HEWLETT PACKARD HP ASSOCIATES

APPLICATION NOTE 904

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THE PIN DIODE

Basic Description

The PIN diode is better described as a variable resistor than as a conventional diode. Its normal use is at a sufficiently high frequency that it does not rectify the applied signal and does not generate harmonics. The resistance of the PIN diode is controlled by a dc or low frequency bias or modulating signal. The high-frequency signal which is being controlled sees a constant resistance independent of polarity although limited by reverse breakdown voltage.

This characteristic of the PIN diode depends upon the minority carrier lifetime being much longer than the period of the controlled signal.

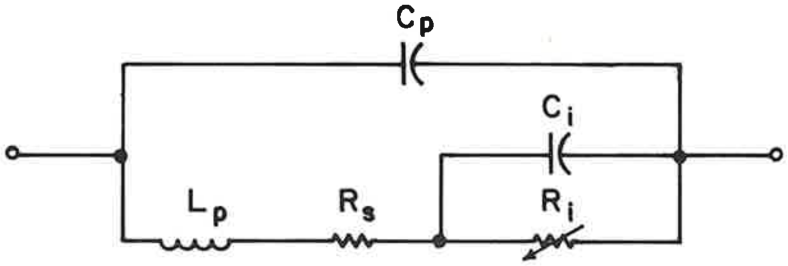
The dynamic resistance of the PIN diode can be larger than 10,000 ohms because of the existence of an exceptionally wide, high resistivity layer next to the junction. Because of this layer, the reverse breakdown voltage of the PIN diode can be very high (several hundred volts). Correspondingly, capacitance per unit of junction area will be very low, and yet conductivity during forward conduction can be high because the conductivity of this layer will be increased by the presence of stored charge (conductivity modulation).

These properties make PIN diodes useful as variable series or shunt resistive elements in microwave transmission lines. Maximum switching ratios can be achieved by operating PIN diodes in structures wherein they become series resonant at the microwave frequency for reverse bias and parallel resonant under forward bias, or vice versa.

In order to gain the maximum spread between the low and the high impedance condition for the PIN diode, it is required that the residual series resistance and junction capacitance be as low as possible.

A frequent conflict in the application of the PIN diode arises from the requirement that the minority carrier lifetime must be compromised between low rectification and harmonic generation on one hand, and reasonably fast switching speed on the other. It is generally possible to achieve speeds faster than 30 ns with low harmonic generation down to about 500 mHz.

Equivalent Circuit



L_p - package inductance ≈ 3 nh, depends upon mounting.

C_p - package capacitance ≈ 0.12 pf.

C_i - capacitance across I layer ≈ 0.07 pf.

R_s - contact resistance ≈ 1 ohm.

R_i - resistance of I layer (see text).

FIGURE 1 - Overall Equivalent Circuit

From the foregoing equivalent circuit, it can be seen that C_i remains essentially fixed and independent of bias condition, whether forward or reversed. This behavior is quite different from that of varactor diodes, for instance, where effective capacitance is very much bias dependent. The reason for this difference lies in the much higher resistivity of the PIN diode I layer so that the reactance of the capacitance of both the depleted and undepleted regions under reverse bias will be less than the resistances of these regions. Accordingly, the dissipative component (which is expressed here as resistance R_i) will vary with bias, but the capacitance C_i will not.

Under forward bias, the injection and subsequent storage of minority carriers acts to reduce the resistance of the I region in a uniform fashion.

The variation of R_i with bias can be described in the following terms:

At zero bias, the bulk resistance of the I region will be 7K to 10K ohms. This value comes from consideration of the junction area, I region width, and resistivity. Under reverse bias, a depletion region develops and the dissipative losses associated with this region will be less than that of the I region. Therefore, as reverse bias increases, the depletion layer widens, and the losses that are associated with this I layer capacitance will decrease, and so R_i increases. At about 20 volts reverse bias, R_i will have risen to about three times its zero bias value.

Going toward forward bias, conductivity modulation will cause R_i to drop very rapidly with forward current. At high forward current this relationship will be:

$$R_i = \frac{K_g}{I^{0.87}}$$

where = I is forward bias current-ma
K_g varies from 20 to 50 ohms

At low forward bias, R_i will be approximately the parallel combination of this value and the zero bias value.

Applications

There are two general areas of application for the PIN diode; it may be used as a microwave switch to be operated by abrupt changes in bias or it may be used as a variable resistance microwave amplitude modulator. In either case, the impedance of the diode is controlled by external bias, and it approximates a linear passive impedance to the applied microwave signal.

