Ultra-Wideband Differential Measurements Using PSPL BALUNs

James R. Andrews, Ph.D., IEEE Fellow

INTRODUCTION

Almost all high-performance test instruments, including sampling oscilloscopes and vector network analyzers, are single-ended, ground-referenced, 50 Ohm instruments. There are now a growing number of electronic applications, both digital and analog, that are using differential circuit techniques and also balanced transmission lines. The test instrument manufacturers have been slow to recognize this trend. As a result, many engineers are being tasked to design new differential circuits without the benefit of having proper test instruments. PSPL offers ultra-wideband BALUNs which permit differential measurements to be made over extremely wide frequencies extending from a few kHz to many GHz. The Model 5320A covers from 5 kHz to 11 GHz, while the Model 5315 covers from 200 kHz to 17 GHz. The Model 5320A is the most popular.

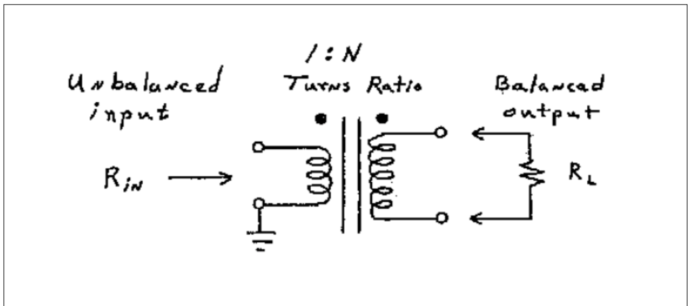

Figure 1: BALUN Transformer

Historically, when engineers needed to do differential measurements with conventional test instruments, they used a BALanced to UNbalanced transformer, or BALUN for short. Figure 1 shows the typical schematic diagram for a BALUN. It consists of a simple transformer with one wire of the primary winding being the ground terminal for the unbalanced side. The balanced secondary winding is not connected to the ground terminal and is thus considered to be "floating" with respect to ground. Impedance transformation is also possible if the number of wire turns on the primary and secondary are unequal. The impedance transformation is equal to the square of the turns ratio, N. An example of a BALUN everyone is familiar with is the antenna transformer supplied with every TV receiver. It is used to match 300 Ohm flat ribbon lead to 75 Ohm coax cable. For a 300 Ohm / 75 Ohm transformation, a 2 : 1 turns ratio is required.

Figure 2 shows another example of a BALUN. In this case the balanced secondary consists of two identical windings that are connected as a center-tapped secondary. The center tap is usually then connected to the common ground. Coax connectors might now be used for all three terminals. Note that the black dots are polarity indicators for the various transformer windings. With the arrangement shown in Figure 2, one of the secondary outputs is "in-phase" with the input and is thus labeled as the (+), or non-inverting, output. The other secondary output is "out-of-phase" with the input and is thus labeled as the (-), or inverting, output. There are now three output impedances to be considered. R+ and R- are the impedances referenced to ground seen looking into the (+) and (-) outputs, respectively. There is also a differential impedance, R_{diff}, which is the impedance seen between the two center pins of the (+) and (-) output coax connectors. The impedance transformation is still determined by the turns ratio, N, of the secondary and primary windings.

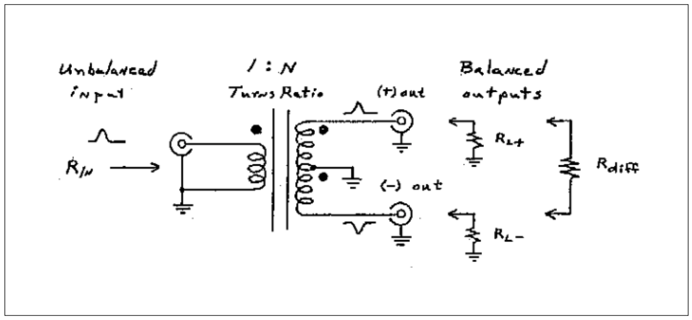

Figure 2: BALUN Transformer with Center-Tapped Output

The BALUN designs shown in Figures 1 and 2 are very widely used and are available from many manufacturers. They can be used for Balanced to Unbalanced transformations and also to shift impedance levels by altering the turns ratio, N. The major limitation of these designs is bandwidth. They are built using conventional transformer designs and techniques. The transformer core material, number of wire turns, etc., are dictated by the desired operating frequency. It is difficult to design transformers, including BALUNs, to operate over more than one or two decades of bandwidth.

