Chapter 3

Transformers and Hybrids

Introduction

At RF frequencies Transformers are used to:

1 Invert signals by producing a 180 degree phase shift.

2 Change Impedances, to ensure that devices are matched correctly, thus ensuring that most of the power is transferred into or out of the devices.

3 Change balanced signals from a TV antenna to unbalanced signals for transmission using coaxial cables and connecting to a TV set.

4 Change unbalanced signals to balanced ones for use in mixers.

5 Provide DC isolation and permit DC and RF signals to be carried on the same coaxial cable for masthead amplifiers and other remote powered applications.

RF Transformers differ from audio and 50 Hz mains transformers in that:

1 Ferrites are normally used for the magnetic material.
2 The windings may be an appreciable fraction of the wavelength.
3 Capacitive coupling between the primary and secondary windings must be taken into account.
4 The transformers may need to operate over several decades of frequency.
5 At VHF frequencies and above, transmission lines may be used as transformers, without the use of ferrites. Such transformers operate over a relatively small frequency range.

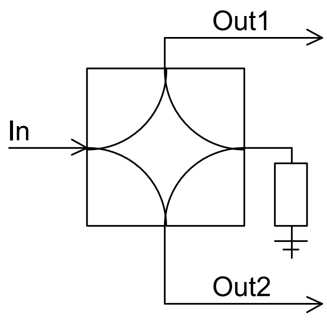

Figure 1. Hybrid symbol.

Hybrids are used to split or combine signals, while providing isolation between those signals.

Figure 1 shows the commonly used symbol for a hybrid. The input signal is divided equally between Out1 and Out2. Out1 and Out2 are isolated from each other. This allows us to drive two amplifiers, thereby improving amplifier stability and increasing the output power handling capability.

The power-handling capability of RF transistors operating up to 1 GHz is typically 100 Watt. Figure 2 shows how two such 100 Watt amplifiers, together with two hybrids can be used to produce a 200 Watt amplifier. This also gives some redundancy against failure of an amplifier. If one amplifier fails, the output will drop by 6 dB, but the system still operates. For higher power output requirements, many of these modules can be combined in a similar manner. As a result, solid state amplifier modules with output powers of several kW can be made.

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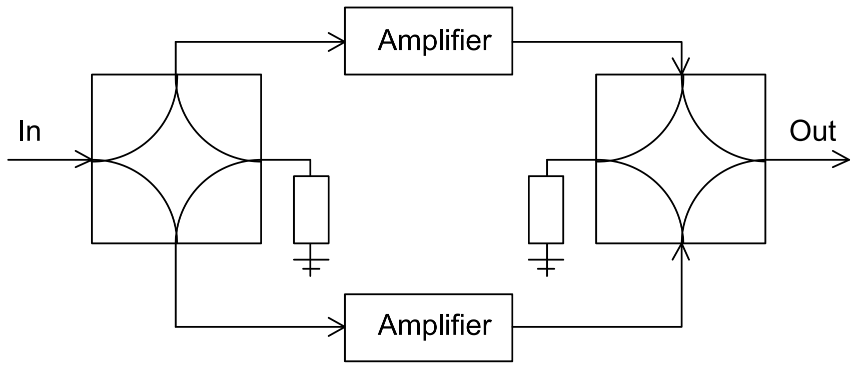

Figure 2. Parallel operation of amplifiers.

At VHF frequencies the hybrids are normally made using transmission lines. At lower frequencies the hybrids can be made using transformers. Most telephone handsets have either a transformer hybrid or an active hybrid using an ASIC (Application Specific IC).

Wideband Transformers

For a conventional ferrite transformer, the upper length of the winding is limited to approximately 10% of the wavelength. At 1 GHz the wavelength is 300 mm and the maximum winding length is thus 30 mm. If the windings are like a transmission line, as used in TV baluns shown in figures 7 and 8, this limit does not apply.

The corresponding lower limit [1] is:

$$l_{\min} = \frac{R_l}{2(1+\mu_r)f_{\min}} \quad \text{Eqn.1}$$

Where R_l is load impedance in ohm, $f_{\min}$ is the lowest operating frequency of the transformer in MHz and $l_{\min}$ is the length of the winding in metres. For a Neosid F14 material with a μ_r of 220, operating at 1 MHz in a 50 Ω system, the minimum winding length is thus 113 mm. This minimum winding length should be allowed for in transformers made using ferrites.

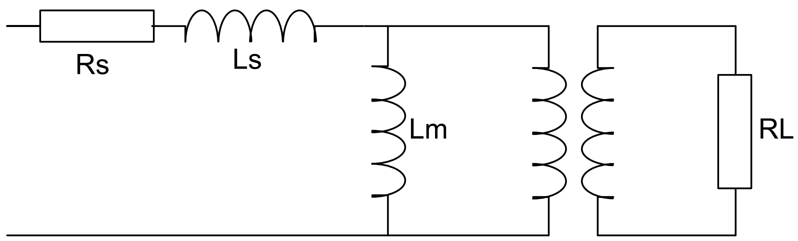

Figure 3. Simplified RF transformer model.

