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RF

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WHY DO BALUNS BURN UP?

A common complaint about baluns is their lack of power handling capability. Hams want a broadband 3 to 30 MHz balun they can use with an antenna tuner—to load up any balanced antenna on any HF band. A balun is used to connect a balanced antenna, such as a center fed dipole, to an unbalanced coaxial feedline and tuner. It is not unusual for high-power baluns to exhibit overheating and even failure when operated at the 100 W level. I'll explain why this happens and suggest ways to prevent the destruction of radio equipment.

What is balance?

The first step to understanding baluns is to learn what is meant by "balanced." Transmission lines do not radiate in the far field if you can arrange the fields on the conductors to cancel each other. With open wire or twin lead, this is accomplished by placing currents of equal magnitude but opposite phase on the two conductors. If the magnitudes are different, complete cancellation will not occur and the line will radiate.

This also occurs with coax—if the current on the inside of the shield is equal to the current on the center conductor, the fields cancel. However, due to the skin effect, the inside of the shield and the outside of the shield are two separate conductors. No big surprise, the shield is just doing its job. What about a current on the outside of the shield? There is no current to cancel it, so it radiates, just like an antenna element.[1, 2] This is why a balun is required: When open wire is connected to coax, something is needed to keep current from flowing on the outside of the shield, while maintaining equal and opposite currents on the open wire transmission line. A failure to keep current off the shield or unbalanced currents will result in unwanted transmission-line radiation.

Unbalanced currents can easily occur if the antenna is not balanced, for example if one side of a dipole is significantly longer than the other side. Nearby objects, such as other antennas or metal masts can also unbalance the currents. Unlike coax, open wire is sensitive to nearby metal objects and must be spaced away from conductors. Coax can actually be wound around metal objects with little detrimental effect—unless the winding is so tight that mechanical damage results. Coax manufacturers typically specify a minimum turn radius—for Times Microwave LMR-400 the radius is 1 inch, while 3 inches is specified for Belden 9913F7.

Now, we can see the effect of not using a balun. Fig 1 shows a balanced antenna: a center fed dipole. Fig 2 shows how the balance is upset by feeding the dipole directly with coax. The shield of the coax unbalances the antenna, as it is connected to only one side of the dipole. Not surprisingly, the outside of the shield now forms part of the antenna. The center conductor of the coax does not balance the shield because it is hidden by the shield of the coax. Fig 3 shows how balance is maintained with a twin-lead feeder—each side of the feeder connects to one half of the dipole. Notice how symmetry is maintained. Fig 4 shows how a balun is suppose to work—the balun stops the shield current, ideally looking like an open circuit, so that symmetry is maintained.

A balun allows the connection between a two-conductor system and a three-conductor system with minimal unwanted current flow. A coaxial cable is actually a three-conductor system: center conductor, outside of the shield and the inside of the shield. Because the skin effect only allows current to flow on the surface of a highly conductive material, current can flow from the inside of the shield to the outside of the shield only at breaks in the cable. The shield forms two distinct conductive paths for RF. For direct current or very low frequency ac, the shield forms a single conductor. This difference is essential for understanding the purpose of a balun.

[1]Notes appear on page 58.

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To simplify analysis of balun power loss, I separate the total current into common-mode and differential-mode currents. The differential-mode current is the desired current flowing through the balun; ideally, it flows with little or no loss. The common-mode current is the undesired shield current. The common-mode loss is complicated. One might assume that greater current produces more loss. This isn't always true. If the common-mode impedance is very low, much current can flow with little loss. The impedance could also be highly reactive—highly reactive impedances often do not dissipate much power. However, high current flow indicates poor balun performance, even if the balun does not burn up. The balun is not accomplishing its intended function. This is analogous to a dam that did not break, but only diverted a fraction of the water, allowing a city to be devastated by a flash flood.

The theory behind using baluns is quite sound—up to a point. The balun provides sufficiently high impedance to shield currents. The difficulty is finding a real balun that will choke the shield current to zero. Practical baluns typically don't have enough impedance to reduce the feedline current to negligible levels under all conditions. This is just like building a dam high enough to stop all floods. What typically works each year often is inadequate over many years. For example, a gauge that never measured over 2600 cubic feet/s over 20 years recorded 31,200 cubic feet/s in a flash flood.[3] I'll present a model of a typical situation that can destroy baluns and present computer results to quantify the situation.

