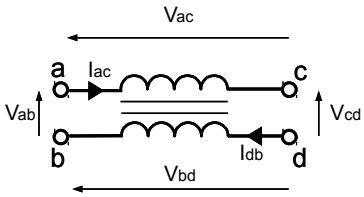
Introduction

Baluns can be difficult components to analyse and understand fully; however it's possible to get a good basic understanding of how they operate by treating them as combinations of idealised common-mode RF chokes. This paper uses that method to explore the advantages and disadvantages of some of the common baluns used by Radio Amateurs.

Ideal Choke

The schematic of a typical choke is shown in Drawing 1. The choke comprises two windings a-c and b-d that have the same number of turns and share a common flux path. Typically the windings will comprise a bifilar pair or a length of coaxial cable; in the case of coax, a-c might be the centre conductor and b-d the braid. The choke is used in "transmission line mode" - in other words a signal is applied between terminals a-b and appears as an output at terminals c-d.



Drawing 1: Ideal Choke

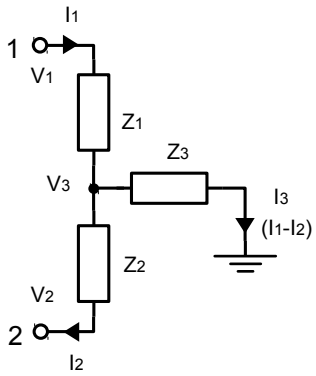
An ***ideal*** choke will have the following properties:

- P1: It is lossless, and the winding length is very small compared to a wavelength, so $\mathbf{V_{cd}=V_{ab}}$. We will refer to this as the "*Differential-Mode*" voltage applied to the choke.
- P2: Because the windings are identical and share the same flux, $\mathbf{V_{ac}=V_{bd}}$. We refer to this as the "*Common-Mode*" voltage across the choke.
- P3: The choke is assumed to have infinite Common-Mode impedance, so the Common-Mode current must be zero no matter how high the Common-Mode voltage is; so $\mathbf{I_{ac}-I_{db}=0}$ or $\mathbf{I_{ac}=I_{db}}$

Of course no real-world choke is ideal, but using these properties we can easily gain useful insight into how the various balun types operate.

Test Load

Each balun's operation will be discussed working into the load shown in Drawing 2. The load has two terminals - labelled 1 & 2 - which could represent, for example, the connections to a dipole or a beam at its feedpoint; or they might represent the connections to a length of ladderline feeding a doublet antenna.



Drawing 2: Test Load

In the vast majority of Amateur applications we want to balance the ***currents*** I_1 and I_2 flowing into and out of the load. For example, balancing those currents in a beam antenna helps preserve the radiation pattern; and balancing the currents in ladderline minimises radiation from the line during transmissions and noise pick-up during reception.

However, all real-world antenna systems are actually 3-terminal loads - the third terminal being ground, as shown in the drawing. The primary load components are Z_1 & Z_2, but the inclusion of Z_3 provides a path for common-mode current to ground. Clearly, if we do not include the path to ground through Z_3, currents I_1 and I_2 ***must*** be equal, and <u>there is then no need for a balun</u>!

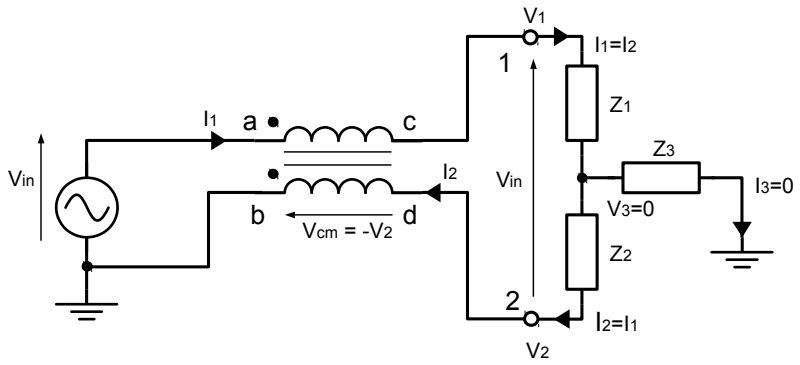
Using Ohm's Law the load's electrical properties properties are related by:

- $I_1 = (V_1-V_3) / Z_1$
- $I_2 = (V_3-V_2) / Z_2$
- $I_3 = V_3 / Z_3$
- $I_3 = I_1 - I_2$

Note that, if the load currents I_1 and I_2 are balanced, I_3 must be zero and V_3 must be zero.

In general, impedances Z_1, Z_2 and Z_3 are complex quantities- in other words they have reactance as well as resistance. Z_3 can be anything from a few Ohms to many thousands of Ohms depending on the particular system. If $Z_1 = Z_2$ the load is said to be balanced.

A) 1:1 Guanella (current) Balun



Drawing 3: 1:1 Guanella (current) Balun

Drawing 3 shows an unbalanced RF source connected to the Test Load through a 1:1 Guanella balun - identical to a simple Common Mode choke.