The advantages of PIN diodes over ordinary diodes in switching applications are mainly, low capacitance, high breakdown voltage, low series resistance, and inability to follow instantaneous signal changes at microwave frequencies because minority carrier lifetime is much longer than the microwave signal period. Accordingly R_i does not change appreciably during a cycle of the applied RF signal and therefore the device behaves as a passive resistance. In switching applications this means that R_i will effectively remain at its biased value despite large excursions of applied signal, and consequently a PIN diode can handle almost twice as much signal voltage as a conventional diode with the same reverse breakdown voltage. Furthermore, the conventional diode requires a reverse bias equal to the peak signal voltage in order to maintain a low-conduction condition through a signal cycle, while a PIN diode does not require a reverse bias, although in some applications it might be desirable to use reverse bias in order to reduce leakage.

Basic Switch Applications of the PIN Diode

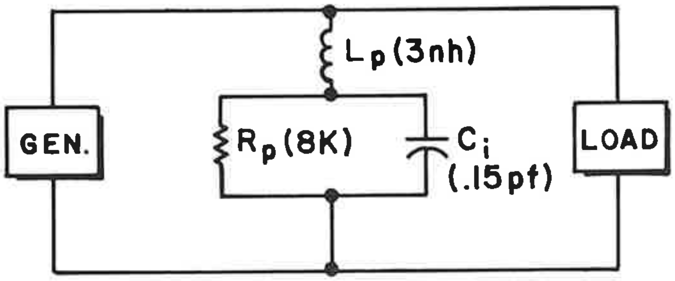
In switching applications there are two basic types of switches: broadband and resonant. These may each be further classified as series or shunt. As a matter of definition, a switch will be regarded as "closed" when it permits most of the RF power from the generator to reach the load, and "open" when most of the RF power from the generator fails to reach the load, being either absorbed or reflected.

Broadband switches operate on the principle of changing resistance, and the inevitable parasitic reactances constitute their upper frequency limit of operation. Insertion losses and isolation properties are determined by the upper and lower limits of the resistance change. Figure 2 - Broadband Switches Equivalent Circuits, gives these limits in terms of the diode equivalent circuit elements. The typical values used are given in parentheses and correspond to 50 ma forward or zero bias, as appropriate. Somewhat better operations could be obtained by going to higher forward current on the one hand and reverse bias on the other.

2A. SHUNT SWITCH

$$a = 20 \log_{10}\left(1+\frac{Z_o}{2R_p}\right) = .027 \text{ db}$$

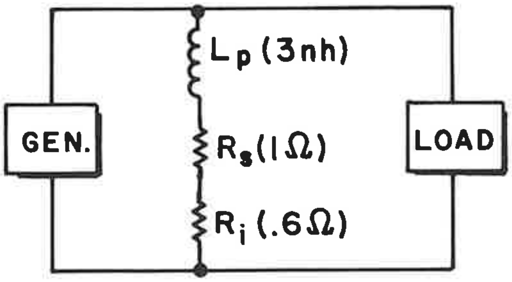
$$f_c = \frac{-Z_o}{4\pi L}\left(1-\sqrt{1+\frac{4L_p}{C_i Z_o^2}}\right) \approx 6 \text{ gHz}$$



1. Closed - RF passes to load (zero bias)

$$a = 20 \log\left(1+\frac{Z_o}{2(R_s+R_i)}\right) = 24 \text{ db}$$

$$f_c = \frac{R_s+R_i}{2\pi L} = .085 \text{ gHz}$$



a = Isolation (or insertion loss) in db

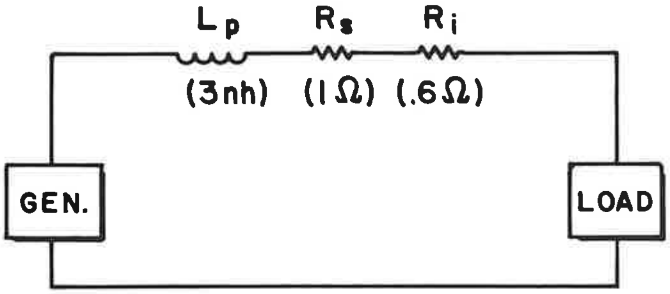
f_c = Upper frequency at which performance is degraded by 3 db.

