Differential VNA Measurements Using Single-Ended, Two-Port Instruments and BALUNs

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INTRODUCTION: Almost all high-performance test instruments, including sampling oscilloscopes and Vector Network Analyzers (VNA) 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. As a result, many engineers are being tasked to design new differential circuits without the benefit of having proper test instruments.

The VNA test instrument manufacturers have been slow to recognize this trend. More recently, however, they have added optional, expensive, multi-port switch boxes to their two-port VNAs. PSPL offers a much lower-cost alternative. Instead of using switch boxes, BALUNs can be used with conventional two-port VNAs to perform differential measurements. PSPL offers ultra-wideband BALUNs that permit differential measurements to be made over extremely wide frequencies extending from a few kHz to many GHz.

This application note shows how to assemble a 10 GHz Differential VNA using the PSPL model 5305 VNA Differential Kit, which includes a pair of PSPL model 5310A BALUNs. It has a dynamic range of >60 dB for insertion loss (IL) and >55 dB for return loss (RL) and a resolution of < 0.01 dB and < 2 ps for measuring small losses.

BALUNs: 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 Ω flat ribbon lead to 75 Ω coax cable. For a 300 Ω/75 Ω transformation, a 2:1 turns ratio is required.

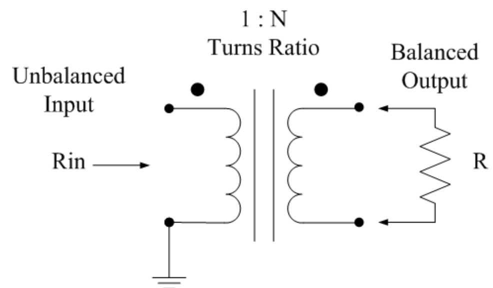

Fig. 1 BALUN Transformer

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 is a 180 degree phase difference between the (+) and (-) outputs. 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. $R_{diff} = R(+) + R(-)$. The impedance transformation is still determined by the turns ratio, N, of the secondary and primary windings.

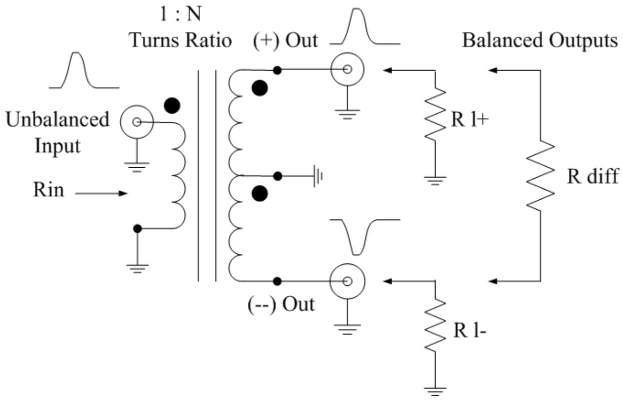

Fig. 2 BALUN Transformer with Center-Tapped Output

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 in 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", RF applications, ultrawide bandwidth is not a requirement. For example, the TV antenna transformer mentioned earlier only needs to work for 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.

PSPL ULTRA-WIDEBAND BALUN DESIGN: PSPL has developed an ultra-wideband BALUN design that works over many decades of bandwidth. The basic PSPL BALUN design is shown in Figure 3. It consists of a 50 Ω, impedance-matched, 6 dB resistive tee, a power divider, a 50 Ω coaxial inverting 1:1 transformer, and a length of 50 Ω coax cable.

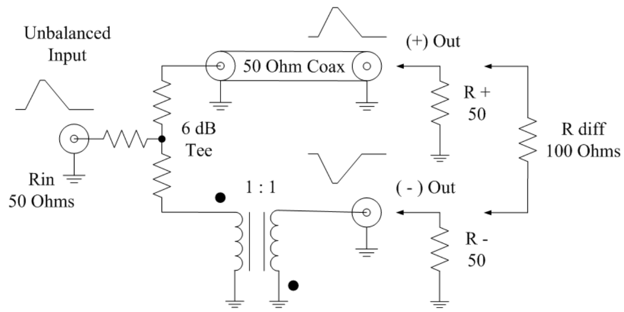

Fig. 3 PSPL Ultra-Wideband BALUN design

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 Ω. The differential output impedance is thus 100 Ω. The 1:1 inverting transformer is a special PSPL proprietary design that is a hybrid of coax cable and conventional transformer designs. This design concept results in 1:1 inverting transformers with more than six decades of bandwidth. The major limitations in this BALUN design is 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 Ω differential output to 50 Ω single-ended input).