For typical "wireless" applications, ultrawide bandwidth is not a requirement. For example, the TV antenna transformer mentioned earlier only needs to work from 50 MHz to 800 MHz. However, for digital data, ultrawide bandwidth is a mandatory requirement. Digital data systems, such as SONET, Gigabit Ethernet, and Fiber Channel, require bandwidths extending from a few kHz to many GHz. For these data applications, the BALUN designs of Figures 1 and 2 are unsatisfactory.

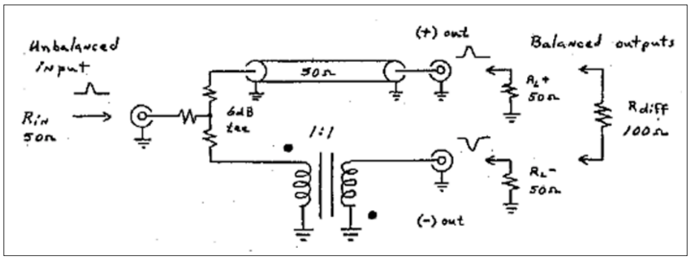

Figure 3: PSPL Ultra-WideBand BALUN

PSPL BALUN DESIGN

PSPL has developed an ultra-wideband BALUN design which works over many decades of bandwidth. The PSPL BALUN design is shown in Figure 3. It consists of a 50 Ohm, 6 dB resistive power divider, a 50 Ohm coaxial inverting 1:1 transformer, and a length of 50 Ohm coax cable. The input signal is split into two identical signals by the 6 dB power divider. One of these signals is then inverted (180 degree phase shift) by the 1:1 inverting transformer. The other signal is sent through a coax cable whose length is chosen to match the propagation delay time of the 1:1 inverting transformer. The input impedance is 50 Ω. The output impedances of both the (+) and (-) coaxial outputs are also 50 Ohm. The differential output impedance is thus 100 Ohm. The 1:1 inverting transformer is a special PSPL proprietary design which is a hybrid of coax cable and conventional transformer designs. This design results in an ultra-wideband transformer covering 6 ½ decades. The PSPL Model 5320A BALUN has a -3 dB bandwidth from 5 kHz to 11 GHz. Its risetime is 31 ps. The two outputs are matched in amplitude and phase to 0.2 dB and within less than ±2 ps. The major limitations in this design are the 6 dB insertion loss suffered in the 6 dB power divider and that the impedance transformation is limited to 2:1, i.e., 100 Ohm differential output to 50 Ohm single-ended input. Other impedances, such as 150 Ohm/ 75 Ohm, would require the use of 75 Ohm coax components.

The Model 5320A BALUN was originally designed in the mid 80s by PSPL for use in an ultra-wide bandwidth, traveling-wave tube oscilloscope. It split a 50 Ohm single-ended input signal into two 50 Ohm push-pull signals to drive the scope's CRT 100 Ω balanced deflection plates. The scope was only used to measure extremely fast risetime, single transient pulses in a time window of 5 ns or less. The customer's design requirements for the 5320A BALUN were that it needed to provide the fastest possible risetime, flat pulse response, and balanced drive only for a 5 ns time window. It did this extremely well. Its differential risetime was 31 ps, and the diff. balance between the (+) and (-) outputs was < 0.2 dB for times < 7 ns. Figure 4 shows the pulse transmission response at 20 ps/div. of the 5320A BALUN. The input test signal was a 10 ps risetime step function.

