CHAPTER - 3

PIN DIODE RF ATTENUATORS

NOTES

PIN DIODE VARIABLE ATTENUATORS

INTRODUCTION

An Attenuator [1] is a network designed to introduce a known amount of loss when functioning between two resistive impedances: $Z_{in} = Z_1$ and $Z_{out} = Z_2$. Z_1 and Z_2 are defined to be terminal impedances to which the attenuator is connected.

MATCHED ATTENUATORS

If the input of the attenuator is matched to Z_1 and the output to Z_2, the circuit is a matched attenuator and the loss is entirely due to Transmission Loss and not to Reflection Loss. The source (input) and the load (output) may be reversed since resistive networks are reciprocal. If $Z_1 = Z_2$, the resulting matched attenuator design is said to be symmetrical, or to exhibit network symmetry. Matched Attenuator Networks may be either balanced or un-balanced (with respect to ground), depending on the exact nature of the source impedance and the load impedance.

Examples of the principle attenuator configurations and their balanced, unbalanced, and symmetrical forms, appear in figures 3.1, 3.2, and 3.3. These will be referred to later in the chapter as PIN diode attenuator designs are obtained.

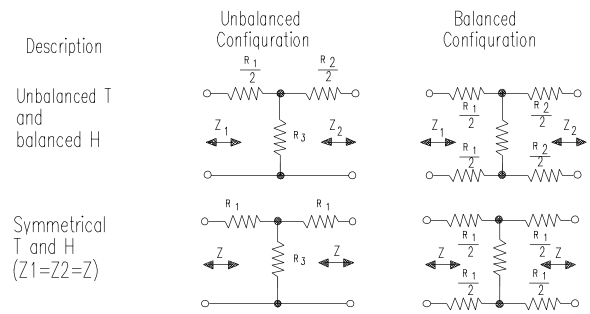


Figure 3.1 Unbalanced T, Balanced H, and Symmetrical T and H

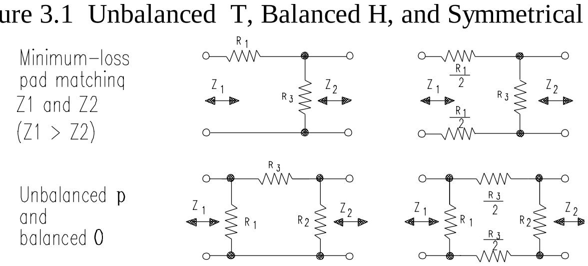


Figure 3.2 Unbalanced ✍, Balanced O, and Symmetrical ✍ and O

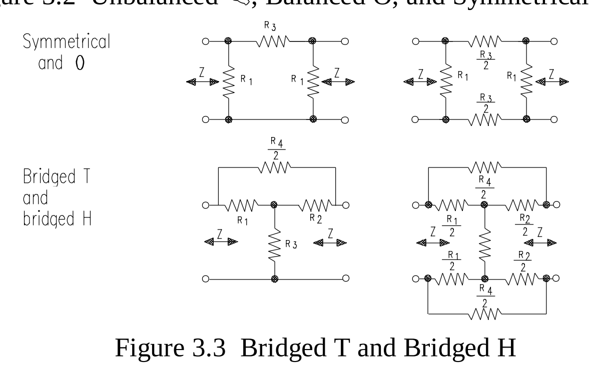


Figure 3.3 Bridged T and Bridged H

Design equations for the unbalanced - symmetrical cases are given below, because of their usefulness in later sections. Symbols used in these design equations have the following meaning:

Z_1 and Z_2 are the terminal Impedances (resistive) to which the attenuator is matched.

$Z = Z_1 = Z_2$ (Symmetrical Case)

N is the ratio of the power absorbed by the attenuator from the source, to the power delivered to the load.

K is the ratio of the attenuator input current, to the output current into the load.

$K = (N)^{1/2}$ for the symmetrical case.

A = attenuation (dB) = 10 log(N) or 20 log (K)

SYMMETRICAL T

$R_1 = Z\ [1 - 2/(K+1)]$ $\qquad$ $R_3 = 2Z\ /\ [K - 1/K]$

SYMMETRICAL π

$R_1 = Z\ [1 + 2/(K-1)]$ $\qquad$ $R_3 = Z\ [K - 1/K]\ /\ 2$

BRIDGED T

$R_1 = R_2 = Z$ $\qquad$ $R_3 = Z\ /\ (K-1)$ $\qquad$ $R_4 = Z\ [K - 1]$

Design equations for the other cases are given in Reference [1].

