

Fixed Frequency Cable and Wide-Band Magnetic Baluns

Introduction:

For this project three baluns were designed, built, and tested. The first two baluns were quarter-wave and half-wave baluns. These baluns are useful for fixed high frequency applications. The half-wave balun is particularly useful for 4:1 impedance matching, while the quarter wavelength balun should be applied to matched loads. The third design was a Guanella magnetically coupled balun. This Balun features a 4:1 impedance ratio and wide-band operation. Unfortunately, the design is not useful for frequencies above several hundred megahertz.

Balanced vs. Un-balanced:

The term balun refers to the transfer of electrical signals from a **balanced** to an **un**-balanced condition. A balun is often used when a balanced antenna receives a signal and then transfers the signal to an unbalanced coaxial s12 line. However, for transmitting signals, the reverse is true. An unbalanced coaxial signal is fed through a balun to a balanced antenna.

An unbalanced line has an unequal magnitude of current or voltage in each conductor of the s12 line. A line with unbalanced current is problematic because the line can radiate, yielding a condition where power intended to be transmitted or received is not fully realized. Driving a line with unbalanced voltages will cause one lead of an antenna to radiate far better than the other generating undesired radiation patterns. The same holds true for balanced antennas with more than two leads.

The most common situation in which a balun is utilized involves connecting an antenna with twin leads or twisted pair to a coaxial driver or receiver. Most coaxial cables have the voltage signal on the center conductor while the shield remains at ground potential. The grounded lead cannot drive voltage to an antenna lead. Additionally, the coaxial cable can pick-up radiation from the antenna along the low impedance shield generating distorted radiation patterns. Twin leads are naturally balanced in regards to EMF pick-up because radiation induces equal signals on each conductor.

Cable Baluns:

Balun types can be broken up into two categories: baluns intended to drive fixed frequency loads and baluns operable over a large frequency range. In general, fixed high frequency baluns are based on quarter-wave and half-wave impedance matching. These Baluns can operate at high frequencies. Wide-band baluns are usually of a ferrite-core transformer design and operable to a few hundred megahertz.

The most commonly used of the cable type baluns is one of many variations of a quarter-wave type shown in Figure 1. This Balun is also referred to as the "bazooka" Balun.

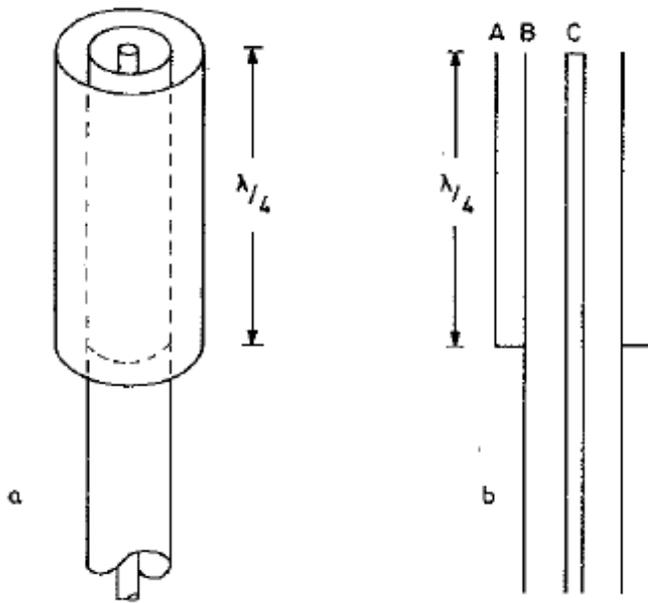


Figure 1: Quarter wave or "Bazooka" balun

In the quarter-wave balun of figure 1, points B and C are each connected to one lead of an antenna. Point A is left open. To minimize inductance the current generated in the center conductor must return along the B-shield. However, without the A-shield it is easy to induce additional current on the B-shield from stray radiated fields. When this "noise" current is induced on the B shield it will then travel up the A-shield, reflect at the open, and provide a 180° phase shifted noise to exactly cancel the induced noise, and therefore present an open circuit to any induced noise. This creates a situation where the current in B and C match and the coaxial line is current balanced.

A second type of Balun commonly deployed is the half-wave balun depicted in figure 2 below:

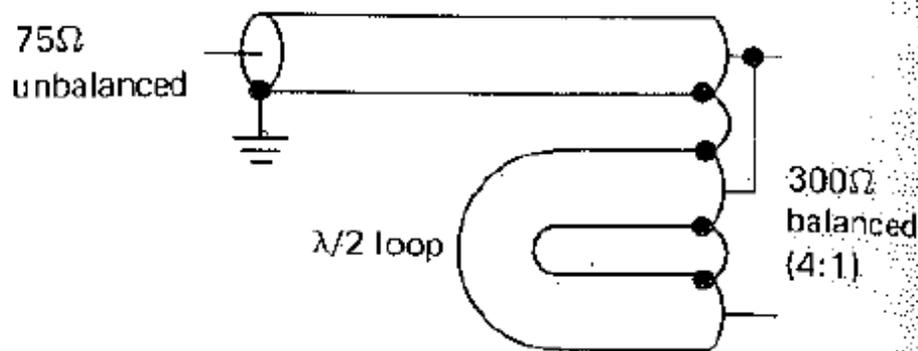


Figure 2: Half-wave balun

In the half-wave Balun the first antenna lead is hooked-up to the center conductor of the amplifier (or receiver) coaxial cable. From this node, another half-wave delay line provides a 180° phase shifted signal to the second antenna lead. The 180° phase shifted antenna lead has the result of doubling the output voltage generating a 4:1 impedance match given that impedance scales as V^2 . This impedance scaling is especially useful in connecting 75Ω coaxial cable to twin lead cable that has

an impedance of $\sim 300\Omega$. It should be noted that low frequency cable baluns such as those displayed in figures 2 and 3 can be approximated using capacitors and inductors.

