75 Ohm, 26 GHz Vector Network Analyzer and 30 ps TDR - TDT

James R. Andrews, Ph.D., IEEE Fellow
PSPL Founder & former President (retired)

INTRODUCTION Historically, 50 Ω coaxial systems have been used for RF and microwave applications, while 75 Ω systems have been used for the video and television industries. The original reasons for these impedance choices were that high RF power handling was optimized in 50 Ω coaxial cable, whereas minimum coax attenuation was obtained at 75 Ω. The requirements for utilizing high RF power, and thus 50 Ω coax, at microwave frequencies (> 1 GHz) dates back many years to WWII. The video/TV industry historically never required performance beyond 1 GHz. A typical color video camera's signal only extended up to 4.2 MHz. RF transmission of TV signals, either broadcast over the air or within cable TV systems, was in the spectrum from 50 to 800 MHz. Today, there are new pressures on the frequency performance of 75 Ω coax systems. The new high definition TV now requires sending 1.5 Gb/s HDTV digital data over 75 Ω coax cables within TV studio plants. Also, interconnect cable impedances higher than 50 Ω are becoming more desirable for various digital circuits operating at Gigabit data rates. The compelling reason for 75 Ω vs. 50 Ω here is the 1/3 reduction in current drive required to maintain the same logic voltage levels.

A key test instrument used for evaluating many electronic components is the Vector Network Analyzer (VNA). 50 Ω VNAs are offered by several manufacturers to frequencies as high as 110 GHz. For 75 Ω, only a few VNAs are available up to a maximum of 4 GHz [1]. They include Anritsu (to 2 GHz), Agilent (to 3 GHz), Advantest (to 3.8 GHz), and Rohde & Schwarz (to 4 GHz). They all use 75 Ω N connectors. Their N calibration kits are only rated up to 3 GHz.

Several years ago, PSPL received a customer request to build custom, 75 Ω bias tees capable of operating at frequencies from a few kHz to in excess of 5 GHz. We immediately were faced with the problem of not having suitable 75 Ω coax connectors or test equipment, including a TDR or VNA. We were able to solve these problems, using 75 Ω SMA connectors and by building our own VNA, using our model 4015, 15 ps pulse generator and a 50 GHz, HP oscilloscope. We are now using our new, 7 ps model 4020 TDR/TDT pulse generator. This application note documents our 75 Ω, combined 30 ps (*10 ps risetime with normalization*) TDR/TDT and 26 GHz TDVNA instrument.

SMA 75 Ω CONNECTORS Historically, almost all RF and microwave test instruments have been standardized to 50 Ω coaxial interconnects. 50 Ω instruments typically use BNC (< 1 GHz), N (< 18 GHz), SMA (< 18 GHz), 3.5mm (< 26 GHz), K (< 40 GHz), 2.4 mm (< 50 GHz), or V (< 65 GHz) connectors. 75 Ω test instruments have used BNC (< 1 GHz), N (< 3 GHz), or rarely F (< 1 GHz), 75 Ω coaxial connectors. A potential major breakthrough in 75 Ω instrumentation is now possible with the introduction of 75 Ω, SMA connectors. In the late 90s, the QMI company (Quality Microwave Interconnects) foresaw the need for higher performance, 75 Ω microwave connectors and developed an extensive line of 75 Ω, SMA connectors, adapters, cables, and SMA-N and SMA-BNC adapters [2]. The 75 Ω SMA items from QMI were only specified up to 3 GHz because that was the upper test limit of their 75 Ω, type N, commercial VNA. PSPL has found, however, that these QMI, 75 Ω, SMA connectors work very well up to 18 GHz and in some cases to 26 GHz, and are comparable in performance to their 50 Ω SMA counterparts. They form the basis of our 75 Ω, 26 GHz TDVNA and 30 ps TDR/TDT.

