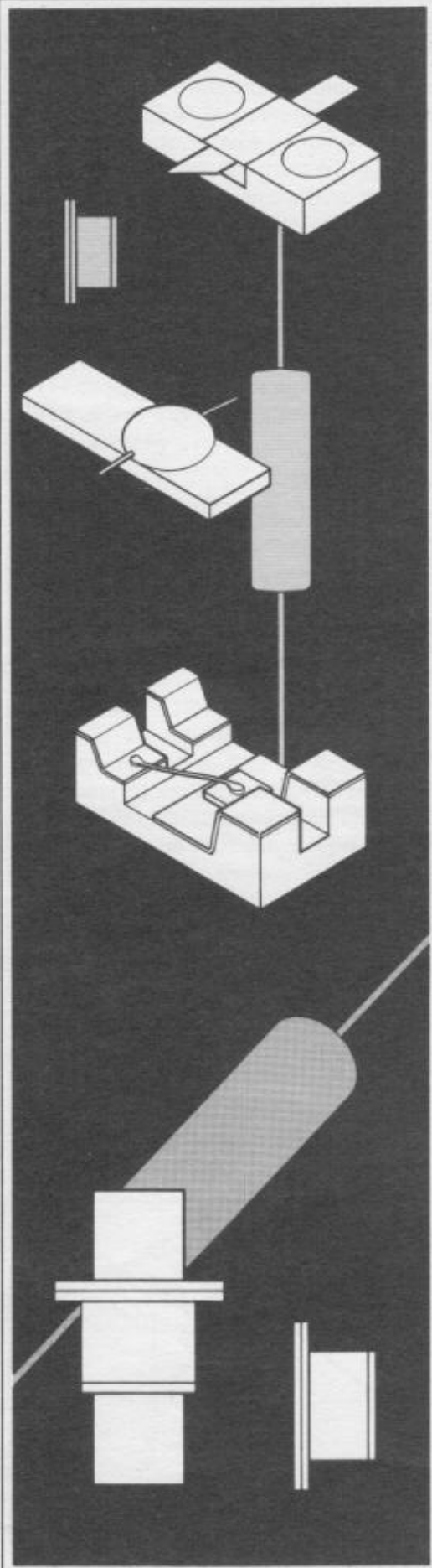


# Applications of PIN Diodes

APPLICATION NOTE 922



HEWLETT  PACKARD  
COMPONENTS

W126

### Introduction

The most important property of the PIN diode is the fact that it appears as an almost pure resistance at RF whose resistance value can be varied over a range of approximately 1-10,000 ohms by a direct or low frequency control current.

When the control current is varied continuously, the PIN diode is useful for attenuating, leveling and amplitude modulating an RF signal. When the control current is switched "on" and "off" or in discrete steps, the device is useful for switching, pulse modulating, and phase shifting of an RF signal.

In addition, the PIN's small size, weight, high switching speed, and freedom from parasitic elements make it ideally suited for use in miniature, broadband RF signal control components.

This application note describes the important properties of the PIN diode and illustrates how it can be applied in a variety of RF control circuits. Related HP publications of special interest are:

1. Special Note #4, Harmonic Distortion in PIN Diodes.
2. AN 929, Fast Switching PIN Diodes.
3. AN 936, High Performance PIN Attenuator for Low Cost AGC Applications.

## Characteristics of the PIN Diode

A PIN diode is a silicon semiconductor consisting of a layer of intrinsic (high resistivity) material of finite area and thickness which is contained between highly doped  $p$  and  $n$  type material. When the diode is forward biased, charge is injected into the intrinsic or "I" region. This charge consists of holes and electrons which have a finite lifetime before recombination. The density of charge in the intrinsic region and its geometry determines the conductance of the device, while the lifetime (denoted by  $\tau$ ) determines the approximate low frequency limit of useful application.

The conductance of the diode is proportional to the stored charge and the charge is in turn related to the diode current by

$$i_d = \frac{dQ_d}{dt} + \frac{Q_d}{\tau} \quad (1)$$

where  $i_d$  = Diode current  
 $Q_d$  = Charge stored in the diode  
 $\tau$  = Recombination lifetime

If the diode is biased with only a constant current, the stored charge is constant and is equal to:

$$Q_d = I_d \tau \quad (2)$$

If the bias consists of both a constant current and a low frequency RF or time varying signal, then the dc component of stored charge will be "modulated" by the presence of an ac component. The degree of modulation depends on the relative level of the two charge components and the frequency of the RF signal. This dependence on frequency can be readily seen by solving the Laplace transform of Eq. (1) which yields

$$Q_d(\omega) = \frac{i_d \tau(j\omega)}{1 + j\omega\tau} \quad (3)$$

This is plotted in Figure 1(a) and illustrates that at signal frequencies below  $f_o = \frac{1}{2\pi\tau}$ , the RF signal has about the same effect as the dc bias. Above  $f_o$  however, the modulation effect decreases by about 6 dB/octave.

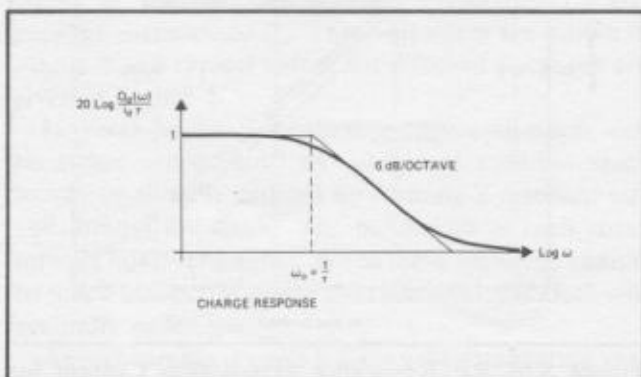


Figure 1. PIN Behavior as a Function of Frequency

The lifetime of PIN diodes is determined by design and is usually based on the desired switching speed. Typically,  $\tau$  can be in the range of  $0.03 \mu\text{sec}$  to well over  $3 \mu\text{sec}$ . For a value of  $100 \text{ nsec}$ ,  $f_o$  is  $\approx 1.6 \text{ MHz}$ . Thus, the diode can be simply visualized as follows: At frequencies well below  $f_o$ , the PIN diode behaves as an ordinary PN junction diode. The RF signal incident on the diode will be rectified and considerable distortion of the signal will occur. In the vicinity of  $f_o$ , the diode begins to behave as a linear resistor with a small nonlinear component. The signal consequently suffers some degree of distortion. At frequencies well above  $f_o$ , the diode appears essentially as a pure linear resistance whose value can be controlled by a dc or a low frequency control signal.

### a) Low and High Frequency Equivalent Circuits

Because of this behavior, the equivalent circuit of the PIN diode also depends on the frequency. At frequencies much less than  $f_o$ , the equivalent circuit is as shown in Figure 2(a) and is that of a normal PN junction diode.

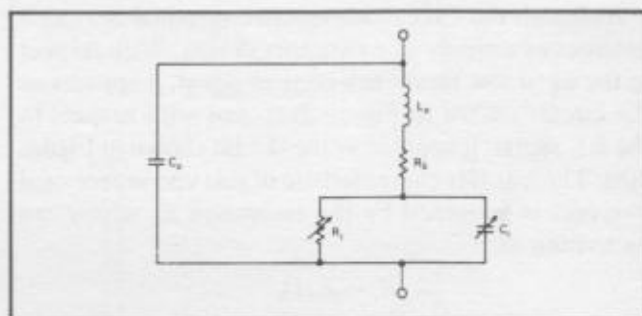


Figure 2(a). PIN Low Frequency Equivalent Circuit

In this circuit

$L_p$  = Package Inductance  
 $C_p$  = Package Capacitance  
 $R_s$  = Series Resistance

$$R_j = \text{Junction Resistance} \approx \frac{nkT}{qI_{dc}}$$

For a typical  $n = 1.8$  and at room temperature

$$R_j \approx \frac{48}{I_{dc(mA)}}$$

$I_{dc}$  = Forward dc Bias Current  
 $C_{j(v)}$  = Junction Capacitance = a function of applied voltage

At frequencies much higher than  $f_o$ , the equivalent circuit is as shown in Figure 2(b). Here the elements  $L_p$ ,  $C_p$  and  $R_s$  are the same as in Figure 2(a). The element  $C_i$  represents the I-layer capacitance which is constant and dependent only on the geometry of the I-layer. This capacitance can be measured by con-

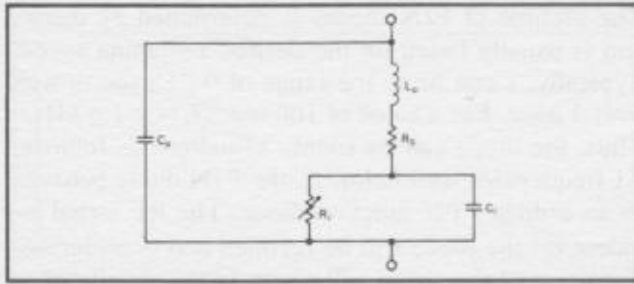


Figure 2(b). PIN High Frequency Equivalent Circuit.

ventional bridge techniques and at a low (usually 1 MHz) frequency if the diode is reverse biased past the punch-through voltage to assure that the *I*-layer is fully depleted. Typical values of  $C_1$  for present HP PIN diodes are in the range of 0.15 to 0.06 pF, depending on diode design. The element  $R_1$  represents the effective RF resistance of the *I*-layer. Although shown as variable, this resistance is constant with respect to the RF signal, providing the frequency of the signal is much higher than  $f_0$ . It is, however, variable by the dc or very low frequency control current.