2. Open - RF reflected back to generator (50 ma forward bias).

2B. SERIES SWITCH

$$a = 20 \log_{10}\left(1+\frac{R_s+R_i}{2Z_o}\right) \approx .14 \text{ db}$$

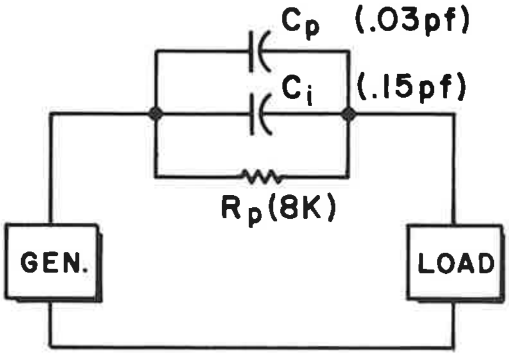
$$f_c \approx \frac{Z_o}{\pi L} \approx 5.3 \text{ gHz}$$



1. Closed - RF passes to load (50 ma forward bias)

$$a = 20 \log_{10}\left(1+\frac{R_s}{2Z_o}\right) \approx 38 \text{ db}$$

$$f_c = \frac{1}{2\pi R_p (C_p+C_i)} = .11 \text{ gHz}$$



2. Open - RF reflected back to generator (zero bias).

FIGURE 2. Broadband Switches - Equivalent Circuits

Associated with the closed or open state of each switch there is a critical frequency, f_c, in the neighborhood of which there is a degradation of performance. For the closed shunt switch (Figure 2A, 1) the resonance of the package inductance with the I layer capacitance, occurring at about 7gHz, will raise the insertion loss to 3 db at about 6 gHz. For the open state of the shunt switch, degradation results when the reactance of L_p becomes large with respect to the effective series resistance, and hence the isolation will decrease at the rate of about 6 db per octave, beginning at .085 gHz. The series switch, however, would operate well up to 1 gc. Insertion loss degradation occurs only when the reactance of L_p becomes appreciable with respect to 2 Z_o, hence the high critical frequency for 3 db degradation. Isolation starts at a fairly high value and decreases at the rate of only 20 db per decade so that at 1gHz it is still 18 db. Furthermore, by making the package inductance become part of the transmission line's distributed inductance, the critical frequency for insertion loss can be as high as 20 gHz.

Resonant switches (Figure 3) operate over narrow bandwidths. The principle of operation is to produce a large reflection with a sharply resonant circuit for the "open" state, and to merely spoil the Q of this resonance to achieve the closed state. It is possible to obtain good switching with very little forward bias. It should be noted, however, that in simple circuits such as those in Fig. 3, the isolation and the bandwidth of this isolation are inseparably related. The bandwidth, expressed in terms of the

Q is $\Delta f = \frac{f_o}{Q}$ and $Q = \frac{R_p}{w_o L_A}$

hence $R_p = QW_o L_A$ $\quad a = 20 \log_{10} \left(1 + Q \frac{W_o L_A}{2 Z_o}\right)$

Thus good isolation can be obtained only at the expense of bandwidth and vice versa.

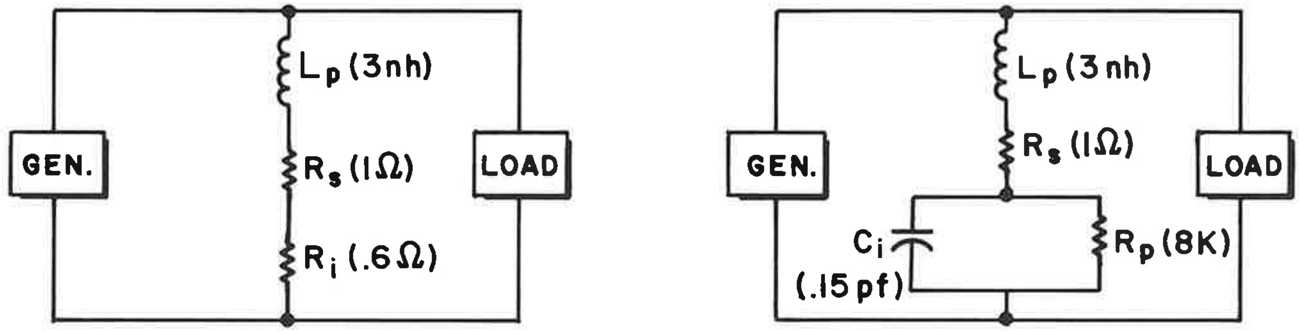
3A. SHUNT SWITCH

$$a = 20\log_{10}\left(1+j\frac{Z_o}{2W_oL}\right) = 1.3\ \text{db}$$

$$a = 20\log_{10}\left(1+\frac{Z_o}{2R_{equiv.}}\right) = 18.2\ \text{db}$$

$$W_oL = \frac{L}{\sqrt{LC}} = \sqrt{\frac{L}{C}} \approx 141\Omega$$

$$R_{equiv.} \approx R_s + \frac{R_p}{1+\left(\frac{R_p}{W_oL}\right)^2} \approx 1\Omega + 2.5\Omega = 3.5\Omega$$