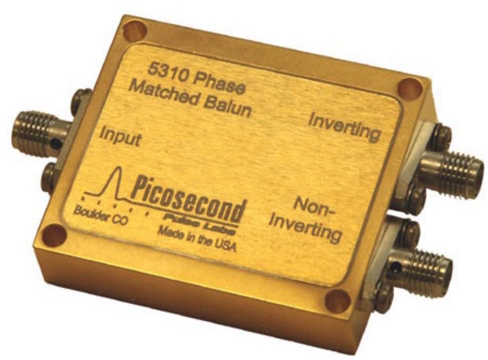

Fig. 4 PSPL 5310A, 4 MHz to 6.5 GHz BALUN

Model 5310A BALUN: The BALUN used for this particular application note is the model 5310A; see Figure 4. The key performance specs are: -3 dB bandwidth from 4 MHz to 6.5 GHz, ±0.1 dB amplitude balance (0.1-3 GHz), and ±0.5 degree phase balance (0.5-2 GHz). This BALUN is much smaller (2.5"x1.5"x0.46") and more convenient to use compared to the wider bandwidth (5kHz to 11GHz) PSPL model 5320B, which is the size and weight of a brick. Figures 5 and 6 show the 5310A BALUN's insertion loss and return loss plots. Detailed specifications for the 5310A are available from the PSPL web site: www.picosecond.com.

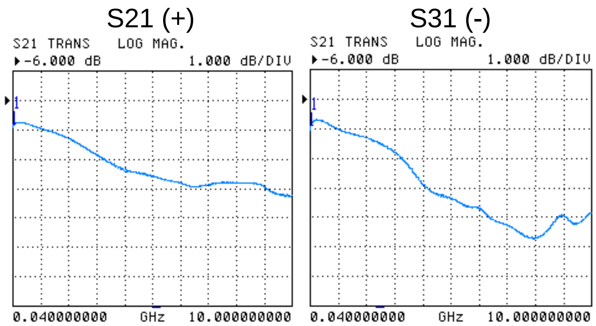

Fig. 5 PSPL model 5310A BALUN Insertion Losses between input and (+) output (left) and (-) output (right). 40 MHz to 10 GHz sweep 1 dB/div & 1 GHz/div

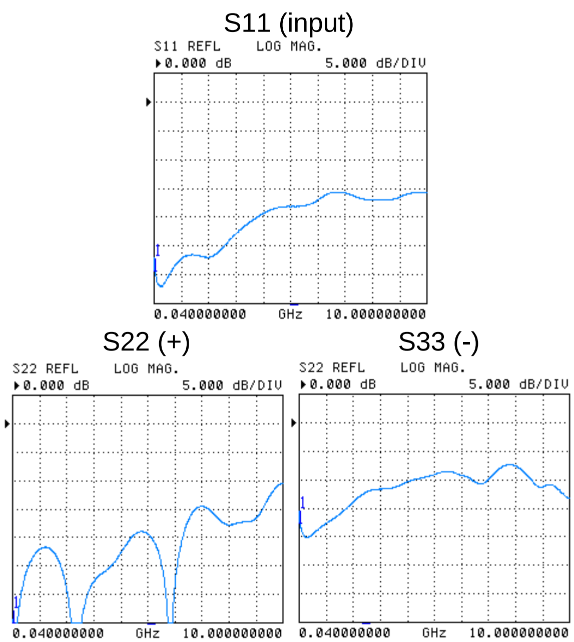

Fig. 6 PSPL model 5310A BALUN Return Losses for the input (top), non-inverting (+) port (left), and inverting (-) port (right). 40 MHz to 10 GHz sweep 5 dB/div & 1 GHz/div

DIFFERENTIAL VNA: A conventional, two-port, Vector Network Analyzer (VNA) can easily, and inexpensively, be configured into a 10 GHz, four-port, Differential VNA using a pair of PSPL model 5310A BALUNs. Figures 7 and 8 show how this is accomplished. Ports 1 and 2 of the VNA are connected to the "input" ports of the BALUNs. The (+) non-inverting and (-) inverting output ports of the baluns now become the differential ports of the four-port Differential VNA.