Types of Baluns

There are several different methods of implementing a balun. The simplest is just a coil of coax, formed into a parallel resonant tuned circuit. The outside of the coax shield forms an inductor, which resonates with the stray capacitance to form a tuned circuit. It works great on a single band, and may offer multiband performance in non-critical applications, such as trapped Yagi antennas. Adding a ferrite or iron powder core can increase the balun bandwidth. This generally results in a lower Q balun—the performance isn't as optimized for a single band, but "acceptable" performance over a wider bandwidth is obtained. Power is a function of the core size; a bigger core handles more power. However, a larger core requires longer wires, which generally reduces bandwidth. A higher permeability core requires less wire, but increasing permeability generally results in greater core losses, resulting in a balun that can't handle as much power. Such a balun is usually less effective in blocking shield currents than one with a more optimized ferrite material. Effective baluns can also use the impedance transformation obtained with λ/4 transmission lines, transforming a low-impedance ground connection to a high-impedance open circuit. This technique is more common at VHF, where the dimensions become more practical.

A Balun in Distress

Fig 5 shows an 80 meter dipole fed with 70 feet of coax. The goal is to operate this antenna on 20 meters as a DX antenna. Working distant stations is much easier on 20 meters than 80 meters, even if a compromise antenna is used. A balun is placed between the antenna feedpoint and the 70-foot coax cable. The transmitter end of the coax cable is grounded. The shield is modeled as a bare 0.405-inch-diameter wire. The challenge for the balun is to provide excellent choking action, so the feedline does not act like an antenna. A 1 λ vertical antenna is too high to be an effective low angle radiator; it will have undesirable high angle lobes. The task is not easy. A center fed 2 λ dipole has a relatively high feedpoint impedance. Conversely, a grounded 1 λ vertical presents a low impedance at the balun. The balun will need to present very high impedance to make the coaxial shield path unattractive compared to the center fed 2 λ dipole.

This situation is easily modeled with Roy LeWallen's *EZNEC* and a *NEC*-4 computing engine, with some small simplifications. Instead of modeling the coaxial shield at the feedpoint, I offset it by one foot. This allowed me to center feed the dipole. It is also possible to offset the feed point and put the shield at the center. The program does not want to see wire junctions and sources at the same point. I also modeled the shield as a bare 0.405-inch wire, ignoring the insulation. In practice, the insulation will slightly lower the velocity factor, making the wire appear electrically longer than its physical length. The results are shown in Table 1. Thanks to Steve, WF3T, for publishing measured balun data on the Web.[4]

The only practical balun that worked well was a 12-turn coaxial choke design. Other air-wound choke designs were ineffective at choking off the shield current. The W2DU bead balun showed significant loss—its impedance was not high enough to be effective. Walt slipped 50 type 73 ferrite beads over Teflon coax to make a simple balun.[5] Parallel-resonant baluns of different impedances were also modeled. At parallel resonance, the impedance is not only maximized, but it becomes purely resistive. The resistance had to be quite high for the

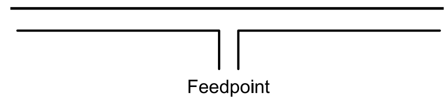

Fig 1—A balanced dipole.

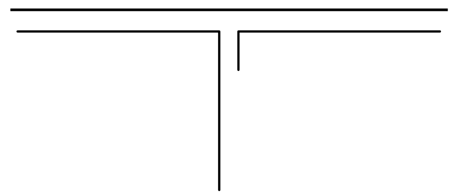

Fig 2—Coax shield unbalanced dipole.

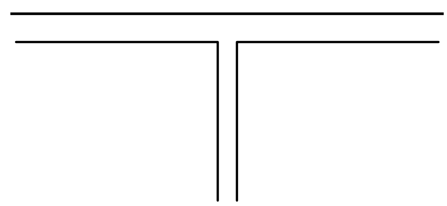

Fig 3—Balanced line keeps the antenna system balanced.

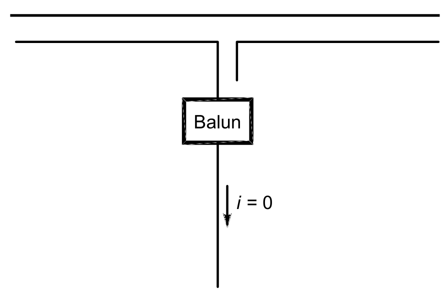

Fig 4—Balun stops the shield current.

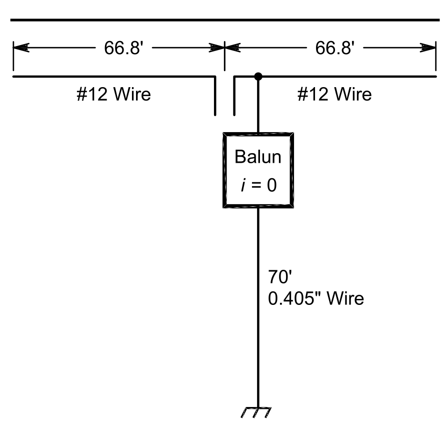

Fig 5—Model of the dual band 80/20M dipole.

balun to become effective—even a 2000 Ω resistance showed significant loss.