#### b) The RF Resistance Characteristic

Although the PIN diode is a two-terminal device, it behaves essentially as a two-port device. With respect to the dc or low frequency control signal, it appears as the circuit shown in Figure 2(a), and with respect to the RF signal, it appears as the circuit shown in Figure 2(b). The transfer characteristic of this unconventional two-port is governed by the resistance  $R_1$  which can be written as

$$R_1 = K/I_{dc}^x$$

where  $R_1$  is the effective high frequency resistance and  $I_{dc}$  is the dc bias current in mA. The dependence of  $R_1$  on  $I_{dc}$  is similar in form to the dependence of  $R_j$  on  $I_{dc}$  in the low frequency equivalent circuit; however, the constant  $K$  and the exponent  $x$  are different. For comparison, both of these functions are plotted in Figure 3 for 5082-3003 and -3004 diodes. Due to a variety of mechanisms that exist in the diode at RF frequencies, both  $K$  and  $x$  must be determined empirically. For a specific diode design, the exponent  $x$  is usually a constant. For a typical HP PIN diode,  $x$  is nominally 0.88. The constant  $K$  and therefore  $R_1$ , however, are highly dependent on the fabrication and process control and its value can vary by as much as 3:1 from diode to diode. For switching or pulse modulating application, the variation of  $R_1$  between diodes at a given bias is not significant since the diode is usually switched between a very high and a very low value of resistance by the control current. For analog applications such as attenuating and modulating, and particularly where repeatability and tracking of the attenuation with bias current is desired, this variation of  $R_1$  from unit to unit can impose a design and per-

formance limitation. The 5082-3003 and -3004 are precisely controlled in manufacturing, and resistance values at specific bias points, as well as the slope of resistance vs. bias, are specified within narrow limits. The typical specification limits of these parameters are:

#### HP 5082-3003 and 3004 PIN SPECIFICATIONS

| Parameter                   | 5082-3003     | 5082-3004     | Test Conditions     |
|-----------------------------|---------------|---------------|---------------------|
| High Resistance Limit $R_H$ | 920-1380 Ohms | 690-1040 Ohms | 10 $\mu$ A          |
| Low Resistance Limit $R_L$  | 16-24 Ohms    | 12-18 Ohms    | 1 mA                |
| Resistance vs. Bias Slope   | -0.86 to -0.9 | -0.86 to -0.9 | 10 $\mu$ A and 1 mA |

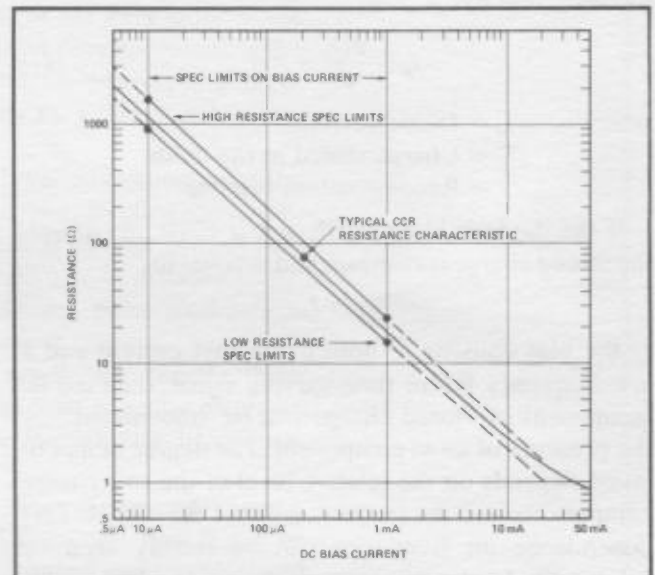


Figure 3(a). RF Resistance versus Bias Current for 5082-3003.

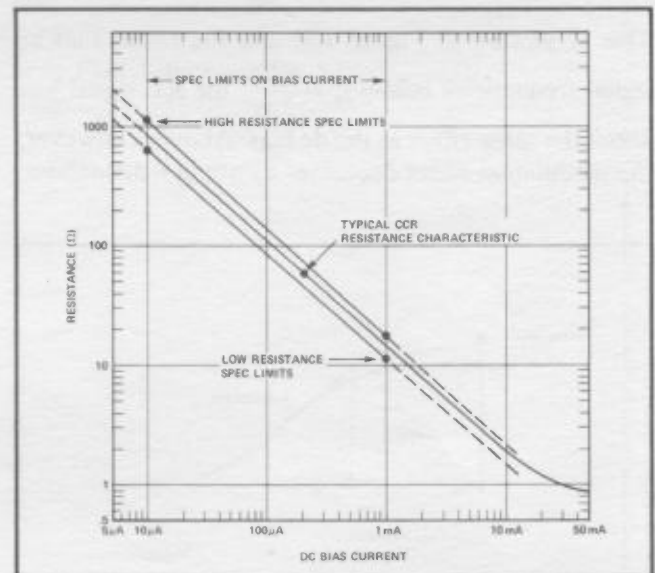
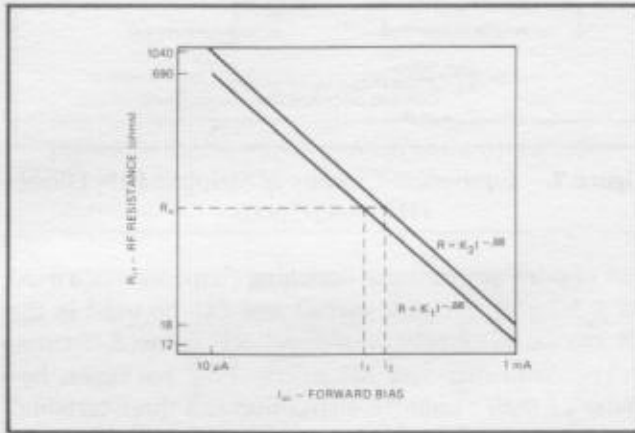


Figure 3(b). RF Resistance versus Bias Current for 5082-3004.

Both of the resistance limits and the slope are determined by measurement at a test frequency of 100 MHz. These resistance limits are shown graphically in Figure 4 for the 5082-3004. The placement of resistance limits on both extreme values of resistance



**Figure 4.** Matching of PIN Diodes by Offset Current Bias

and independently on the slope, assures that the resistance vs. bias curves for individual diodes will be essentially parallel lines lying within the tunnel defined by the high and low resistance limits. Extremely close tracking between diodes can therefore be achieved by offsetting the bias on one diode with respect to the other. The offset current ratio required to achieve this is given by

$$\frac{I_2}{I_1} \approx \left( \frac{K_2}{K_1} \right)^{1.14}$$

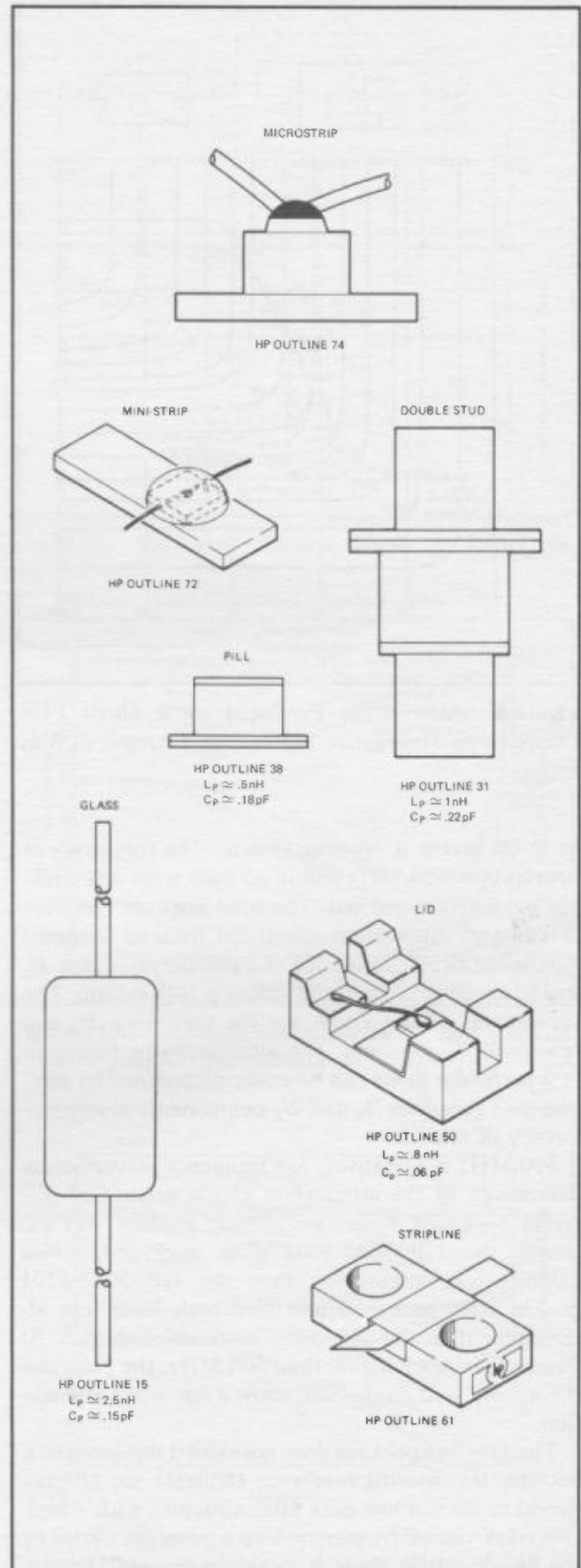
The  $K$  values of the individual diodes can be readily determined by measuring the RF resistance of the diodes at a 1 mA dc bias current.