Transformers can be designed using the above equations, however by considering the simple conventional transformer model [2] shown in Figure 3, containing a Leakage inductance Ls and a Magnetising inductance Lm, the optimum number of turns required for RF transformers can be easily determined. To simplify the calculations assume that the transformer has a 1:1 turns ratio, so that the load R_L is also the load reflected into the primary. For other turns ratios, the load impedance reflected into the primary, is the impedance used for calculations.

At low frequency the Magnetising inductance Lm shunts the output load. The lower cut off frequency is thus when $j\omega L_M = R_L$. At high frequencies the Leakage inductance is in series with the output. The upper cut off frequency is thus when $j\omega L_S = R_L$.

The leakage inductance can most easily be measured by short circuiting the secondary winding of the transformer. Under those conditions the input impedance of the transformer is $R_s + j\omega L_S$. When the transformer is open circuited, the input impedance is $R_s + j\omega L_S + j\omega L_M$. Since L_m is typically 1000 times larger than L_s, the leakage inductance can be ignored as part of the lower frequency calculation.

If one normally wants to operate the transformer at a frequency F_c then it is desirable to make this $F_c = \sqrt{F_{low} F_{high}}$ where F_{low} and F_{high} are the upper and lower cut off frequencies of the transformer. As described above, the upper and lower cut off frequencies are determined by the leakage and magnetising inductance respectively.

The input impedance of the transformer at the centre frequency is thus:

$$Z_c = \sqrt{Z_{Ls} Z_{Lm}} = \sqrt{\omega L_s \omega L_m} \qquad \text{Eqn. 2}$$

For a 50 Ω system, one wants this Z_c to be 50 Ω. Under those conditions $R_s + j\omega L_S$ is much smaller than R_L and $j\omega L_M$ is much larger than R_L, so that virtually all the input power is transferred to the output.

Since the inductance is proportional to the number of turns squared, the characteristic impedance of the transformer is also proportional to the number of turns squared. The number of turns chosen for the transformer winding is such that the characteristic impedance of the transformer matches the system impedance. Since in many cases the detailed properties of the ferrite may not be known, the characteristic impedance is most easily determined by winding a trial winding on the transformer and using the measured open and short circuited impedances to then calculate the correct number of turns required.

In practice the magnetising inductance has some losses associated with it and the resistive losses of the windings are in series with the leakage inductance. The resistive losses are normally very small. Since the inductance is proportional to the frequency, at the upper and lower frequency limits the inductance dominates, so that in the calculation for the upper and lower frequency limits, the resistive part of the measured input impedance can be ignored.

Example: ***RF Transformer Design***

A ferrite coil has an 11 turn bifilar trial winding on it. At 1 MHz, input impedance with the secondary winding short-circuited is Z_{Ls} = j0.4 Ω, corresponding to a leakage inductance of 64 nH. The input impedance measured with the secondary open-circuited is Z_{Lm} = j400 Ω, corresponding to a magnetising inductance of 64 μH. From equation 2, the characteristic impedance is thus $Z_c = \sqrt{(400 \times 0.4)} = 12.65$ Ω.

The inductance is proportional to the square of the number of turns. Thus, for a 50 Ω transformer we need $11 \times \sqrt{(50/12.65)} = 22$ turns. For the 22 turn winding one will thus have a leakage inductance of 256 nH and a magnetising inductance of 256 μH.

The ratio of the open circuit to the short circuit impedance is 1000:1. The ratio of the upper and lower cut off frequency is thus also 1000:1, with the centre frequency being

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at the geometric mean of the upper and lower cut off frequencies. The upper cut off frequency is thus 1∗√ (1000) MHz = 32 MHz. The lower cut off is 1/√ (1000) MHz = 32 KHz.

The measured performance normally agrees closely with the calculated one. The actual upper corner frequency is often a little lower than the calculated one, since the losses in the ferrite increase non-linearly with frequency and are thus proportionally lower at the centre frequency, where the measurements of the leakage and magnetising inductance are made. RF transformers using bifilar and trifilar windings operate well at frequencies up to several GHz.

Bifilar and Trifilar Windings

For a bifilar winding, two wires are twisted together to form a primary and secondary winding of a transformer, with close capacitive coupling between the windings, which result in a wide frequency response. Bifilar windings are used for inverting transformers. Trifilar windings use three wires twisted together as shown in figures 4 and 5. Trifilar windings are used for Baluns (Balanced-Unbalanced transformers) [3] and for transformers with a 4:1 impedance transformation ratio, as shown in figure 4. For most TV antennae, the output from the antenna is a balanced signal, on two active wires carrying signals of opposite polarity. For low loss transmission without interference, a coaxial cable is normally used to transmit this signal between the antenna and the TV set. A Balun is used to convert the balanced signals from the antenna to the match the unbalanced signal for the coaxial cable.