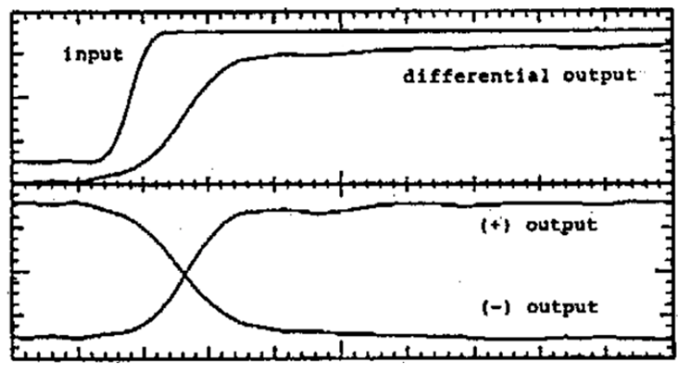

Figure 4: PSPL Model 5320A BALUN Pulse Response
Input Step has 10 ps Risetime. Time Scale is 20 ps/div.

PSPL still sells the 5320A as a standard catalog item. Today, however, customers are using the 5320A for dramatically different purposes. The two major uses are for (1) differential measurements of balanced transmission lines and other balanced components with a single-ended, 50 Ohm network analyzer (see Figure 8), and (2) splitting or combining Gigabit data signals into differential or single-ended signals. For these purposes, the 5320A performs in a less-than-optimum manner. Users of the 5320A are cautioned to carefully study the 5320A's limitations. PSPL's future plans are to design new BALUNs that will be optimized for Gigabit data applications.

5320A LIMITATIONS

The fundamental limitation of the 5320A is an impedance mismatch in the internal pulse-inverting transformer. This mismatch is shown on the TDR plot found on the 5320A's specification sheet. A TDR measurement made looking into the (-) Inverting Output port shows a -12% reflection coefficient. Reflections from the transformer are also seen on the TDR plots for the input port and (+) Non-Inverting output port. The reflections seen on the input and (+) output are smaller due to the attenuation introduced by the 6 dB power divider. An input signal will be partially reflected from the transformer and will eventually appear later in time on the (+) output. A step response measurement, similar to Figure 4 but at a slower sweep speed, shows that, starting at t = 7 ns, the (+) output and also the differential output have a small negative shift in voltage level. For t > 7 ns, there is an imbalance of about 0.5 dB (i.e., -6%) between the (+) and (-) outputs.

When one single 5320A BALUN is used to split a signal into separate (+) and (-) signals, the single 7 ns reflection is not too severe. A 5320A BALUN can also be used to combine differential signals into a single, unbalanced signal. If the differential signals come from a well matched source, then the results are satisfactory. If the source is not well matched to 50 Ohm, then the results are not satisfactory due to multiple reflections.

The real problem arises when one uses a pair of 5320A BALUNs in a back-to-back configuration. Figure 5 shows the resultant "thru" signal at a sweep speed of 10 ns/div. for a pair of 5320As joined with a pair of 6", 50 Ohm coax cables. This step response is objectionable for intermediate times from t = 7 ns to about 50 ns. For times less than 7 ns, the output is very well-behaved. Likewise for times > 50 ns, the output is very well-behaved. For intermediate times, the ragged step response (Figure 5) is due to multiple reflections occurring due to the -12% mismatches of the 1:1 inverting transformers used in the BALUNs. The intermediate time zone of 7 ns to 50 ns will also cause severe problems in the frequency domain between about 150 MHz and 20 MHz (i.e., f = 1 / T). The problem shown in Figure 5 limits the usefulness of a pair of 5320As for Gigabit data applications. However, if additional losses can be tolerated, the multiple reflection problem can be minimized by adding 6 to 10 dB SMA attenuators between the two BALUNs.

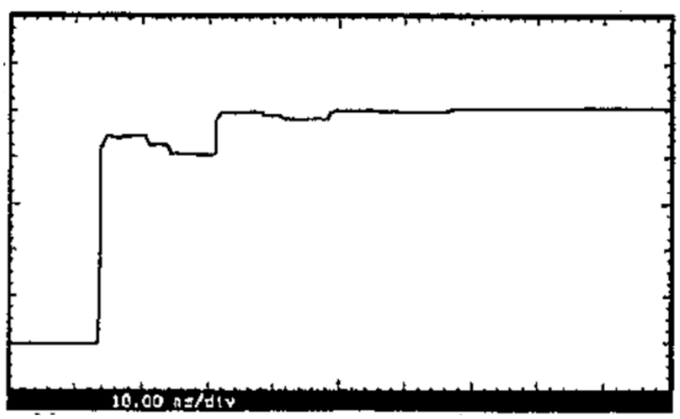

Figure 5: Pulse Step Response of two 5320A BALUNs Connected Back-to-Back. 10 ns/div.

