RAPID APPLICATION NOTE

BUILD YOUR OWN CUSTOM ATTENUATORS (BROADBAND AND PRECISION)

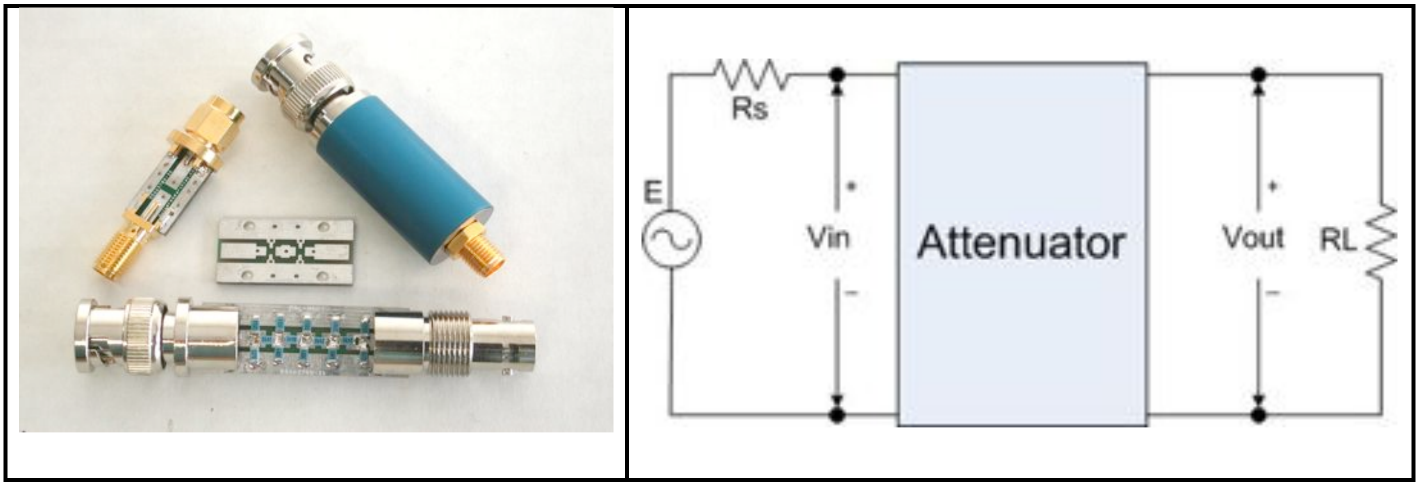

Fig.1

WHY THE NEED?

Attenuators are one of the most frequently used devices in the lab. They are easily misplaced and frequently "borrowed" by colleagues. Although attenuators with standard dB values, such as 3 dB, 6 dB, 10 dB, 20 dB, etc. are readily available commercially, non-standard value devices are not. In non-RF applications, attenuator requirements are also specified in voltage ratios, such as 2X, 4.4X, 15X, 50X, etc., often with tolerance tighter than ±3%, or ± 0.25 dB. Attenuators with non-standard values require custom orders, often carrying setup charges, long lead times, minimum quantities, and higher costs. This App Note illustrates how to build your own custom broadband precision attenuators using the PRL family of MNET, PINET and TNET kits shown above. Subsequent work sheets show the application schematics and component placement diagrams. Using these kits and standard 1% SMT components an attenuator can be built in less than 15 minutes and at a much lower cost compared to custom units from special orders. Ultra precision attenuators can easily be built using off-the-shelf 0.1% resistors.

ATTENUATOR BASICS

An attenuator is a four terminal device with an input port and an output port as shown in Fig. 1. It is normally driven by a voltage source with a source resistance R_S and connected to a load R_L. For a given input voltage V_{IN}, the output is attenuated, or reduced, by a fixed amount. The ratio of V_{IN}/V_O is the attenuation value. A 5X attenuator, for example, attenuates the input voltage V_{IN} by 5, so that $V_{IN}/V_O = 5$.

In RF applications, the attenuation value is usually expressed in dB. By definition,

$$dB = 20\log (V_{IN}/ V_O) \qquad (1)$$

Therefore, if V_{IN}/V_O is 10, then 20log (10) is equal to 20, hence a 20 dB attenuator. If the attenuation in dB is given, then the voltage ratio can be found from (1) as:

$$V_{IN}/V_O = \log^{-1}(dB/20) \qquad (2)$$

For example, a 6 dB attenuator has a voltage ratio of

$V_{IN}/V_O = \log^{-1}(6/20) = 1.9953$, but it is commonly accepted as a 2 to 1 attenuator. In precision amplifier testing, however, a chain of 2X attenuators, instead of 6 dB attenuators, is required. Similarly a 5X attenuator, commonly accepted as a 14 dB attenuator, is actually a 13.979 dB attenuator.