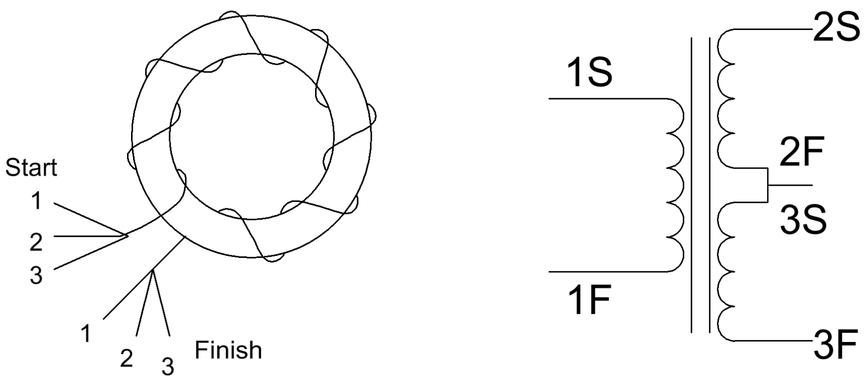

Figure 4. Trifilar winding diagram.

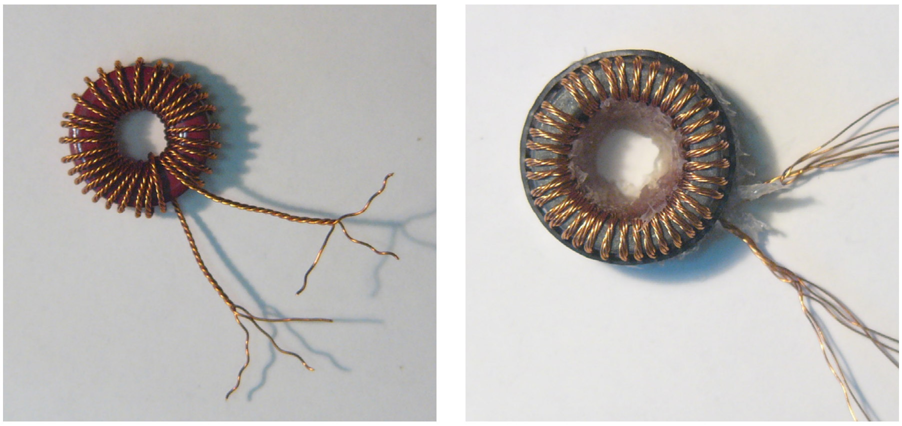

Figure 5. A trifilar wound RF Transformer (left) and a pentafilar transformer (right).

If port 2F-3S is earthed, then the transformer is a balanced to unbalanced transformer, called Balun. For a 75 Ω input impedance, a 300 Ω output impedance is obtained. Such a Balun is often used in TV antenna systems.

For instrumentation grade double balanced mixers a very good balance in the output signals is required, then an additional core, as shown in figure 6, can be added [3]. This provides winding 1 with a balanced input, thus causing the impedances at 2S to be exactly the same as those at 3F. Often the cost of the additional core is not justified.

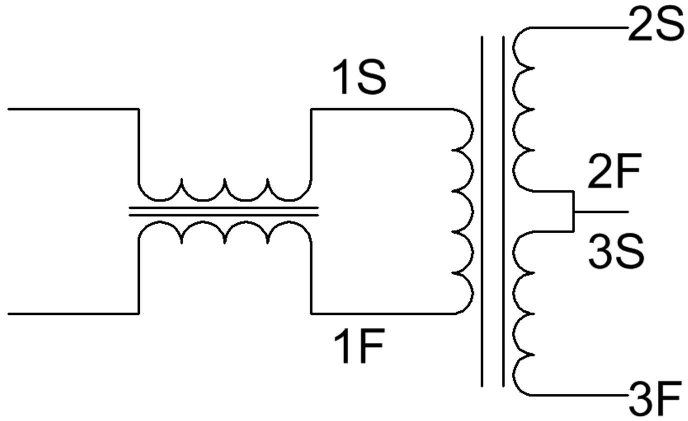

Figure 6. Balun with improved output balance.

Transmission line transformers with ferrite cores

At high frequencies, the primary and secondary windings are sometimes wound using transmission lines, as shown in Figures 7 and 8.

For a 50 Ω system, the characteristic impedance for the transmission lines used for the windings are 100 Ω. There is thus no reflection, at the junction where the two lines are connected in parallel. The two transmission lines are in series at the right hand side and the balanced output then form a 200 Ω system. Since the same propagation delay occurs through both the top and bottom transmission lines, the + and – signals are perfectly balanced at all frequencies.

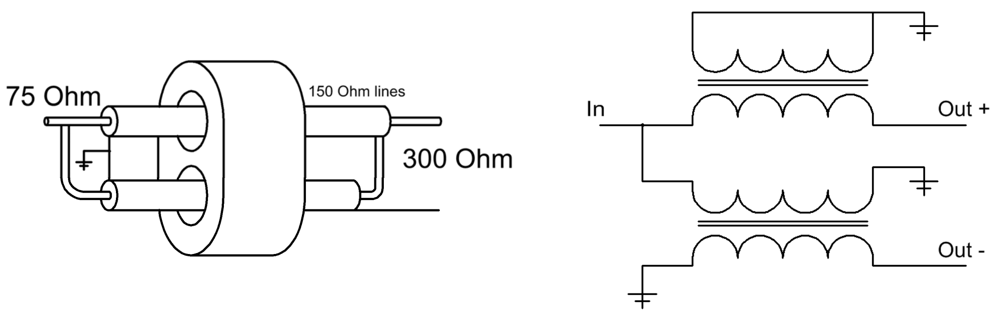

Figure 7. Diagram of transformers with ferrites and transmission lines.