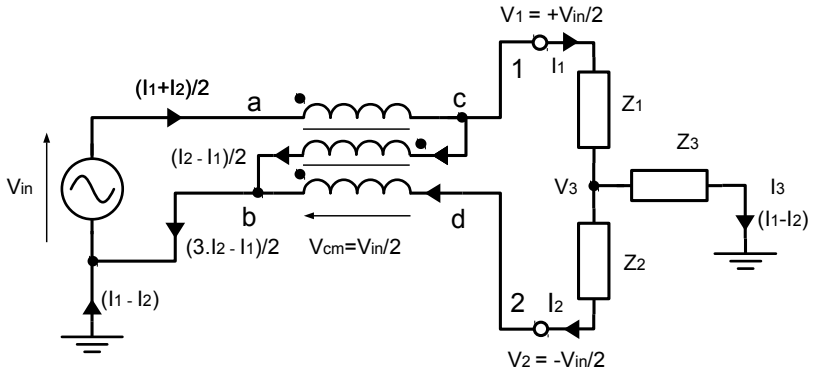
Analysis

- Load currents I_1 and I_2 must be equal, to satisfy property P_3 ($I_{ac} = I_{db}$)
- Therefore $I_3 = 0$ and $V_3 = 0$
- Voltage between load terminals (V_1-V_2) must equal V_{in} to satisfy Choke property P_1 ($V_{cd} = V_{ab}$)
- Common-mode voltage (stress) across the choke $V_{cm} = -V_2$
- Input impedance “seen” by the source = $V_{in}/I_1=(Z_1+Z_2)$

Characteristics:

- This balun drives balanced load currents despite the load impedances being unbalanced
- Differing degrees of load imbalance lead to differing levels of common-mode voltage across the choke
- With a perfectly balanced load ($Z_1 = Z_2$), the choke common-mode voltage V_{cm} will be V_{in} / 2

B) 1:1 Voltage Balun



Drawing 4: 1:1 Voltage Balun

Drawing 4 shows our unbalanced RF source connected to the load through a 1:1 voltage balun. The important feature of this balun is that a third (tertiary) winding (c-b) has been added to the choke with the winding sense indicated by the black dots; it has the same number of turns as the existing windings

This introduces new properties to the choke, such that now:

- P_4: Because all three windings share the same flux **$V_{ac} = V_{bd} = V_{cb}$**
- P_5: Because the net common-mode current must be zero **$I_{db} = (I_{ac}+I_{cb})$**

This new property P_5 has a significant effect on the operation of the balun, as we shall see.

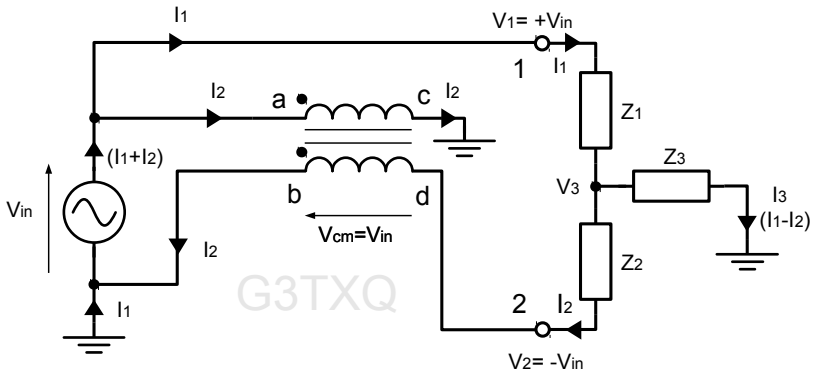
Analysis

- By inspection, $(V_{ac} + V_{cb}) = V_{in}$
- But from P_4: $V_{ac} = V_{cb}$ therefore $V_{ac} = V_{cb} = V_{bd} = V_{in}/2$
- By inspection: $V_1 = (V_{in} - V_{ac}) = +V_{in}/2$
- By inspection: $V_2 = (0 - V_{bd}) = -V_{in}/2$
- By inspection: $I_{db} = I_2$
- Therefore from P_5: $(I_{ac} + I_{cb}) = I_2$ or $I_{cb} = (I_2 - I_{ac})$
- Applying Kirchoff's current law at terminal C: $I_{ac} = (I_1+I_{cb}) = (I_1 + I_2 - I_{ac})$
- Therefore $I_{ac} = (I_1+I_2)/2$ and tertiary winding current $I_{cb} = (I_2-I_1)/2$
- Input impedance “seen” by the source = $2.V_{in} / (I_1+I_2)$

Characteristics:

- This balun drives balanced voltages of $+V_{in}/2$ and $-V_{in}/2$ at the load terminals. Only with a perfectly balanced load will the load currents be balanced; <u>any load imbalance will result in a corresponding current imbalance.</u>
- The choke common-mode voltage is always $V_{in}/2$ and so the common-mode stress on the choke is independent of the degree of load imbalance
- Any common-mode current at the load is accommodated by a related current flow through the tertiary winding; with a completely balanced load, the tertiary winding current will be zero.
- For most load conditions, the tertiary winding handles a much lower current than the two other windings; it is therefore often constructed with thinner gauge wire.

C) 4:1 Ruthroff (voltage) Balun



Drawing 5: 4:1 Ruthroff (voltage) balun

Drawing 5 shows the unbalanced RF source connected to the load through a 4:1 Ruthroff voltage balun. The schematic of the balun may look unfamiliar, but it is electrically identical to the more usual layout, and more clearly illustrates how the balun operates.