Fig. 1 QMI 75 Ω SMA connectors

75 Ω MEASUREMENTS WITH 50 Ω INSTRUMENTS
To make measurements on 75 Ω items with a 50 Ω instrument typically has required the use of either a 50/75 Ω impedance transformer, or a minimum loss 50/75 Ω "L" matching pad, Figure 2, [3]. Typical, commercially available 50/75 Ω impedance transformers offer very low insertion loss, but are usually only useful up to about 500 MHz. If carefully made, the resistive minimum loss pad is useful to considerably higher frequencies. Commercial minimum loss L pads with type N connectors are available up to 3 GHz. The major drawback to the minimum loss pad is its inherent insertion loss of 5.7 dB and attendant loss in measurement system dynamic range. If one doesn't account for this loss in the calibration, then a 0 dB return loss in a 75 Ω system becomes -11.4 dB when measured in a 50 Ω system.

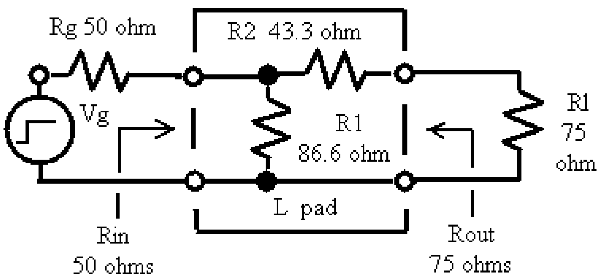

Fig. 2 Minimum Loss 50 / 75 Ω "L" Matching Pad

TD VECTOR NETWORK ANALYZER Figure 3 shows the basic test set for a Time Domain Vector Network Analyzer (TDVNA). It is also the basic test set for making TDR and TDT measurements. PSPL's TDR/TDT and TDVNA application notes, AN-15 and AN-16, [4 & 5] should be referred to at this time as they compliment this application note. Figure 3 is also the classical setup used in the frequency domain for making S parameter insertion and reflection measurements of S_{21} and S_{11}. A sine wave generator is used as the signal source (V_g, R_g) for frequency domain measurements. For time domain measurements, a pulse generator is used as the signal source, and an oscilloscope is used to observe and measure the resultant waveforms, $V_{tdr}(t)$ and $V_{tdt}(t)$. For frequency domain S parameters, the Fast Fourier Transform (FFT) is used to transform the time domain TDT and TDR waveforms into frequency domain data.

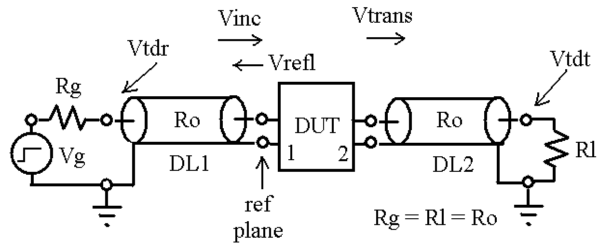

Fig. 3 Basic TDR, TDT and TDVNA Measurement Set-up

$$\tau = V_{trans}(t) / V_{inc}(t) \quad (1)$$

$$S_{21}(f) = FFT[V_{trans}(t)] \ / \ FFT[V_{inc}(t)] \quad (2)$$

$$\rho = V_{refl}(t) / V_{inc}(t) \quad (3)$$

$$S_{11}(f) = FFT[V_{refl}(t)] \ / \ FFT[V_{inc}(t)] \quad (4)$$

TDT / S21 Test Set PSPL has the same problem that other instrument manufacturers have in building a 75 Ω VNA. That is that all our really high bandwidth products were all designed as 50 Ω systems. Our fastest pulse generators that we used for this TDVNA are our 50 Ω models 4020/22 with risetimes of the order of 5 to 10 ps and 2.4 mm, 50 Ω connectors. Likewise the oscilloscope we used was an HP 50 GHz scope with 50 Ω, 2.4 mm connectors. We thus need to modify the basic set-up of Figure 3 to include some form of 50/75 Ω impedance matching or adaptation. See Figure 4. PSPL uses three different Z matching techniques, depending upon the desired upper frequency limit. In order of increasing bandwidth, they are the L pads, Figure 2, one-way 25 Ω series matching resistors, Figure 5, or abrupt junction transitions, Figure 6.