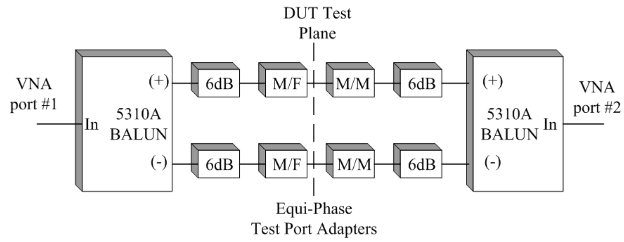

Fig. 7 BALUN configuration for a Differential VNA

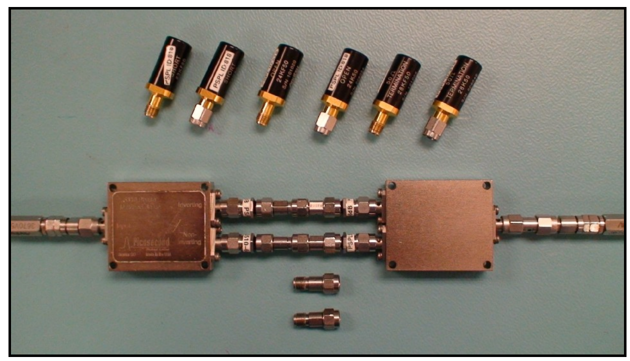

Fig. 8 Photo of a Differential VNA test set using PSPL 5310A BALUNS along with Open, Short, & 50Ω calibration standards

The performance of a 5310A BALUN is not ideal. There are some internal reflections, caused by the inverting transformer. The inverting (-) port's return loss, S33, shown in Figure 6 is less than ideal. When a pair of 5310As are connected directly together in a 'back-to-back' configuration [(+) to (+) and (-) to (-)], the pair's composite insertion loss frequency response shows unacceptable ripples. To suppress these internal reflections and provide much better impedance matches for the differential test ports, PSPL recommends that 6 dB attenuators be attached to each of the four differential test ports. PSPL model 5510-110-6dB, SMA attenuators are ideal for this application. Figure 9 shows the S11 and S21 for this differential test set combination. Due to the 6dB loss in the BALUNs and the 6dB loss in the attenuators, the total composite, low frequency loss for this test set is 19dB. PSPL does not recommend this differential test set be used above 10 GHz. Unacceptable resonances occur in the BALUNs above 12 GHz.

PSPL also recommends that equi-phase gender adapters be used on each of the 6 dB attenuators to provide the four, test port terminals where the differential Device Under Test (DUT) is attached. An equi-phase adapter has the same identical electrical length regardless of the connector sexes on it.

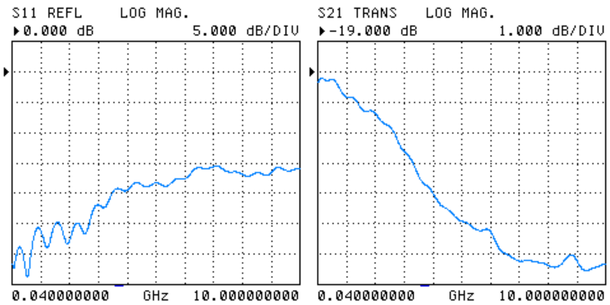

Fig. 9 Return Loss, S11, (5 dB/div) and Insertion Loss, S21, (1 dB/div) for a Back-to-Back pair of PSPL 5310A BALUNs. Note: 6 dB attenuators used on each (+) & (-) port. Sweep 40 MHz to 10GHz, 1 GHz/div

The PSPL VNA Differential Kit, Model 5305, contains all of the above necessary components (see table given below).