### c) Effects of Package Parasitics

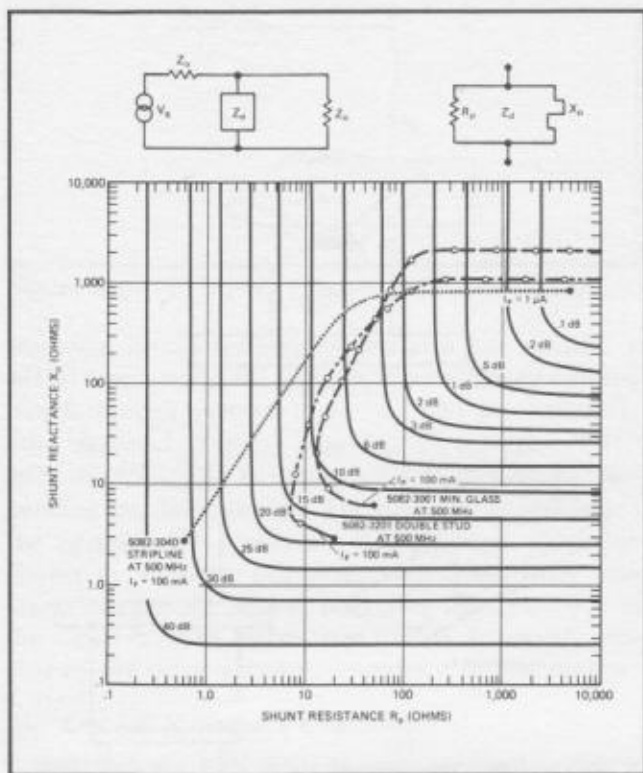
Typical packages in which HP PIN diodes are currently available are illustrated in Figure 5. With the exception of the Mini-strip (Style 72), Microstrip Post (Style 74) and the Stripline (Style 61) packages, all the other packages introduce additional reactive elements in the form of package inductance  $L_p$  and package capacitance  $C_p$ . These elements are shown in Figure 2 and typical values for different packages are given in Figure 5.

In some applications these parasitic elements can be either "tuned-out" by additional external reactances or actually utilized by forming a resonant circuit around the diode. The bandwidth of such structures is however limited. When these elements cannot be tuned out, performance over a broad bandwidth will generally suffer.

As an example, Figure 6 shows the attenuation versus bias characteristics of the same diode in three different packages. In all cases, the device is mounted



**Figure 5.** Package Outlines



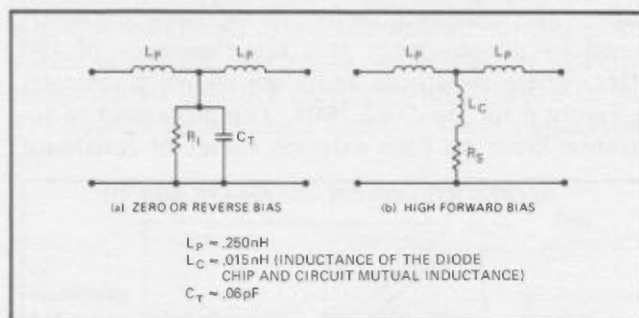
**Figure 6.** Attenuation Produced by a Shunt PIN Diode as Its Impedance Varies with Changes of Bias Current

in shunt across a 50 ohm system. The frequency of operation is 500 MHz and in no case were any package parasitics tuned out. The solid lines are contours of constant attenuation calculated from an assumed equivalent circuit consisting of a parallel resistance  $R_p$  and a reactance  $X_p$  in shunt across a 50Ω system. The coordinates of the graph are the resistance  $R_p$  and reactance  $X_p$  elements. The attenuation performance of a particular diode can be easily determined by plotting its equivalent  $R_p$  and  $X_p$  components at any frequency of interest.

500 MHz is a relatively low frequency, nevertheless differences in the attenuation characteristics of different packaged diodes are already evident. For example, the HP 5082-3001 glass packaged device exhibits less attenuation than the HP 5082-3201 double stud packaged unit and both have less attenuation than the HP 5082-3040 stripline unit. At frequencies much higher than 500 MHz, the glass and the double stud diodes will show even lower attenuation.

The Stripline package does not exhibit this limitation because the internal reactance elements are proportioned to form a low-pass filter structure with a high (30GHz) cut-off frequency. The equivalent circuit of the Stripline PIN diode is shown in Figure 7.

Because of this design, the Stripline PIN diode does



**Figure 7.** Equivalent Circuits of Stripline PIN Diode (HP 5082-3040)

not require any external matching elements when used in a 50 ohm Stripline circuit and can be used in the design of extremely wide-band RF control circuits.

The Mini-strip and Microstrip Post packages, because of their "open" construction and three-terminal features, lend themselves well to both broad-band and narrow-band (resonant) designs, since the required external reactance elements can be readily controlled by the user. They are both essentially a diode chip, but are free of critical bonding and handling problems, and which can be readily installed into hybrid integrated or microcircuit structures.

## PIN DIODE APPLICATIONS

### a) Design of Broadband Reflective SPST Switches and Attenuators

The previously described characteristics of the PIN diode make it ideally suited for use in attenuating or switching of RF signals. Two of the simplest circuits that can be used for this are shown in Figures 8 and 9.

The attenuation in the Series PIN circuit is decreased as the RF resistance of the PIN is reduced by increasing the forward current. The opposite occurs for the shunt configuration. If the control bias is switched rapidly between high and low (zero) values, then the circuit acts simply as a switch. When used as a switch, the residual attenuation that exists when the switch is "ON" is usually called Insertion Loss (I.L.). The attenuation provided when the switch is "OFF" is usually called Isolation (I.S.). If the diode is assumed to be a pure resistance at RF, then the attenuation for each circuit is given as:

$$\alpha_{(series)} = 20 \log \left( 1 + \frac{R_I}{2Z_o} \right);$$

$$\alpha_{(shunt)} = 20 \log \left( 1 + \frac{Z_o}{2R_I} \right)$$

where  $Z_o = R_G = R_L =$  Circuit, Generator and Load Resistance, respectively

$R_I =$  Pin diode RF resistance at the specified bias current

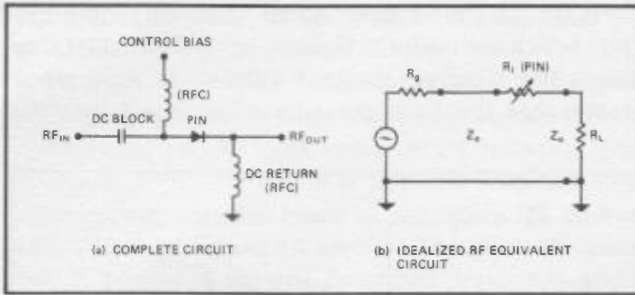


Figure 8. Series PIN RF Attenuator or Switch

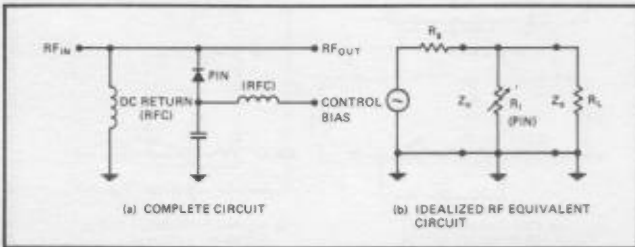


Figure 9. Shunt PIN RF Attenuator or Switch

As can be seen, the attenuation is not dependent on frequency and is a function of the ratio of the circuit resistance to the diode resistance. As the bias on the diode is varied, the load resistance as seen by the source also varies; consequently, attenuation is achieved primarily by reflection and partly by dissipation in the PIN diode. Circuits of this type are generally referred to as reflective switches or attenuators.

As was shown previously, a real diode contains several reactance elements due to the diode and the package. Consequently, when a real diode is used, the attenuation characteristic becomes frequency dependent. For an equivalent circuit shown in Figure 10, the attenuations for the two circuits are given by:

$$\alpha'_{(series)} = 10 \log \left[ \frac{\left( \frac{R'_S}{Z_0} + 2 \right)^2 + \left( \frac{X'_S}{Z_0} \right)^2}{4} \right]$$

$$\alpha'_{(shunt)} = 10 \log \left[ \frac{\left( \frac{R'_S Z_0}{R_S'^2 + X_S'^2} + 2 \right)^2 + \left( \frac{X'_S Z_0}{R_S'^2 + X_S'^2} \right)^2}{4} \right]$$

where  $R'_S$  and  $X'_S$  are the series equivalent resistance and reactance of the diode impedance, i.e.,  $Z_d = R'_S + jX'_S$ .