The determination of the number of turns required for this transformer is exactly the same as for the bifilar or trifilar winding outlined above. The lower corner frequency is determined by the magnetising inductance. The upper corner frequency is determined by the losses in the ferrite. For the transmission line transformer the winding length is no longer limited to be less than 10% of the wavelength, as both outputs have the same propagation delay through the transmission line. Typically these cores are wound on low loss ferrites, giving them very high upper cut-off frequencies.

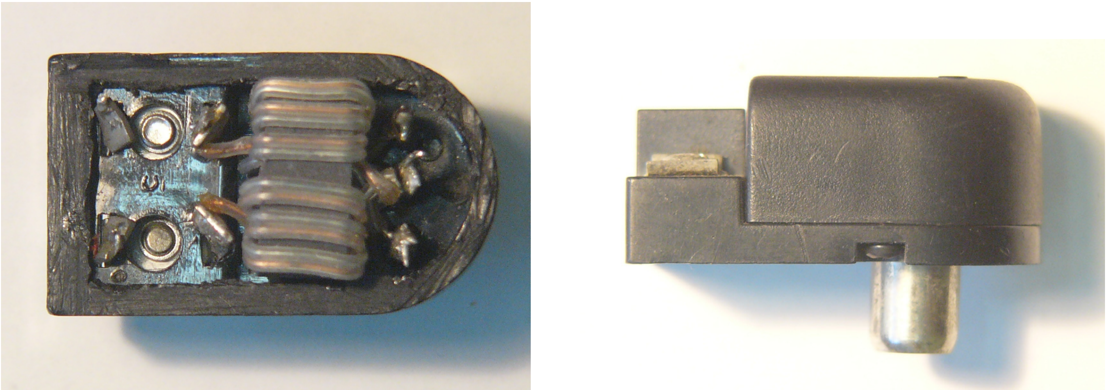

Figure 8. TV Balun using Ferrite RF transformer and transmission line windings.

This arrangement for a Balun is common for 300 Ω to 75 Ω baluns used in TV antenna systems. A typical dipole antenna has a 300 Ω impedance and the signals are balanced. For connecting these received signals to a TV, coaxial cable gives the best results, since it is shielded and does not pick up other radiation. The outer of the coaxial cable is at ground potential and the coaxial cable is 75 Ω impedance. The transmission line balun is this an ideal match at the high frequencies.

A transformer, using transmission lines for the windings, can be used as an isolating transformer, by connecting opposite sides of the transmission line to ground as indicated in figure 10. The lower frequency of this transformer is determined by the magnetising inductance of the former. This can be increased by simply adding more cores or having the transmission line go through the hole in the core many times.

By simply wrapping a coaxial lead around a ferrite or steel former, a non-inverting transformer, like figure 10, is obtained. This will provide isolation between both ends of the coaxial cable. Such a lead is useful in preventing earth loops with low voltage measurements.

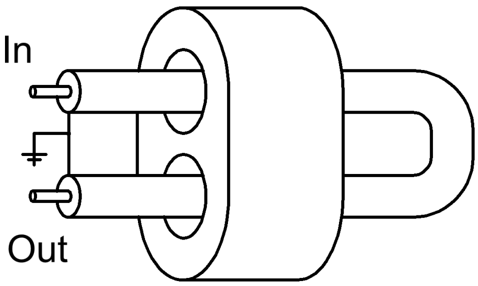

Figure 9. Non-inverting transformer.

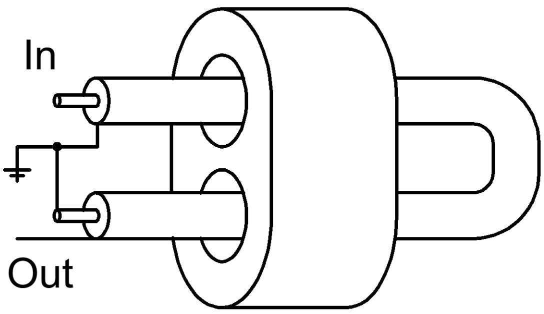

Figure 10. Inverting transformer.

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Transformer Hybrids

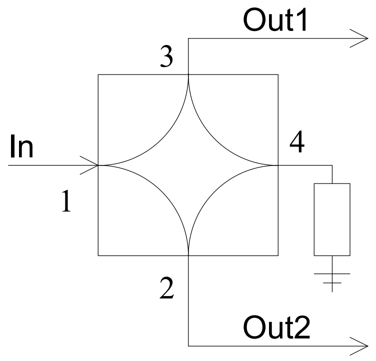

Figure 11. Hybrid.

In a hybrid, the input power at port 1 is split two ways to adjacent ports 2 and 3. Port 4, opposite the input port is isolated from the input port, and should have no energy going to it. A hybrid can thus be used as a power splitter.

