further enhanced by the effects of transmission-line delay that also become noticeable above 50 MHz.

In the last column, the input SWR figures have been calculated, showing this transformer to be applicable from below 0,5 MHz. to over 50 MHz.

Measuring harmonics

From our calculations we found this transformer to be applicable to a maximum of about 250 Watt of continuous loading. The calculations for maximum allowable induction permitted even higher voltages so we do not expect linearity problems to occur with this device.

To check, two identical Ruthroff 1 : 2,25 transformer have been connected back to back to a generator delivering 350 Watt of continuous power at 3,6 MHz., 14,2 MHz. and 21,3 MHz., with the second transformer terminating into a high-power, 50 Ohm 'dummy-load' resistor with a - 46 dB output. Measurements have been performed using a HP Spectrum analyzer with an over 60 dBc measurement range. No (additional) harmonics could be measured which again ensures confidence to the calculations.

The last article in this series is on measurements to ferrite materials. This may be useful to determine type and quality of materials already in your possession or to determine peculiarities in components in your system.

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