The source voltage is connected directly to one load terminal (1). The same source voltage is also connected across the input of the choke (a-b). The choke produces an identical voltage at its output (c-d), but one which is "isolated" from its input; this isolation means that either of its output terminals can be grounded with impunity. By grounding choke terminal c we generate an inverted copy of the input voltage at terminal d, and this is applied to the other load terminal (2). In this way we develop twice the source voltage across the load, as required for a 4:1 balun.

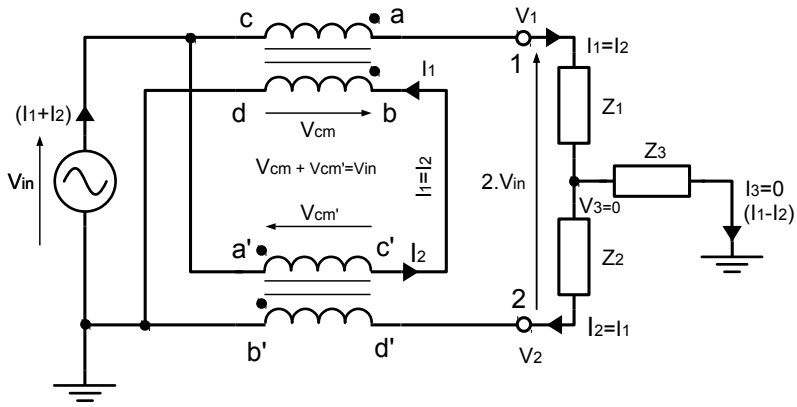
Analysis

- Load terminal voltage V_1 must be $+V_{in}$ because it is connected directly to the source
- The choke input is connected directly across the source, therefore $V_{ab} = V_{in}$
- From property P_1: $V_{cd} = V_{ab} = V_{in}$
- Because choke terminal c is grounded, $V_d = V_2 = -V_{in}$
- By inspection, choke common-mode voltage $V_{cm} = V_{in}$
- By inspection: $I_{db} = I_2$
- Therefore from property P_3: $I_{ac} = I_2$
- Applying Kirchoff's current law, the output current from the generator = (I_1+I_2)
- Therefore, the impedance seen by the source = $V_{in} / (I_1+I_2)$

Characteristics:

- This balun drives balanced voltages of +Vin and -Vin at the load terminals. Only with a perfectly balanced load will the load currents be balanced; <u>any load imbalance will result in a corresponding current imbalance.</u>
- The choke common-mode voltage is always V_{in} and so the common-mode stress on the choke is independent of the degree of load imbalance
- Although we have assumed an ideal choke where $V_{cd}=V_{ab}$, in practice there will be a phase difference between the two voltages caused by the delay in the transmission line forming the choke winding; this causes a phase difference between the load terminal voltages V_1 & V_2. The phase difference increases with frequency and limits the SWR bandwidth of this type of choke.

D) 4:1 Guanella (current) Balun



Drawing 6: 4:1 Guanella (current) Balun

Drawing 6 shows the unbalanced RF source connected to the load through a 4:1 Guanella current balun. The balun comprises two chokes - terminals on the lower choke are distinguished by the ' symbol. The input of each choke is connected directly in parallel with the source. Because each choke effectively isolates its output from its input, we can connect their outputs in series - thereby generating a voltage across the load of twice the source voltage, as required for a 4:1 balun.

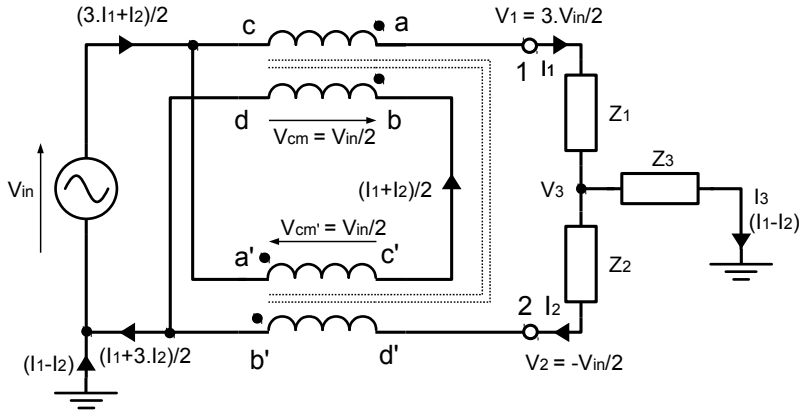
Analysis

- By inspection: $I_{ca}=I_1$
- Therefore from property P3: $I_{bd} = I_{ca} = I_1$
- By inspection: $I_{d'b'}=I_2$
- Therefore from property P3: $I_{a'c'} = I_{d'b'} = I_2$
- But $I_{a'c'} = I_{bd}$ because the choke windings are connected in series; therefore $I_1=I_2$ and $I_3=0$
- By inspection: $V_{cd}=V_{in}$ and $V_{a'b'}=V_{in}$
- Therefore from property P1: $V_{ab} = V_{cd} = V_{in}$ and $V_{c'd'} = V_{a'b'} = V_{in}$
- By inspection: $V_{12} = V_{ab} + V_{c'd'}$
- Therefore differential load voltage $V_{12} = 2.V_{in}$
- From Ohm's Law: $I_1 = I_2 = 2.V_{in} / (Z_1+Z_2)$
- From Kirchoff's current law, output current from the source $(I_{ca} + I_{a'c'}) = (I_1 + I_2) = 2.I_1$ or $2.I_2$
- By inspection, lower choke common-mode voltage $V_{cm'} = -V_2$
- By inspection, upper choke common-mode voltage $V_{cm} = (V_1-V_{in})$
- By inspection: $V_{cm}+V_{cm'}=V_{in}$
- Impedance “seen” by the source = $V_{in}/(I_1+I_2) = V_{in} /(4.V_{in}/(Z_1+Z_2)) = (Z_1+Z_2)/4$