These  $\alpha$  functions are plotted as a function of frequency in Figures 11(a) and 11(b) which show what values of isolation and insertion loss might be typically obtained for single packaged diodes in either shunt or series reflective attenuators. These curves are based on typical values of diode and package parameters. The upper frequency performance can be improved slightly by tailoring the circuit geometry around the diode package. For example, the high

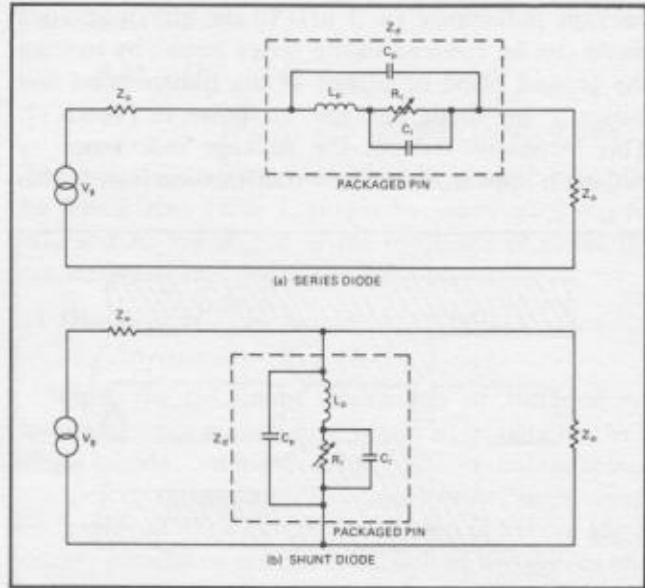


Figure 10. Packaged Diodes Used as Reflective Attenuators

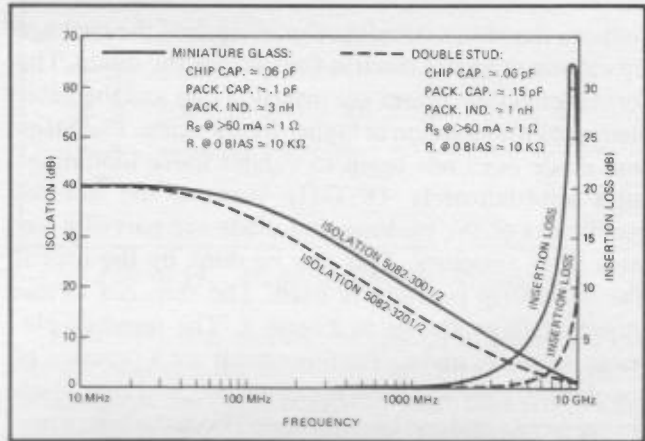


Figure 11(a). Attenuation of Series Diodes Used as a Switch in a 50 Ohm System

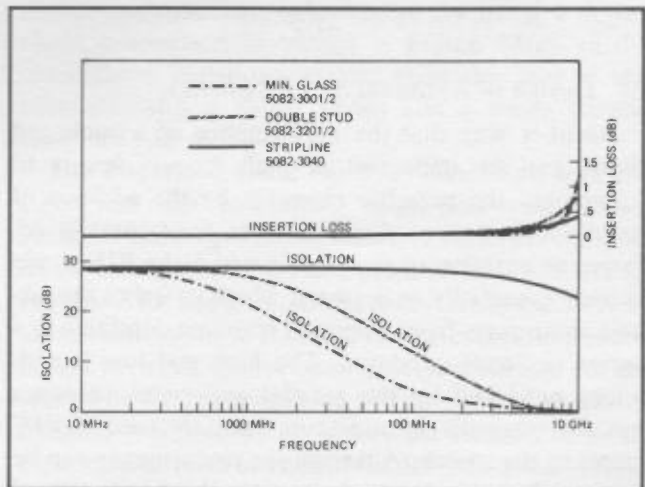
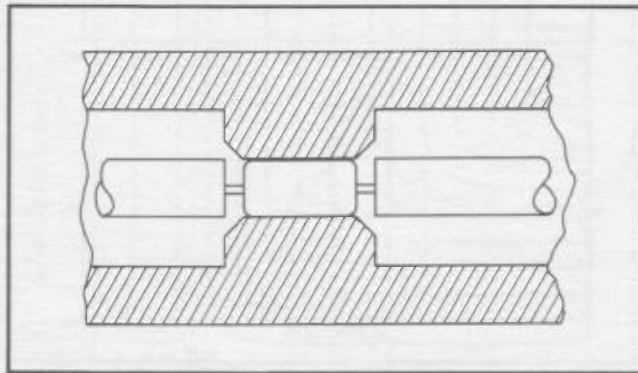


Figure 11(b). Attenuation of Shunt Diodes Used as a Switch in a 50 Ohm System

package inductance ( $\approx 3$  nH) of the glass packaged diode can be reduced in the series circuit by moving the ground plane or planes of the transmission line closer to the diode package, as shown in Figure 12. This technique reduces the package inductance by making it appear more like a transmission line. It also



**Figure 12.** Optimizing a Glass Packaged Diode for Series Reflective Attenuating in a Coaxial Line

reduces the series coupling capacitance of the package by cutting the axial electric field across the diode. The former effect decreases the insertion loss and the latter increases the isolation at higher frequencies. The Stripline diode does not begin to exhibit these limitations until approximately 18 GHz because the internal reactances of the package and diode are part of a low pass filter structure. This can be done by the user if the Mini-strip package is used. The required circuit structure is as shown in Figure 7. The required element values  $L_1$  and  $C_1$  for this circuit are a function of the desired characteristic impedance  $Z_0$  and the cut-off frequency  $f_c$ , and can be determined from the following:

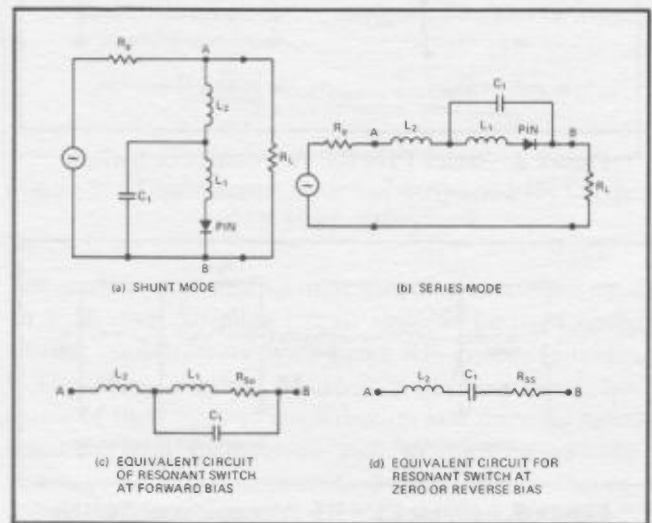
$$L_1 = \frac{Z_0}{2\pi f_c}$$

$$C_1 = \frac{1}{\pi f_c Z_0}$$

#### b) Design of Resonant SPST Switches

Another way that the performance of a packaged diode can be improved at high frequencies is to "tune-out" the parasitic elements by the addition of external reactances. Such circuits are generally referred to as resonant switches in which the PIN diode is used essentially as a switch which switches the circuit parameters from a parallel resonant condition to a series resonant condition. The high and low impedances produced by the parallel and series resonant circuits, respectively, constitute the "ON" and "OFF" states of the switch. Although the performance can be improved at the design frequency, the bandwidth of resonant switches is necessarily limited, usually to  $\approx 10\%$ .

Figure 13 shows two typical resonant switch circuits which are useful at frequencies below 1 GHz, or where the required external inductance  $L$  is much greater than the diode parasitic inductance  $L_p$  and the



**Figure 13.** Resonant PIN Switch Circuits

external capacitance  $C$  is much greater than the package capacitance  $C_p$ . Under these conditions, the diode parasitic elements have a negligible effect on performance. The equivalent circuits for the two states of this resonant switch are shown in Figure 13 (c) and (d). When the diode is forward biased, the elements  $L_1$  and  $C_1$  are in parallel resonance and the circuit between  $A$  and  $B$  appears as a high impedance. When the diode is reverse biased, the elements  $L_2$  and  $C_1$  are in series resonance and the circuit between  $A$  and  $B$  appears as a low impedance. In both cases, the impedances between  $A$  and  $B$  are finite due to the presence of diode resistance and finite element  $Q$ 's. Both of these effects are represented as loss resistances  $R_{sp}$  and  $R_{ss}$ , respectively. The expected insertion loss, maximum attenuation, and bandwidth can be obtained from the formulas given in Table 1. For  $L_1$  and  $L_2$  being equal, the resonant frequency in both cases is approximately

$$f_0 \cong \frac{1}{2\pi\sqrt{L_1 C_1}}$$

the approximation being due primarily to the fact that diode parasitic elements affect the two resonant states differently. In the parallel resonance state, there will also be a secondary series resonance at approximately  $f_2 = 1.4 f_0$ .

At frequencies higher than 1 GHz, the circuits shown in Figure 13 are difficult to design because the values of the external reactances begin to approach those of the diode parasitic reactances and considerable interaction between the various elements occurs.



Although this mode is still possible, the synthesis will generally have to be empirical.

