Ferrite and Wire Baluns with Under 1dB Loss to 2.5 GHz

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ABSTRACT

This paper presents a ferrite and wire balun with performance similar to coaxial baluns. This balun makes two significant improvements over current technology: the wire impedance is adjusted for the ferrite and wire winding loading; and a trifilar wire is used to minimize skin effect losses. Insertion loss below 0.9dB is achieved from 5MHz to 2.5GHz.

INTRODUCTION

Broadband baluns are very useful in hybrid networks and balanced amplifier designs. Existing products typically use semi-rigid coaxial lines loaded with ferrite for broadband baluns operating to 2GHz [1]. This paper presents a significant improvement in the state of the art of ferrite and wire baluns. Precision broadband baluns in the range 5MHz to 2.5GHz typically use coax transmission lines surrounded by ferrite [1]. Coaxial baluns are relatively large and expensive compared to ferrite and bifilar wire baluns. Commercial ferrite and wire baluns have insertion losses on the order of 2.5dB at 2.5GHz, and 10dB return loss [2]. However, these baluns are inexpensive and consume only 4x5mm of PCB real estate. This paper presents two significant improvements over current technology. First, ferrite and wire loading is considered so the net balun impedance is 50 ohms while the bifilar wire impedance is less than 50 ohms. Second, the bifilar wire is actually a trifilar wire in a bifilar connection. This construction is more like coplanar waveguide than balanced twin lead, and reduces the skin effect losses while allowing the optimum wire impedance and number of turns on the core. These improvements allow baluns with 0.9dB maximum loss and 15dB minimum return loss from 5MHz to 2.5GHz to be made.

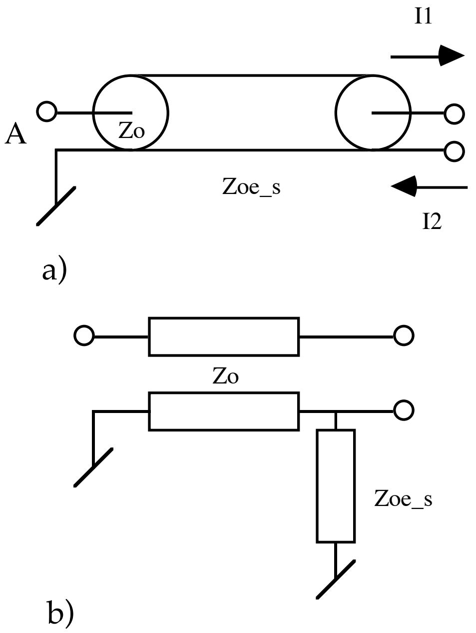

Figure 1. a) Simple coaxial balun, and b) equivalent circuit

BALUN THEORY

Balun design has been the subject of many excellent papers [3,4,5]. In order to understand the complexities of a twisted wire balun on ferrite, we will start with a coaxial balun. Figure 1a) shows a simple coaxial balun. The goal of a balun is to create an unbalanced signal between a single conductor and ground out of a balanced circuit. A balanced circuit will have equal and opposite currents on two conductors which are therefore “balanced” about ground. Figure 1a) has port A as the unbalanced port, and port B as the balanced port. To be a perfect balun, if a load were placed across terminals B, I1 would equal I2. Also, I1 would equal the input current with some delay.

The equivalent circuit for this coaxial balun, shown in Figure 1b), demonstrates the fundamental flaw in this balun. The inner conductor of the coax is shielded from ground an so has practically an infinite impedance to ground. The outer shield does have a finite impedance to ground as it appears as a transmission line with respect to ground with impedance *Zoe_s*. We can separate the balun into two circuits, a four-port transmission line with differential impedance, *Zo*, equal to the coaxial line impedance (and an even mode impedance to ground of infinity), and a shorted stub characterizing the shield impedance to ground. Obviously the impedance to ground is different for the noninverting (top) and inverting (bottom) terminals at port B for all frequencies except those where the shunt stub is a quarter wavelength. Loading the outside of the coax with ferrite will create a high and lossy impedance over a broad band for *Zoe_s*, but this balun still has a basic flaw.

Anyone trying to build a precision coaxial balun uses the circuit of Figure 2a). This balun can also be realized with twisted pair wire wrapped around ferrite as the three-wire Ruthroff balun [3]. Figure 2a) shows a secondary conductor, of equal dimensions to the coax shield, connected to the noninverting output. As shown in Figure 2b), the two outputs now have identical impedances with respect to ground and the output is balanced for all frequencies. All of this discussion of coaxial baluns will help in understanding the problems with ferrite and wire baluns. Coaxial baluns perform very well to 2.5GHz, however, if we measure a good commercial three-wire ferrite balun we typically get a response similar to that of Figure3.

There are two problems with the balun in Figure 3. First, the wire impedance is not optimized and so the return loss is high even below 1 GHz. Second, the insertion loss difference between the two outputs increases rapidly with frequency. Interestingly enough, it is the noninverting response that has a steep roll off with frequency, the inverting response can be made essentially flat. Note that the broadband balun of Figure 3 does have a low end of around 1MHz where the finite inductance of each wire to ground begins to short out the signals.