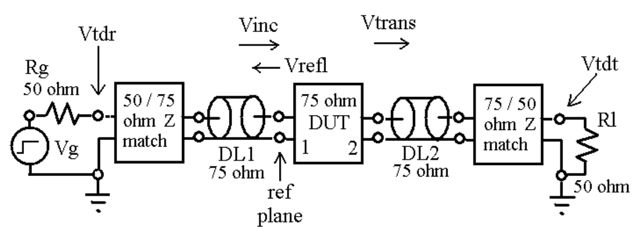

Fig. 4 75 Ω TDT and S21 TDVNA, using Z matching networks and 50 Ω test equipment

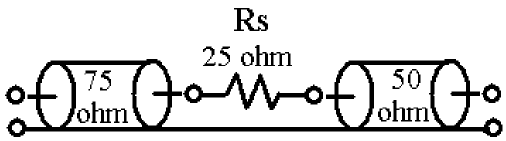

Fig. 5 One-way 25 Ω series matching resistor

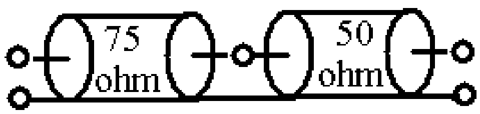

Fig. 6 Abrupt junction 75 / 50 Ω transition

The classical technique is to use minimum loss L pads on either side of the 75 Ω Device Under Test (DUT). We have built experimental SMA, L pads, using 0603 chip resistors and QMI connectors. Our L pads have a risetime of 23 ps and a -3 dB bandwidth of 15 GHz. ($BW \approx 0.35/T_r$). For a pair of these L pads, the risetime and bandwidth would be about 33 ps and 11 GHz. Thus we feel they are useful for VNA measurements from DC up to 5 GHz.

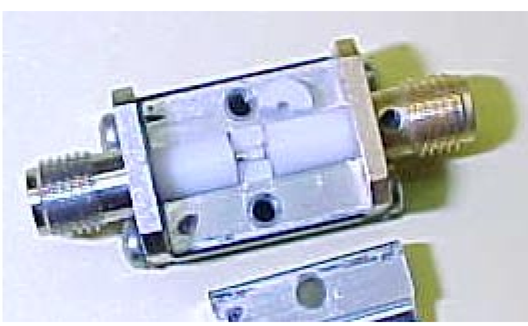

Fig. 7 75 Ω to 50 Ω series matching resistor. The 25 Ω chip resistor is mounted between the center pins of the 75 Ω and 50 Ω coax connectors.

A higher bandwidth arrangement is to use one-way series matching resistors on either side of the 75 Ω DUT. These are a single 25 Ω resistor mounted in series between a 50 Ω coax line and a 75 Ω coax line, Figure. 5. When the 50 Ω connector is terminated in 50 Ω, then a matched impedance of 75 Ω is seen looking into the 75 Ω connector. There is, however, a mismatch of 100 Ω (ρ = +1/3) when viewed from the 50 Ω side. If the signal generator, R_g, and the termination, R_l, are relatively well matched to 50 Ω, then serious, multiple reflections will be suppressed. Oscilloscopes usually are rather well matched to 50 Ω. (Caution — One manufacturer's 70 GHz sampler is a severe mismatch of 70 Ω!) Pulse generators are usually not as well matched to 50 Ω. However, if one has a higher than necessary pulse generator amplitude, then a good quality, coax attenuator can be attached to the pulse generator output to provide good impedance matching. We built experimental 25 Ω series matching resistors in a coaxial housing, Figure 7. The resistor is a 0603 chip. Extended Teflon dielectric, flange mount, SMA connectors were used. The 75 Ω SMA connector is a QMI p/n 3-E926-190-12 (jack) or 3-E926-110-10 (plug). The 50 Ω SMA connector is a CDI p/n 5220CC (jack) or 5340CC (plug). The risetime of this unit is 11 ps. The risetime for a pair would be about 16 ps, with a resultant -3 dB bandwidth of 22 GHz.