Characteristics:

- This balun drives balanced load currents despite the load being unbalanced
- The input impedance is equal to $(Z_1+Z_2)/4$ whatever the load imbalance
- The common-mode voltages across the two chokes - a measure of stress on the choke - always sum to V_{in}. However they are unequal - in fact with a perfectly-balanced load the common-mode voltage across the upper choke is zero, and that across the lower choke is equal to the input voltage!
- With some types of load imbalance, reversing the balun output terminals can reduce the common-mode voltage disparity.

E) 4:1 Guanella (current) Balun - single core



Drawing 7: 4:1 Guanella (current) Balun - single core

We continue to see designs - both Commercial and home-made - where the two chokes forming a 4:1 Guanella balun have been wound on a common core. This is indicated in Drawing 7 by the common core lines; the winding senses are indicated by the “dots”.

Because all 4 choke windings now share the same flux, we get a new set of properties:

- P_6: $V_{cm} = V_{cm'} = V_{ac} = V_{bd} = V_{a'c'} = V_{b'd'}$
- P_7: $(I_{ca}+I_{d'b'}) = (I_{a'c'}+I_{bd})$

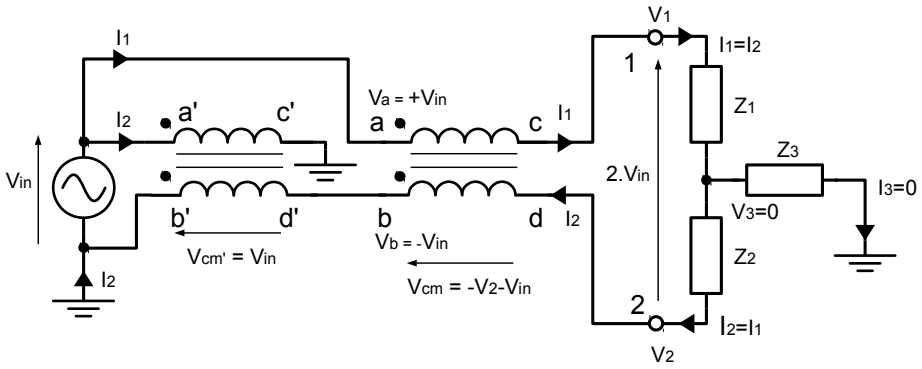
Analysis

- By inspection: $V_{a'c'} + V_{bd} = V_{in}$ (as before)
- But from property P_6, $V_{a'c'}$ must equal V_{bd}, so $V_{a'c'} = V_{db} = V_{in}/2$
- Therefore Vcm = V'cm = Vac = Vbd = Va'c' = Vb'd' = Vin/2
- Thereby driving the load terminal voltages to $V_1 = 3.V_{in}/2$ and $V_2 = -V_{in}/2$
- From property P_7, $(I_1+I_2) = (I_{a'c'}+I_{bd})$
- But because they are connected in series, $I_{a'c'} = I_{bd}$
- Therefore $I_{a'c'} = I_{bd} = (I_1+I_2)/2$
- From Kirchoff's current law, source current is $(I_{ca}+I_{a'c'}) = (I_1+(I_1+I_2)/2) = (3.I_1+I_2)/2$
- Impedance “seen” by the source = $V_{in}/(3.I_1+I_2)/2 = 2.V_{in}/(3.I_1+I_2)$

Characteristics:

- This type of balun **must** always drive its output voltages to $+3.V_{in}/2$ and $-V_{in}/2$ with respect to ground, whatever the load
- These unbalanced terminal voltages drive a large load current imbalance in most loads, **even one which is perfectly balanced;** in this respect it is a worse choice than the 4:1 Ruthroff balun!!!! Despite these failings it continues to be marketed as a **current** balun.
- The load current imbalance is accommodated because property P_3 has been destroyed - opposing choke currents no longer have to be identical. Any imbalance between I_1 and I_2 leads to a compensating current flowing a'- c'- b - d to produce zero net core flux
- Its one virtue - apart from saving one core - is that the common-mode voltage stress across each choke is identical, and is limited to half the input voltage, no matter what the load. This may explain why it is promoted by at least one manufacturer for use with asymmetric loads such as the Off-Centre-Fed dipole.

F) 4:1 Hybrid balun



Drawing 8: 4:1 Hybrid balun

We can combine the useful attributes of a voltage balun and a current balun by concatenating them to form a 4:1 current balun, as shown in Drawing 8. Here a 4:1 voltage balun (left hand choke a'b'c'd') provides the impedance transformation and a 1:1 current balun (abcd) drives balanced currents into the load. I attribute this design to Andrew Roos, ZS1AN.