REFLECTIVE ATTENUATORS:

If the matched condition is not required, simpler networks can be designed as reflective attenuators. These may consist of a simple variable series or a shunt resistive element, that attenuates by exhibiting the necessary mismatch or reflection on the transmission line. In these instances, the attenuation loss is almost entirely due to Reflection Loss although some small amount of Transmissiom Loss may occur. Examples of Reflective Attenuators occur later in this chapter.

PIN ATTENUATOR DIODES

All the basic attenuator configurations can be realized by inserting Current Controlled Resistors (PIN Diodes) in the place of the variable resistances in Figures 3.1, 3.2, and 3.3. In the case of the Symmetrical Microwave Bridged T Attenuator, $R_1 = R_2 = Z_o = 50$ Ohms, and R_3 and R_4 are the variable resistors, replaced by PIN diodes.

Variable attenuators, with PIN diodes as the variable resistance elements, use the forward biased resistance characteristic (Figure 3.4) of the device over nearly its complete forward bias range. The extremely low current range is to be avoided because (see Appendix A) at low current values, the PIN diode's stored charge ($Q_s = I_f \times \tau$) is small and the diode may rectify, causing the attenuator's signal distortion to increase.

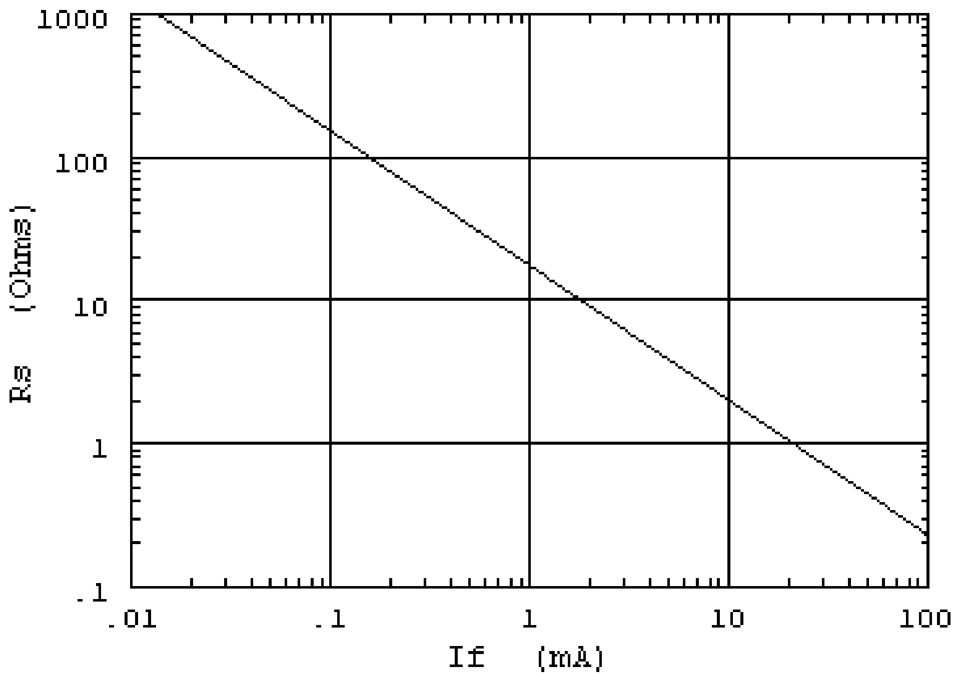


Figure 3.4 Typical Forward Biased Resistance vs Current, UM9552

PIN DIODE ATTENUATOR CIRCUIT APPLICATIONS

PIN diode attenuator circuits are used in automatic gain control (AGC) circuits and power leveling applications. They are also used in high power modulator circuits, which is the subject of Chapter 4. A typical AGC configuration is shown in Figure 3.5.