Resonant switches can also be built by utilizing the package parasitics and the diode chip capacitance  $C_I$  if these are of the right value, or by tailoring these package parasitics; which is possible with the Mini-strip package. In this mode of operation, the equivalent circuit of Figure 14 applies. The mode of operation is similar to the one described previously and is evident in Figures 11(a) and 11(b) where it can be ob-

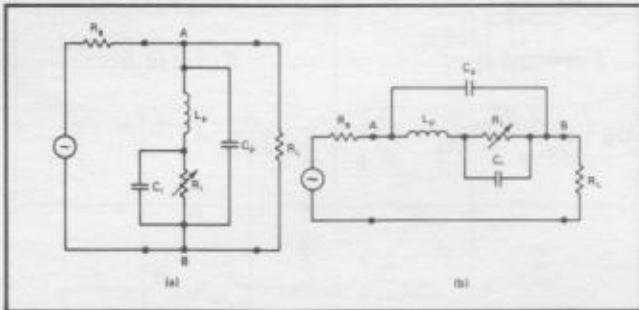


Figure 14. Equivalent Circuit of Diode in Shunt (a) and Series (b) Mode of Operation

served that as the frequency increases, the insertion and isolation curves approach each other and finally reverse roles as the equivalent circuits approach parallel and series resonance.

The element values are chosen such that  $L_p$  and  $C_I$  are in series resonance when the diode is reverse or zero biased, and the elements  $L_p$  and  $C_p$  are in parallel resonance when the diode is forward biased. For maximum isolation and minimum insertion loss, the two resonant frequencies must be equal which dictates that  $C_I = C_p$ . This, of course, requires a careful choice of the diode and the package for the frequency of interest. In many applications, however, a sufficiently high isolation to insertion loss ratio can be achieved by working on the slopes of two resonant responses of dissimilar frequencies. Consequently,  $C_I$  need only be approximately equal to  $C_p$ .

In a packaged diode,  $C_p$  can be varied over narrow limits by addition of external capacitance if  $C_p < C_I$  which is generally true for large diodes, or by reducing the axial electric field around the diode in the manner described previously. The inductance can be controlled by external addition if  $L_p$  is less than required. The synthesis of the circuit is therefore very much controlled by the proper choice of the diode chip capacitance  $C_I$ , since this parameter cannot be controlled by the user.

The impedance appearing across A-B for the two resonant conditions is then

Series Resonance

$$R_{SR} \text{ where } R_{SR} = \frac{R_I}{1 + \frac{R_I^2}{X_{C_I}^2}}$$

Parallel Resonance

$$R_S(1 + Q^2) \quad Q = \frac{X}{R_S}$$

and  $R_S = R_I$  @ high forward bias

The isolation, insertion loss, and bandwidth may also be found from Table 1, simply by substituting  $R_{SR}$  for  $R_{SS}$  and  $R_S$  for  $R_{sp}$ .  $X$  is the reactance of either the resonating inductance or capacitance.

### c) Design of Multiple Diode and Multi-throw Switches and Attenuators

When the maximum attenuation or isolation requirements are greater than what can be obtained by a single diode, multiple diode circuits using series, parallel or series-parallel arrangements can be used. Examples of such circuits are shown in Figure 15. A simple parallel or series connection of two diodes will only increase the attenuation by a maximum of 6 dB and will also increase the insertion loss.

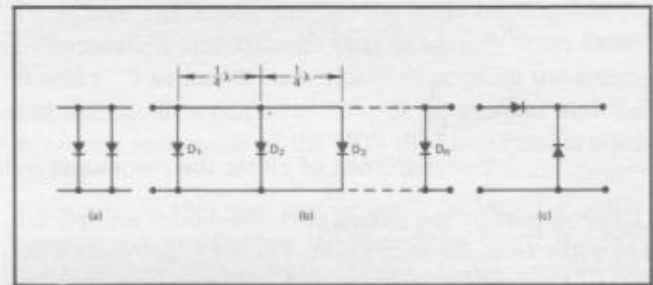


Figure 15. Reflective Mode Attenuators

However, if  $n$  diodes are spaced at quarter wavelength intervals, as shown in Figure 15(b), the overall attenuation can be increased by more than  $n$  times that of a single diode. The insertion loss, if it is due to parasitic elements, may also decrease because the  $1/4$  wavelength spacing produces cancellation of these reactances. Where  $1/4 \lambda$  spacing is not practical, higher isolation can be achieved by using a series-shunt connection as shown in Figure 15(c). In this connection, isolations greater than the sum of that obtained with a single series and a single parallel diode may be obtained.

The discussion so far has been concerned with circuits that are essentially single-pole single-throw switches or two-port attenuators. A variety of multiple throw arrangements are also possible as shown in Figure 16. The design considerations for these circuits are similar to those outlined above except that interaction between diodes must be considered in the design. The SPDT circuit of Figure 16(a) operates as follows: When diode  $D_1$  is forward biased and diode  $D_2$  is zero or reverse biased, the RF power flows from Port 3 to Port 2 and Port 1 is isolated. When the two bias conditions are reversed, RF power flows to Port 1 and Port 2 is isolated. To minimize reactive loading of

TABLE 1

|                             | ATTENUATION ( $\alpha$ )  | INSERTION LOSS  | BANDWIDTH  |
|-----------------------------|---|---|--|
| Series Mode Resonant Switch | Forward Bias<br>$20 \log \left( \frac{R_{sp}^2 + X^2}{2Z_o R_{sp}} + 1 \right)$ | Reverse Bias<br>$20 \log \left( \frac{R_{ss}}{2Z_o} + 1 \right)$                  | Forward Bias<br>$[4\pi Z_o C_1 X 10^{\alpha-20}]^{-1}$   |
| Shunt Mode Resonant Switch  | Reverse Bias<br>$20 \log \left( \frac{Z_o}{2R_{ss}} + 1 \right)$                | Forward Bias<br>$20 \log \left( \frac{Z_o R_{sp}}{2(R_{sp}^2 + X^2)} + 1 \right)$ | Reverse Bias<br>$\frac{Z_o}{4\pi L_2} X 10^{-\alpha/20}$ |

Applicable when  $R_g = R_L = Z_o$

where:

$$R_{sp} = \left( \frac{Q_1}{1 + Q_1^2} \right) X$$

$$R_{ss} = \frac{X}{Q_2}$$

$X$  = reactance of either the resonating inductance or capacitance

the open port by the closed port, the diodes are spaced  $\lambda/4$  away from the feed point. The RFC provides a dc return for the bias currents and an open circuit for the RF signal. The capacitors  $C_1$  and  $C_2$  provide an RF ground for the diodes and an open circuit for the bias current. For increased isolation, additional diodes can be used which are spaced  $\lambda/4$  away from the first set.

When  $\lambda/4$  spacing is impractical or its bandwidth restriction is undesirable, a series configuration, as shown in Figure 16(b), can be used.

In this circuit, increased isolation can be provided by placing shunt diodes singly or in  $\lambda/4$  spaced pairs at the output ports after the series diodes. This configuration is particularly useful for design of multiple-throw wideband switches. For multiple-throw configurations, additional series or series/parallel sections are added to the common feed point.

d) *Design of Constant Impedance Switches and Attenuators*

For some RF systems, the high reflection coefficient at the RF ports of the reflective switches cannot be tolerated. For such applications, a variety of constant impedance switches and attenuators can be built using PIN diodes. Several such circuits are shown in Figure 17. The circuits of Figure 17(a), (b), and (c), operate by absorbing the undesired RF signal power in the PIN diodes. The circuits of 17(d), (e), and (f) operate by reflecting the power to a different RF port. In Circuits

a and b, the control current variation through each diode is arranged in such a way that the impedance at both RF ports remain essentially constant at the design value, while the overall attenuation can be varied over a range of less than 1 dB to greater than 20 dB. In Circuit c, the input impedance is kept constant by using