There are cable based baluns that allow for wide-band matching. Figure 3 below displays a tapered balun:



Figure 3: Tapered balun

In the tapered balun there is a long diagonal slice which separates the coaxial cable into two leads that drive an antenna. The diagonal slice is much longer than the longest desired half wave frequency. In this design the coaxial wave-front spreads out and gradually modifies itself into a twin lead wave-front. This design is particularly useful to match a wide range of impedance. The design shows similarities to waveguide horn antennas.

Magnetic Baluns:

Low frequencies require unacceptable lengths of cable and often call for a magnetic balun design. The simplest magnetic balun design involves a basic transformer or autotransformer where the turns ratio corresponds with the appropriate impedance. However, the parasitic capacitance and inductance only accommodates extremely low frequencies. For simple current balancing where voltage matching in reference to ground is not critical, a high frequency choke is adequate. In this design, a coaxial cable is simply wrapped multiple times around a magnetic core. Unbalanced current cannot flow in the shield because it is blocked by the high magnetic core inductance.

A straightforward design for a 4:1 balun is the Ruthroff balun displayed below:

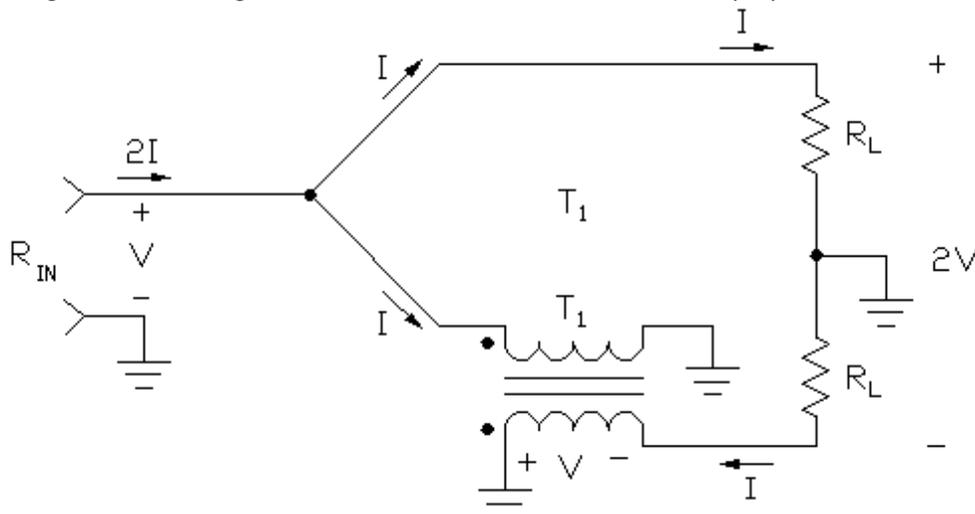


Figure 4: Ruthroff Balun

The Ruthroff balun uses a minimal amount of turns to achieve a 4:1 impedance match. The center conductor of a coaxial cable directly drives one antenna lead (represented here as R_L). In addition, the center coax also drives the primary of a transformer. The secondary is connected across the

other antenna lead and ground providing a 180° phase shift. The output is therefore twice the input voltage yielding a 4:1 impedance ratio. Unfortunately the Ruthroff balun is limited to low frequencies because the lead directly connected to the coax's center conductor does not see the parasitic elements associated with the other lead's transformer including primary and secondary leakage inductance, transformer capacitance, and increased path length. These parasitic effects can contribute to both phase and amplitude differences between the two antenna leads.

To account for the Ruthroff balun's parasitic transformer effects, a dual transformer Guanella balun can be implemented as shown below:

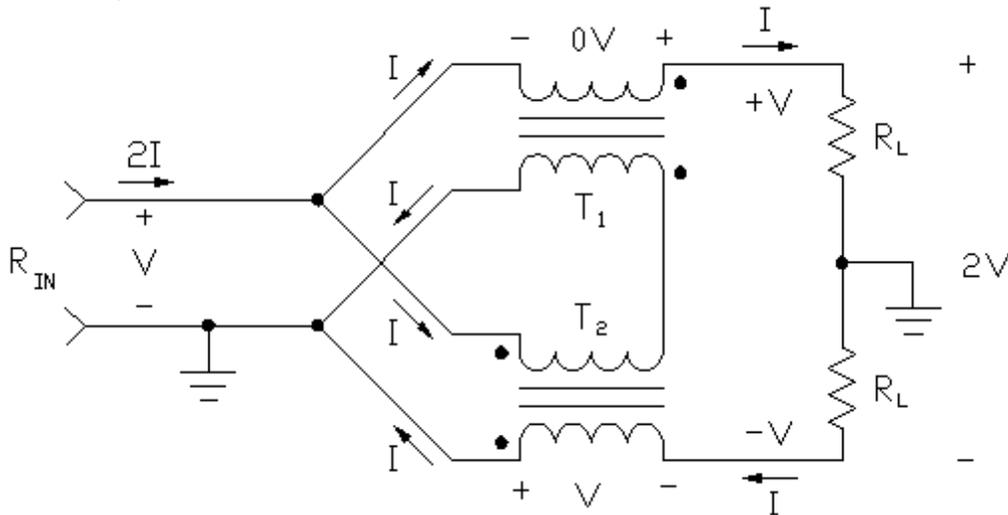


Figure 5: Guanella Balun

The Guanella Balun is similar to the Ruthroff balun. The main difference is that the center conductor feeds the original transformer that provides the 180° phase shift as well as a second transformer that is implemented to guarantee each lead is transformer driven and therefore subject to the same parasitic effects. It should be carefully noted that the upper transformer is a current transformer with no voltage drop. In fact, other than matching the path length, inductance, and capacitance, by ensuring similar electrical paths for each lead, the upper transformer plays no significant role in the circuit.