5320A FREQUENCY RESPONSE

The frequency response of a single 5320A BALUN is shown on the specification sheet. The insertion loss and return loss plots appear to be "noisy". The "noise" is, however, an actual ripple in the frequency response that is due to the 7 ns internal mismatch reflection. Figures 6 and 7 show the insertion loss and return loss frequency responses from 10 kHz up to 10 GHz of a pair of 5320A BALUNs connected back-to-back. The input and output ports were the unbalanced 50 Ohm input ports of the BALUNs. The 7 ns mismatch problem discussed earlier is very apparent in these plots. Figure 6b is a "smoothed" response which suppresses the mismatch ripple. The 50 Ohm input and output ports' return losses are -15 dB. The insertion loss of the back-to-back pair is -7 dB, with a -3 dB bandwidth of 6.5 GHz.

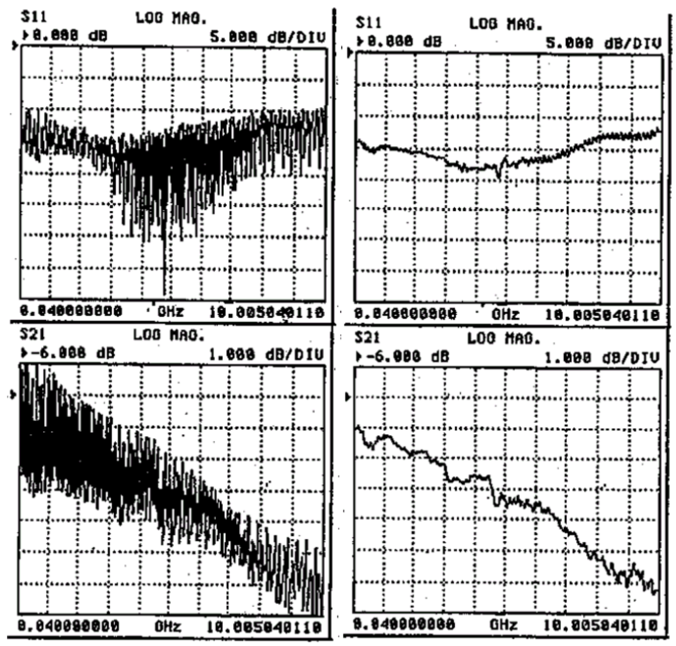

Figure 6: High Frequency Response of two PSPL 5320A BALUNs Connected Back-to-Back
Plots on right are "smoothed" data to show general trends. Measured on Wiltron 37360A VNA. 1 GHz/div.

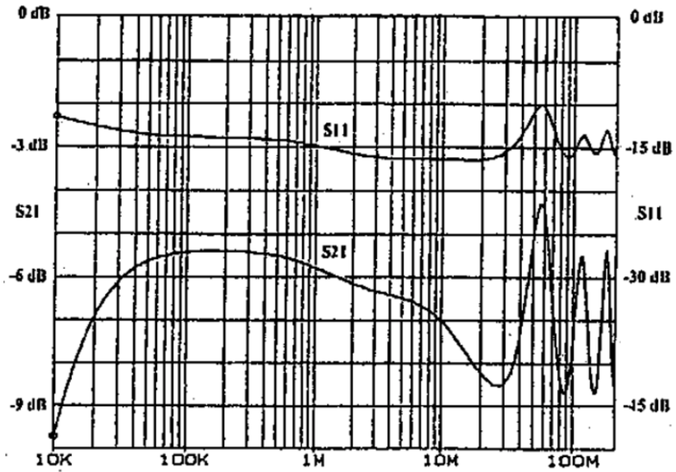

Figure 7: Low Frequency Response of two 5320A BALUNs Connected Back-to-Back
Log sweep 10 kHz to 200 MHz. Ripple noted above 10 MHz is due to 7 ns mismatch. Measured on HP 3577A network analyzer.