Hybrids are normally symmetrical and bi-directional. Port 2 can thus also be used as an input, and under those conditions, half the power appears at port 1 and the other half appears at port 4. Under these conditions port 3 is isolated. If we now apply another input signal at port 3, that will also split two ways with half appearing at port 1 and the other half at port 4. For most hybrids, the phase angle at port 4 is 180 degrees out of phase for inputs at either port 2 or port 3, so that if equal signals are applied to ports 2 and 3, the sum of the signals will appear at port 1 and the difference will appear at port 4. If the signals applied to port 2 and port 3 are the same, the powers are combined at port 1. A hybrid can thus be used as a power combiner as well.

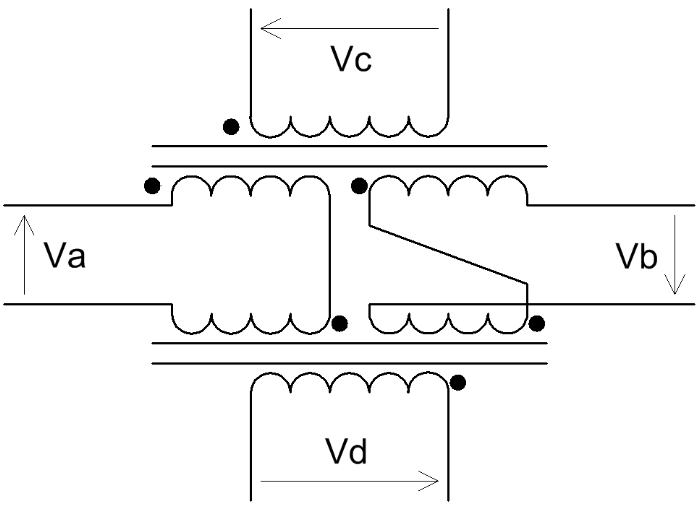

Figure 12. Audio transformer hybrid.

Transformer hybrids like the ones in figure 12 are used in telephony networks, where the signals to and from the normal telephone are sent in both directions on two wires.

Assume that all the windings on the transformers have the same number of turns. For the Audio transformer hybrid in figure 12, the voltages at each of the ports are related as:

$$\begin{aligned} Va &= Vc + Vd \\ Vb &= Vc - Vd \\ 2Vc &= Va + Vb \\ 2Vd &= Va - Vb \end{aligned} \qquad \text{Eqn. 3}$$

By changing the turns ratio to 0.707, the same equations are obtained for all the ports:

$$Va = 0.707Vc + 0.707Vd$$
$$Vb = 0.707Vc - 0.707Vd \qquad \text{Eqn. 4}$$
$$Vc = 0.707Va + 0.707Vb$$
$$Vd = 0.707Va - 0.707Vb$$

This ensures that the impedance levels in each port are the same. Note that Va does not couple into Vb and Vc does not couple into Vd and vice versa. A 40 dB isolation is typical under properly matched conditions.

Figure 13 shows how this audio hybrid can be wired up for use with amplifiers to produce a bi-directional amplifier, to amplify signals travelling in both directions along a wire. If the 2 wire circuit is not terminated properly, then part of the energy travelling out of this amplifier will be reflected and come back as input to the amplifier and be amplified again. If the gain of the amplifier is A dB and the isolation is B dB, then the singing margin is 2(B-A). The singing margin is the gain around the amplifier/hybrid loop. If the gain around the loop is more than 0 dB, then oscillations will occur. In practice the singing margin should be better than 6 dB. We should thus have more than 6 dB loss around the loop, even in the worst conditions.

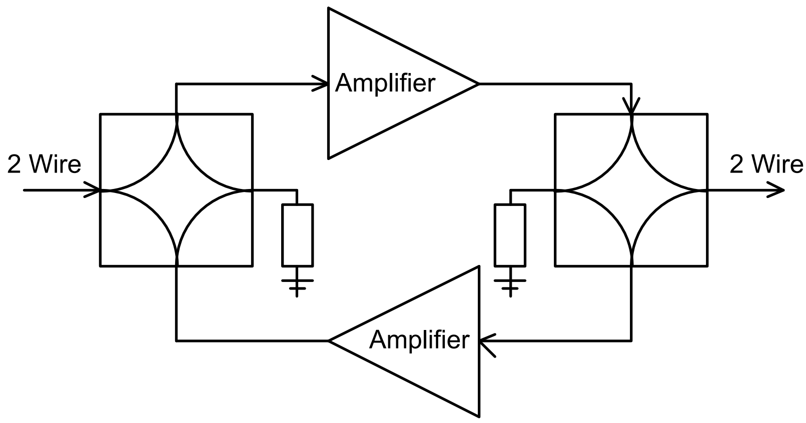

Figure 13. Bi-directional amplifier.

Power Combiner / Splitter

In a power combiner or power splitter, the terminating port is not brought out. The power combiner or power splitter is thus a 3-port device. Since linear passive devices are bi-directional, the same device can be used as both a power splitter and a power combiner. Often these devices are still called a hybrid. A common transformer based power splitter is a Wilkinson Hybrid. The two-way power splitters sold by department stores to permit two TVs to be operated from one antenna are Wilkinson Hybrids.