Experimental Set-up for Cable Type Baluns:

To test the cable type baluns two 250 MHz "fishing rod" dipole antennas were set-up 10 feet apart. The low operating point of 250MHz was chosen to avoid parasitic effects due to connector impedance mismatches. Each antenna was driven by a pair of twisted leads as shown below:

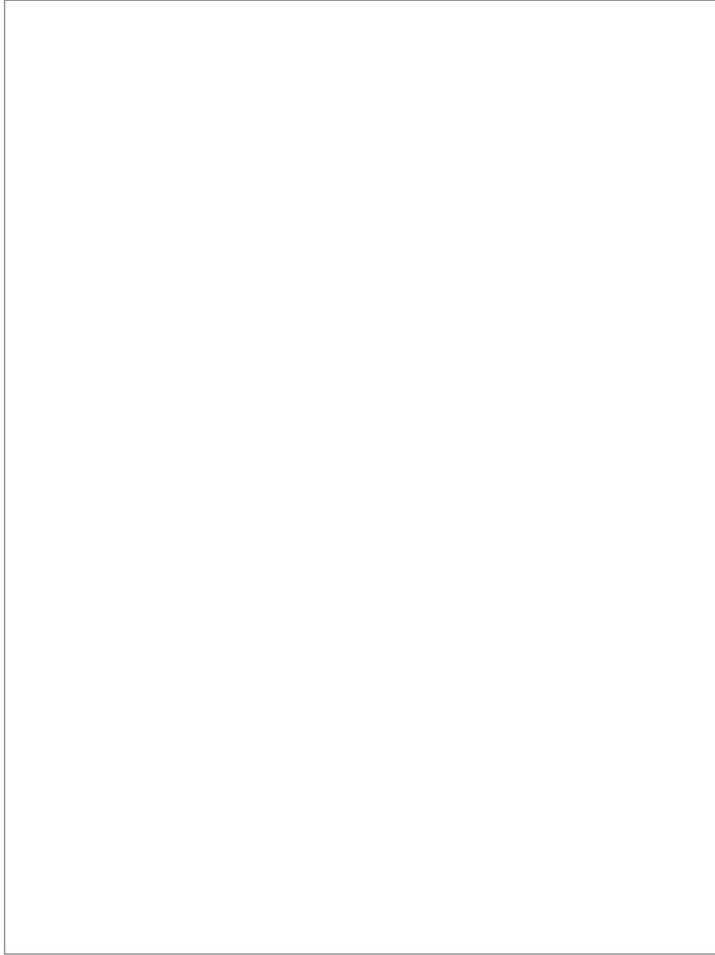


Figure 6: "Fishing rod" antenna with twisted pair leads

First the baluns were driven directly from the coaxial cables of a network analyzer at a power level of -10 dBm. The s-parameter results for return loss and s12 are shown below:

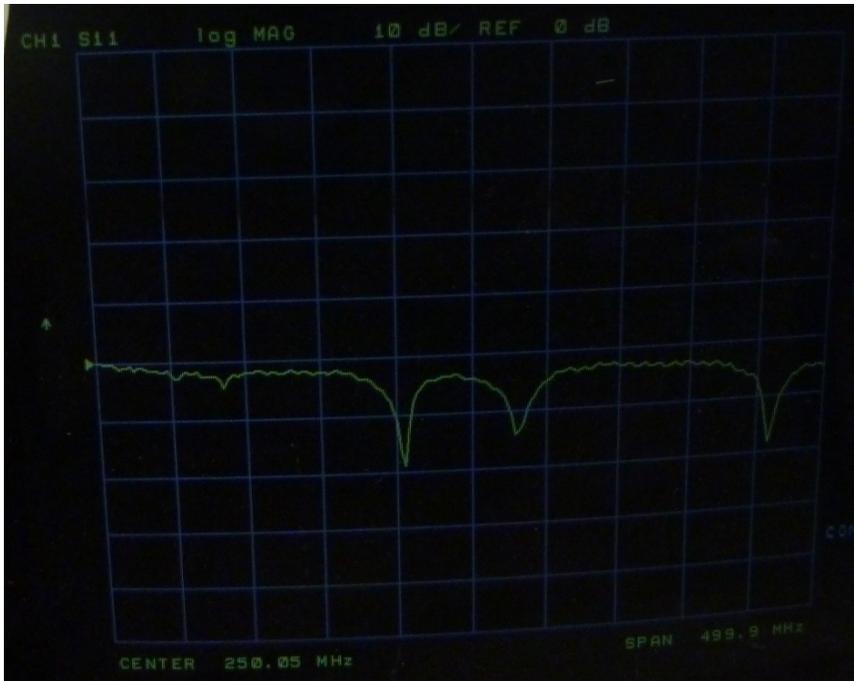


Figure 7: Return loss with no baluns

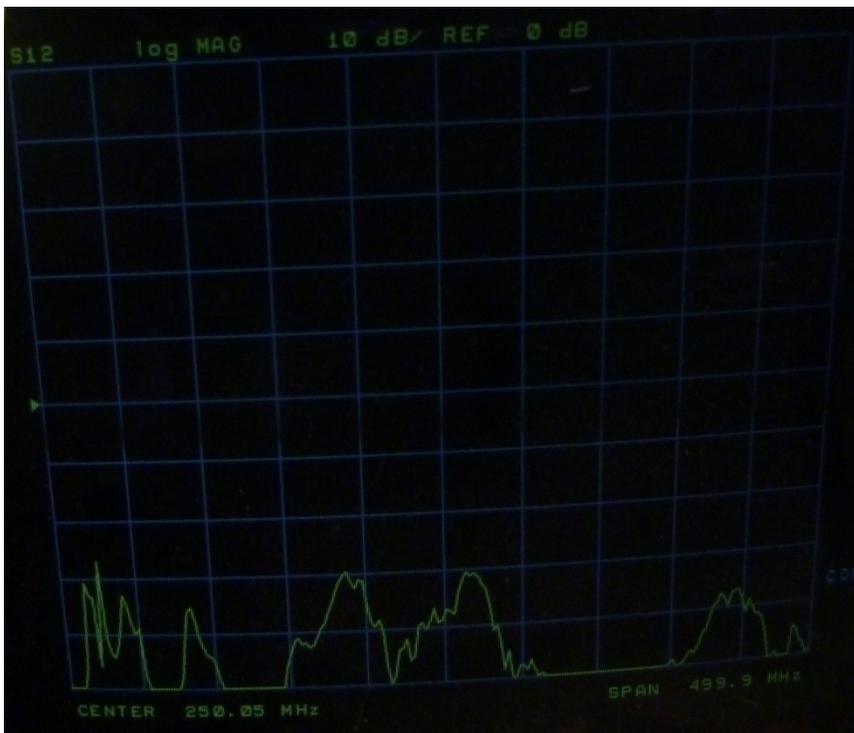


Figure 8: s12 with no baluns

There are three peaks for the return loss shown. The peak of interest, nearest to 250MHz occurs at ~275MHz and displays a return loss of 12dB. s12 at this frequency is 20dB. It should be noted that with no balun several other return and s12 frequencies are similar in magnitude and caused by secondary antenna transmissions. This indicates that a "fishing rod" antenna without a balun performs poorly.

Testing of Quarter-Wave Balun:

A quarter wave balun was connected to each antenna as shown below:

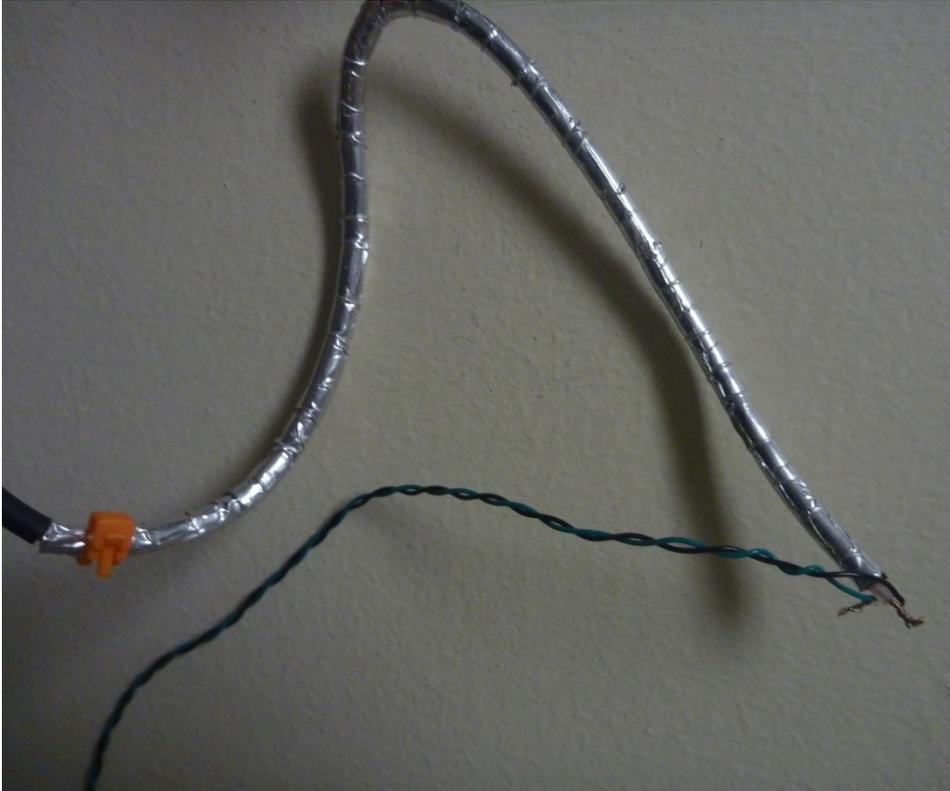


Figure 9: Quarter-wave balun

Double sided tape makes up the second shield of the coaxial cable. The connection to the inner shield is made using a cable-tie. Frequently a conductive paint is used instead of a foil. It is critical to calculate the length of the quarter wave outer shield based on the wave propagation in air because the electric and magnetic fields of interest are exterior to the outer shield. The results of the quarter wave balun connected to each antenna are displayed below:

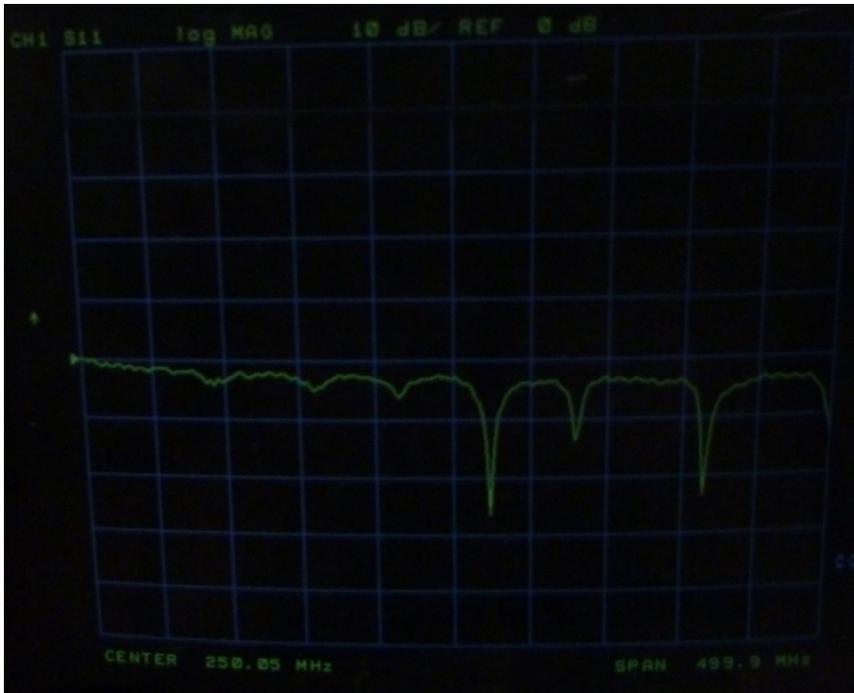


Figure 10: Return loss with quarter-wave baluns



Figure 11: s12 with quarter-wave baluns

The return loss of the quarter wave balun increased to 25dB. The s12 of quarter wave balun decreased to 13dB although the definition of the peaks was sharpened. The decrease in s12 amplitude can possibly be attributed to B port antenna performing poorly either due to errors in the antenna construction, network analyzer, or environmental differences between the two antennas. Although not shown here, the quarter wave balun did not show significant improvement in s22 which should measure identical to s11 because the nominal set-up is the same.

Testing of Half-Wave Balun:

A half-wave balun was connected to each antenna as shown below:



Figure 12: Half-wave balun

It should be noted that if the balun is connected exactly as shown in figure 2, the resulting return loss is poor. For better performance it is necessary to only ground the delay cable at the end which is not driving the second antenna. It is also important to position the coax far from the antenna, otherwise the coax itself can constructively or destructively interfere with the radiation pattern. When calculating the length of the cable, the .66 propagation coefficient of the cable dielectric must be taken into account. The results of the half-wave balun are shown below:

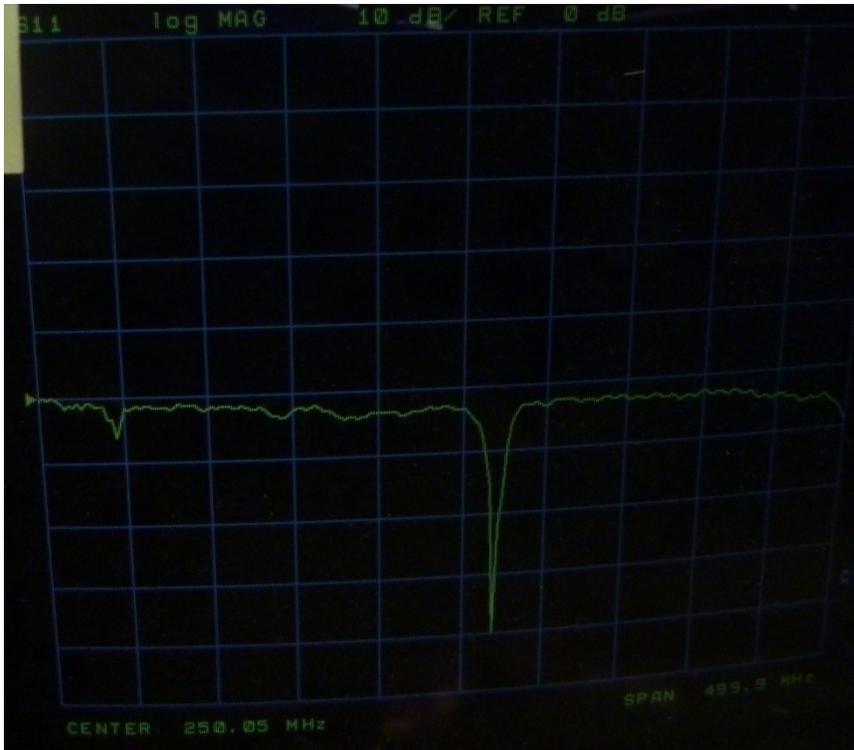


Figure 13: Return loss with half-wave baluns

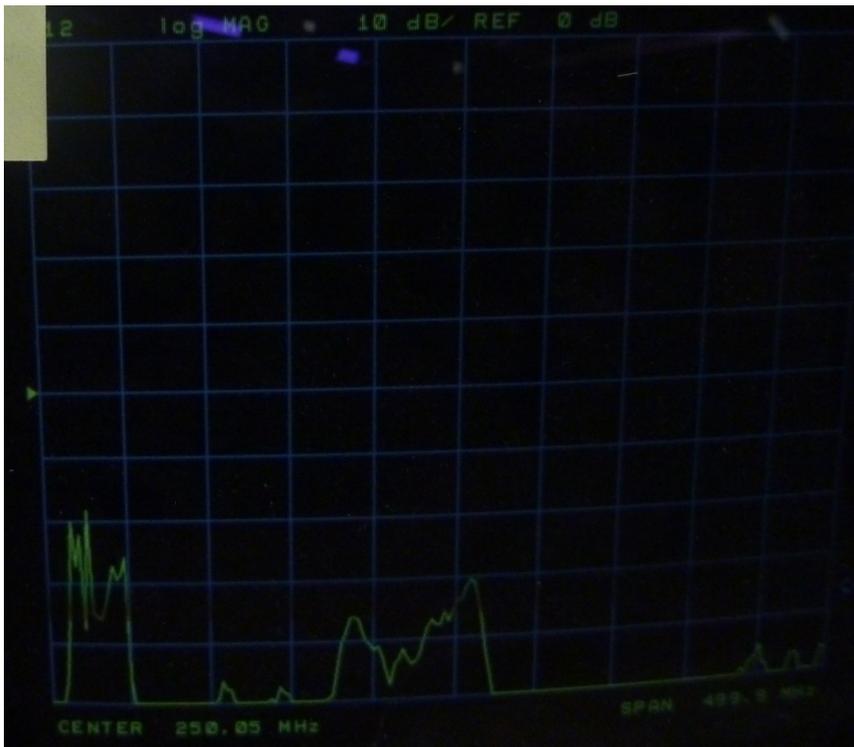


Figure 14

The return loss of the half-wave balun increased to 40dB. The s12 of the quarter wave balun is 20dB. This result is similar to the quarter-wave balun where poor s12 increases were evident. However,

the return is loss is better than the quarter-wave balun. This can be attributed to the 4:1 impedance matching where 200Ω represents a better impedance match than 50Ω .

Cable Balun Conclusions:

	S11 (dB)	S12 (dB)
No Baluns	12	20
Quarter-Wave Baluns	25	12
Half-Wave Baluns	40	20

The s12 results for the baluns seems inconclusive. While there is clearly a peak at 275 MHz, there is no meaningful increase in s12 amplitude. As stated before, this may be due to the network analyzer, construction defects, or environmental parameters. It may also be that two “fishing rod” dipoles, designed for 250 MHz, is simply not a great antenna pair. However, the S11 data clearly displays a dramatic increase in return loss when baluns are introduced. Furthermore the half-wave balun displays much better reflection coefficients than the quarter wave balun, likely due to better impedance matching.

The Magnetic Guanella Balun Test Set-up:

A Guanella balun was designed, built, and tested. Due to lead time restrictions, simple ferrite EMF suppression beads were used to construct the balun. This style of bead has the unfortunate characteristic of having significant frequency dependent resistive core losses to dissipate EMF energy as shown below. Between 20 and 30MHz the resistive impedance takes on a similar order of magnitude as the reactive impedance and the transformer qualities of the material are no longer dominant. Balun cores specially design with two holes and operation frequencies up to 300MHz are available (1).

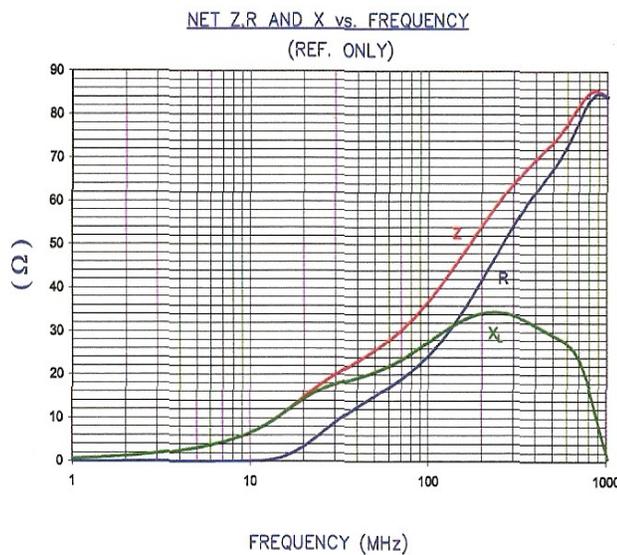


Figure 15: Core impedance graph

The Guanella balun was designed using twisted pair wire, two cores, and three windings per transformer as shown below:



Figure 16: Guanella Balun

The input to the balun is generated from the left. The balun is terminated into two 100Ω resistors on the right providing a matched load considering the balun is a 4:1 design and the driving impedance is 50Ω . Because the Balun operates at a maximum of 30 MHz, testing using dipole antennas was unrealistic. However, it was possible to use a network analyzer to study the return loss:

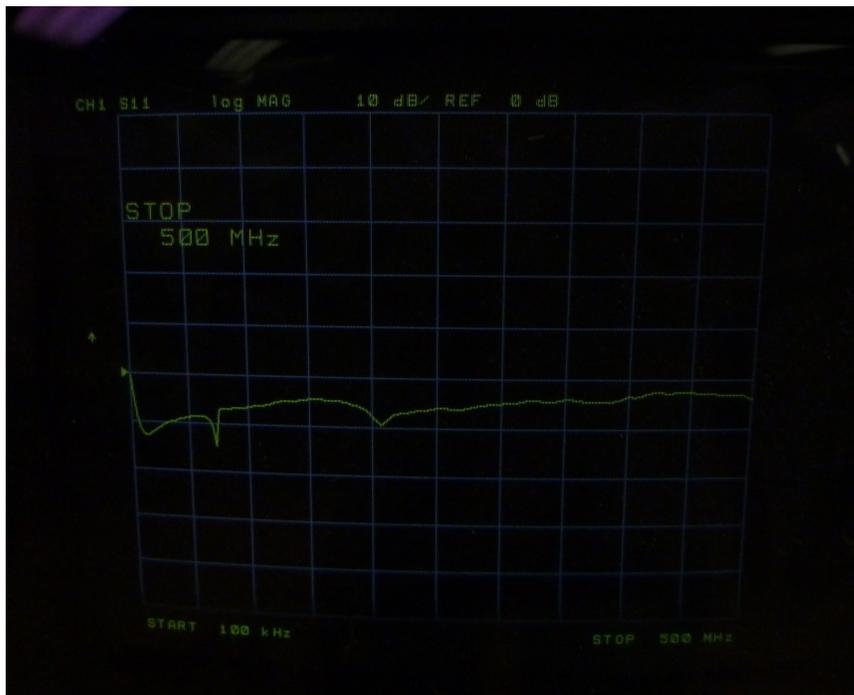


Figure 17: S11 of Guanella Balun

Ignoring the spikes present at 75 MHz and 200 MHz, likely due to parasitic resonances, the general trend of the return loss is to peak at 12dB around ~ 20 MHz and then slowly return to zero. This indicates that the maximum amount of voltage is transferred through the balun at ~ 20 MHz. This data is consistent with data taken from a voltage generator and oscilloscope shown below:

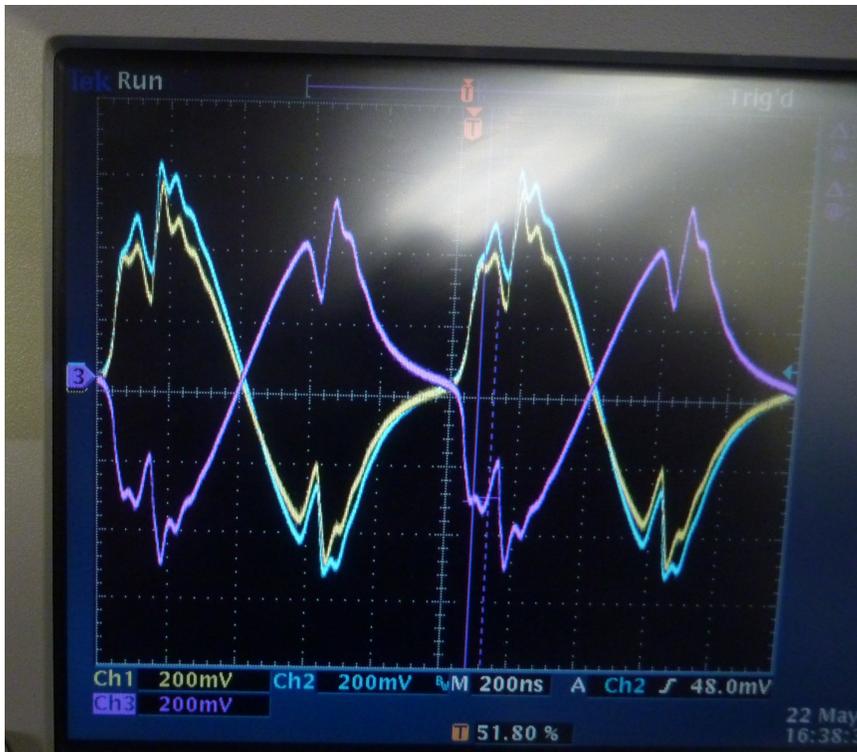


Figure 18: Guanella balun at 1MHz. Blue is input. Purple and yellow are outputs.

The voltage generator is set-up to drive a sinusoidal wave at 1 MHz with 1 Volt peak to peak. The input waveform is highly distorted because at such a low frequency the core is highly magnetized presenting a difficult impedance varying load to the generator. This corresponds to the low frequency region where the return loss is roughly zero. However, It is clear that the balun is operating as intended. The yellow output waveform is in phase with the blue input waveform. There is also a second purple output waveform 180° out of phase with the input waveform. Both output waveforms are roughly the same amplitude as the input waveform.

The screen shot below shows the operation of the balun at 20MHz:

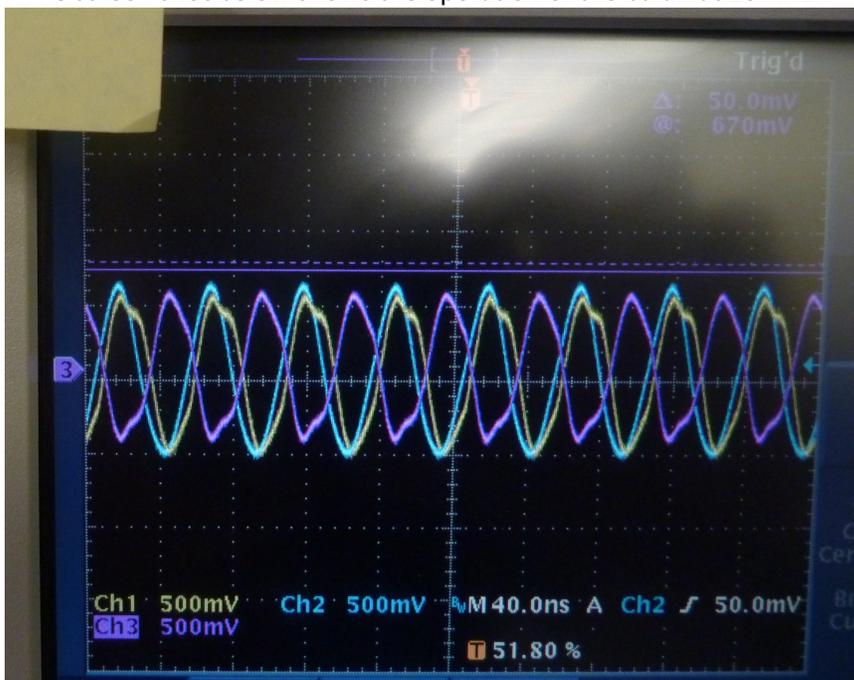


Figure 19: Guanella balun at 20MHz. Blue is input. Purple and yellow are outputs.