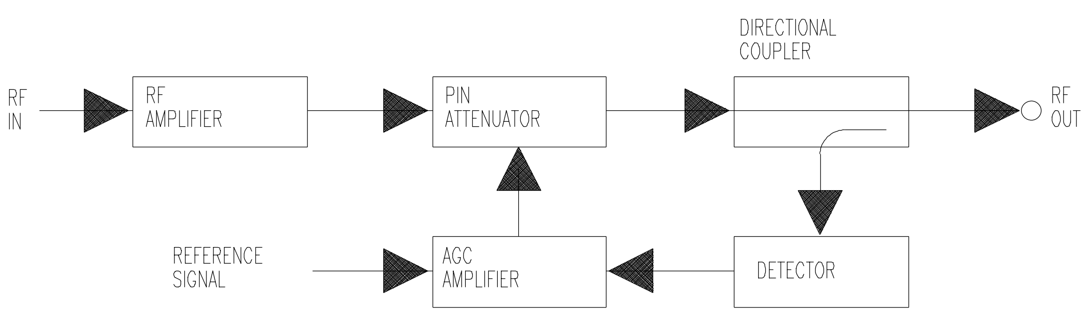


Figure 3.5 RF AGC / Leveler Circuit

The PIN diode attenuator may be a simple reflective attenuator, such as a series or shunt diode mounted across the transmission line. Some AGC attenuators are more complex networks that maintain impedance match to the input power and load as the attenuation is varied across its dynamic range. Other methods are used to implement the

AGC function, such as varying the gain of an RF transistor stage. The PIN diode AGC circuit results in lower frequency pulling and lower signal distortion.

Microsemi Corp. provides a number of PIN diodes designed for attenuator applications, such as the UM2100, UM7301B, UM4301B, UM9552, and the UM9301, which can provide high dynamic range and low signal distortion at frequencies from 100 KHz to 2 GHz. These devices are available in packages designed for standard PC board construction or in packages suitable for Surface Mount Technology.

MICROWAVE MATCHED ATTENUATOR CIRCUITS

The design equations for various matched attenuator circuits configurations have already been given. We now look at the practical implementation of these designs for microwave attenuators.

QUADRATURE HYBRID ATTENUATORS

Quadrature hybrids are commercially available from 10 MHz to 2 GHz, with inherent bandwidths up to a decade. Figures 3.6 and 3.7 are typical quadrature hybrid circuits with series or shunt configured PIN diodes. For 50 Ohm Quadrature Hybrids and branch lines, the attenuation as a function of diode resistance is shown in Figure 3.8.

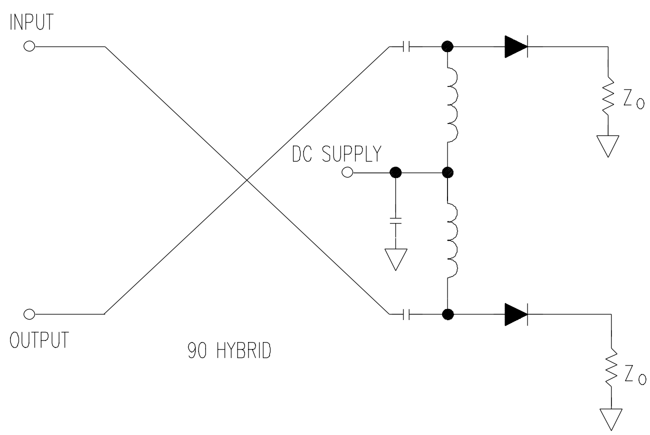


Figure 3.6 Quadrature Hybrid Matched Attenuator (Series Mounted PIN Diodes)

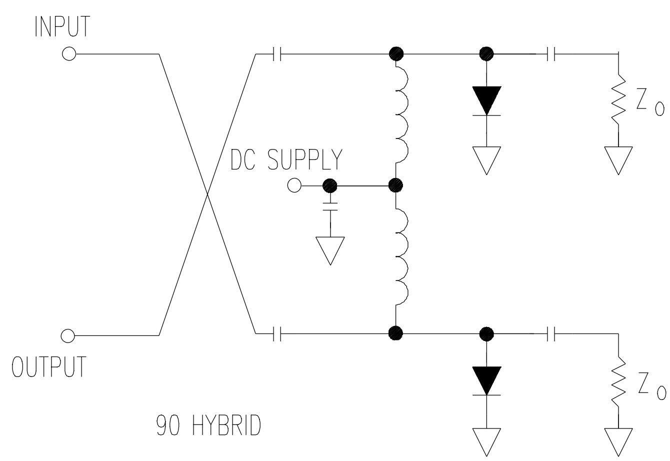


Figure 3.7 Quadrature Hybrid Matched Attenuator (Shunt Mounted PIN Diodes)