DIFFERENTIAL NETWORK ANALYZER

PSPL's Model 5320A BALUNs can be used successfully with modern vector network analyzers to perform differential measurements. See Figure 8. We do not recommend that they be used with scalar network analyzers. The accuracies of scalar network analyzers are strongly dependent upon the quality of the hardware used and in particular are strongly influenced by the impedance mismatch of the source and loads. Due to the poor mismatch of a back-to-back pair of 5320A BALUNs, unacceptable results are usually obtained with a scalar network analyzer. New modern vector network analyzers can provide acceptable performance with poorer hardware due to their use of elaborate mathematical calibration routines which calibrate out the hardware imperfections. Caution should be exercised when using an older VNA that does not include an elaborate calibration scheme. PSPL has a new Wiltron Model 37369A, 40 MHz to 40 GHz vector network analyzer which uses a 12-term calibration scheme. This instrument was found to be capable of calibrating out the mismatch errors of the PSPL 5320A BALUNs and providing good differential measurements.

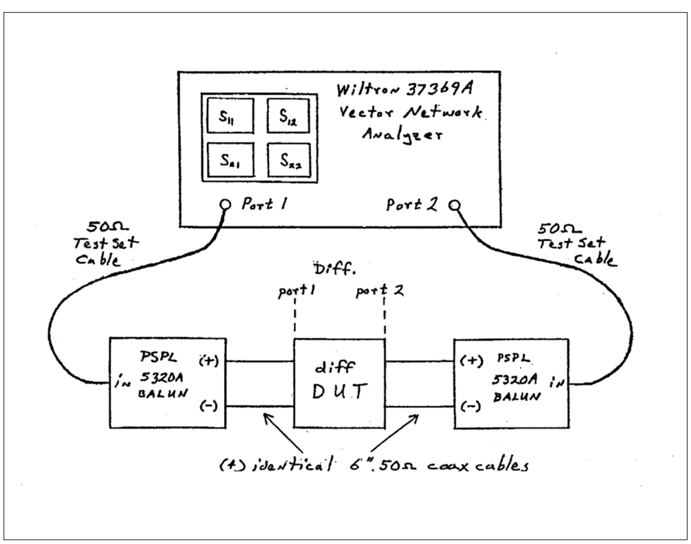

Figure 8: PSPL/Wiltron, 100 Ohm Differential, 10 GHz Vector Network Analyzer, Test Set

Figure 9 shows the results of a Wiltron 37369A differential measurement system calibration up to 10 GHz. The S_{21} and S_{11} scale factors are 0.2 dB/div and 10dB/div, respectively. The noise levels are < 0.05 dB and -50 dB, respectively. To perform the differential calibrations at the 100 Ω differential test ports, Figure 8, we used SMA calibration standards for opens, shorts, and broadband terminations. Two of each standard were required to simultaneously terminate each of the BALUNs' (+) and (-) ports. To demonstrate the usefulness, we measured two differential cables. The first test was a differential cable made up of two identical PSPL Model 5915-59", 50 Ohm, SMA semi-flex coaxial cables. Figure 10 shows the S_{21} and S_{11} of this very high quality, 100 Ohm differential cable up to 10 GHz. The second differential cable tested was a typical, low-cost cable commonly used for differential interconnects. It was a 20-foot length of shielded, twisted pair of #24 wires. Four SMA connectors were attached to this cable to connect it to the 5320A BALUNs. Figure 11 shows the measured differential insertion loss, group delay, return loss, and VSWR of this low-cost cable up to 1 GHz.