1234 Francisco Street, Torrance, CA 90502
Tel: 310-515-5330 Fax: 310-515-0068
Email: sales@pulseresearchlab.com
www.pulseresearchlab.com

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The Pi and Tee configurations are most commonly used for high-speed applications, and they are shown in Fig.2A and Fig. 2B, respectively. Although the simple two resistor divider attenuators are also widely used, they are not suitable for matched impedance applications and will, therefore, not be discussed here. For the Pi configuration shown in Fig.2A, the values for the shunt resistors R1 and the series resistor R2 are governed by the equations:

$R1 = Z_0(\alpha+1)/(\alpha-1)$ (3)

$R2 = Z_0(\alpha^2-1)/2\alpha$ (4), where

$\alpha = V_{IN}/V_O$ is the attenuation ratio, and Z_0 the characteristic impedance of the attenuator.

For the Tee configuration shown in Fig. 2B, the applicable equations are:

$R1 = 2\alpha\, Z_0/(\alpha^2-1)$ (5)

$R2 = Z_0(\alpha-1)/(\alpha+1)$ (6)

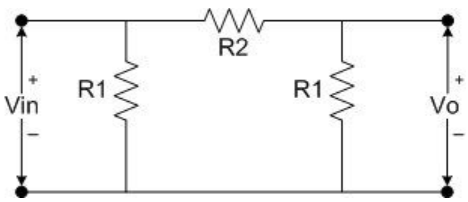


Fig. 2A: The Pi Attenuator

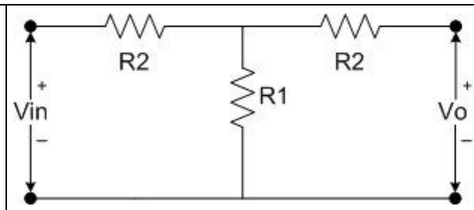


Fig. 2B: The Tee Attenuator

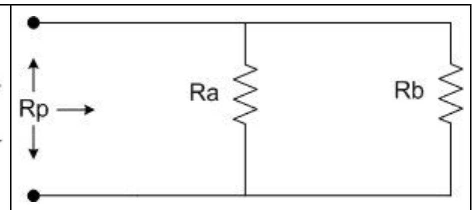


Fig. 3: Parallel Resistors

These attenuators have the unique property that when $R_S = R_L = Z_0$, then the I/O impedances of the attenuator are both equal to Z_0. Therefore they are desirable for matched impedance applications. The Pi configuration has one additional desirable feature in that each shunt leg can be biased at a different voltage. This capability allows the Pi attenuator to be used as a level shifter. For example, a TTL signal can be converted to an NECL signal, and an NECL signal can be converted to a ground-referenced signal for scope viewing, etc. The most common values for Z_0 are 50 Ω (RF/Microwave), 75 Ω (TV), 93 Ω and 600 Ω.

THE DESIGN AND IMPLEMENTATION OF THE 50 Ω Pi ATTENUATORS

Due to time and space constraints, the Tee configuration will not be discussed in this application note.

In the design of attenuators, the calculated resistor values from (3) and (4) are seldom found in the standard 1% resistor table, except for a very few cases. It is, therefore, necessary to use series and/or parallel combinations to obtain the desired values. In general, parallel combinations are simpler and require less board space. The basic design approach is illustrated below.

When an exact value is not available, the next higher standard value is first chosen, and the required parallel component can be calculated. The value of two resistors connected in parallel, as shown in Fig. 3, is given by:

$R_p = (R_a \times R_b)/(R_a + R_b)$ (7)

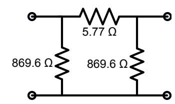
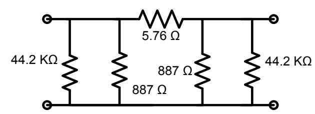
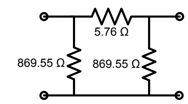
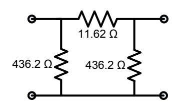
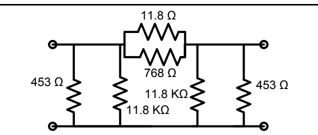
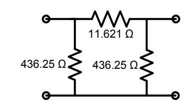
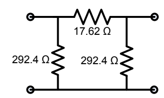
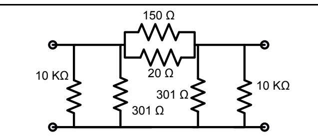
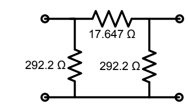
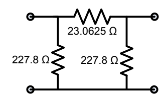
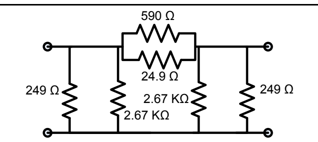
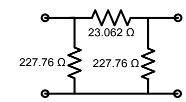
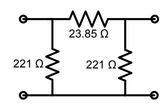
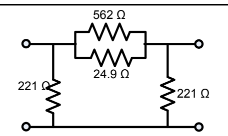
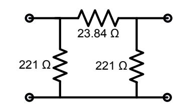
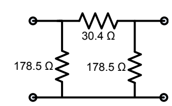
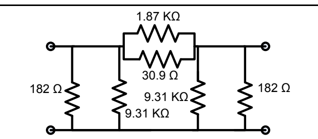
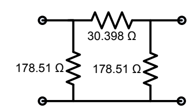
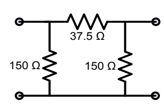
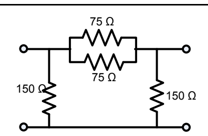
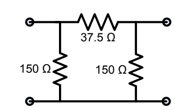
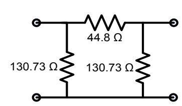
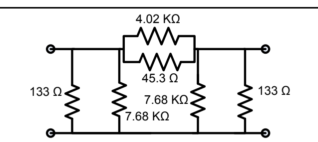
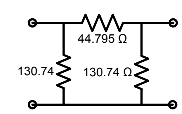
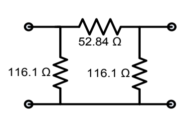
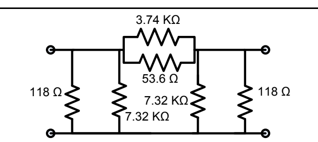
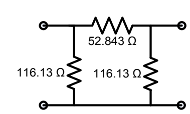
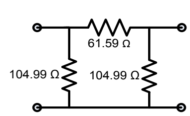
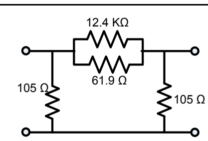
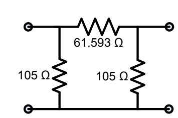
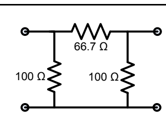
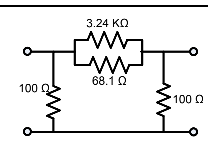
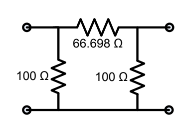
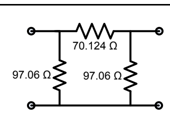
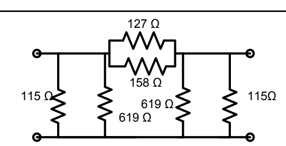
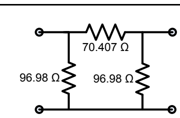
If the required resistor value is calculated to be R_P and the next higher value available from the 1% table is chosen to be R_a, then the parallel resistor R_b required is, from (7),