Is the 12-turn coaxial balun really a useful solution for the all-band center fed dipole? Not really; it only works well on a single band. The proper way to see this is to keep our reference—the 80 meter antenna operated on 20 meters, with choking impedances measured for other bands. Thus, we plug in the impedances for 40 and 10 meters, and see if the balun provides adequate performance. It is clear from Table 1 that it does not. While the balun loss is low, the current is excessive.

Why not evaluate balun performance by looking at the performance of the balun on all the different bands, and choosing the best one? The difficulty is the number of variables. Not only does the antenna feedpoint impedance change, but the effect of the feedline changes with frequency. As more variables are introduced, it becomes more difficult to figure out what is really happening. This can result in erroneous conclusions. By changing only one variable at a time, the effect of changes is much easier to track.

However, once you have a good understanding of the situation it may be practical to design more sophisticated antennas that use elements that complement each other's strengths and weaknesses.

Dual band antennas are relatively easy to design once you understand the theory. Adding extra bands adds complexity, possibly making good solutions impossible to find.

The 80/20 meter dipole shown in Fig 5 is an example. It works well on both 80 and 20 meters. It doesn't need a balun on 80 meters—the grounded λ/4 shield presents a high impedance on 80 meters, so the current is small even without a balun. Table 2 shows the effect of using different baluns—the shield current is low in all cases. Unfortunately, it is generally not possible to use a λ/4 shield on all bands of an all-band HF antenna. The feedline length is usually fixed.

One solution may be to use the balun losses to our advantage. High loss is easily measured as a temperature rise. If we install a remote thermometer at the balun, we can easily detect high balun loss, just by measuring the absolute temperature. We know the balun is in trouble if a certain threshold is exceeded. This is like measuring the amount of oil burned by an engine that burns a lot of oil. When a certain quantity of oil has burned, we know it is time for an oil change. This is even simpler than using an odometer reading or a clock—no knowledge of past history is required. Just like too little oil in a car can cause damage, it is a specific temperature that can damage a balun, not the temperature rise.

Table 1 also shows the effect of purely resistive baluns—a rather high resistance is required to make the shield current negligible. Purely resistive baluns are quite common. To obtain maximum bandwidth, a balun is typically operated above and below its parallel-resonant frequency. Thus, at midband, the balun is at its parallel-resonant frequency. The balun presents purely resistive impedance at this frequency. At low frequencies, the balun is inductive. At high frequencies, the balun becomes capacitive. The sign of the reactance is quite important when you cascade different baluns to improve multiband performance. The reactances can cancel, so you will not get the performance enhancement one might expect from adding additional baluns.

The poor multiband performance of an air-wound coaxial choke balun does not apply to antennas with a resistive 50 Ω feedpoint impedance, such as a well designed multiband Yagi. Consider the requirements of an RF choke used to supply phantom power to a tower mounted relay. A highly reactive impedance of just 200 Ω is often entirely adequate, while a 200 Ω resistance would soak up 20% of the power. Thus, while a choke may have much less impedance at frequencies away from resonance, it is often adequate if the feed point is well behaved. In contrast, the 80-meter dipole presents a feed-point impedance of $2834 + j1214$ Ω on 20 meters. The vertical feedline is a much better load than the dipole wires—no wonder it wants to radiate. Similarly, the W2DU balun is an excellent design when properly used.

Table 1
A Difficult Situation for a Balun

A high-impedance antenna and a low-impedance path to ground via the coax shield. The applied power is 1-kW at 14.0 MHz.

Balun	*Shield Current (A)*	*Balun Loss (W)*	*(dB)*
1000 Ω	0.5	253	1.3
2000 Ω	0.3	211	1.0
4000 Ω	0.2	144	0.7
10000 Ω	0.08	72	0.3
20000 Ω	0.04	39	0.2
W2DU bead balun 1300 $-j400$	0.44	258	1.3
6t RG-213 4-1/4" dia 6 + $j514$	0.74	3	0.01
12t RG-213 4-1/4" dia 449 + $j5833$	0.14	9	0.04
12t RG-213 @7.00MHz 5 + $j561$	0.72	2.6	0.01
12t RG-213 @28.00MHz 30 $-j482$	1.34	54	0.2

Table 2

The balun makes little difference with this 80M antenna. The applied power is 1kW at 3.5 MHz.