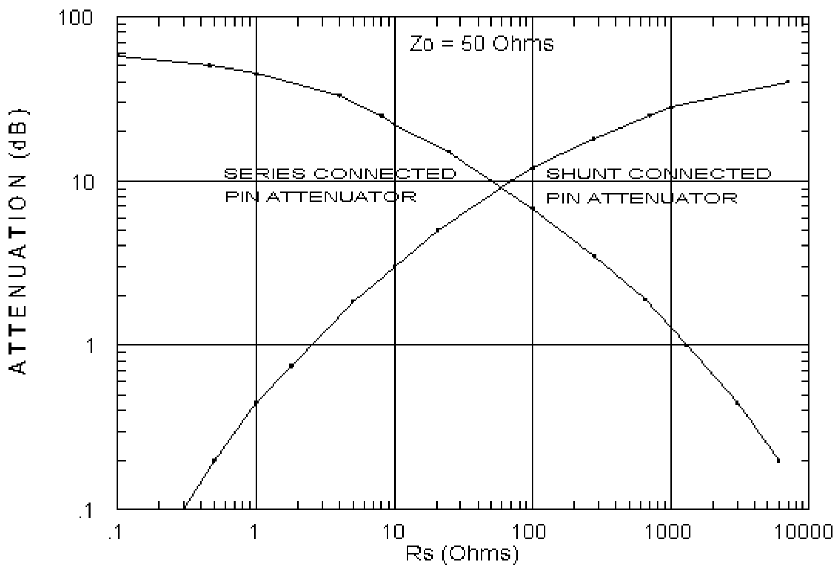


Figure 3.8 Attenuation of Quadrature Hybrid Attenuators

The following equations summarize the performance of these quadrature hybrid attenuators:

Series Connected PIN Diodes	Shunt Connected PIN Diodes
Attenuation = 20 log $\{1 / (1 + 2Z_o / R_s) \}$, dB	Attenuation = 20 log $\{1 / (1 + 2R_s / Z_o)]\}$, dB

The quadrature hybrid configuration can control twice the power of the simple series or shunt diode attenuators because the incident power is divided into paths by the hybrid. Reference [1] shows that the maximum power dissipated in each diode is only 25 % of the total incident power and this occurs at the 6 dB value of attenuation. However, the branch load resistors must be able to dissipate 50% of the total incident power at maximum attenuation. The purpose of the branch load resistors is to make the attenuator less sensitive to differences between individual diodes and to increase the attenuator power handling by 3 dB.

Both types of hybrid attenuators exhibit good dynamic range. The series configured hybrid attenuator is preferable for attenuation levels greater than 6 dB, whereas the shunt configured hybrid attenuator is preferable for attenuation ranges below 6 dB.

QUARTER-WAVE ATTENUATORS

Matched attenuators can also be configured using quarter-wavelength circuit techniques, using either lumped or distributed circuit elements. A quarter-wavelength matched attenuator with series connected diodes is shown in Figure 3.9 and with shunt connected diodes in Figure 3.10. Performance equations are given below the circuit diagrams, and the attenuation vs R_s characteristics are plotted in Figure 3.11 for a transmission system with a characteristic impedance of 50 Ohms.

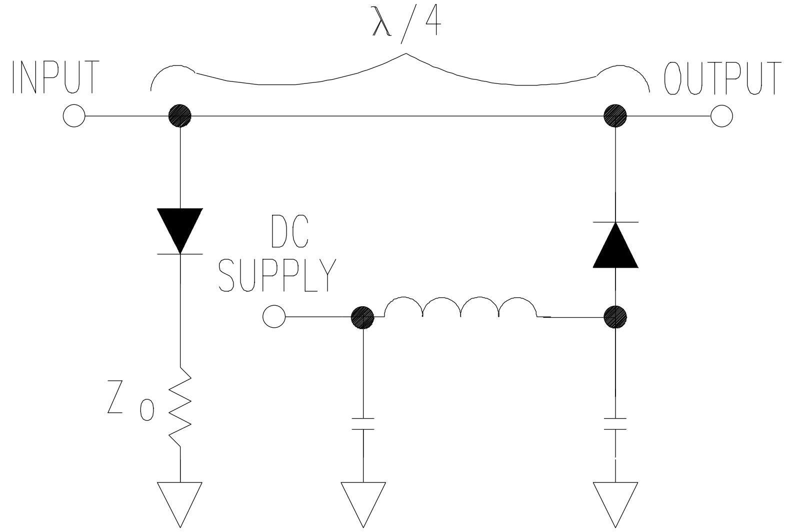


Figure 3.9 Quarter-Wave Matched Attenuator (Series Connected Diodes)