The highest bandwidth arrangement is shown in Figure 6. In this case, no attempt is made to match either the 50 Ω source or 50 Ω termination to the 75 Ω cables or DUT. If the 50/75 Ω abrupt transitions are built properly, then the minimum risetime degradation is introduced and, thus, the bandwidth is maximized. There is, however, a definite lower frequency limit imposed by the necessity to avoid measuring any of the many multiple reflections that will occur in this set-up. The reflection-free time window of observation is established by the two way transit time of the cables, DL_1 and DL_2. We have built experimental abrupt transitions with the same SMA connectors and coax housing as shown in Figure 7. The risetime of a single 50/75 Ω transition is 5 ps. The risetime and bandwidth for a pair would be 7 ps and 50 GHz.

TDR / S11 Test Set TDT and S_{21} measurements are the easiest to perform, and the maximum bandwidth is achieved for them. There is added complexity to TDR and S_{11} measurements. They are complicated by the necessity to pick off the signal, V_{tdr}. The extra components required for TDR tend to slow down the system risetime and lower the S_{11} bandwidth. Figure 8 shows how to use a 75 Ω , 6 dB power divider tee along with a pair of 25 Ω series matching resistors. To minimize the risetime degradation, the two separate 25 Ω resistors shown in series could be consolidated into a single 50 Ω resistor. See Figure 9. A special 75 Ω TDR tee was built for the PSPL 75 Ω TDR and S_{11} TDVNA, using chip resistors in the circuit of Figure 9 in a coax tee housing similar to the in-line housing shown in Figure 7.

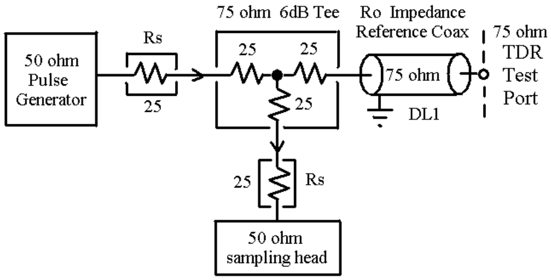

Fig. 8 75 Ω TDR using a 75 Ω , 6 dB Tee

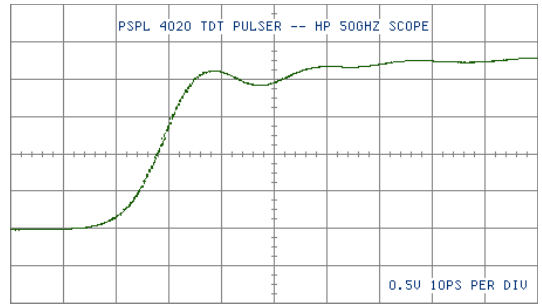

Fig. 10 PSPL 4020 TDT pulser measured on HP 50 GHz oscilloscope, 0.5 V/div and 10 ps/div