1. Closed - RF passes to load (50 ma forward)

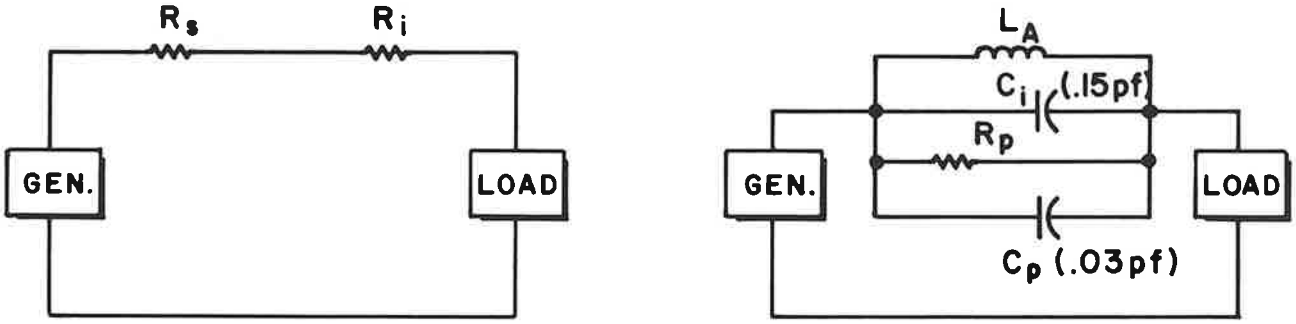
2. Open - RF reflected back to generator (zero bias)

3B. SERIES SWITCH

$$a = 20\log_{10}\left(1+\frac{R_s+R_i}{2Zo}\right) = .14\ \text{db}$$

$$a = 20\log_{10}\ 1+\frac{R_p}{2Zo} = 38\ \text{db}$$

$$f_o = \frac{1}{2\pi\sqrt{L_A(C_i+C_p)}} = 3.75\ \text{gHz}$$



1. Closed - RF passes to load (50 ma forward bias)

2. Open - RF reflected back to generator (zero bias)

FIGURE 3. Resonant Switches

Typical Designs of PIN Diode Switches

The diode package can be represented as shown in Figure 1 by high Q reactances which can be taken into account in the circuit design. Suppose, for example, that we have a receiver with a simple broadband mixer and a local oscillator at 1 gHz. The intermediate frequency is 30 mHz and it is desired to make a switchable stop filter to reject either 970 or 1030 mHz at will. The circuit of Figure 4 shows how high Q -hpa-3001 diodes may be used to perform this function. We assume a 50 ohm input transmission line and diodes represented by L_p, C_i and R_s.

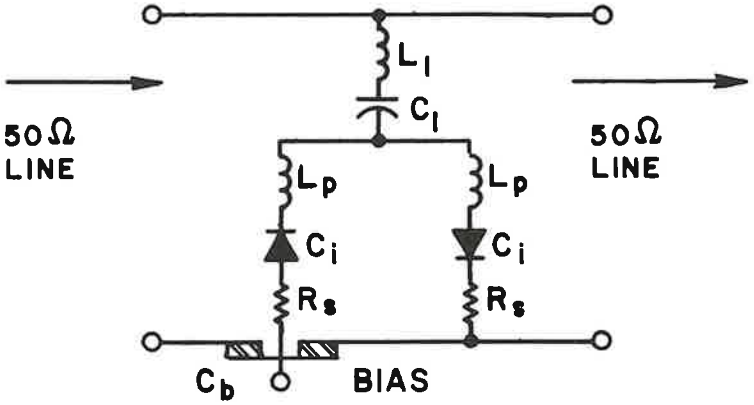


FIGURE 4. Frequency Shift Band Stop Filter

The package capacitance is neglected. The diode symbol is included in the capacitor symbol (C_i) to indicate polarity and to show that this element is switchable. The capacitance C_b is a bypass capacitor for the bias input lead. The two diodes are in series for bias but in parallel for RF. The diode parameters might be C_i = 0.159 pf, R_s = 1Ω. The capacitance C_i is made small compared to the diode capacitance so that switching the diodes from forward to reverse bias will change the total capacitance just enough to shift the resonant frequency of the network from 970 to 1030 mHz. The inductance L_i is required in addition to the diode lead inductance to resonate with the total capacitance at the desired frequencies.