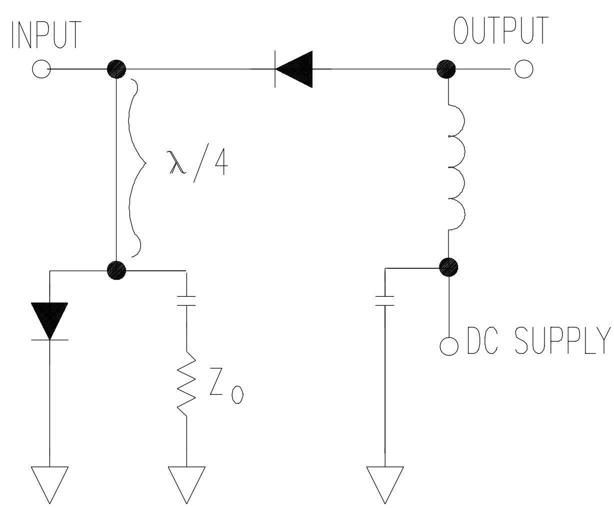


Figure 3.10 Quarter-Wave Matched Attenuator (Shunt Connected Diodes)

The following equations summarize the performance of these Quarter-Wave Attenuators:

Quarter-Wave Attenuator performance equations:

(Series Connected Diodes) Shunt Connected Diodes

Attenuation = 20 log (1 + Z_o / R_s), dB Attenuation = 20 log (1 + R_s / Z_o), dB

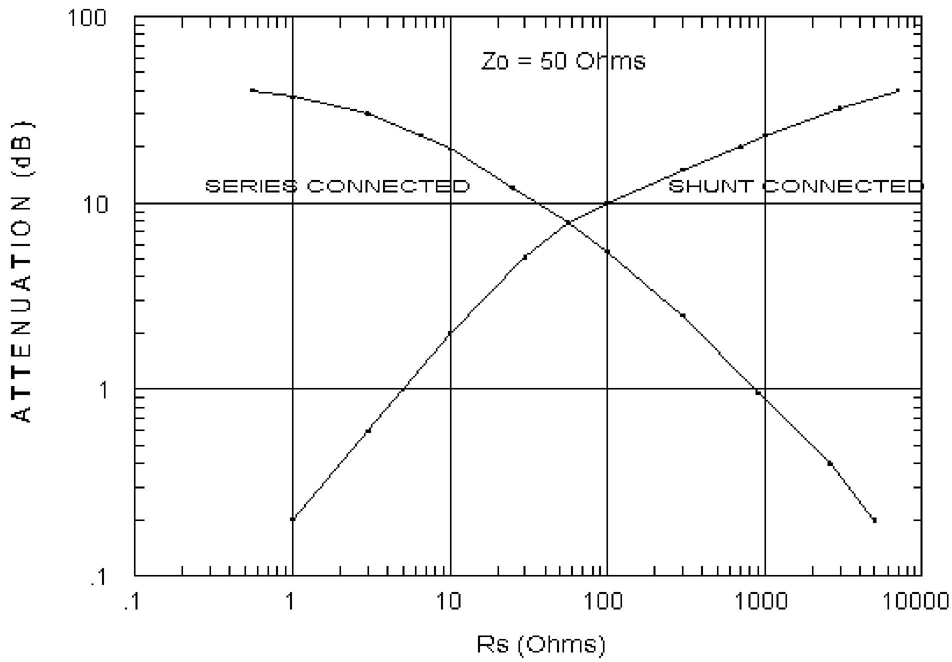


Figure 3.11 Attenuation of Quarter-Wave Attenuators

Quarter-Wavelength Attenuators are matched when both diodes are biased to the same resistance. This usually occurs since both diodes are connected in series to the d-c current supply, and so the same forward bias current flows through both diodes. The series connected configuration is preferable for higher values of attenuation and the shunt connected configuration is preferred for lower attenuation levels.