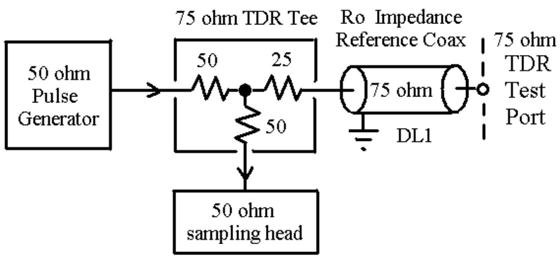

Fig. 9 Special 75 Ω TDR Tee for use in a 50 Ω system

75 Ω Calibration Standards A set of 75 Ω, SMA calibration standards were built to use with this TDVNA. In both sexes, they included offset shorts, offset opens, 75 Ω terminations, and equi-phase sex change adapters. The shorts, opens, and equi-phase adapters were all built using the extended Teflon dielectric, flange mount, QMI, SMA connectors and the coax housing shown in Figure 7. The time window isolation lines, DL_1 and DL_2 were either the equi-phase adapters or short lengths of 0.141", semi-rigid coax cable (Haverhill, EZ-141-75). The 75 Ω reference termination was a long length of EZ-141-75 coax cable terminated at the far end by a QMI 75 Ω termination (p/n 3-E809-790-11).

PULSER and OSCILLISCOPE All measurements were performed using a Hewlett-Packard model 54750 oscilloscope with a 50 GHz bandwidth (9 ps risetime) sampling head. The pulse generator used was a Picosecond Pulse Labs model 4020 TDR pulser. The pulse head used was the positive polarity, transmission head, model 4020RPH-TP, which produced a 2.2 V, 7 ps risetime, 38 ns duration, step pulse. Figure 10 shows the leading edge waveform from this pulser as measured on the HP 50 GHz o'scope.

75 Ω TDT and TDR PERFORMANCE Figures 11-13 demonstrate the typical performance of this equipment for performing TDT and TDR measurements in 75 Ω coax. For the TDT measurements, the time window isolation lines were a pair of PSPL 75 Ω equi-phase adapters, which gave a reflection-free window of 450 ps. Figure 11 shows the leading edge of the TDT test pulse, using the three different Z matching networks of either the 50/75 Ω abrupt junctions, 25 Ω series resistors, or L pads. The measured risetimes were 17 ps, 26 ps, and 37 ps, respectively. The equivalent -3 dB bandwidths were 20 GHz, 13 GHz, and 9 GHz. Figure 12 shows the 75 Ω TDR test pulse as reflected from an open, short, and 75 Ω termination at the end of a 3", 75 Ω semi-rigid coax, which was used as the reference line, DL1. The TDR arrangement used the special 75 Ω TDR tee (see Figure 9). The falltime of the reflected short was 29 ps. The equivalent -3 dB bandwidth is thus 12 GHz. It is possible to effectively decrease the TDT and TDR system risetimes down to 10 ps, using deconvolution and digital filtering. This capability is firmware built into the HP and Agilent oscilloscopes [6] and is called 'normalization'. Figure 13 shows the result of normalizing to 10 ps risetime the TDT and TDR pulses from Figures 11 and 12.

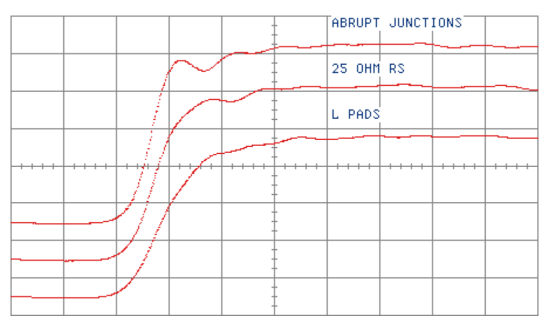

Fig. 11 75 Ω TDT test pulses with various Z matching networks, 100 mV/div and 20 ps/div