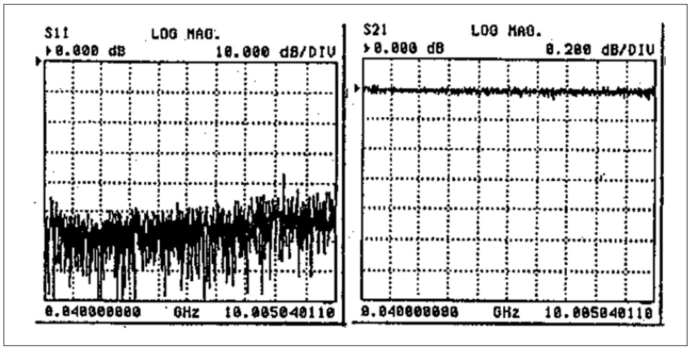

Figure 9: System Calibration Results for PSPL 100 Ohm Differential 10 GHz VNA
Linear sweep from 40 MHz to 10 GHz. Insertion loss, S_{21} scale is 0.2 dB/div. Return loss, S_{11} scale is 10 dB/div.

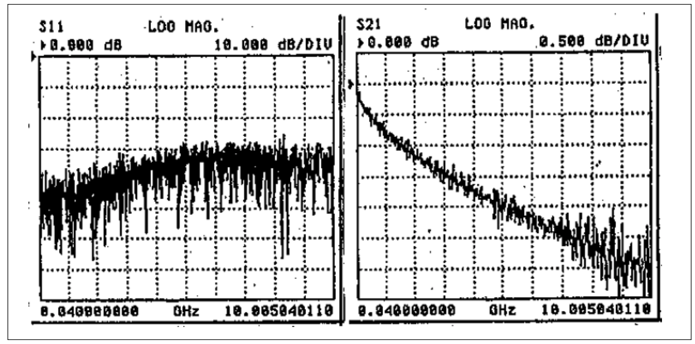

Figure 10: Differential Measurement of S21 and S11 Differential 10 GHz VNA on high quality, 100 Ohm Differential Coaxial Cable
Cable consisted of an identical pair of PSPL Model 5915-50", 50 Ohm semi-flex cables. Insertion loss, S_{21} scale is 0.5 dB/div. Return loss, S_{11} scale is 10 dB/div. Linear sweep from 40 MHz to 10 GHz.

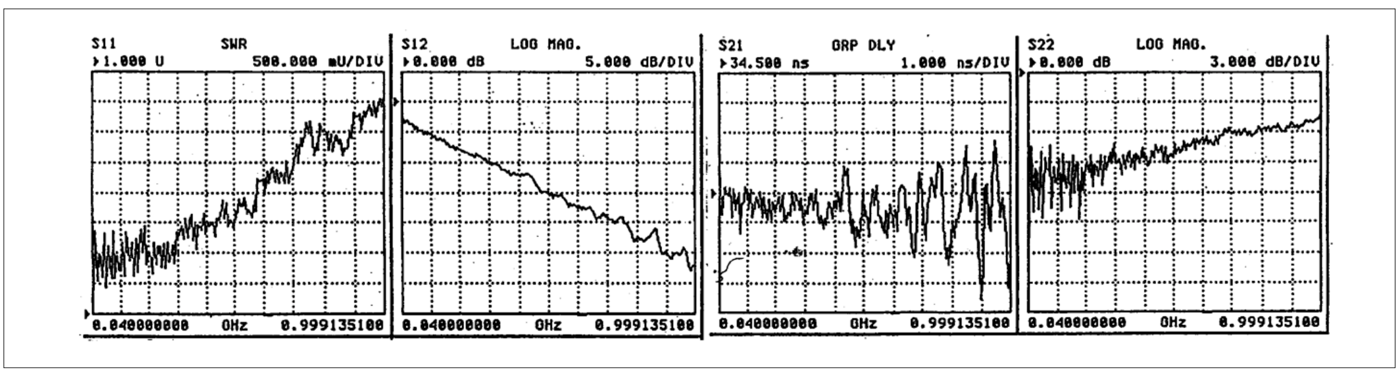

Figure 11: Differential Measurements of a Shielded #24 Twisted Wire Pair Cable
Cable length was 20 feet. Plots are of S_{11} VSWR (0.5 /div), S_{12} insertion loss (5 dB/div), S_{21} group delay (1 ns/div) and S_{22} return loss (3 dB/div). Linear frequency sweep from 40 MHz to 1 GHz.