BRIDGED TEE & p ATTENUATORS

The fundamental attenuator design configurations, together with the design equations, were described in the initial section of this chapter. The most appropriate for matched broadband attenuator applications, especially those in the RF bands from HF Band through UHF Band, are the Bridged TEE & the π circuits. The upper cutoff frequency of these circuits often depends on the bias circuit isolation that can be obtained with practical circuit components. Feed through leakage at higher values of RF may also affect the highest value of attenuation that a particular design can achieve. The Bridged TEE circuit is shown in Figure 3.12 and the π circuit, in Figure 3.14.

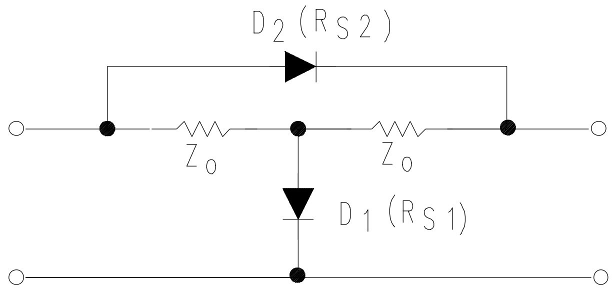


Figure 3.12 Bridged TEE Attenuator Circuit

The attenuation for the Bridged TEE circuit is obtained from the following equations[1,2]:

Attenuation = 20 log (1 + Z_O / R_{S1}), dB, and $Z_0^2 = R_{S1} \times R_{S2}$

These equations can be solved to show that the attenuation depends on the ratio of R_{S2} to R_{S1}, whereas the attenuator match conditions (Z_O) depends on the product of R_{S1} and R_{S2}.

The relationship between the forward biased resistance ($R_{S1,2}$) of the PIN diode and the forward bias current is also needed to determine the sets of values of diode driver currents that are needed to maintain impedance match for each value of attenuation desired. Figure 3.4 shows R_S vs I_f for the UM9552. The design procedure for the Bridged TEE circuit using UM9552's is available [2]. The attenuation curves for the Bridged TEE Attenuator are shown in Figure 3.13.

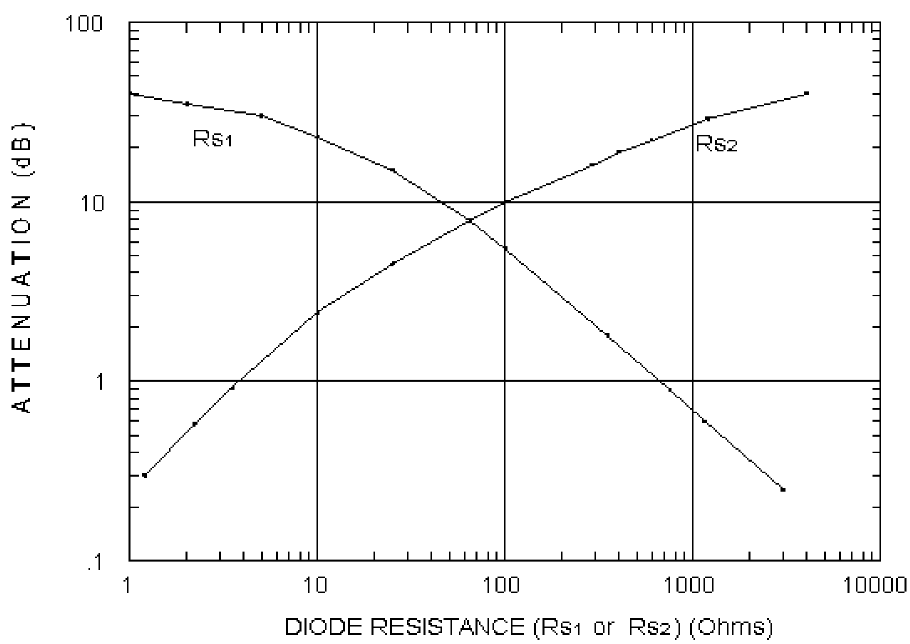


Figure 3.13 Attenuation of Bridged TEE Attenuators

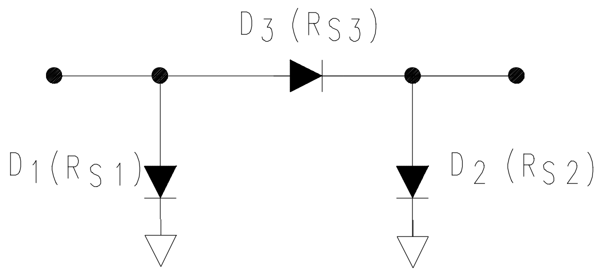


Figure 3.14 π Attenuator Circuit

The π attenuator circuit also has a set of equations that define the dependence of the attenuation state on the values of the three diode resistances[1].