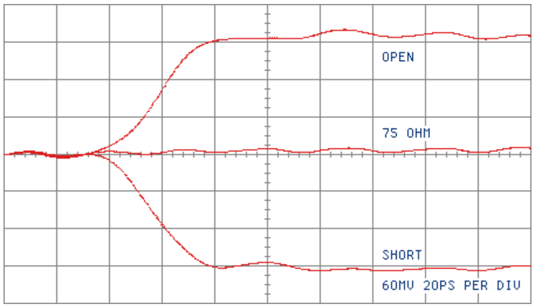

Fig. 12 75 Ω TDR — reflections from open, 75 Ω, and short; 60 mV/div & 20 ps/div

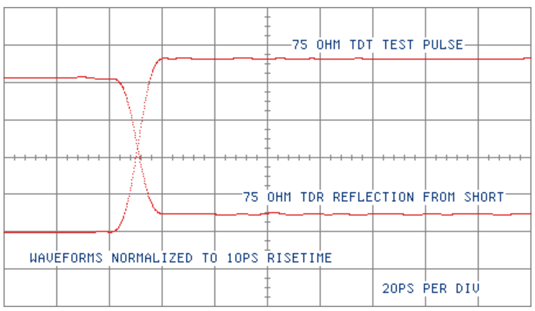

Fig. 13 10 ps normalized TDT and TDR test pulses, 20 ps/div

TDVNA PERFORMANCE For the tests shown here, the test set shown in Figure 4 was used for S_{21}. The time window isolation lines, DL1 and DL2, were 24" lengths of 75 Ω semi-rigid coax. Two equi-phase sex change adapters were used at the DUT insertion plane. Two 25 Ω series matching resistors were used for the Z matching networks. For S_{11}, the special TDR tee shown in Figure 9 was used along with a 24", 75 Ω, semi-rigid coax for the impedance reference line, DL1. The 24" coax lines gave reflection-free time windows of 6 ns.

To operate this equipment as a TDVNA, the reader is referred to PSPL's application note AN-16a [5]. The measured TDT and TDR waveforms are processed by PSPL's MatLab program, ***TDVNA.m*** to compute S_{21} and S_{11} vs. frequency. (*TDVNA.m is available in *.txt format for free from the PSPL website, www.picosecond.com, and it is available upon request from the author at jrandrews@picosecond.com*).

AN-16a explains how to perform a set of 'self-tests' to evaluate the performance of a TDVNA. Test conditions were N = 1024, T_w = 5 ns, 256 averages. Figure 14 shows the dynamic range 'self-test', while Figure 15 shows the 0 dB 'self-test'. These show that this 75Ω TDVNA produces useful measurements out to 26 GHz. The dynamic range is in excess of 80 dB below 1 GHz. At 26 GHz, it is 40 dB for S_{21} and 20 dB for S_{11}.

The hi-bandwidth S_{21} arrangement of Figure 6 produces useful measurements even further out beyond 26 GHz, but is troubled by higher order moding in the SMA connectors.

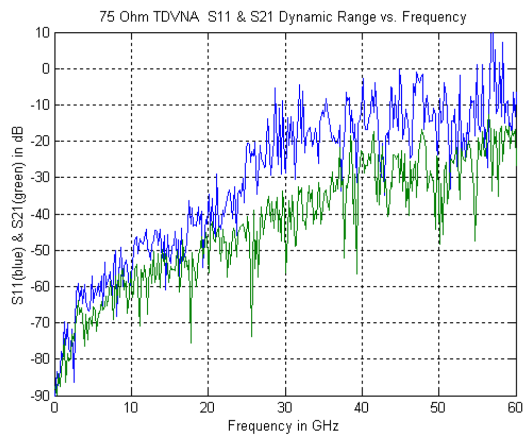

Fig. 14 75Ω TDVNA system self-test for dynamic range; S_{21} (green) and S_{11} (blue)

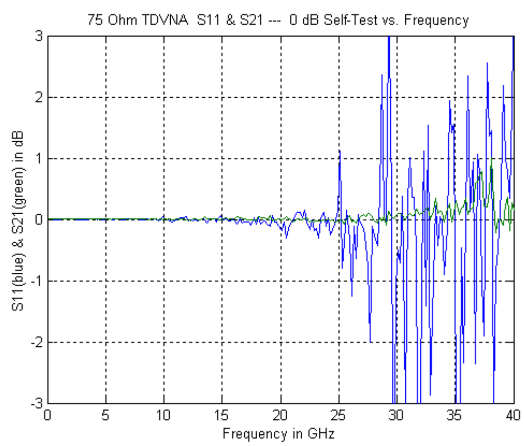

Fig. 15 75Ω TDVNA 0 dB self-test of repeatability and maximum frequency; S_{21} (green) and S_{11} (blue)