Wilkinson Transformer Hybrid

Figure 14 shows the circuit diagram of a Wilkinson Transformer Hybrid. If the same voltage input is applied to both ports A and B, then there is no voltage drop across the terminating resistor or transformer and port C is at same voltage as ports A and B. If the impedance levels for ports A and B are Z_0, then for power conservation, the impedance level at port C must be ½ Z_0. For those situations where the output impedance should be Z_0 then a 3:2 turns ratio transformer will change the impedance level by 2.25, which is close enough to 2:1.

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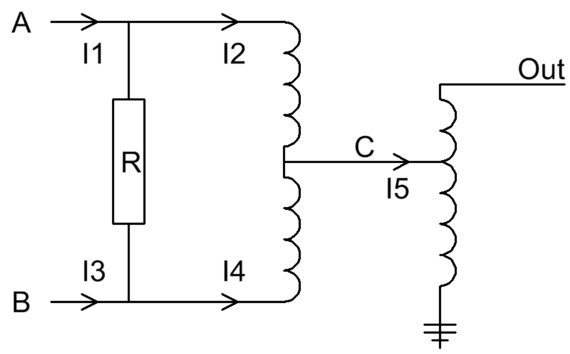

Figure 14. Wilkinson Transformer Hybrid.

If a voltage is applied to port A and 0 Volt is applied to port B, then the voltage at port C is ½ of that at port A. If the input current at port A entering the transformer is I_2 then through transformer action an equal and opposite current is flowing through the bottom part of the transformer, so that $I_2 = I_4$, under all conditions. If the load impedance at port C is ½ Z_0 as before then the input impedance seen at port A at the input of the transformer is 2 Z_0 since the transformer has a 2:1 turns ratio and a 4:1 impedance transformation ratio, since at port C one has half the voltage and twice the current.

Consider figure 14. For complete isolation between ports A and B, if a signal is applied at port A then the voltage at port B is zero, so that $I_3 = 0$. The current I_4 must thus flow through the resistor. The value of R required to ensure complete isolation between ports A and B can now be calculated. The voltage across the resistor is:

$$V_a = \frac{I_4}{R} = \frac{I_2}{2Z_0} \qquad \text{Eqn. 5}$$

Since $I_2 = I_4$, we must have $R = 2Z_0$ to achieve isolation between both input ports. Under those conditions the impedance seen at the input port A is Z_0, being the transformer input impedance of $2Z_0$ in parallel with the terminating resistor of $2Z_0$.

If this hybrid is used as a power splitter and the loads on ports A and B are matched, then no current will flow through the terminating resistor. Under those conditions that can be removed, at the expense of a poor isolation if unequal loads are present. For a power combiner in an antenna systems, where the output from two identical antenna elements are combined, a hybrid can be used that does not contain any isolating resistor, since the signals arriving at each of the antennae is identical and as a result no power is dissipated in the isolating resistor.

The Wilkinson transformer hybrids are commercially available as wideband power-splitters and power-combiners manufactured by companies such as Minicircuits.

The conventional TV splitter is a cut down version of the Wilkinson hybrid. Since the cable losses will mask any unequal loads, the terminating resistor is not normally present and since impedance variations can be tolerated, no output transformer is used. The omission of those components reduces the cost for this consumer-oriented circuit.

If a Wilkinson Transformer hybrid is used to combine the output from two transmitters, any unbalance will be dissipated in the resistor R. For two 100 watt transmitters, 50 watt will be dissipated in the resistor and 50 watt will be radiated if one of the amplifiers fails. The resistor must thus be selected with this power requirement in mind.

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Design Example

Use the same transformer as in the example for the construction of a Wilkinson hybrid and design the hybrid to operate at 1 MHz as before. If the basic hybrid is unbalanced (an input is applied to port 2 but no input is applied to port 3), it behaves like a 25 Ω to 100 Ω transformer. The transformer of the previous example had an 11 turn winding with a characteristic impedance of 12.65 Ω. For the 25 Ω side 11√(25/12.65) turns = 15.5 turns is required. Since this has to be an integer number, 16 turns are used. The leakage inductance will then be $64(16/11)^2$ = 135 nH and the magnetising inductance will be 135 μH. The 25 Ω to 50 Ω impedance transformation transformer will have a 2:3 turns ratio auto-transformer, with an 8 turns trifilar winding, so that the 25 Ω winding will consist of two 8 turn windings in series, resulting in the required 16 turns. The 50 Ω port 1 will thus see 24 turns, corresponding to a leakage inductance of 270 nH and the magnetising inductance will be 270 μH.