Balun (Ω)	*Shield Current (A)*	*BalunLoss (W)*	*(dB)*
50	0.02	0.022	0.0
200	0.020	0.08	0.0
2 k	0.015	0.45	0.002
5 + $j561$	0.022	0.0024	0.0
30 $-j482$	0.021	0.013	0.0
No balun	0.021	0.000	0.0

Ferrite Power Handling Capability

Thanks to the work by Jerry Sevick, there are extremely efficient balun designs using ferrite cores—there are designs that are 99.5% efficient. Thus, a 1 kW balun may lose only 5 W under the intended design conditions. Many amateurs think that any 1-kW balun ought to be suitable for 100 W under any conditions. Some actual calculations can indicate the fallacy of this thinking.

The high efficiency is obtained by carefully designing the windings to specific impedances. A high efficiency 4:1 balun will typically work well from 12.5 to 50 Ω or 50 to 200 Ω, but not both. Changing the impedances will degrade the efficiency and increase the losses, reducing the power handling of the balun. Suppose the loss is degraded to 1 dB—20.6% of the applied power is lost as heat. If 100 W is applied, 20.6 W is lost as heat. This is considerably more than what 99.5% efficient 1-kW balun loses in normal operation. It would be more reasonable to rate with the balun with 1 dB of loss at 24 W.

Conjugate matching theory could be used to roughly estimate the maximum loss of the balun—half the loss is in the balun and the other half is lost in the rest of the circuit. This would set the worst case loss at 3 dB. Thus, the efficient 1-kW balun may have a rating of just 10 W. This is *not* the absolute worst case—which occurs when the balun has to absorb all of the power. However, it may be reasonable to assume that some sort of antenna system will be provided to absorb half the power—that the user will not try to force feed a balun with no antenna attached.

The difference between best- and worst-case losses becomes less pronounced as the quality gets worse. Fortunately, elaborate measurements are not required to characterize the power handling capability of baluns for worst-case losses. We already know the worst-case loss—we just need to calculate the power level that corresponds to that amount of loss. This is a simple equation based on power, surface area and temperature rise.[6]

$$\Delta T = \left(\frac{P_{dis}}{A}\right)^{0.833} \quad \text{(Eq 2)}$$

where
ΔT = Temperature rise (°C)
P_{dis} = Power dissipation in milliwats
A = Surface area in cm^2

The calculated power ratings are surprisingly low—about 4 W continuous duty for a big 2-inch toroid, allowing for 25°C of temperature rise. The problem is the difficulty of removing heat from the core. The thermal conductivity of cores is low compared to solid metal, such as copper windings. Since the heat is generated throughout the core, and not just at the surface, it can take a long time for the heat to be dissipated. Ceramics with good thermal conductivity are extremely rare; highly toxic Beryllium oxide is one of the few examples. At lower frequencies, it may be possible to shift the loss to the copper windings, to ease the extraction of heat. Generally, this is not practical with broadband RF circuits, where core losses are dominant. Air-core techniques eliminate the core-loss problem, at the expense of size and bandwidth.

Conclusion

Present day balun technology does not meet the expectations of most hams. A broadband 3 to 30 MHz 1-kW balun cannot be used without consideration for the stresses it must endure, even if the transmit power is just 100 W. Another decade of power reduction—to just 10 W, is necessary for a 1-kW balun to survive any likely operating condition. High balun stress is likely to occur when high antenna feed point impedance is combined with a coaxial shield that presents low impedance at the balun. The difficulty of removing heat from ferrite materials adds to the problem. Air-core baluns can handle the power, but multiband balun performance leaves a lot to be desired. Practical solutions are to monitor the temperature of the balun for improper performance, and to only use baluns in properly designed applications. Ferrite-core baluns should not be used haphazardly at high power levels.

Notes

[1] J. Taylor, W2OZH, has designed a dipole that uses the shield as half of the antenna. "A Resonant Feed-Line Dipole," *The ARRL Handbook for Radio Communications*, 2003, p 20.17; *QST*, Aug 1991, pp 24-27.

[2] Z. Lau, "Making Off-Center Fed Dipoles Work," RF, *QEX*, Mar 2001, pp 55-56.

[3] **sd.water.usgs.gov/projects/1972flood/photos.html**

[4] **www.k1ttt.net/technote/airbalun.html**

[5] W. Maxwell, W2DU, "Some Aspects of the Balun Problem, " *QST*, Mar 1983, pp 38-40.

[6] Z. Lau, W1VT, "Calculating the Power Limit of Circuits with Toroids," RF, *QEX*. Mar 1995, pp 24-30.