PSPL Model 5305 VNA Differential Kit Contents

Description	Qty
Model 5310A BALUNs	2
Model 5510-110-6dB Attenuators	4
2.92 mm Male/Male Equi-phase Adapters	4
2.92 mm Male/Female Equi-phase Adapters	4

VNA CALIBRATION: To demonstrate an actual Differential VNA, an Anritsu model 37397C, 40 MHz to 65 GHz, single-ended, two-port VNA was used. The differential VNA test set was configured using a pair of PSPL 5310A BALUNs as shown in Figures 7 and 8. Prior to performing measurements, the VNA must first be calibrated. A full 12-term calibration was performed, including 'isolation'. The calibration standards used (see Figure 8) were "K" standards from an Anritsu model 3652 calibration kit. They included precision Opens, Shorts, and 50 Ω terminations of both sexes. Normally when calibrating a single-ended two-port VNA, one only needs a single Open, Short, and 50 Ω termination. However, when calibrating a four-port Differential VNA, two Opens, two Shorts, and two 50 Ω terminations are required.

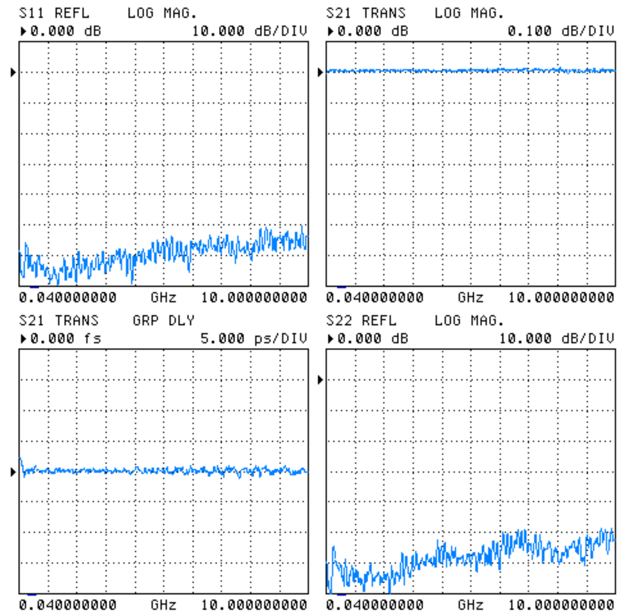

Fig. 10 10GHz, Differential VNA system calibration. Sweep from 40 MHz to 10 GHz, 1 GHz/div

Figure 10 shows the results of a Differential VNA calibration. They compare very favorably to those achieved doing a normal calibration of the single-ended, two-port, Anritsu 37397C VNA. The differential, four-port dynamic range for S11 is seen to be better than 55 dB. It is greater than 65dB for the two-port VNA. The differential, four-port dynamic range for S21 is better than 60dB, while it is better than 70dB for the two-port VNA. The 10dB differences are due to the added insertion loss of the BALUN test set. For measuring very small S21 insertion losses, the VNA 'noise' is < 0.01dB and < 2ps for both the four-port, differential VNA and the two-port VNA.

DIFFERENTIAL VNA MEASUREMENT EXAMPLES: Several examples are presented to show the usefulness of this 10 GHz, Differential VNA. These are shown over the full range from 40 MHz to 10 GHz. The first examples use matched pairs of SMA components inserted as the DUT. Figure 11 is a differential measurement of a pair of SMA, 10 dB coaxial attenuators. Figure 12 is for a phase-matched pair of 48" long coaxial cables. The skin-effect loss in the cables is obvious in the S21, upper-right plot.