The frequency shift to be obtained is 6%. A 12% change in capacitance is required since resonant frequency varies as the square root of capacitance. The total capacitance of the two diodes is 0.318 pf and the formula for capacitance of two capacitors in series may be applied to determine the value of C_1.

$$C_1 = 1.12 \left(\frac{C_1 \times 0.318}{C_1 + 0.318}\right) = \frac{0.356\, C_1}{C_1 + 0.318}$$

$$C_1 + 0.318 = 0.356$$

$$C_1 = 0.038 \text{ pf}$$

With the diodes forward biased, the effective loss resistance is one-half R_s or 0.5 ohm . The unloaded Q of the circuit is 4000. The insertion loss at 970mHz is determined by applying Ohms Law to a 50 ohm line with 0.5 ohm across it. This gives about 34 db. At 1030mHz a similar calculation shows that the insertion loss will be little more than 0.01 db. With the diodes reverse biased, the notch will move to 1030mHz with the same attenuation and the insertion loss at 970mHz will be about 0.01 db. A construction suitable for the circuit of figure 4 is shown in figure 5.

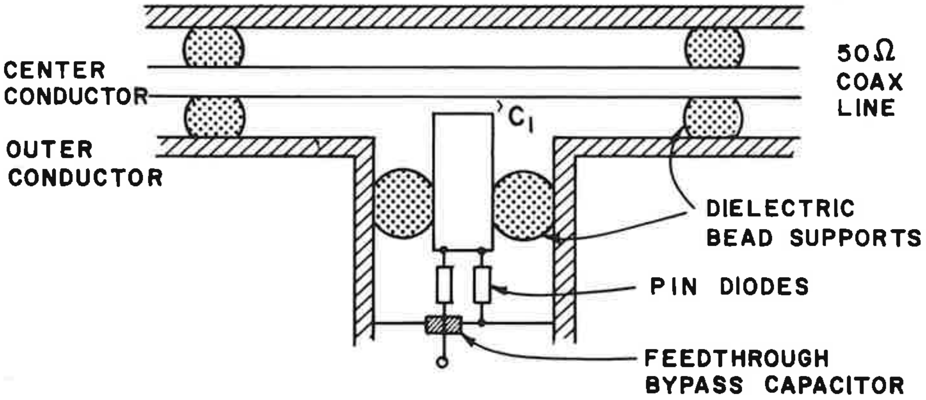


FIGURE 5. Construction Concept for Notch Filter.

The capacitance, C_1, is readily provided by a gap between conductors while the length of the shunt stub plus diode leads is made nearly $\lambda/4$ at 1gHz to obtain the inductance, L_1. One diode lead is brought out through a bypass capacitor for the bias connection. Because of the low loss of the -hpa-3001 diode, low loss construction techniques must be used to obtain performance close to that calculated. Similar methods can be used to construct high Q resonant circuits for oscillators in frequency jump applications. Planar tubes, external cavity klystrons, transistor, and tunnel diode oscillators should all be tunable by this technique. Power levels may be as high as several kw because little power is dissipated in the diode.

The PIN diode is well suited for these applications also because the junction capacitance does not vary with reverse bias voltage or forward current. Another important characteristic is the storage of charge during forward bias which permits these diodes to hold off high powers when used in shunt switching applications. As an example, suppose that the diode in Figure 6 is carrying a forward bias of 50 ma and has a lifetime of 200 ns.