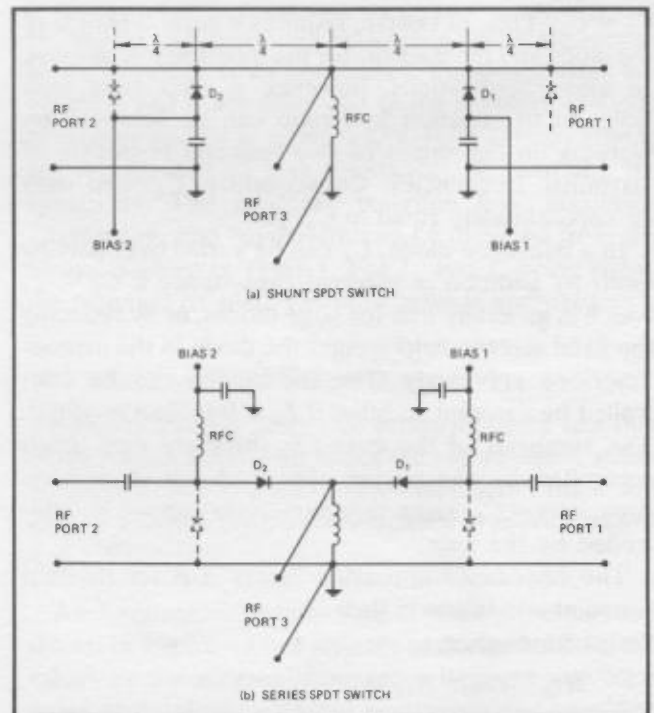


Figure 16. Multiple Throw PIN Switches

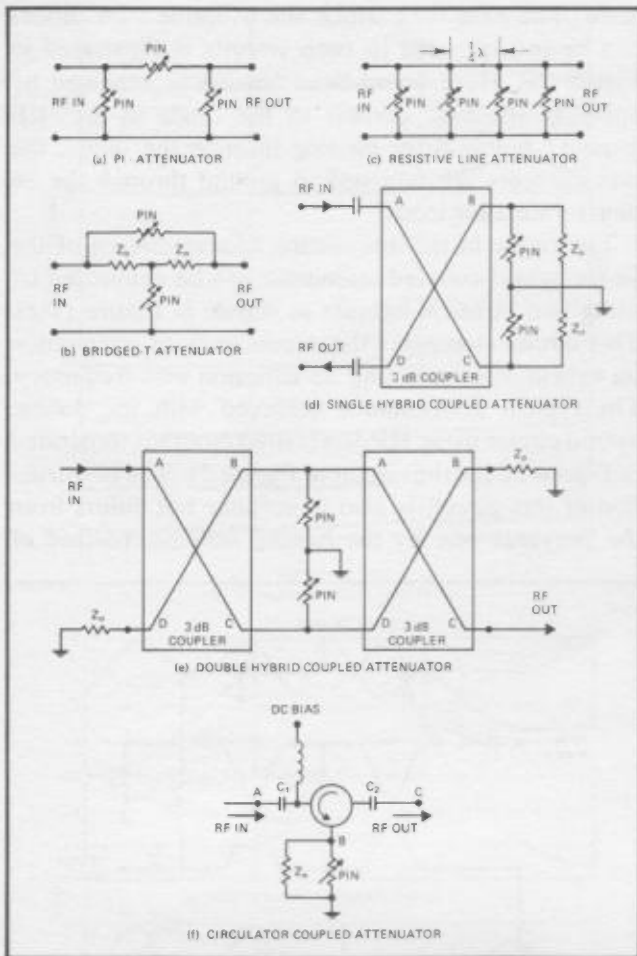


Figure 17. Constant Impedance PIN Diode Attenuators

a distributed structure with a large number of diodes. The impedance variation of each diode is also shaped so that the diodes in the center of the structure vary more than those near the ports. The resulting tapered impedance structure results in an essentially constant impedance at the ports, while the overall attenuation can be varied up to a range of 40-80 dB, depending on the length of the structure. The  $\pi$  and  $T$  circuit structures are generally very compact and are particularly useful at low frequencies in the range of 10 MHz to 500 MHz. In addition to being constant impedance, they exhibit very little change of phase with attenuation and are very useful for providing gain control in RF transistor amplifiers in which bandpass and phase characteristics must be maintained over a large range of gain variation. Detailed design information on the  $\pi$  attenuator is contained in HP Application Note 912.

Because of its distributed nature, the circuits of Figure 17(c) are generally too large to be useful at lower frequencies but are very useful above 1 GHz. This circuit is particularly attractive when very large attenuation ranges are required. Additional design

information on this type of attenuator is contained in Ref. 1.

The attenuator circuits of Figure 17(d), (e), and (f) achieve constant impedance characteristics by virtue of the properties of the coupling elements which are placed between the RF ports and the PIN diodes. In the circuit of 17(d), the power incident on Port A of a 3 dB,  $90^\circ$  hybrid divides equally between Ports B and C, and Port D is isolated. The mismatch produced by the PIN diode resistance in parallel with the load resistance at Ports B and C reflects part of the power. The reflected powers at B and C combine and exit out of Port D. Port A, in this case, is isolated and therefore appears matched to the input signal. The maximum attenuation that can be achieved with this scheme depends on the directivity of the coupler and the quality of the terminations at Ports B and C when the diodes are unbiased. The VSWR at Port A will depend on the equality of the power split in the hybrid and the equality of the reflection coefficients at Ports A and B. To assure the latter, the diodes must be reasonably well matched and must be spaced equally from Ports B and C. The insertion loss will depend on the losses and the equality of power split in the coupler and the minimum resistance of the PIN diodes when biased forward.

Circuits of this type can be easily and economically constructed in 50 ohm stripline form using the HP 5082-3040 Stripline PIN. These diodes require no external matching structure and are very consistent in respect to the position of the effective internal reflection plane. The typical performance that was obtained with this type of circuit is illustrated in Figure 19 for the circuit of Figure 18. As can be seen, this kind of attenuator is useful over a wide frequency range. However, due to the hybrid directivity, there will be a considerable ripple in the high attenuation

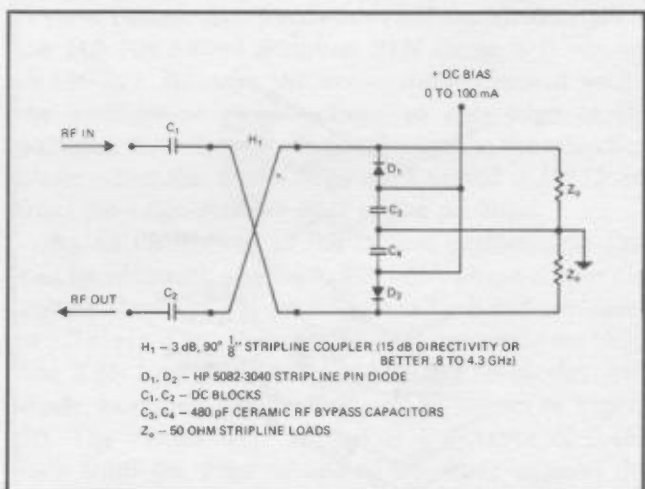


Figure 18. S-Band Single Hybrid Coupled PIN Attenuator

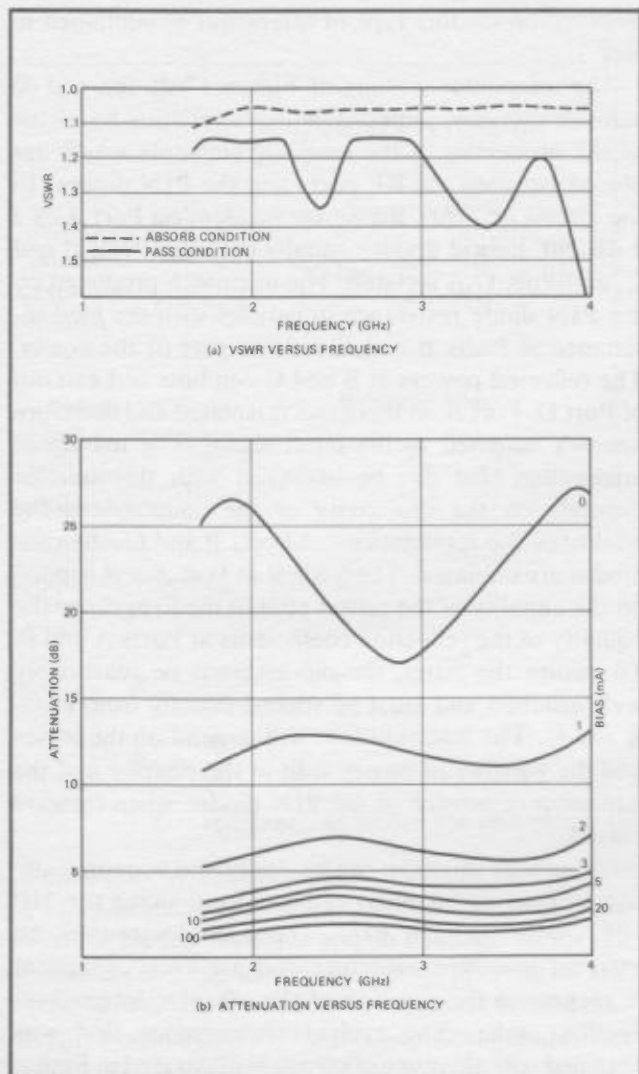


Figure 19. Performance of an S-Band Single Hybrid Coupled PIN Attenuator.

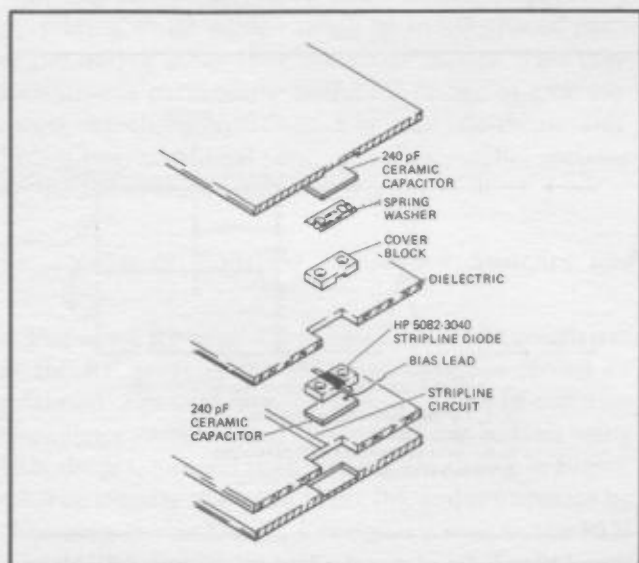


Figure 20. PIN Diode Biasing in Stripline Structures

state. The ease with which the Stripline PIN diodes can be incorporated in such circuits is illustrated in Figure 20. Here broad-band biasing is achieved by applying the bias current to the diode at an "RF ground" point. After passing through the diode, the bias currents are returned to ground through the 50 ohm terminating loads.