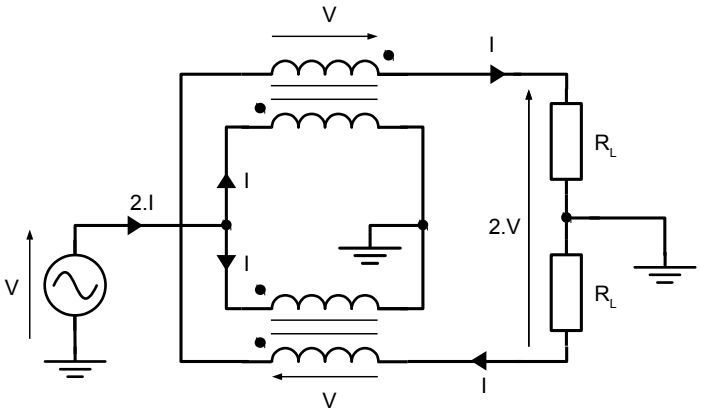
Analysis

- From the earlier analysis of the 4:1 voltage balun: Va = +Vin and Vb=-Vin
- Therefore the voltage across the load, $(V_1-V_2) = V_{cd} = V_{ab} = 2.V_{in}$
- By inspection $V_{cm'} = V_{in}$
- From property P_3 applied to choke abcd: $I_1 = I_2$ and therefore $I_3 = 0$ and $V_3 = 0$
- By inspection $V_{cm} = -V_{in}-V_2$
- From Kirchoff, source current is $(I_1+I_2) = 2.I_1$ or $2.I_2$
- From Ohm's Law, load current $I_1 = I_2 = 2.V_{in}/(Z_1+Z_2)$
- Impedance “seen” by the source $V_{in}/2.I_1 = (Z_1+Z_2)/4$

Characteristics:

- This balun drives balanced load currents despite the load impedances being unbalanced
- The common-mode voltage stress across the voltage balun choke is always equal to the source voltage, whatever the load.
- The common-mode voltage stress across the current balun choke depends on the degree of load imbalance, but it is typically much less than the stress on the lower choke of a 4:1 Guanella balun; with a balanced load it is zero.
- The SWR bandwidth will likely be determined by the voltage balun, for the reasons outlined in Section C.
- This design will exhibit more common-mode impedance than a 4:1 Guanella balun constructed from two chokes identical to the current balun element here.

G) Trask 4:1 current balun on single core

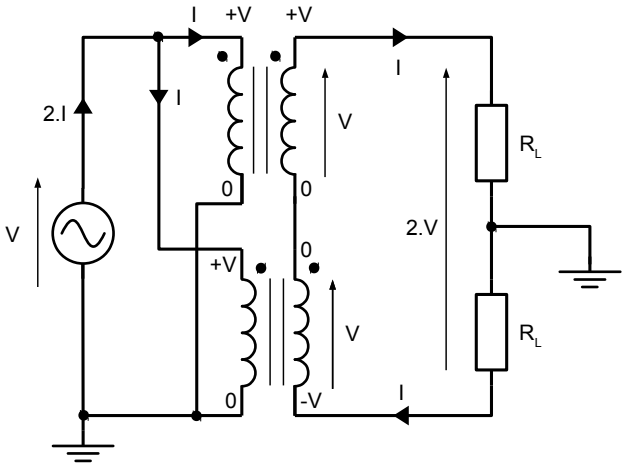


Drawing 9: Trask 4:1 current balun on single core

In the search for a 4:1 current balun that could be implemented on a single core, Chris Trask / N7ZWY arrived at the design shown in Drawing 9. A full description can be found here: http://www.home.earthlink.net/~christrask/Trask4to1Balun.pdf

The manner in which the balun operates may not immediately be obvious, because of the way the schematic is drawn. Note in particular the important reversal of the winding "dots" in the upper "choke"; and note that the input signal is not being applied to the chokes in "transmission-line mode" but is being applied directly as a common-mode signal across them.

The mode of operation becomes clearer when we re-arrange the schematic as shown in Drawing 10:



Drawing 10: Trask balun re-drawn

Re-drawn this way it becomes clear that this is a conventional 4-winding transformer. Two of the windings are wired in parallel to form the input, and two are wired in series to form the output.

Simply by inspection, we can see that:

- The output voltage is 2.V as required of a 4:1 balun
- The currents into and out of the load terminals must be equal - whatever the load imbalance - because they form the input and output currents of the transformer secondary; therefore the balun does indeed operate as a current balun
- The common-mode voltage across each winding is fixed at V, whatever the load imbalance
- All windings are able to share a common flux path without violating property P3; the balun therefore can be constructed on a single core.
- The differential-mode voltage at input and output of the upper choke is zero, despite there being a differential-mode current of I flowing; this indicates that the choke is not operating as a transmission line, but as a conventional flux-coupled transformer.

Given these attributes the reader may wonder why it is not more widely used. One answer is that, because it operates in a conventional transformer mode rather than in a transmission-line choke mode, its bandwidth is more limited than some of the other current baluns; and as we shall see in the next section its common-mode impedance is almost entirely reactive, which can be problematic in some installations.