75 Ω COMPONENTS To demonstrate the usefulness of this TDVNA, the results of measurements on a few experimental PSPL, 75 Ω, SMA, broadband coaxial components are shown in Figures 16 and 17. The items include a DC Block (X7520), a Bias Tee (X7540), and a 6 dB Tee (X7535). The -3 dB bandwidths of these items were found to be >26 GHz, 25 GHz, and 20 GHz, respectively. For S_{11}, a 25 Ω series, 75 to 50 Ω terminator (X7501) is also shown.

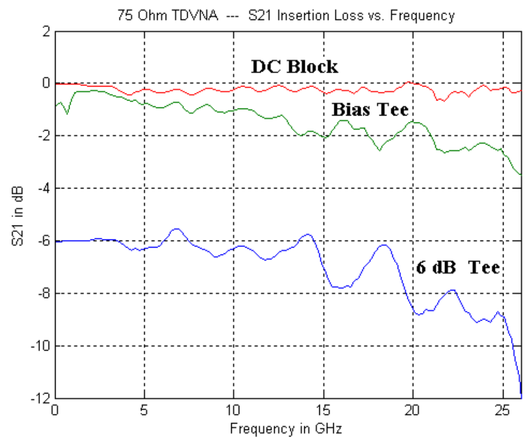

Fig. 16 S_{21} of 75Ω broadband coaxial components; DC Block (red), Bias Tee (green), and 6 dB Tee (blue)

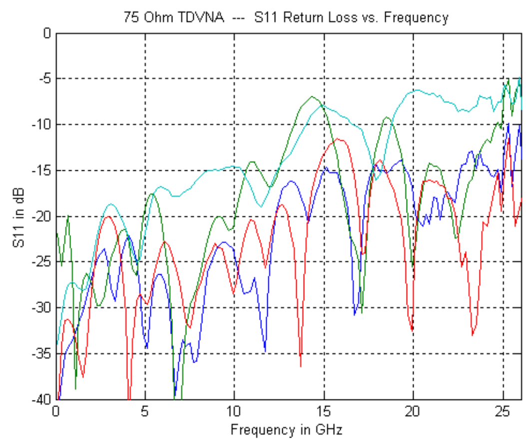

Fig. 17 S_{11} of 75Ω broadband coaxial components; DC Block (red), Bias Tee (green), 6 dB Tee (blue), and 25 Ω Series, 75 to 50 Ω Terminator (cyan).

REFERENCES and FOOT NOTES

[1] 75 Ω VNA information found on company web sites: www.anritsu.com , www.agilent.com , www.advantest.com , and www.rsd.de

[2] Note: QMI was bought out by Tensolite. Tensolite's web site, www.tensolite.com, claims they offer 75 Ω BNC, N, and SMA connectors. A recent inquiry to Tensolite, however, reveals that they now consider 75 Ω SMAs to be special order parts and only available for a very large quantity order.

[3] J. Liu, B. Whitaker, "Characterizing [S] parameters of 75 Ω circuits with 50 Ω lab equipment", RF Design, April, 2004, p. 80

[4] J.R. Andrews, "Time Domain Reflectometry (TDR) and Time Domain Transmission (TDT) Measurement Fundamentals", App. Note AN-15, Picosecond Pulse Labs, Boulder, CO, Nov. 2004, available at www.picosecond.com

[5] J.R.Andrews, "Time Domain Spectrum Analyzer and S-Parameter Vector Network Analyzer", App. Note AN-16a, Picosecond Pulse Labs, Boulder, CO, Nov. 2004, available at www.picosecond.com

[6] "Improving TDR/TDT Measurements Using Normalization", App. Note 1304-5, Agilent, April, 2001, available at www.agilent.com