The problems with the three-wire ferrite and wire balun can be understood with Figure 4. Figure 4a) shows a two-wire ferrite and wire balun. Figure 4b) shows the equivalent circuit. If a third wire existed, it would create another shunt output stub of impedance *Zoe*, just as the coaxial balun did in Figure 2.

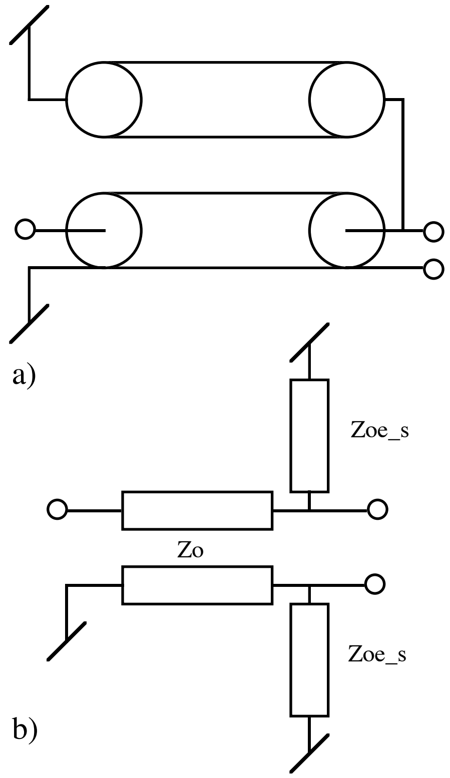

Figure 2. a) Standard coaxial balun, and b) equivalent circuit of standard coaxial balun.

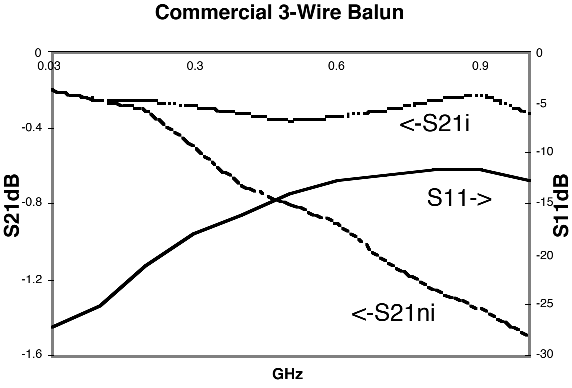

Figure 3. Three-wire commercial ferrite and wire balun response. Note 1GHz maximum frequency.

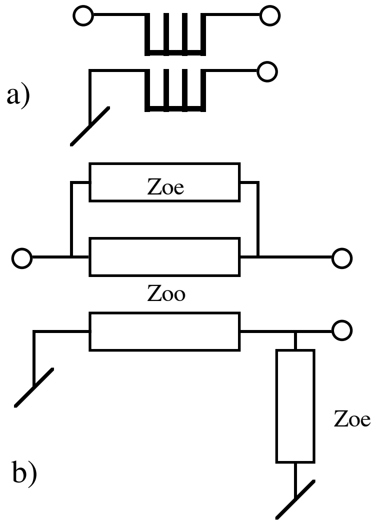

Figure 4. a) Two-wire ferrite and wire balun, and b) equivalent circuit.

The two-wire balun in Figure 4a) has a different equivalent circuit from the coax circuit in Figure 1. The noninverting line is not shielded from ground as in the coax case, and the ferrite loading of this line causes the increasing loss versus frequency slope shown in Figure 3. The inverting line appears as just a lossy stub which can be made a high impedance by choosing the right ferrite and using several turns of wire. In the case of ferrite and wire, adding a third wire only helps the low end balance, and actually hurts the high end balance by adding in another half dB or so of loss.

IMPROVEMENTS IN BALUNS

Balun performance is a trade-off between ferrite permeability, ferrite loss, wire impedance, and wire loss. The ferrite and wire losses directly affect the broadband performance. These losses are characterized by the ferrite permeability, the bifilar wire diameter, and the wire length. Even the core type affects the balun loss, because two-hole cores require less wire, and so have less loss, than toroid cores for the same shunt inductance (i.e. low frequency performance). The wire impedance is affected by the wire dimensions, coating, and twisting [6], as well as the ferrite permeability, permittivity, core type and winding characteristic. The interaction of all the variables, some of which are easier to measure than predict, has caused ferrite balun design to be mostly empirical.

Figure 4a) shows the type of ferrite balun used here. For broadband work a three-wire balun is not used because of excessive high end roll off. A simple network of 400 to 1000 ohms in series with 75 to 120 nH, depending on the ferrite and wire turns, can be added to the noninverting output to balance the inverting output at the low end and not affect the high end. The odd mode impedance is dominated by the wire construction [6], but perturbed by the ferrite, core style, and winding configuration. The even mode impedance is dominated by the ferrite. In order to understand the affects of ferrite loading, a coaxial line which used ferrite as a dielectric was constructed. The insertion loss of this line is shown in Figure 5.