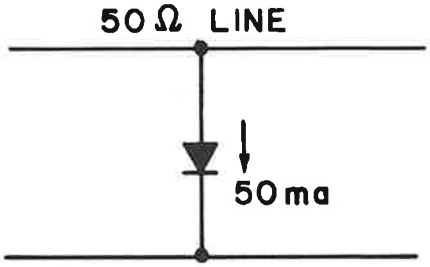


Figure 6. Simplified Shunt Diode Switch

The charge Q stored in the diode is the product of current and lifetime.

$$Q = I\tau = 0.05 \times 200 \times 10^{-9} = 10^{-8} \text{ coulomb}$$

The diode nearly short circuits the line so that any incoming signal causes the corresponding short circuit current to flow through the diode. If the current, I, is sinusoidal ($I = I_o \sin wt$) then the charge drawn from the diode during the negative half cycle is

$$Q = \frac{I_0}{\pi f}$$

Since the diode cannot be driven into reverse bias until all the stored charge is exhausted, we can equate charge to obtain a relation among bias current I, lifetime τ, frequency f, and peak short circuit ac current I_o.

$$Q = \tau I = \frac{I_o}{\pi f} \quad \text{or} \quad I_o = \pi I \tau f$$

So for $I = 50$ ma, $\tau = 200$ ns, $I_o = \pi f \times 10^{-8}$ and for $f = 10^9$ Hz= 1gHz

$I_o = 10\pi$ amperes.

This corresponds to an RF power of about 6 KW. So these diodes should be capable of holding off several kilowatts provided that the pulses are short and the duty cycle low enough that the maximum operating temperature is not exceeded by the RF heating caused by power dissipation. The temperature limited CW dissipation rating is 0.4 watt for the -hpa-3001.

The switching time of these diodes is related to the lifetime only because the stored charge must be extracted before the diode impedance will change from its forward to its reverse bias value. The speed with which charge is removed from the diode depends on the risetime and amplitude of the reverse switching voltage pulse applied to the diode and by diffusion time of the charge. By using spiked waveforms, the switching time of these diodes can be made 20 - 30 ns. Ordinary square waveforms will provide switching times of 100 ns or less if the source impedance is 50 ohms or less so that high reverse currents can flow.

Switching circuits can use a single diode in shunt or in series, or a combination of diodes close spaced or at quarter wavelength intervals. More outputs can be added to simple configurations to make SP4T and more complex switches. Each arrangement has certain advantages and limitations. With a single diode in shunt, the package inductance will reduce the isolation at high frequencies by preventing the diode from shorting out the line during forward bias. This effect becomes unimportant when the inductive reactance is only a few ohms,i.e.,at frequencies below 100 mHz.

With a single diode in series, the package inductance can be incorporated into the transmission line. This effect can be much enhanced by bringing the outer conductor very close to the diode near the center of the glass package. One way to do this, as shown in Figure 7, is to use a metal partition across the line with the diode mounted in a small hole using conductive epoxy. The effect of this device is to reduce the internal diode inductance and to use the excess inductance together with most of the package capacitance as a pi-section low pass filter during forward bias.

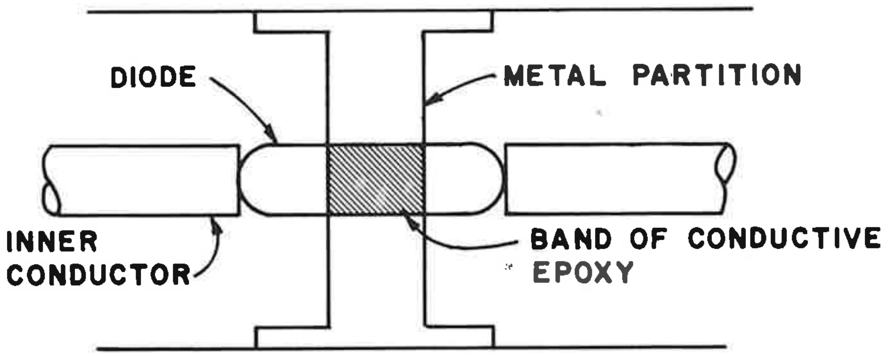


FIGURE 7. Method of Mounting -hpa-3001 to Shield Package Reactance

By this means, the frequency range of the series mounted -hpa-3001 may be extended to 5gHz and perhaps higher. About one third of the diode length should be within the shield.

Even if the inductance and capacitance of the package could be completely overcome, the junction capacitance of the diode would limit the obtainable isolation of the series mounted diodes. An expression for this effect may be obtained by analyzing the case of a single series capacitance shown in Figure 8.