$R_b = (R_a \times R_p)/(R_a - R_p)$ (8)

Using the next higher value from the 1% table for R_a generally yields the more accurate result, because the choice for R_b is then less critical. If the next higher value from the 1% table is not available, a common practice is to choose an available value for R_a and then calculate the needed value for R_b from (8). If this is still not satisfactory, another parallel resistor may be added. From the PCB footprints of the MNET, PINET and TNET kits, it is shown that each shunt component site (top and bottom) can accommodate up to four components and each series site can accommodate two. If still higher accuracy (or higher power) is required two or more resistors can be soldered and “stacked” on top of each site. Using 0.1% resistors for ultra precision applications is also an option.

Table I contains a collection of attenuators with the most commonly used dB and voltage ratio values. The calculated models, the implementation using parallel resistor combinations and the resultant equivalent models are displayed in separate columns for easy visualization and comparison. Pulse response for a number of attenuation values is also included.

1234 Francisco Street, Torrance, CA 90502
Tel: 310-515-5330 Fax: 310-515-0068
Email: sales@pulseresearchlab.com
www.pulseresearchlab.com

Nominal Values			Implemented	Resultant Values		
dB	V_{IN}/V_O	Schematic		Schematic	V_{IN}/V_O	dB
1	1.122				1.12	0.998
2	1.259				1.26	2.001
3	1.413				1.41	3.005
3.876	1.5625				1.56	3.876
4	1.585				1.58	3.999
5	1.778				1.78	5.000
6.025	2.0				2.00	6.021
7	2.239				2.24	6.999
8	2.512				2.51	8.000
9	2.82				2.82	9.000
9.542	3				3.00	9.545
9.897	3.125				3.13	9.922

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1234 Francisco Street, Torrance, CA 90502
Tel: 310-515-5330 Fax: 310-515-0068
Email: sales@pulseresearchlab.com
www.pulseresearchlab.com