The ripple in the attenuation characteristics of the single hybrid coupled attenuator can be eliminated by using two identical hybrids as shown in Figure 17(e). This circuit eliminates the dependency of attenuation on hybrid directivity and its variation with frequency. The typical performance achieved with the double hybrid circuit using HP 5082-3040 diodes is illustrated in Figure 22 for the circuit of Figure 21. The construction of this circuit is also in stripline but differs from the previous one by the biasing scheme. Instead of

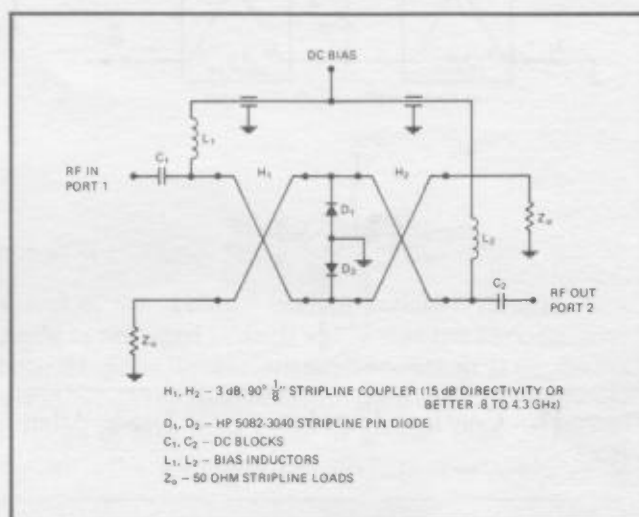


Figure 21. S-Band Double Hybrid Coupled PIN Attenuator

using ceramic RF bypass capacitors, the diodes make direct contact with the RF ground planes and bias is applied through inductors  $L_1$  and  $L_2$ , which appear as a high impedance to the RF signal. As in the previous circuit, the spacing of the diodes from the hybrid ports must be equal and the diodes must be reasonably well matched.

The circuit of Figure 17(f) achieves constant impedance characteristics by virtue of the isolation properties of the circulator. The PIN diode shunts the matched B port impedance  $Z_o$ . When the PIN appears as a high resistance, all power is absorbed in  $Z_o$  at Port B. As the PIN impedance changes, Port B is progressively mismatched and power is reflected and passed by circulator action to Port C where it is absorbed in a matched load. The maximum attenuation attainable in this circuit depends on the matched port circulator isolation and the quality of the match of the circuit at Port B when the PIN diode is zero or reverse

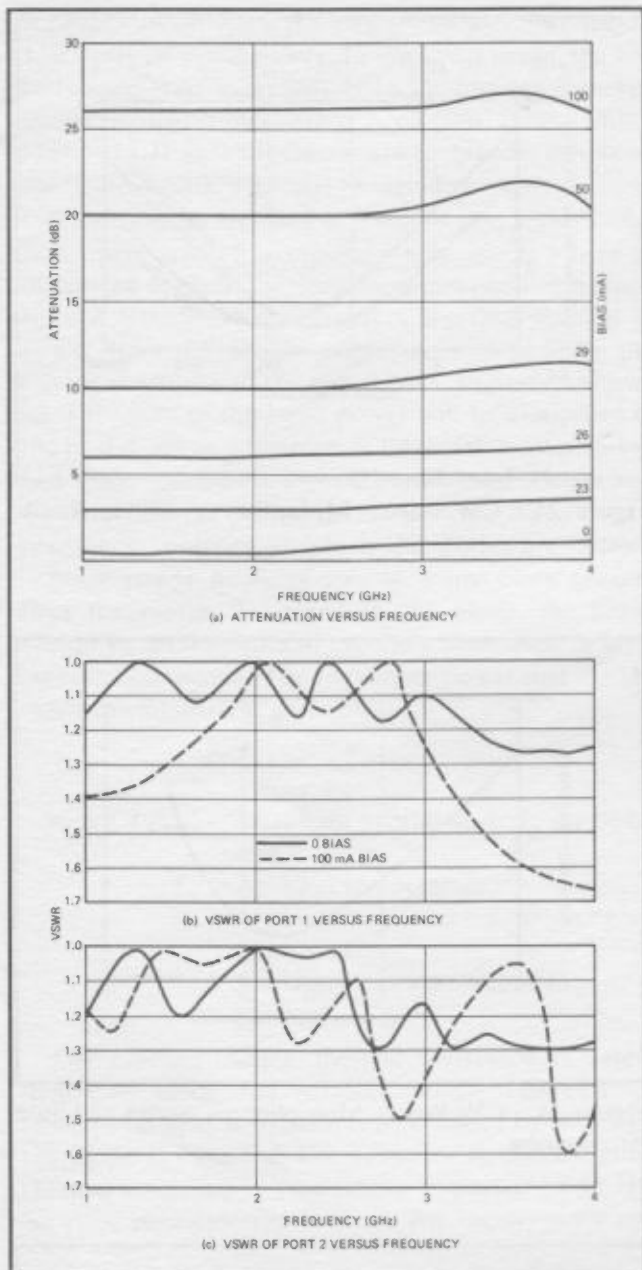


Figure 22. Performance of an S-Band Double Hybrid Constant Impedance PIN Attenuator.

biased. The mechanical and electrical properties of the Stripline PIN diode make it ideally suited for direct integration into the usual stripline ferrite circulator structures.

#### PIN Diode Phase Shifters

The high speed switching capabilities and the low "ON" and high "OFF" impedance states of the PIN diode make it also very useful for many types of high speed, current controlled phase shifter applications. Figure 23 shows a number of practical PIN diode phase-shifter circuits. All of these circuits are easily realized in economical stripline form and require no

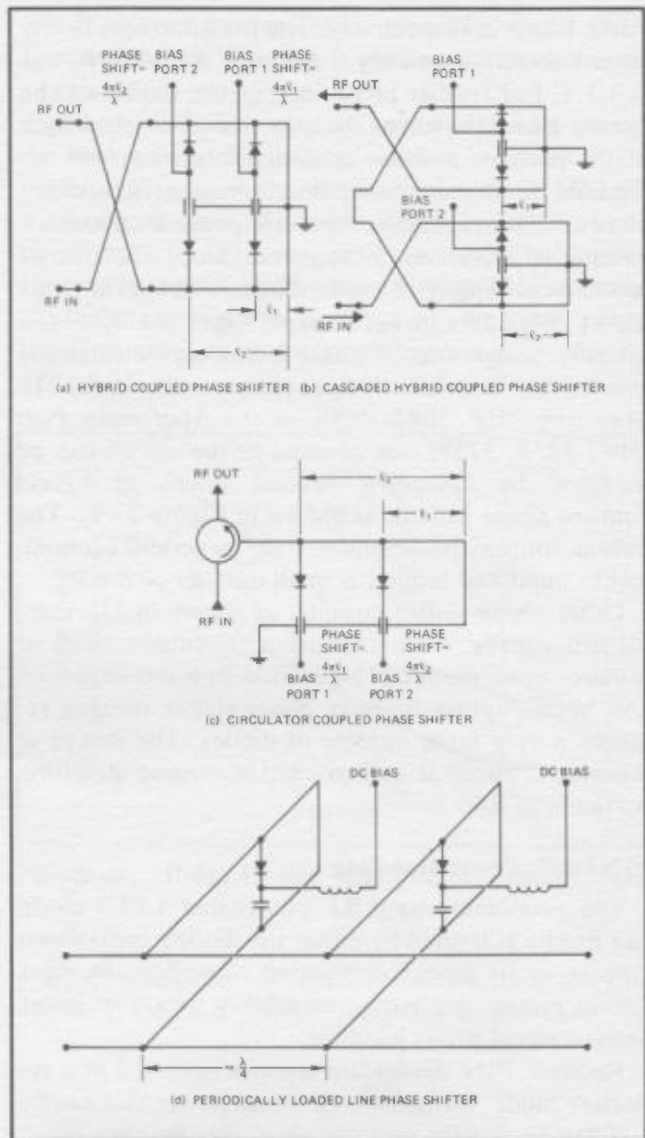


Figure 23. PIN Diode Phase Shifters

diode matching structures when using the HP 5082-3040 Stripline PIN diode. When the diode is zero or reverse biased, the effective overall electrical length of the HP 5082-3040 Stripline PIN diode is 0.955 cm (0.376 in.). Because the active diode element within the package is placed closer to one edge of the package, the effective electrical length to the reflection plane when the diode is forward biased is 0.355 cm from the Logo-marked edge of the package.