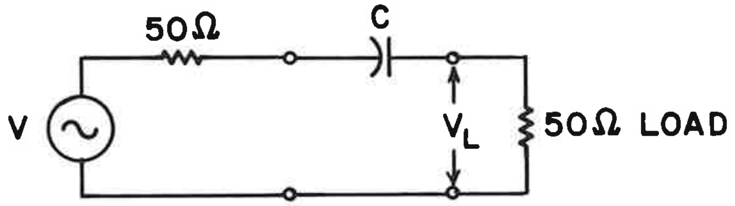


FIGURE 8. Simplified Reverse Bias Series Diode Circuit

The fraction of the available generator voltage, V, which reaches the 50 ohm load is

$$\frac{V_L}{V} = \frac{50}{100 + jX_C}$$

The power, P_{L1} reaching the load is $P_L = \frac{{V_L}^2}{50}$. Since the power P_{av}, available from the generator is $P_{av} = \frac{V^2}{4 \times 50}$, we can define the insertion loss L in db by the equation

$$L = 10 \log \frac{P_{av}}{P_L} = 10 (\log \frac{V^2}{4{V_L}^2}) .$$

Upon substitution, this becomes

$$L = 10 \log \left| 1/4 \left(\frac{100 + j X_c}{50} \right)^2 \right|$$

$$= 10 \log \left| \left(1 + j \frac{X_c}{100} \right)^2 \right|$$

$$= 10 \log \left(1 + \left(\frac{X_c}{100} \right)^2 \right)$$

For example, to obtain 20 db isolation we require that the bracket of the logarithm be 100, so that X_c must be nearly 1000 Ω. The reactance, X_c , is given in terms of capacitance and frequency by

$$X_c = \frac{159}{fC} \text{ ohms} \qquad \begin{array}{l} f \text{ in gHz} \\ C \text{ in pf} \end{array}$$

So to obtain 20 db isolation at 10 gc we would require a capacitance of 0.0159 pf. The -hpa-3001 with about ten times the capacitance will have 20 db isolation at 1 gHz.

There are two ways to increase the isolation obtainable from these diodes. One is to use two or more diodes in series with the transmission line but spaced $\lambda/4$ apart near the high frequency end of the band of interest. Then at the frequency where the diodes are so spaced, the isolation of "n" diodes is n times the isolation of one diode (in db). The insertion loss also increases, but if small diode reactances (at forward bias) are partly responsible for insertion loss, then quarter wavelength spacing will reduce the insertion loss by tuning out the reactances. By using two or more diodes, insertion loss of about 1 db with isolation of about 40 db or more can be obtained through S-band.

The other way to increase isolation is to resonate the diode. By this means, high performance can be obtained even in multiple throw switches at the expense of bandwidth. An equivalent circuit for analysis purposes is shown in Figure 9 and a means of constructing this circuit in Figure 10. The diode is placed inside the inner conductor of coaxial line across a gap. The capacitance of the gap is equal to the diode capacitance. During reverse bias, the diode capacitance and inductance are series resonant and effectively only the diode series resistance appears across the gap. Forward bias eliminates the diode capacitance leaving the inductance and gap

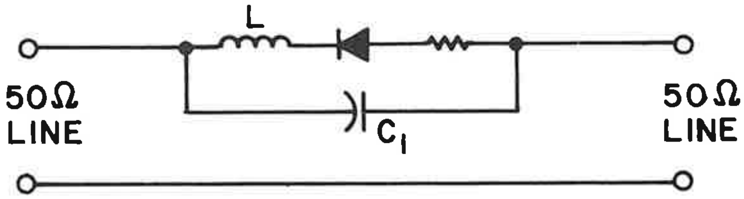


FIGURE 9. Equivalent Circuit For a Resonant Diode

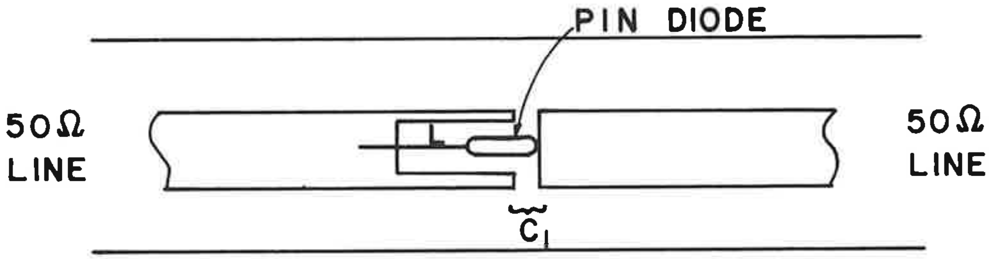


FIGURE 10. Construction of the Circuit in Figure 9.

capacitance to form a parallel resonant circuit in series with the line. The resonances are at the same frequency and provide a low insertion loss during reverse bias and a high isolation during forward bias.