At 20 MHz the input waveform shows no distortion. The output waveforms are only slightly distorted. This frequency is where the balun operates most effectively and corresponds to the return loss peak at 20 MHz from the network analyzer.

The screen shot below shows the operation of the balun at 30 MHz:

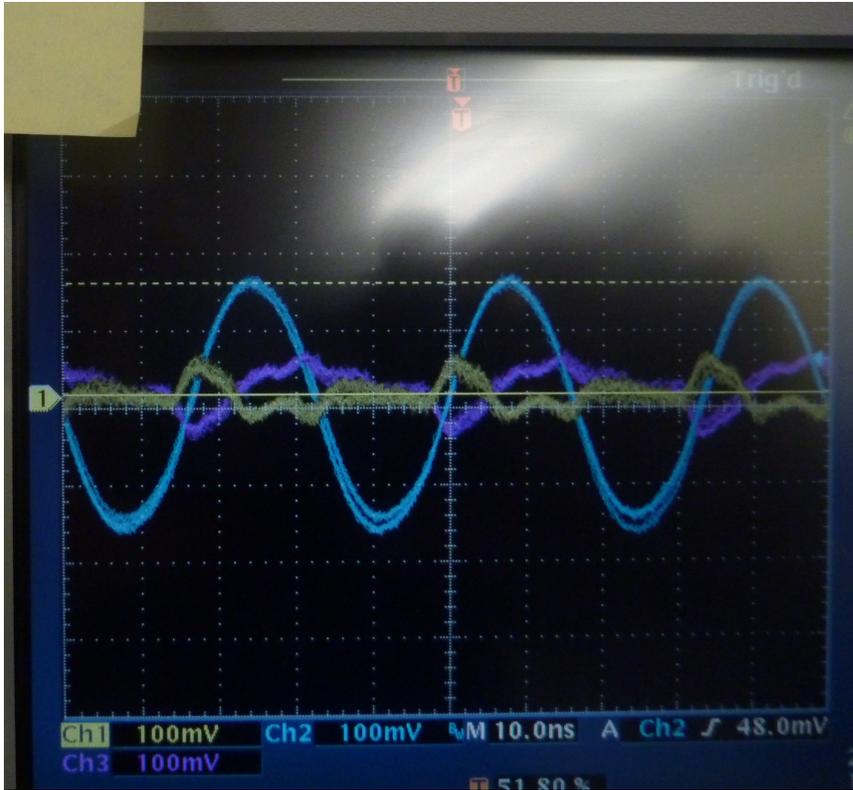


Figure 20: Guanella balun at 30MHz. Blue is input. Purple and yellow are outputs.

At 30MHz the input is a clean sinusoid, but the output shows great amplitude reduction and distortion. This is because the resistive loss of the material becomes substantial at 30MHz and dominates the characteristics of the balun. The transformer effect is almost entirely negated.

Guanella Balun Conclusions

The Guanella balun designed exhibited reasonable voltage amplification from 1MHz to 20MHz, demonstrating wide-band operation. However, 1 MHz operation displayed some input and output distortion. Above 20MHz, the output signals quickly diminish due to the resistive losses of ferrite core. Off the shelf cores capable of 300MHz are available and should be used for future designs.

References (note: discussion below figures largely from references):

Figure 1) The Handbook of Antenna Design, Volume 2. A.W. Rudge, K. Milne, A.d. Olver, P. Knight. 1983. Peter Peregrinus Ltd. London, UK. Pg. 920.

Figure 2) The Art of Electronics. Horowitz and Hill. 1989. Cambridge University Press. Cambridge, UK.

Figure 3) The Handbook of Antenna Design, Volume 2. A.W. Rudge, K. Milne, A.d. Olver, P. Knight. 1983. Peter Peregrinus Ltd. London, UK. Pg. 922.

Figure 4) <http://www.dxzone.com/cgi-bin/dir/jump2.cgi?ID=16726> "A Single-Core 4:1 Current Transformer With Improved Performance". Chris Trask. 7-25-05

Figure 5) <http://www.dxzone.com/cgi-bin/dir/jump2.cgi?ID=16726> "A Single-Core 4:1 Current Transformer With Improved Performance". Chris Trask. 7-25-05

Figure 15) Steward HFB095951-100 core data sheet.

- (1) <http://lairdtech.thomasnet.com/item/two-hole-balun-cores/two-hole-balun-cores-2/pn-6128?&plpver=10&origin=keyword&by=prod&filter=0>

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- 3) <http://en.wikipedia.org/wiki/Balun>
- 4) <http://www.comportco.com/~w5alt/antennas/notes/ant-notes.php?pg=6>
- 5) <http://www.minicircuits.com/pages/BalunApplicationNote.htm>
- 6) Antenna Engineering Handbook. Jasik. 1961. McGraw-Hill Book Company, Inc. New York, NY.
- 7) Antennas, 2nd edition. John D. Kraus. 1988. McGraw-Hill, Inc.