$$\text{Attenuation} = 20 \log \{(R_{S1} + Z_0) / (R_{S1} - Z_0)\} \text{ dB}$$

where: $R_{S1} = R_{S2}$ (Ohms) and $R_{S3} = 2 R_{S1} Z_0^{\,2} / (R_{S1}^{\,2} - Z_0^{\,2})$ (Ohms)

The π attenuator equations can be solved to obtain the performance curves shown in Figure 3.15. We see that the minimum value of Rs_1 and Rs_2 is 50 Ohms. $Rs_1 = Rs_2$ simply means that the attenuator is symmetrical, ie, the power source and load impedances are the same and equal to 50 Ohms.

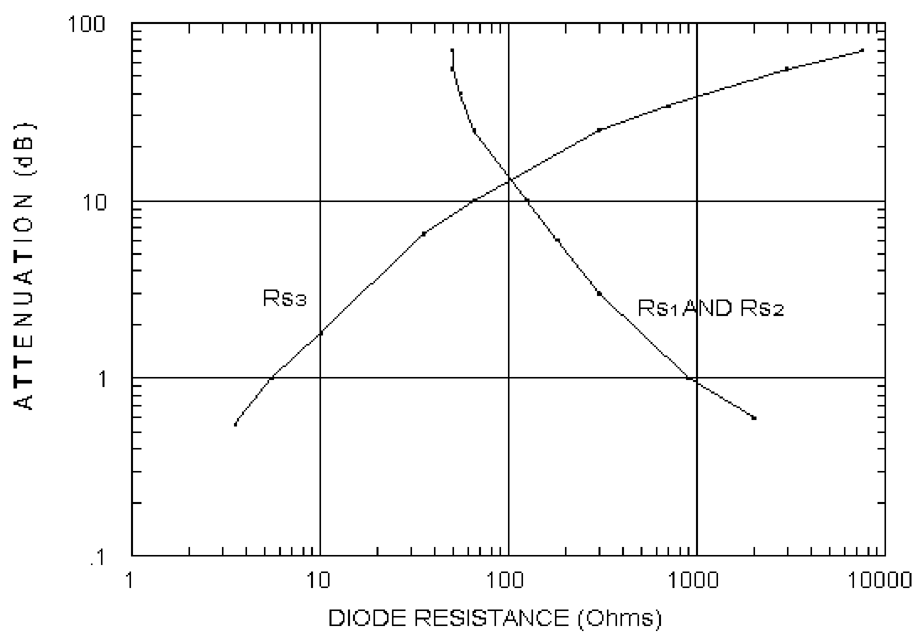
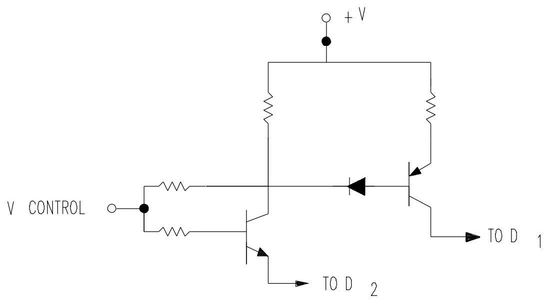


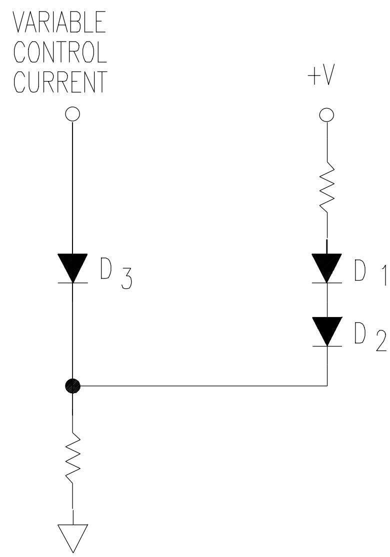
Figure 3.15 Attenuation of ✌ attenuators

In both the Bridged TEE and the π Attenuator circuits, the PIN diodes are biased at two different values of resistance simultaneously and these must track so that the attenuator remains matched as different values over the dynamic range of the attenuator. Suggested voltage controlled bias circuit are shown in Figure 3.16 for the Bridged TEE attenuator and in Figure 3.17, for the π attenuator.