The bandwidth of a resonant switch is determined by the loaded Q of the diode taking into account the source and load resistances. It is possible to obtain low insertion loss and high isolation over bandwidth of 10 - 25% using this circuit. The geometry is symmetrical and free from higher order modes and the action of the diode takes place at a well defined point on the line - the inner conductor gap. Two such diodes can be placed with their gaps separated by $\lambda/4$ to increase the bandwidth for both insertion loss and isolation, and simultaneously double the isolation.

This circuit, like the simpler shunt diode switch, can hold off high peak power because the diode is in forward bias for the "off" condition. The heat dissipation will be about the same for glass packaged diodes either way but ceramic packaged diodes can stand more cw dissipation if the stud on which the diode is mounted is connected solidly to a metal block. This is the case for the shunt diode configuration.

Attenuator Applications

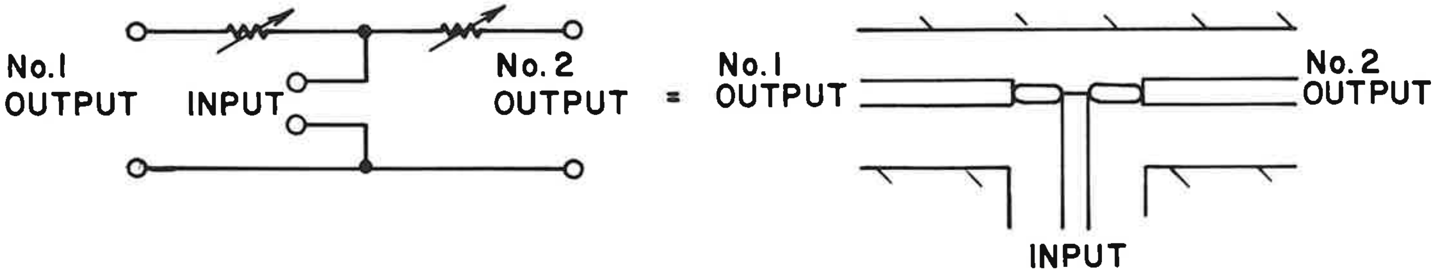
In addition to their use as switching elements, PIN diodes offer unique versatility as electrically-continuously variable resistances. Conventional diodes have been put to such use in the past, but because of their short lifetimes and high capacitance, the change of resistance during an excitation cycle produced serious harmonic distortion of the signal unless extremely low signal levels (<0.1 VRMS) were applied. Also, at high frequencies, the junction capacitance would predominate. The use of a PIN diode as an electrically variable resistance permits the application of microwave voltages higher by several orders of magnitude without the production of serious harmonic distortion. If instead of switching the bias from reverse voltage to forward current, we vary it continuously, the diode's capacitance remains fixed but a conductance appears in parallel with it. The magnitude of this conductance, G_i, varies with forward current almost linearly. The range of variation is so great that the diode changes from a high Q capacitance at 50 volts reverse bias, through increasing conductance to a near short circuit at 50 ma forward bias.

The high charge storage of -hpa-3001 also prevents harmonic generation and intermodulation of signals when the diode is used as a continuously variable attenuator. The reason is that so long as charge is stored in the diode by forward current, the diode conductance is very little affected by the alternating injection and extraction of charge by a high frequency signal. As a variable attenuator, the diode is operated with peak signal amplitudes less than one watt. Such small amplitudes hardly change the diode conductance during the ac cycle.

Since the conductance of the -hpa-3001 can be continuously varied by means of applied bias, a variety of attenuation and switching networks become possible. Some of these are shown in Figure 11.

a) TEE-Pad using three diodes

b) H-Pad using three diodes



c) SPDT switch and input matched attenuator

FIGURE 11. Variable Attenuator Circuits

Only the basic concepts are shown and additional connections using inductive chokes or quarter wavelength lines are required for applying dc bias to the diodes.

Other Applications

Although signal switching is perhaps the oldest of the control functions for which diodes have been used, other more sophisticated applications are growing in importance. The use of PIN diodes as harmonic free variable attenuators was a logical outgrowth of switching. More recently these diodes have been used in digital phase shifters and in the future will find an increasing number of uses as flexible, low loss control elements and variable resistances. The ability of these diodes to switch the frequency response of microwave filters without degrading Q opens up many new component and system design possibilities.