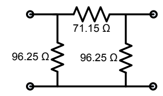
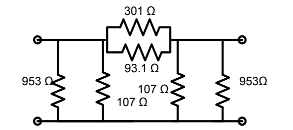
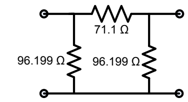
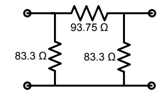
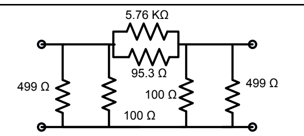
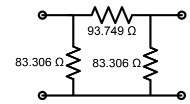
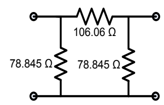
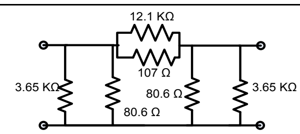
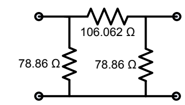
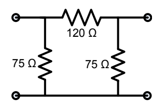
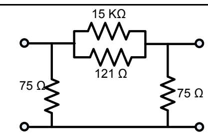
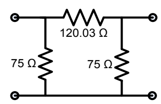
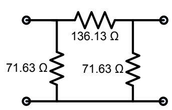
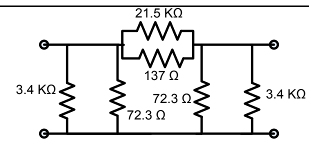
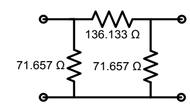
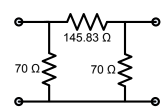
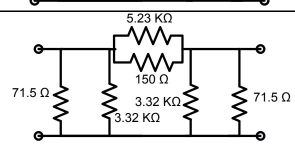
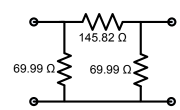
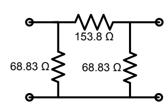
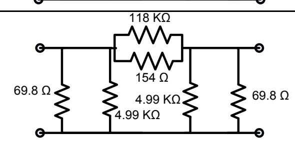
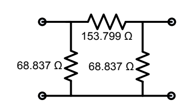
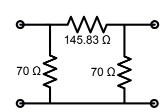
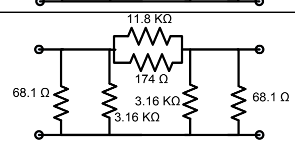
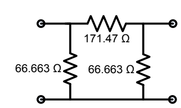
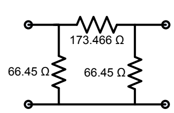
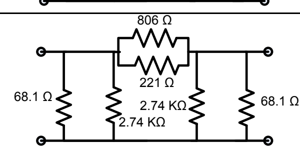
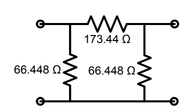
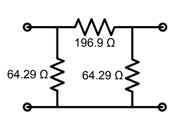
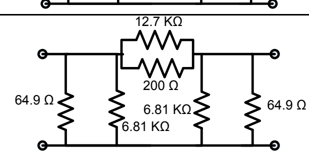
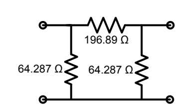
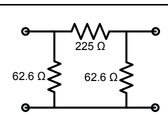
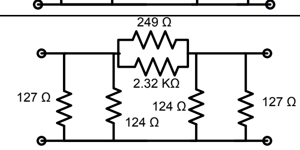
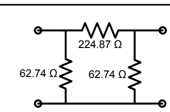
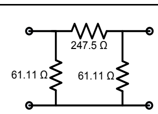
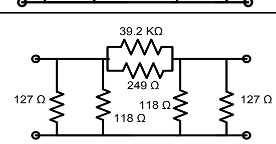
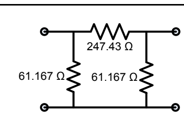
Nominal Values				Resultant Values		
dB	V_{IN}/V_O	Schematic	Implemented	Schematic	V_{IN}/V_O	dB
10	3.1623				3.16	9.997
12.04	4.0				4.00	12.042
13	4.4668				4.47	12.999
13.979	5.0				5.00	13.981
15	5.623				5.62	14.999
15.563	6				6.00	15.563
16	6.3096				6.31	16.001
16.9	7				7.00	16.904
17	7.079				7.08	16.999
18.062	8				8.00	18.062
19.085	9				9.08	19.163
20	10.0				9.99	19.995

Table I. Schematic Diagrams of Pi Attenuators

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Email: sales@pulseresearchlab.com
www.pulseresearchlab.com

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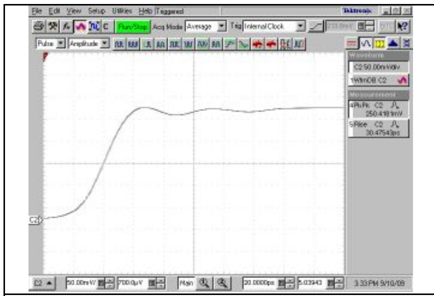
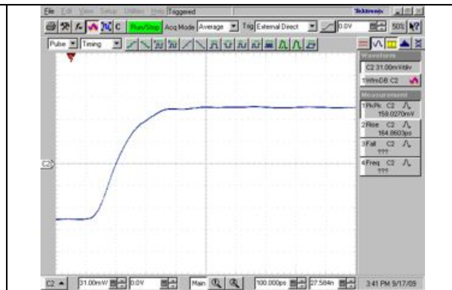
Pulse Response for SMA I/O Attenuators driven by Tektronix 80E04, t_r = 30 ps, and PRL-470B Outputs, t_r = 660 ps

When driven by an extremely fast rise time signal, such as the Tektronix 80E04 TDR pulse generator, the parasitic capacitance across series resistor R2 (see Fig. 2A) produces output overshoots with increasing attenuation ratio, as shown in Fig. 7, Fig. 9 and Fig. 11. The overshoots can be significantly reduced using a two-stage design, as in Fig. 10 and Fig. 12, or a slower rise time signal, say 660 ps as in Fig.13,

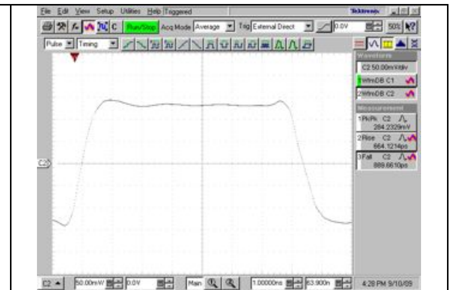
When dealing with signals in the 200 ps rise time range, these attenuators show very little overshoot (see BNC I/O attenuators on next page). In general, for attenuation higher than 20 dB and t_r <200 ps, a two stage design produces less overshoot. Fig. 13 shows a 40 dB, 4-stage 10 dB design, with little overshoot for a 660 ps rise time step input. Single stage attenuators in the 3 dB-12 dB range, as shown in Figs. 5-8, using the SMA PINET kit, can achieve bandwidth better than 6 GHz, where BW(GHz) x t_r (ps) = 350.