Non-ideal chokes

So far we have considered the chokes to be "ideal" (as defined by properties P_1 thru P_3) because that helps us gain an understanding of the fundamental mechanisms by which the baluns operate; but of course in the real world they are not ideal, and it's worth looking at how the "non-ideal" characteristics influence balun operation.

Property P_1: typically the choke output voltage V_{cd} wont be exactly the same as the input voltage V_{ab}, for at least three reasons: the amplitude will be smaller because of losses; there will be a phase lag because of the delay through the choke; and there could be a voltage transformation between input and output if the transmission line (TL) forming the choke is not terminated in its characteristic impedance (Zo).

We can minimise these effects by keeping the (TL) as short as possible and by choosing a value of Zo appropriate for the load - they generally do not become the major worry in practical balun design. The effect that manifests itself most is likely to be the phase delay - particularly in the 4:1 Ruthroff balun where it inherently causes a phase difference between $+V_{in}$ applied to one load terminal and $-V_{in}$ applied to the other; the result is a lower SWR bandwidth than, for example, the 4:1 Guanella balun where both terminal voltages are delayed by similar amounts.

Property P_2: careful winding of the chokes generally makes real world effects insignificant.

Property P_3: typically, choke currents Iac and Idb will not be equal because we cannot produce chokes with infinite common-mode impedance. We strive to make the impedance as high as possible over the operating bandwidth by choice of winding characteristics and core material, and we try to make the impedance resistive for reasons explained elsewhere, but any shortfall here can lead to unbalanced currents in the load and overheating in the balun. It is **the** major challenge in balun design.

Given the importance of property P_3, it is interesting to see how the "real world" common-mode impedances (Zcm) of the different balun topologies compare. Here are measured results for the various balun designs; in every case the constituent choke(s) each comprised 7 bifilar turns on an FT240-43 core:

Balun type	3 MHz	10 MHz	30 MHz
1:1 Guanella (current)	894 ∠ +62°	1855 ∠ +36°	2765 ∠ -32°
1:1 Voltage	0*	0*	0*
4:1 Ruthroff (voltage)	0*	0*	0*
4:1 Guanella (current)	475 ∠ +63°	924 ∠ +36°	1514 ∠ -22°
4:1 Guanella - single core	0*	0*	0*
4:1 Hybrid	900 ∠ +60°	1850 ∠ +35°	2768 ∠ -30°
4:1 Trask	1278 ∠ -88°	387∠ -88°	119 ∠ -88°

Note:

- 0* indicates a value sufficiently close to zero that there is no meaningful common-mode impedance - values of less than 10 Ohms were typically measured
- The 4:1 Guanella values are roughly half those of the 1:1 Guanella; this is to be expected because the 4:1 Guanella comprises two chokes that are effectively in parallel as far as common-mode signals are concerned.
- The 4:1 Hybrid values are almost identical to those of the 1:1 Guanella; not surprising given that it comprises a 1:1 Guanella in tandem with a 4:1 Ruthroff balun
- The Trask balun has Zcm values that are unrelated to those of the constituent chokes; the

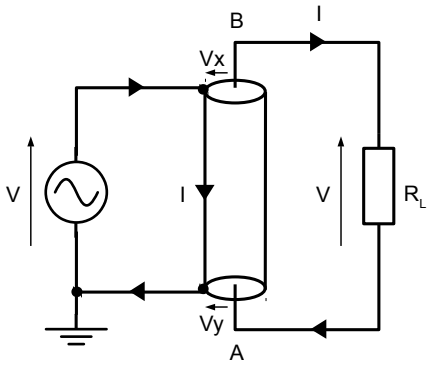
impedances are almost entirely capacitive and inversely proportional to frequency. They are characteristic of a conventional transformer with about 42pF of primary/secondary capacitive coupling - a value that is entirely consistent with the capacitance between the legs of the bifilar transmission-line with which they were wound. See Appendix A for more discussion.

Conclusions

- For applications where we require current balance, but no impedance transformation, the 1:1 Guanella (aka common-mode choke or RF choke) is the obvious choice.
- For applications where we require current balance and a 4:1 impedance transformation, and where high common-mode impedance is more important than extended bandwidth - for example at the output of an HF tuner - the 4:1 Hybrid would be the balun of choice.
- For applications where we require current balance and a 4:1 impedance transformation, and where extended bandwidth is paramount, the 4:1 Guanella would be an appropriate choice.

Appendix A: Trask Balun - “Flux-Coupled” or “Transmission-Line”?

The mode of operation of the Trask balun has been hotly debated on Internet forums over the years. The debate reduces to whether or not the underlying topology of the Trask balun - shown on the right - can be called a Transmission Line Balun (TLB) or not. The fact that it contains a length of transmission line is not sufficient - the important issue is whether energy is coupled from the source to the load due to the coupling of flux (as in a conventional transformer) or by way of a TEM transmission-line mode within the line.



1:1 Current balun

The line is usually wound on a ferrite core, or is loaded with ferrite beads, to extend its low frequency performance. In principle it can be formed from any type of line - coax, bifilar pair, or twisted pair - but coax has been chosen here to clarify the topology.