Bridged TEE Attenuator Bias Circuit

Figure 3.16



π Attenuator Bias Circuit

Figure 3.17

REFLECTIVE ATTENUATORS

In contrast to Matched PIN Diode Attenuator Circuits, Reflective Attenuators can be designed using single series or shunt PIN diode switch configurations (Chapter 2). In this application, the PIN diodes are only biased in the forward direction, utilizing the current control resistance characteristic of the PIN diode. Referring to Figure 3.4, the forward bias current may be continuously varied from high resistance to low resistance values. Attenuation is obtained by introducing impedance mis-match in the transmission line. This causes some of the power to be reflected back toward the power source. This is undesirable in many systems applications because it may cause frequency pulling and power instability. However , Reflective Attenuators are inexpensive to design and build. The attenuation values obtained using these reflective attenuators can be calculated from the following equations:

Series Connected PIN Diode Attenuator: Attenuation = $20 \log(1 + R_S / 2 Z_0)$, dB

Shunt Connected PIN Diode Attenuator: Attenuation = $20 \log(1 + Z_0 / 2 R_S)$, dB

These equations are plotted in Figure 3.18 for series and shunt attenuators with $Z_0 = 50$ Ohms. These equations and curves assume that the PIN Diode Impedance is purely resistive. Above the UHF Band, Capacitive and Inductive Reactances of the packaged PIN diode chip must be taken into account.

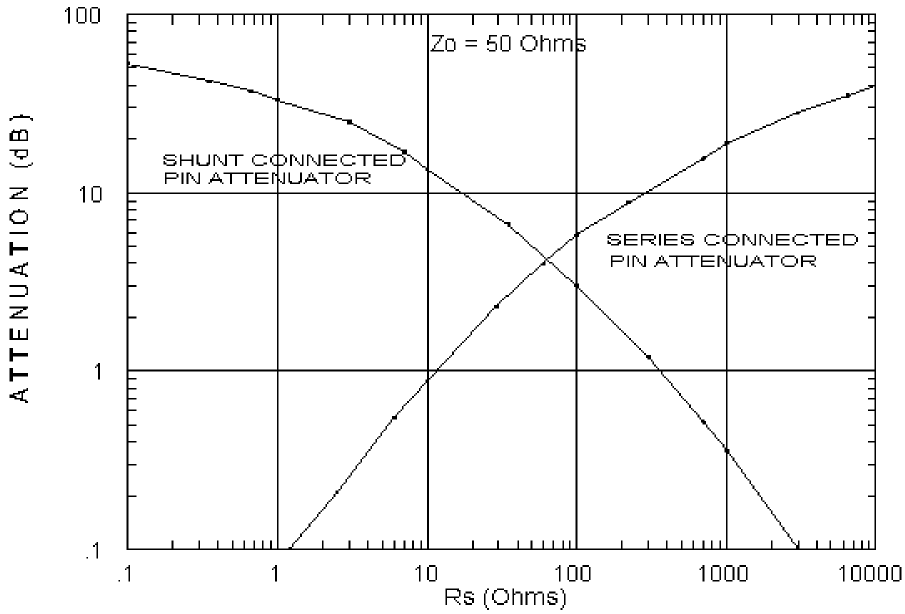


Figure 3.18 Attenuation Of Reflective Attenuators

DISTORTION IN PIN DIODE ATTENUATORS

Distortion is a particularly critical parameter in PIN diode attenuator circuits and is defined, described, and discussed in Appendix E and reference [3].

APPLICATION	**RECOMMENDED PIN DIODE TYPES**
High Power >1 W	UM2100, UM4000, UM4300, UM9552
AGC	UM4000, UM6000, UM7000
Low Frequency	UM2100, UM4000, UM4300, UM9552
Ultra Low Frequency	UM2100, UM9552