Tektronix 80E04TDR Output



PRL-430AN Output



PRL-470B Output

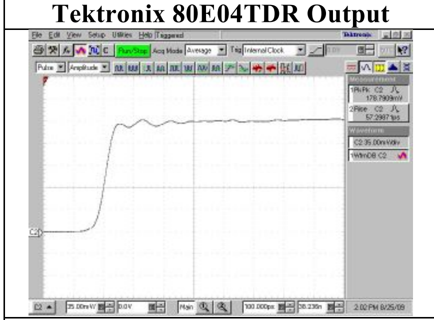


Fig. 5: 3 dB PINET Single Stage

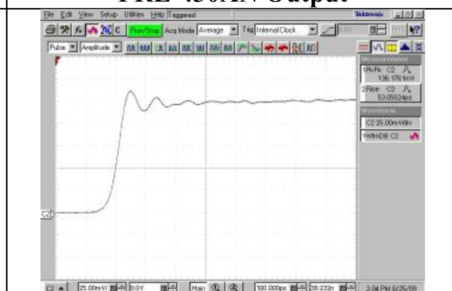


Fig. 6: 6 dB PINET Single stage

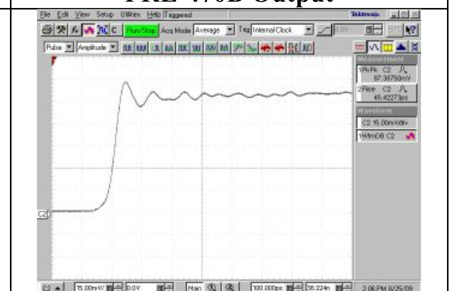


Fig. 7: 10 dB PINET Single Stage

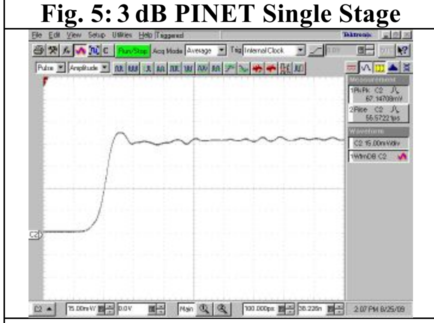


Fig. 8: 12 dB PINET Single Stage

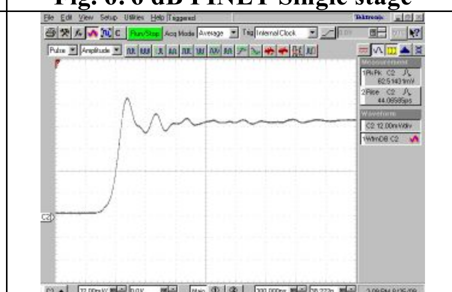


Fig. 9: 14 dB PINET Single Stage

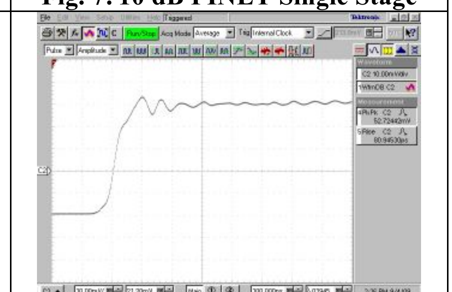


Fig. 10: 14 dB TNET, 10 dB + 4 dB

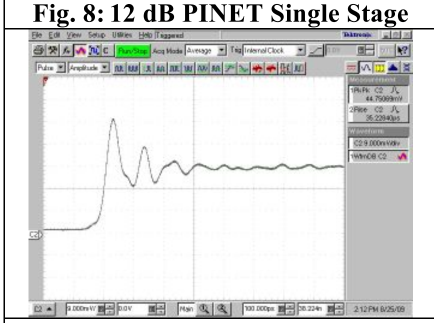


Fig. 11: 20 dB PINET Single Stage

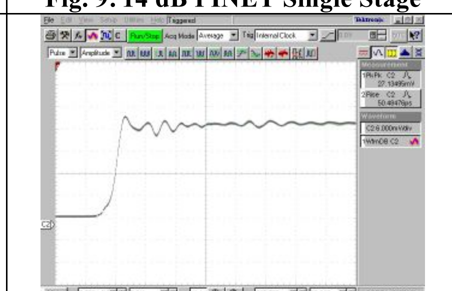


Fig. 12: 20 dB TNET, 10 dB + 10 dB

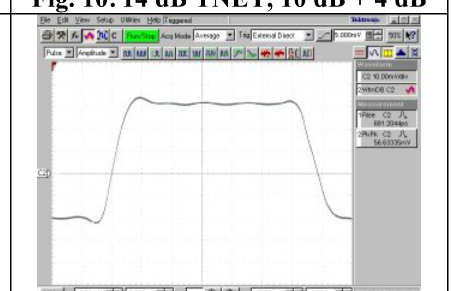


Fig. 13: 40 dB MNET, 4 x 10 dB

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Pulse Response for BNC I/O Attenuators driven by PRL-430AN output, t_r=165 ps

In general, BNC I/O devices have lower bandwidth, because BNC connectors have larger physical dimensions compared to those in SMA connectors. Furthermore, BNC to SMA adapters are generally needed for the I/O connections because the high speed signal source and the measurement equipment usually have SMA I/O connectors.