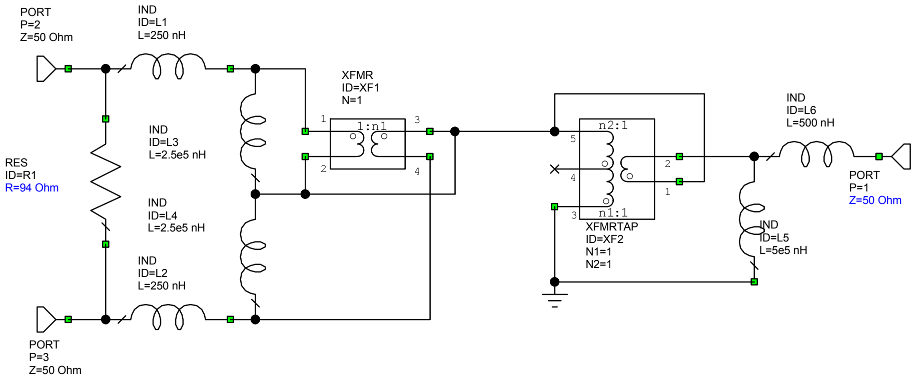

Figure 15. Wilkinson Hybrid model for computer simulation.

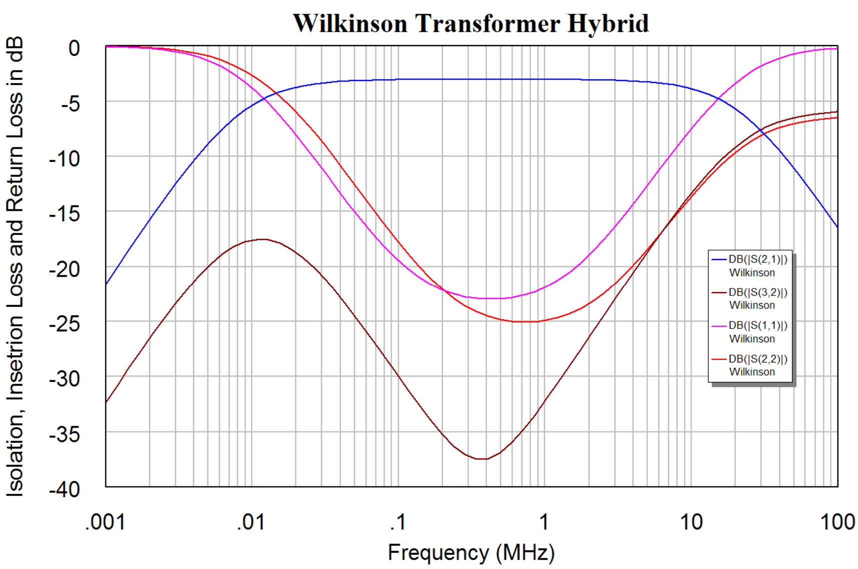

Figure 16. Simulated performance of Wilkinson Hybrid.

The performance of the Wilkinson Hybrid can be determined from computer simulation using Microwave Office as shown in figures 15 and 16. It can be seen that a good isolation and return loss on all ports is obtained at the design frequency of 1 MHz. Constructing this hybrid normally results in a close agreement with the simulation.

Transmission Line Hybrid with Ferrite Cores

A simple hybrid made using standard 50 ohm transmission line hybrid and ferrite cores is shown in figure 17. If the impedance at A and B is Z_0 then at C the impedance is $\frac{1}{2}Z_0$. The impedance seen when B=0 is $2x(\frac{1}{2}Z_0)=Z_0$. The power dissipated in the load resistor is the power associated with the difference in the input signals. For high power operation, the rating of that resistor must be carefully considered. If the input at A and B are the same then no power will be dissipated in the load resistor.

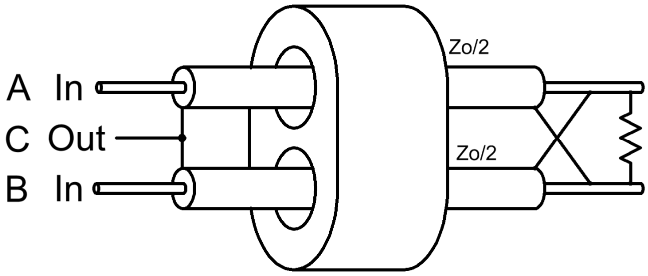

Figure 17. Hybrid with ferrite cores.

The realisation of the hybrid is shown in figure 18 and the circuit can be analysed using the circuit representation in figure 19. In figure 18, the 25 Ω transmission lines are obtained by having two 50 Ω transmission lines in parallel.