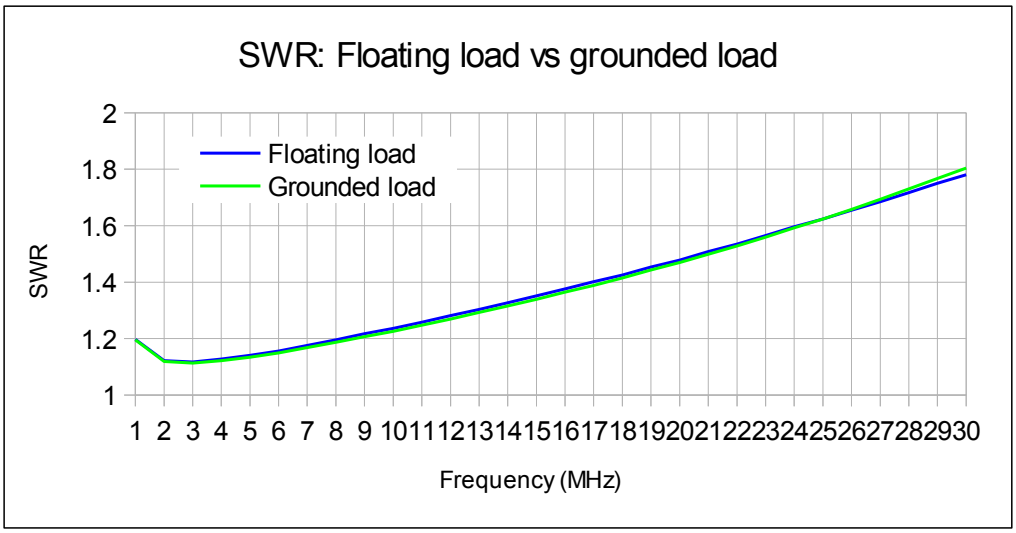
Simple analysis shows that - provided there is no other path for inner conductor current to flow - the currents into and out of the load must be equal, whatever the load configuration; so it does indeed operate as a current balun.

The TEM mode requires that the electric (E) and magnetic (H) field lines are restricted to directions normal (transverse) to the direction of propagation. In coax the E-field lines run radially, while H-field lines run in circles around the centre conductor; and the direction of propagation is along the length of the cable.

There are several tests we might apply to help us decide whether this balun operates in TEM mode - here are a few:

1. Say we ground one side of the load - Point A; this forces the voltage between the inner conductor and the braid to be zero at both ends of the coax (Vx and Vy). If the balun continues working and the coax still flows a differential current (I) despite there being zero differential-mode voltage - the energy coupling mechanism cannot be a TEM wave within the coax.

Here are the measured input SWR_{50} results for a balun with this topology, comprising 7 turns (about 19 inches) of RG-58 on an FT240-43 toroid, when terminated in a 50 Ohm load:

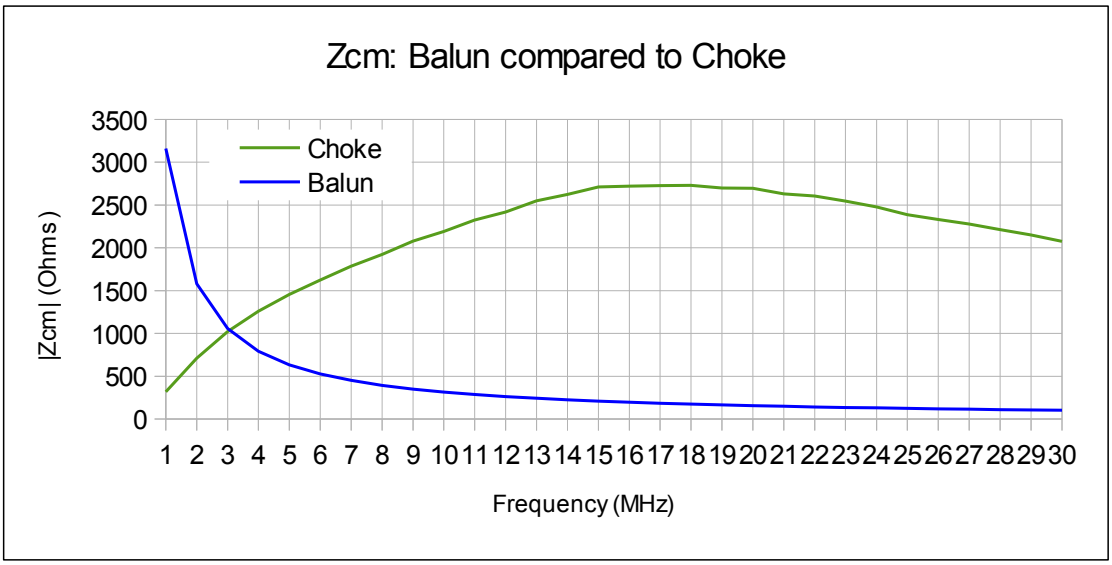


Grounding point A on the schematic has made negligible difference to the performance of the balun!

Question 1: If the transfer of energy is due to a TEM wave along the coax, how does the balun continue to work when there is zero voltage between the inner conductor and braid?