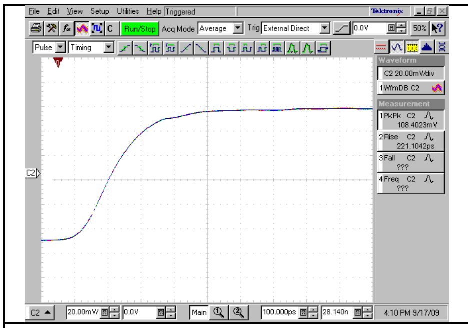

Fig. 14: 3 dB PINETB Single Stage

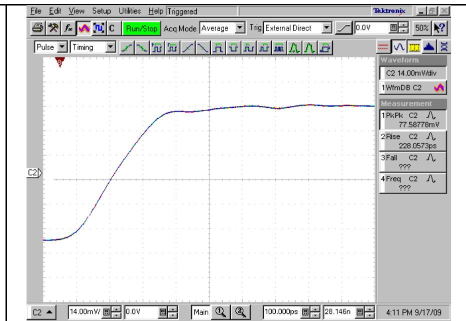

Fig. 15: 6 dB PINETB Single stage

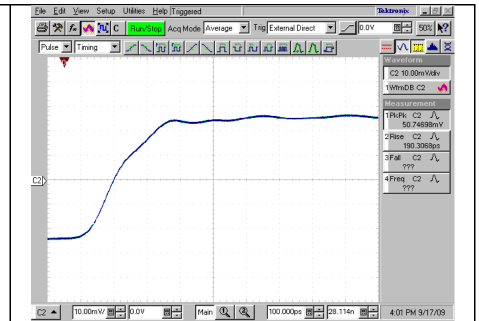

Fig. 16: 10 dB PINETB Single Stage

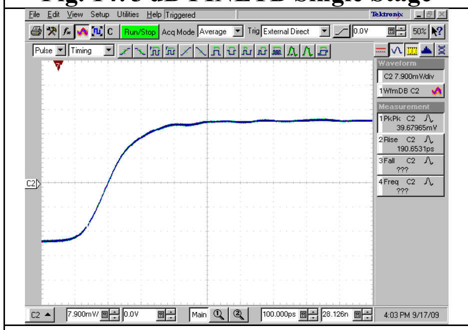

Fig. 17: 12 dB PINETB Single Stage

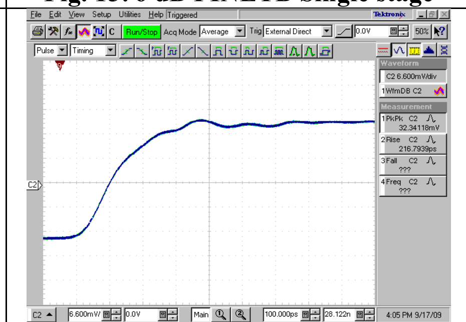

Fig. 18: 14 dB PINETB Single Stage

Fig. 19: 20 dB PINETB Single Stage

Table II shows a number of multi-stage attenuators built using either the TNET or MNET PCB configuration. In constructing the multi-stage attenuator, it will be helpful first to decide which sections are to be combined. Next, the exact values of the parallel combination of the two adjacent shunt legs of the two sections to be combined should then be calculated. The required parallel combination is then found using equation (8). For example, cascading two 10 dB sections yields a common shunt leg of 48.125 Ω (96.25 Ω/2 from Table I). This value can be obtained by using either 82.5 Ω in parallel with 115 Ω (48.04 Ω) or 93.1 Ω in parallel with 100 Ω (48.21 Ω).

It should be noted that attenuators with lower attenuation values have higher resistance values in the shunt legs. Therefore it is desirable in most cases to use the lower value attenuator sections at both ends in order to handle higher power dissipation.

Tables III and IV show examples of assembled SMA and BNC I/O attenuators, showing how the series and parallel combinations of resistors are installed on both sides of the PCB. **When multi-layer ceramic capacitors are used, as in AC coupled attenuators and filters, they should be installed last in order to avoid repeated thermal cycling from the soldering iron.**

Instead of discrete resistors, commercially available ceramic attenuator chips can also be used with these PINET, TNET and MNET kits, but at a higher cost and often limited to standard dB values only.