As an illustration of the typical performance that can be obtained, a two-bit,  $90^\circ$ - $180^\circ$ , phase-shifter circuit as shown in Figure 23(a) was built and evaluated at 1.7 GHz. The circuit employed a conventional stripline 3 dB hybrid and HP 5082-3040 PIN diodes. The diode mounting and biasing was as shown in Figure 20. The diodes were spaced at a distance of 0.462 inch from the edge of one to the same edge of the other. The spacing from the short circuit was 0.549 in.  $90^\circ$  and  $180^\circ$  of phase shift was obtained by biasing

Ports 1 and 2, respectively. The insertion loss in any state was approximately 1 dB and the VSWR was  $< 1.1:1$ . For smaller phase increments, diodes can be spaced closer, however the effective electrical length of the package and the operating frequency will set the limit on the minimum phase increment in this kind of circuit. For example, for a  $45^\circ$  phase increment, a spacing of 0.196 in. is required. Since the overall mechanical length of each diode is 0.162 in., this leaves only 0.034 in. between packages. At higher frequencies and/or smaller phase increments, electrically shorter low parasitic diode packages, such as the HP Mini-strip (HP 5082-3000) or the Microstrip Post (5082-3258, 3259) can be used or the circuit can be modified by cascading several stages of hybrid coupled phase shifters as shown in Figure 23(b). The hybrid coupled phase shifters are generally economical to build and require a small number of diodes.

Other phase-shifter circuits, as shown in 23(c) and (d) are usually more expensive (circulator cost) or require more diodes. The loaded line circuit which had been popular in early phase-shifter designs requires a very large number of diodes. The design of this kind of circuit is well covered in existing literature, particularly Ref. 2.

### PIN Diode Power Handling

The maximum signal RF power that a PIN diode can handle is limited by either the diode's breakdown voltage or its power dissipation capability. In most cases, power dissipation capability sets the lower limit on signal power handling.

Because PIN diodes are usually operated in a reflective mode, the amount of signal power that can be handled by a PIN in a circuit is usually very much larger than the actual power dissipated in the diode. The ratio of the power dissipated in the diode to the incident power depends on the impedance of the diode relative to the circuit impedance, the number of diodes, and their relative spacing. The following calculation sequence refers to figures 24 and 25 which relate the CW Power Multiplier to either resistance or attenuation.

1. Read the power dissipation limit from the absolute maximum ratings given in the appropriate data sheet.
2. Determine the CW Power Multiplier from Figure 24 if diode resistance is known. Alternatively, use Figure 25 if circuit attenuation is known.
3. Multiply the power dissipation limit by the CW Power Multiplier determined in (2).

For example, for the series mode and a diode with a low and high resistance state of 1 and 10K ohms, respectively, approximately 2% (CW Power Multiplier = 50) of the input power will be absorbed by the diode in either the "ON" or the "OFF" state. If such

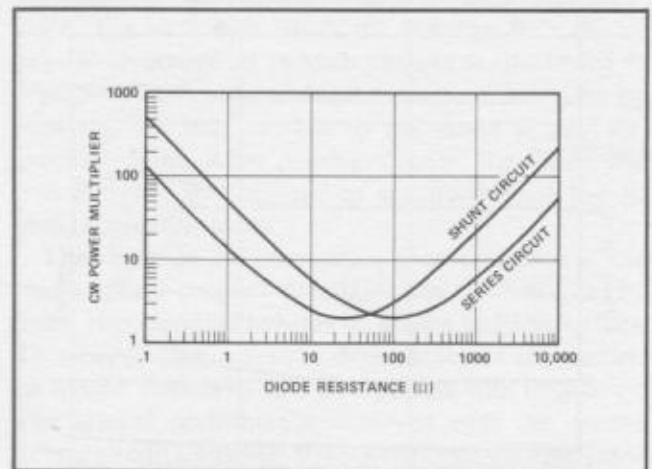


Figure 24. CW Power Multiplier vs. Diode Resistance

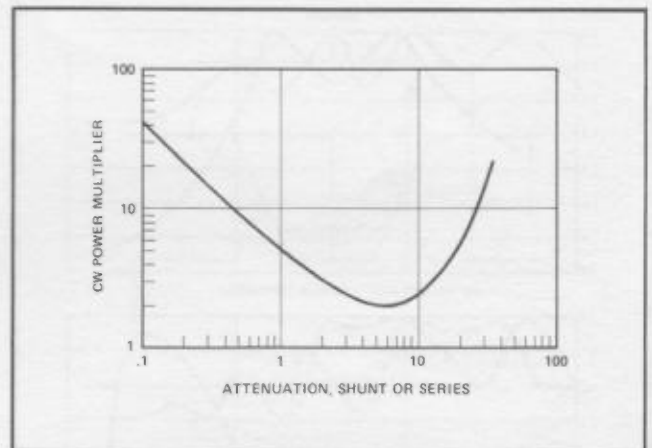


Figure 25. CW Power Multiplier vs. Series or Shunt Attenuation

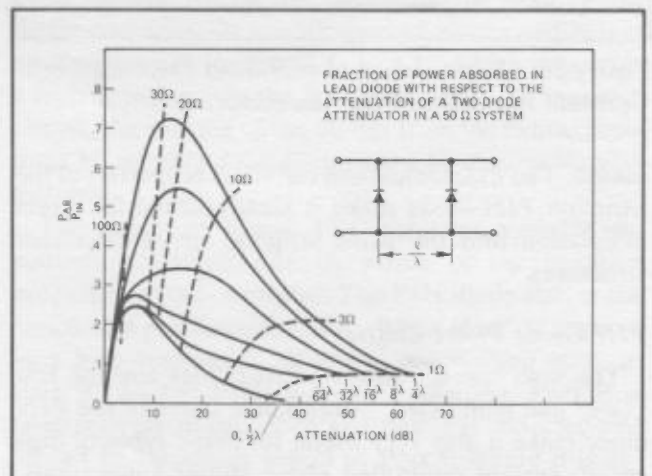


Figure 26. Fraction of Power Absorbed in Lead Diode with Respect to the Attenuation of a Two-Diode Attenuator in a 50  $\Omega$  System

a diode can dissipate 3 watts, it can therefore handle 150 watts of signal power. In the shunt mode, the low resistance state corresponds to the highest absorbed power, which in this case is 7.5% (CW Power Multiplier = 13.3) of the incident power. Hence, this same diode can handle 40 watts of signal power.

If two diodes are used in shunt to gain higher isolation, their spacing determines how much power is dissipated in each. The lead diode in a paralleled diode set will absorb either an equal or a greater amount of power than the second diode, depending upon the electrical spacing of the two diodes. Figure 26 shows what fraction of the input power will be dissipated in the lead diode as a function of total circuit attenuation and diode spacing for a shunt paralleled diode set in a 50 ohm system. Dotted curves indicate the constant resistance contours to which the diodes are biased.

Since power handling can be many times greater than the power dissipated in the diode, the latter should be minimized and carefully controlled in high power applications. The maximum power that a PIN diode can dissipate is given by:

$$P_{max} = \frac{T_{j(max)} - T_A}{\theta_{jc} + \theta_{jA}}$$

where  $T_{j(max)}$  = maximum operating diode junction temperature

$T_A$  = Ambient temperature

$\theta_{jc}$  = Thermal resistance—junction to case

$\theta_{jA}$  = Thermal resistance—case to ambient

The junction-to-case thermal resistance is determined by diode and package design. The case-to-ambient thermal resistance is determined by how well the diode is mounted. For very low  $\theta_{jc}$  diodes, good thermal mounting is particularly important. The HP Stripline package, with its large, flat, copper body and

2-bolt mounting capability, is particularly well suited for applications requiring a minimum overall thermal resistance.

If the PIN diode is used to control pulsed RF power, the peak power that can be handled increases as the pulse width decreases. This is because the effective thermal resistance decreases with pulse width. For a given pulse width, the maximum peak dissipated power can be determined from Figure 27. For example, at a pulse width of 10  $\mu$ sec, the peak power handling capacity is increased by ten times for the 5082-3202.

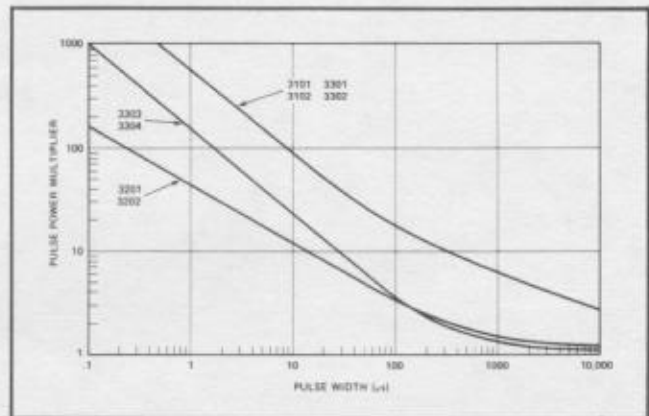


Figure 27. Pulse Power Multiplier vs. Pulse Width

In all cases, the voltage breakdown limit must be checked. For the series circuit this is expressed as:

$$P_A(max) = \frac{V_{BR}^2}{400} W$$

and for the shunt circuit:

$$P_A(max) = \frac{V_{BR}^2}{100} W$$

## REFERENCES

1. J. K. Hunton and A. G. Ryals, "Microwave Variable Attenuators and Modulators Using PIN Diodes," IRE Transactions on Microwave Theory and Techniques, pp. 262-273, July 1962.
2. Richard W. Burns and Louis Stark, "PIN Diodes Advance High-Power Phase Shifting," Microwaves, pp. 38-48, November 1965.
3. Robert V. Garver, "Theory of TEM Diode Switching," MTT, pp. 224-238, May 1961.
4. Jack H. Lepoff, "A New PIN Diode for VHF-UHF Applications" IEEE Transactions on Broadcast & Television Receivers, pp 10-15, Feb. 1971.



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