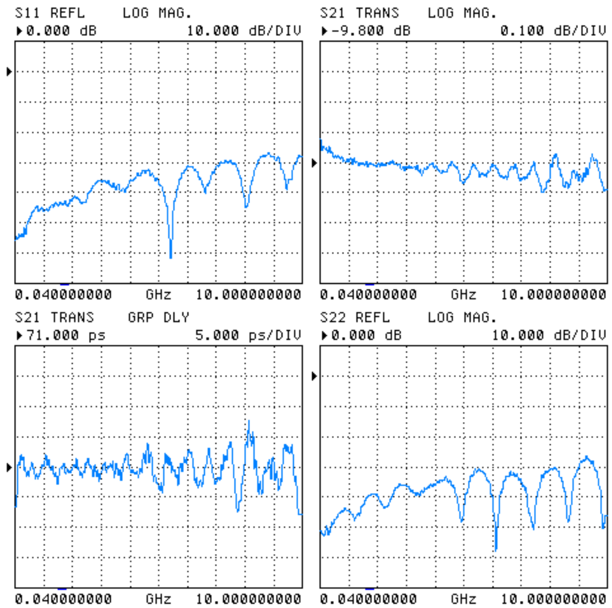

Fig. 11 Differential VNA measurement of a pair of 10 dB, SMA attenuators. PSPL model 5510-110-10dB. 1 GHz/div sweep to 10 GHz

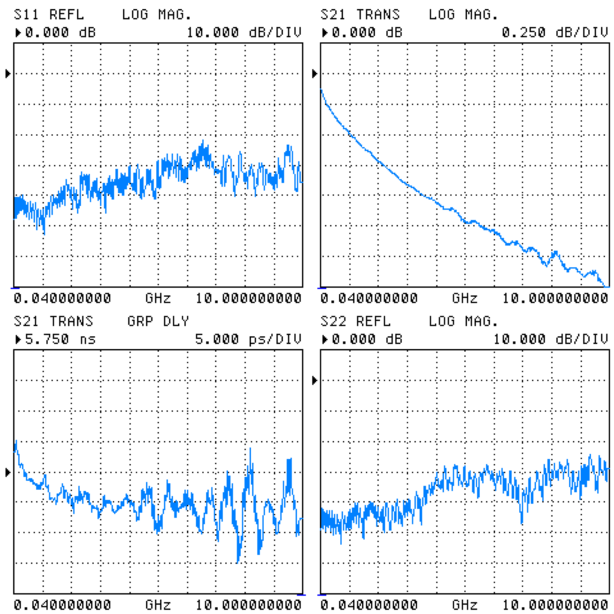

Fig. 12 Differential VNA measurement of a phase-matched pair of 48", semi-flex, SMA coax cables. PSPL model 5015-48. 1 GHz/div sweep to 10 GHz

Figure 13 is an example of a truly differential DUT. This is a shielded, balanced, twisted pair, audio cable. This type of cable is not normally used for RF purposes, but reliable measurements were possible to beyond 500 MHz.

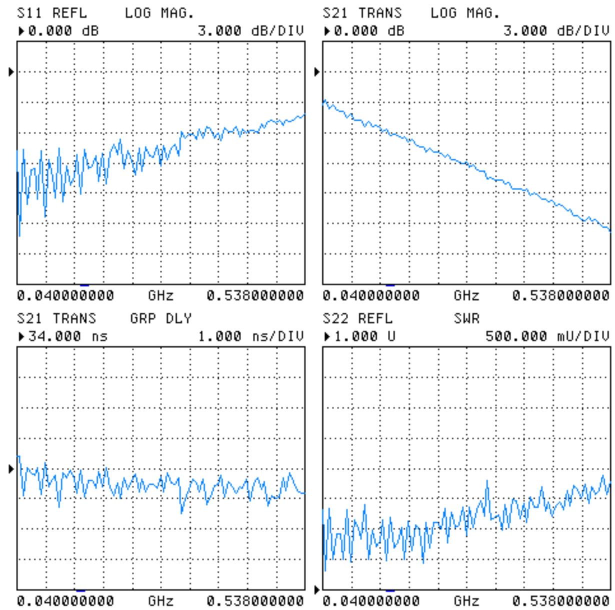

Fig. 13 Differential VNA measurement of a 20 ft, shielded, balanced, twisted pair, #24 AWG, audio cable. 40 MHz to 540 MHz sweep, 50 MHz/div