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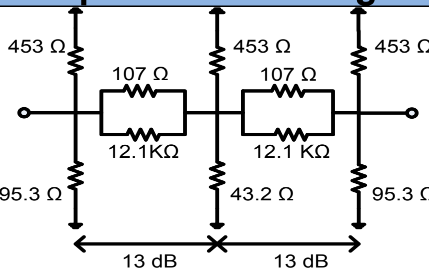
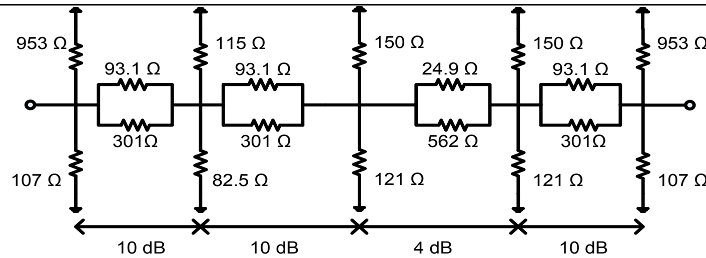
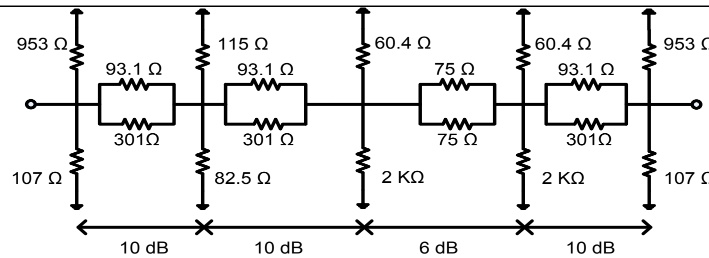
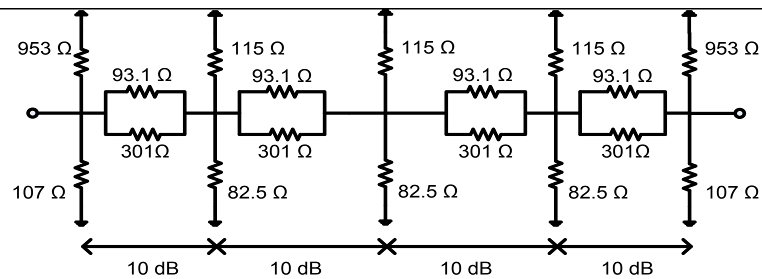
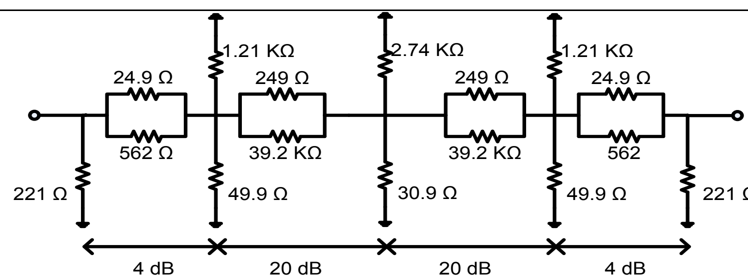
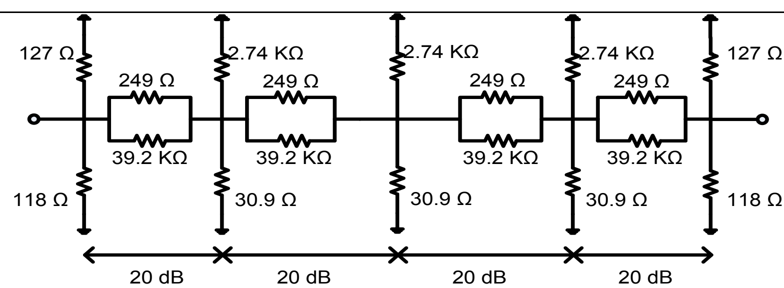
dB	V_{IN}/V_O	Implemented Design
26	20	
34	50.1	
36	63	
40	100	
48	251	
80	10,000	

Table II: Multi-Stage Pi Attenuator Design

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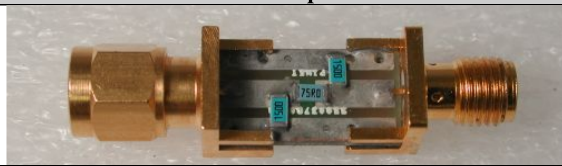
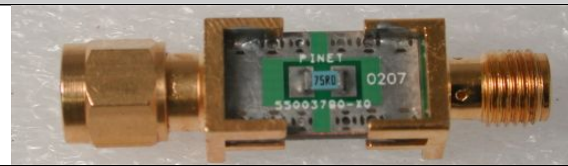
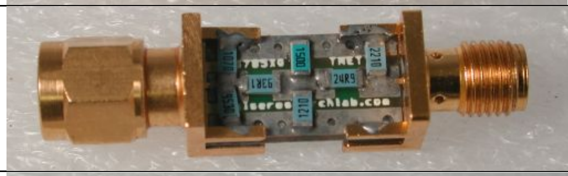
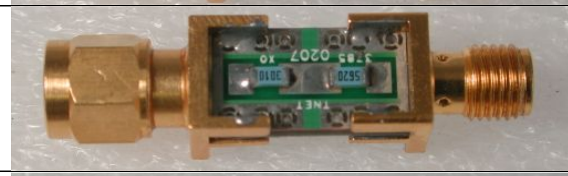
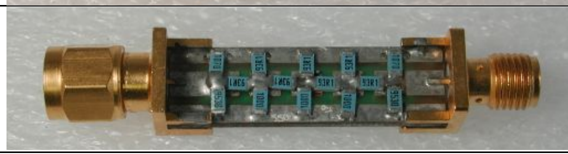
Application	Top	Bottom
PINET SMA **6 dB**		
TNET SMA **10 dB** **(4 dB + 6 dB)**		
MNET SMA **40 dB** **(4 x 10 dB)**		