2. Another test might be to compare the common-mode impedance (Zcm) of the balun with the transverse common-mode impedance of the constituent choke. If the energy transfer through the balun is due to a TEM wave, we might expect the Zcm characteristics to be identical, or at least similar:

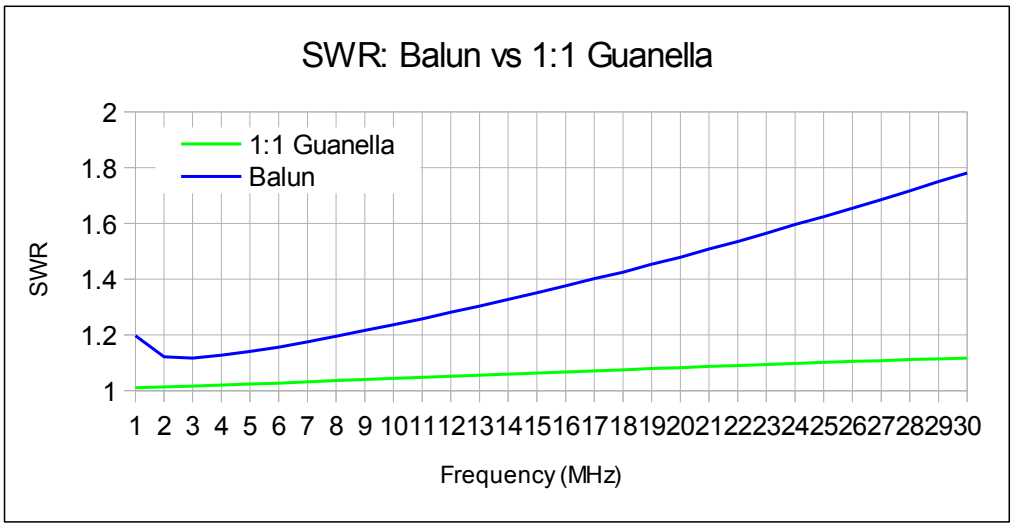
Here are the measured results for the test balun:



Clearly there is no similarity between the CM impedance of the balun and that of the choke. In fact the balun CM impedance is characteristic of a 50pF capacitor, which happens to be the capacitance between the inner conductor and shield of a 19 inch length of RG58!

Question 2: If it was operating in TEM mode, why would a balun exhibit the common-mode characteristics typical of a conventional flux-coupled transformer, rather than those of the transmission line choke from which it is constructed?

3. An attractive property of transmission-line baluns is their extended bandwidth - a result of stray reactances that would otherwise limit the bandwidth of the balun becoming part of the transmission-line forming the TLB. So we might check how the SWR bandwidth of our test balun compares with that of a TLB such as a 1:1 Guanella. Here are the measured input SWR_{50} results for the test balun, compared to using the choke re-configured as a 1:1 Guanella, when terminated with a 50 Ohm load:



Clearly, the balun does not exhibit the extended bandwidth characteristics that you would expect from a TLB.

Question 3: If it were operating as a transmission-line balun, why would its bandwidth be comparatively small?

4. Documents describing TLBs stress the importance of choosing the characteristic impedance (Zo) of the line so that it operates under matched conditions. What value of Zo would we choose for the line in this balun?

If we ground point B on the diagram, the voltage between the inner conductor and braid at both ends of the coax will be V; and because the coax is flowing current I, we would choose Zo = V/I = R_L

Fine so far; but now ground point A instead. We now have the voltage between the inner conductor and braid at both ends of the coax as zero. So do we choose Zo = 0/I = 0 ??

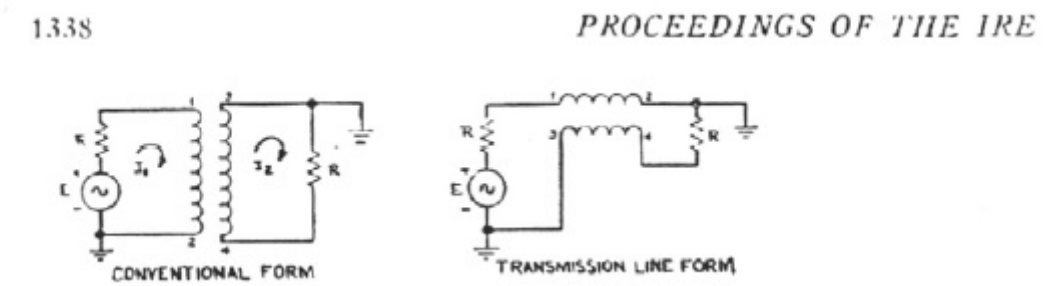
Try a fully balanced load. Vx and Vy are now V/2; so we'd better choose Zo = V/2.I = R_L/2

And what if the load is fully floating? What then are Vx and Vy? What determines the terminating impedance encountered by a TEM wave in this topology?

Question 4: If the TEM wave exists, what determines the terminating impedance it encounters, and how is the line Zo chosen so that it is properly matched?

This balun topology is not new - it was once commonly used for the broadband output transformers of HF solid-state power amplifiers. A length of braid formed the primary of the transformer, and one or more turns of insulated wire threaded through the braid formed the secondary.

In his Proc IRE paper of August 1959 “Some Broad-Band Transformers”, Ruthroff called this toplogy “conventional form” as distinct from “transmission line form”:



Conclusions

The Trask balun is a flux-coupled balun, not a Transmission-Line Balun! It remains the case that a 4:1 Transmission-Line Current balun cannot be constructed on a single core.