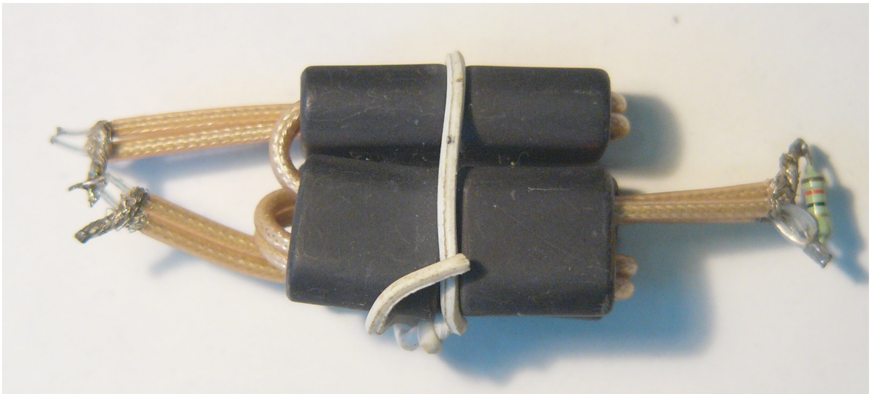

Figure 18. Circuit of hybrid in figure 17

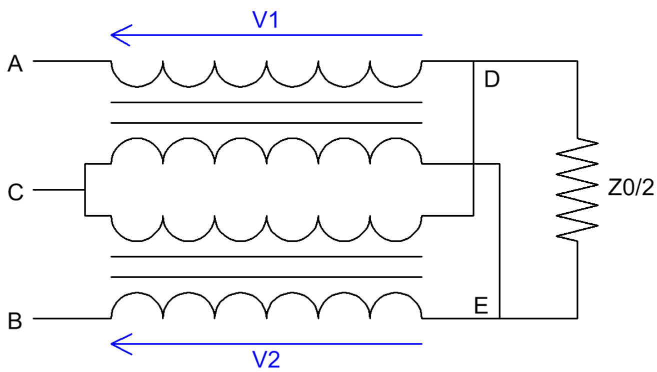

Figure 19. Circuit of hybrid in figure 17.

The equations for this hybrid are:

$$V_a-V_d=V_1$$
$$V_c-V_e=V_1 \qquad \text{Eqn. 6}$$
$$V_c-V_d=V_2$$
$$V_b-V_e=V_2$$

Subtracting the first two equations and the last two equations and adding the resulting equations gives:

$$V_c = \frac{V_a + V_b}{2} \qquad \text{Eqn. 7}$$

Now consider the conditions required for isolation. If $V_b=0$. For isolation between ports A and B, the current through the bottom transformer is zero, since with a load connected to B the voltage must be zero. That means $V_2=0$ and thus $V_e=0$ and $V_d=½V_a$.

For the input impedance at A to be Z_0 then the load resistor must be $½Z_0$. Under those conditions the current into A goes through the load and out of C. The voltages are thus:

At input A	$V_a = Z_0 \bullet I$	Eqn. 8
Across the Load	$½V_a = ½Z_0 \bullet I$	Eqn. 9
At the output C	$½V_a = ½Z_0 \bullet I$	Eqn. 10

The equations are thus consistent and the assumption that $V_b=0$ is justified and we have full isolation when $R=½Z_0$. The circuit works thus as a proper hybrid.

Note: Like the Wilkinson transformer, the impedance at the summing port C has an impedance of $½Z_0$ and a transformer needs to be used to change that to Z_0 if required, similar to that for the Wilkinson transformer of figure 14.

Many way hybrids

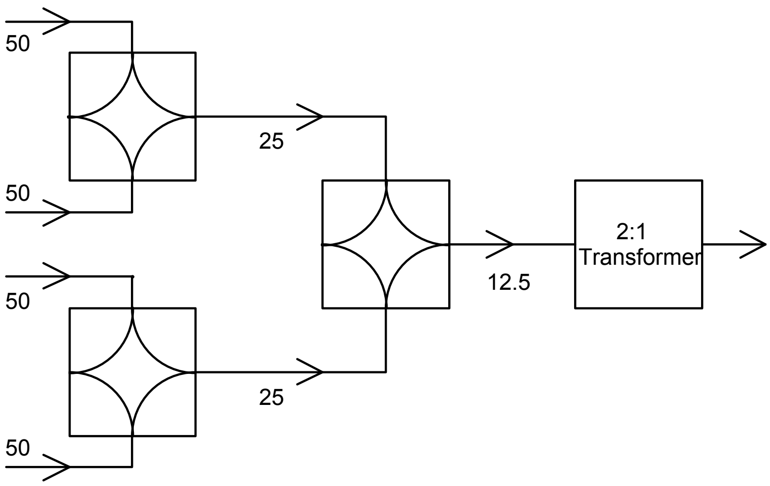

Figure 20. A four-way combiner.

In some instances many signals need to be combined or a signal needs to be split many ways. The hybrids described above can be cascaded to provide a many way splitter/combiner. However each of those hybrids will include a 25 Ω to 50 Ω impedance transformation transformer. Some savings can be made by using a 4 way hybrid as shown in figure 20, where three of two way hybrids are used together to combine 4 input signals and then have a 12.5 ohm output, which can be transformed to 50 ohm by using a 2:1 transformer, as shown in figure 20. This saves two transformers, each of which will have some losses associated with it. In addition the 4:1 impedance transformation is exact, while the 2:1 impedance transformation is actually a 2.25:1 impedance transformation with the 3:2 turns ratio of the transformer. Two of the hybrids below operate at a 50 Ω impedance and one operates at a 25 Ω impedance. The number of turns on the transformer coils needs to be adjusted to allow for this.

References

1. H. Granberg, “Broadband transformers and power combining techniques for RF”, Motorola Application note AN749, Motorola RF Circuits Engineering, 1993.
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