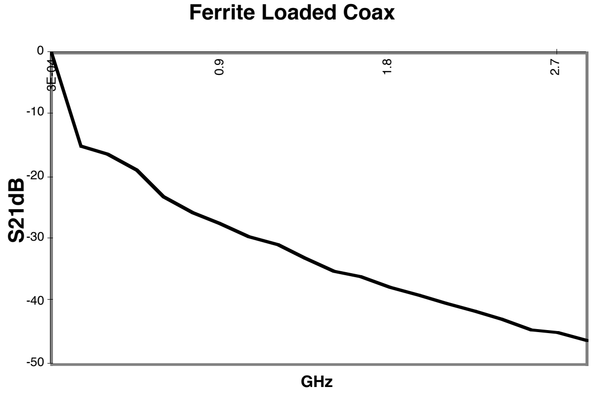

Figure 5. S21 of coaxial ferrite line for even mode characterization.

The line was 1” long and used ferrite of μ_i equal to 2500. Ferrite also has a permittivity. Open circuited line measurements put the relative permittivity of this ferrite at 41. However, relative permittivities of 7 to 48 have been measured for various ferrites, depending on the μ_i. The equation below approximates the ferrite permeability and loss variation with frequency. Experiments show that ferrite permittivity is essentially constant up to 1 GHz, and that ferrite shunt loss is proportional to the imaginary part of the equation below. Note that multiple turns of wire raise the even mode shunt impedance, and that most of the energy through the balun travels in the odd mode.

$$\mu = \frac{1}{j\frac{f_{MHz}}{2250} + \frac{1}{\mu_i\left(1 + j\frac{0.8\mu_i f_{MHz}}{2250}\right)}}$$

The ferrite also affects the odd mode impedance by interacting with the wire fields. By optimizing the wire impedance with considerations both for ferrite loading and wire winding loading, lower return losses and reduced insertion losses are produced. Ferrite loading increases the wire impedance, but lower permeability ferrites ($\mu < 400$) create a greater impedance increase than high permeability cores ($\mu > 1200$) because of disproportionately lower core permittivity. Winding loading reduces the wire characteristic impedance. Toroid cores have less winding loading than two-hole cores because the windings lie side-by-side rather than filling the hole. The ferrite core loading and winding loading perturbs the bifilar wire impedance. This means that the optimum wire impedance, when measured in air, is not 50 ohms for a 50 ohm balun. The optimum free air wire impedance is 43 ohms for the μ_i=370 2-hole core used here. Finally, wire gauge should be as large as possible, yet small enough to fit the required number of turns on the desired core. This balun uses a two-hole balun core that is 2.4x3.5x2 millimeters. The wire uses a novel 3-wire configuration similar to coplanar waveguide. A two-wire transmission line is constructed by connecting together the outside wires of a 3-wire ribbon. The 3-wire ribbon uses 38 gauge wire with 4 insulation thicknesses to achieve the proper impedance and yet be small enough to fit 3.5 turns around the center of the two-hole balun core. These considerations allow an improvement by a factor of two over current production designs.

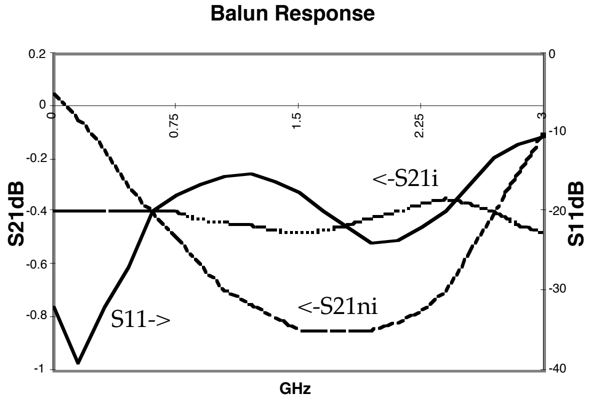

Figure 6. Balun response with 0.2pF across inputs and outputs.

Figures 6 shows the balun insertion loss and input return loss. The balun test fixture used a 25 to 50 ohm minimum loss resistive pad, made from two 35.7 ohm size 805 resistors, on each 25 ohm output. Small capacitors, on the order of 0.2pF across the inputs and outputs, fine tuned the performance above 1GHz. Even without these capacitors the maximum insertion loss was 2.2dB at 3GHz. The noninverting response is sloped downward and dominated by the shunting effect of the even mode ferrite line. The main advantage of coaxial ferrite loaded baluns is that this even mode shunting affect does not occur for the center conductor of the coax due to the coaxial shield. For wire baluns, the even mode line should be as short and as high impedance as possible to reduce loading. Unfortunately, these two goals conflict, and form one of the major compromises in ferrite loaded balun design. The inverting response is essentially a flat high pass response. The shunt output line looks approximately like a resistor, due to the even mode ferrite loss, shunted by an inductor. Increasing the winding turns and/or the ferrite permeability increases this shunt resistance and reduces the inverting side loss. The optimum number of turns in this case is 3.5.

ACKNOWLEDGMENT

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