Table III: Examples of assembled SMA I/O PINET, TNET and MNET attenuators

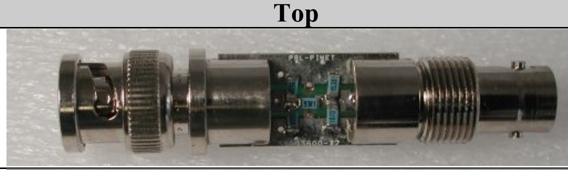
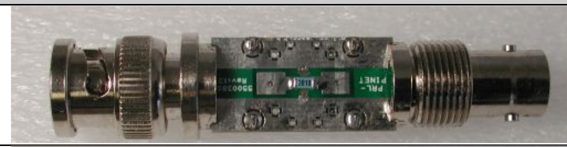
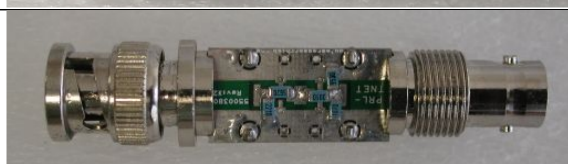
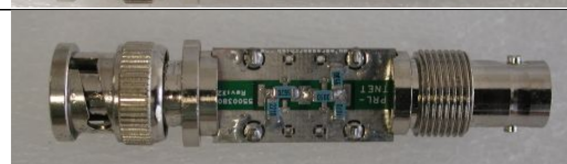
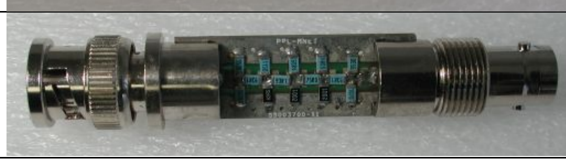
Application	Top	Bottom
PINET BNC **(10 dB)**		
TNET BNC **14 dB** **(4 dB + 10 dB)**		
MNET BNC **40 dB** **(4 x 10 dB)**		

Table IV: Examples of assembled BNC I/O PINET, TNET and MNET attenuators.

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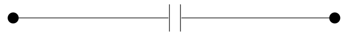
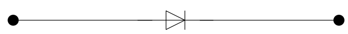
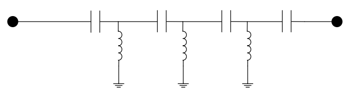
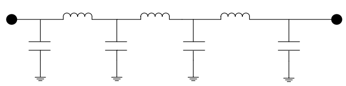
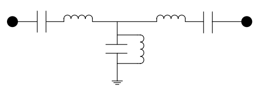
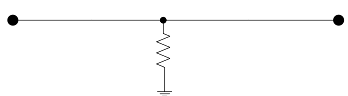
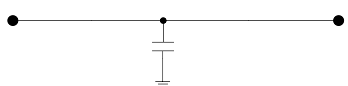
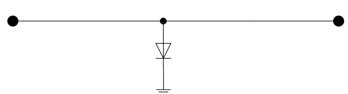
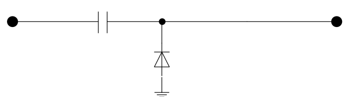
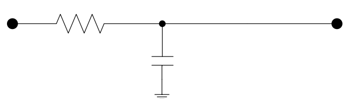
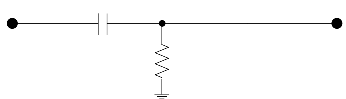
Although this App Note is devoted to attenuator design and assembly, the PINET, TNET and MNET kits are multi-purpose signal conditioning kits suitable for many other applications. Shown below are examples of a number of additional applications used by PRL customers.

Description	Circuit Configuration	Kit Type	Applications
Series Resistor		PINET	Current Source/In-line Probe*
Series Capacitor		PINET	DC Block
Series Inductor		PINET	AC Block/In-Line LF Signal Injection*
Series Diode		PINET	Rectification
Series/Parallel LCs		MNET/ TNET	Filters, High-Pass
Series/Parallel LCs		MNET	Filter, Low-Pass
Series/Parallel LCs		MNET	Filter, Band-Pass
Shunt Resistor		PINET	Feed through Termination
Shunt Capacitor		PINET	Feed through Decoupling
Shunt Diodes		PINET	Line Termination/Signal Clipping
Series C/Shunt Diode		PINET	DC Restoration
Series R/Shunt Capacitor		PINET	Rise Time Integration
Series C/Shunt R		PINET	AC Termination for ECL

PULSE RESEARCH•LAB
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1234 Francisco Street, Torrance, CA 90502
Tel: 310-515-5330 Fax: 310-515-0068
Email: sales@pulseresearchlab.com
www.pulseresearchlab.com