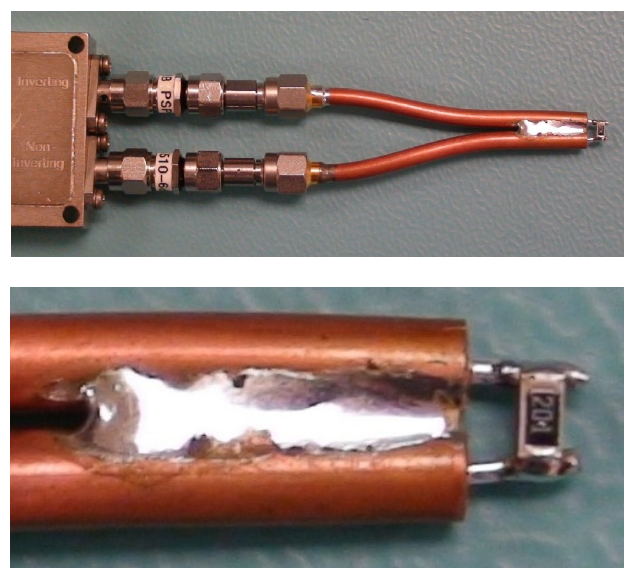

Fig. 14 Differential Test Fixture for Chip Components

To further demonstrate true, differential measurements, a test fixture was built to test chip components. See Figure 14. The test fixture consists of a pair of phase-matched, 2.5" semi-rigid, SMA cables soldered together at the DUT test plane. The chip component to be tested is soldered across the two extended center conductors. Figure 15 shows the S11 results measuring a matched differential termination of a 100 Ω chip resistor (top plot) and a mis-matched 200 Ω chip resistor (bottom plot). The plots show both linear frequency sweep, log plots, and also Smith Charts.

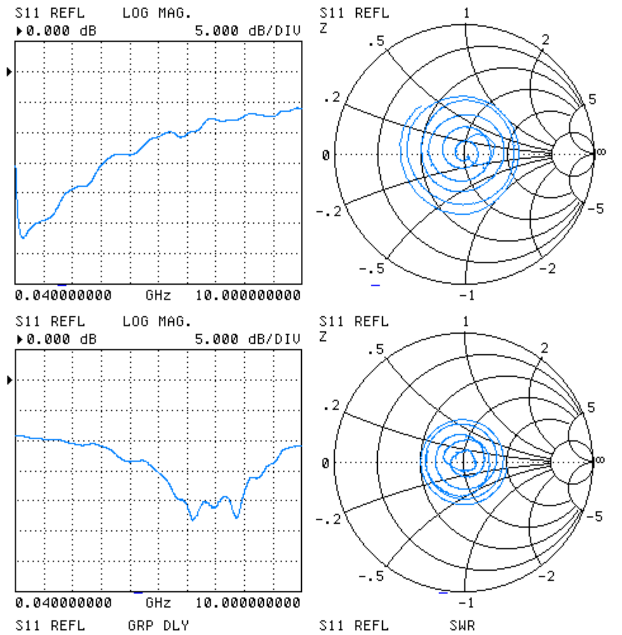

Fig. 15 Differential VNA S11 measurements of 100 Ω (top) and 200 Ω (bottom) chip resistors. 40 MHz to 10 GHz sweep, 1 GHz/div

OTHER DIFFERENTIAL NETWORK ANALYZERS: There also exist lower cost, Scalar Network Analyzers (SNA). Without phase information, they are unable to do the exotic 12 term calibrations possible with vector network analyzers. They rely upon much simpler "normalization" calibrations. For their accuracy, they need much better hardware components than VNAs. PSPL 5310A BALUNs can be used with SNAs, but only for normalized, S21, differential insertion loss measurements. They do not perform well for SNA S11 differential return loss measurements.

For low frequency, differential VNA measurements down into the kHz region, PSPL recommends using the PSPL 5320B BALUNs. They have a 3dB bandwidth extending from 5 kHz to 11 GHz. For further details, see the PSPL application note, AN-8, *"Ultra-Wideband Differential Measurements Using PSPL BALUNs*". AN-8 is available from the PSPL web site: www.picosecond.com.