DIODE SWITCHING TOPICS

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Abstract

Diode switching topics are discussed. These include PIN junction theory, high power properties, and applicable filter theory.

Introduction

The diode switch is a well behaved microwave device in that the theory accurately predicts switching performance; permitting high reproducibility in manufacture. The diode switch has become a basic building block for microwave control devices. The microwave diode is at the heart of every digital diode phase shifter, of PIN diode variable attenuators, of diode limiters, and of solid-state diode duplexers. The advancement of most of these devices is limited by the depth of understanding of basic concepts in diode switching. Some topics yet unresolved are:

Hot Switching- Diode switches can handle high power in the ON or OFF state but not in transition. When trying to go between the ON and OFF states with high incident RF power, the diode goes through an impedance that permits it to absorb a large portion of incident power. If it goes through this impedance too slowly, the diode can absorb energy which prevents it from reaching the impedance level it needs to withstand the incident power. The diode then continues to heat up until it is burned out.

Self-Limiting- Diode duplexers have been made to control power levels above a megawatt, but they must be keyed (switched). Self-switching duplexers have been made up to 10 kW. Self-switching would be desireable at the higher power levels as well, to protect sensitive radar receivers from other transmitters as well as its own.

High Power Switching- Low power switching requirements are fairly well met by inexpensive broadband diode switches. But high power switches must use diodes having large junctions, which dictate large capacitance and narrow bandwidth. Hence for each application the switch must be custom designed, and the design is enhanced by using filter theory. Diode biasing for high power switching is also poorly defined. The theory for biasing to give maximum power handling capability or minimum intermodulation products has never been worked out.

Diode Switching Equations

The set of equations determining the performance of a single diode switch[1] is given in figure 1. The shunt diode is represented by G + jB while the series diode is represented by R + jX. Y_0 or Z_0 represent the characteristic admittance or impedance of the transmission line (bilaterally matched) in which the diode is mounted. In the power equations R_S is the forward bias resistance of the diode while E_B is the reverse breakdown voltage of the diode. The diodes are assumed biased to $E_B/2$ when in the nonconducting state. $\overline{P_D}$ is the average power the diode can dissipate.

PARAMETER	SHUNT DIODE	SERIES DIODE
ATTENUATION	$10\log\left[\left(1+\frac{G}{2Y_0}\right)^2+\left(\frac{B}{2Y_0}\right)^2\right]$	$10\log\left[\left(1+\frac{R}{2Z_0}\right)^2+\left(\frac{X}{2Z_0}\right)^2\right]$
AVG. POWER, $\bar{P}$	$\frac{\bar{P}_D Z_0}{4R_S}\left(1+\frac{2R_S}{Z_0}\right)^2$	$\frac{\bar{P}_D Z_0}{R_S}\left(\frac{R_S}{2Z_0}\right)$
PEAK POWER, $\hat{P}$	$\frac{E_B^2}{8Z_0}$	$\frac{E_B^2}{32Z_0}$

FIG. 1 Diode Switch Equations

PIN Diode Junction Theory

A PIN diode in fact consists of two diodes in series with a piece of resistive material between them[2] as shown in figure 2. The resistance of the material between the two junctions (I region) is determined by the number of free carriers injected into it by the two junctions. When there are no carriers, the resistance is high. When the current is 10-100 mA, the I region resistance drops

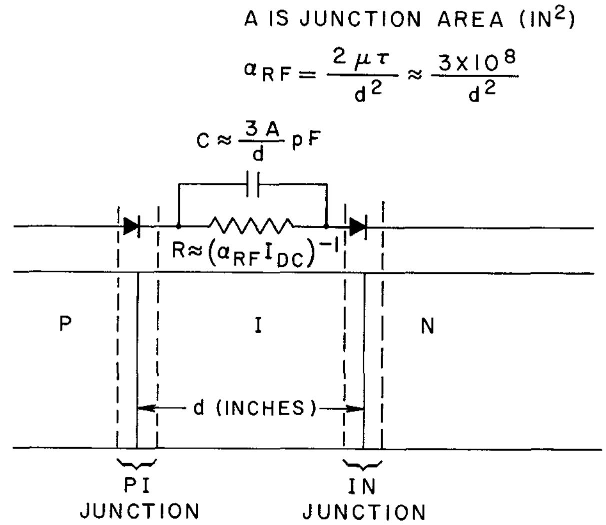

FIG. 2 PIN Junction Equivalent Circuit

to about 1 ohm. For a varactor d is typically about 1/10 mil (1 mil = .001 in). For a limiter diode it is about 3/10 mil, and for high power PIN diodes it is 1 to 10 mils.

At DC and low frequencies the I region has lower resistance than the two diode junctions. Therefore, the PIN diode impedance is dominated by the two diode junctions in series. The DC properties of a diode junction are given by

$$I = I_0 \left(e^{\alpha V} - 1\right) \qquad \text{eq. 1}$$

in which I_0 is saturation current ($\approx 10^{-9}$A) and α is the voltage-current coefficient (≈ 40). But the PIN diode has $\alpha \approx 20$. This is because at DC it is two diode junctions in series.

At low frequencies the capacitance of the two junctions also dominates the reactance as long as its reactance is higher than the 1 to 10 KΩ of the I region with no carrier injection.

At higher frequencies (above about 1 MHz) the capacitance of the two junctions causes them to have a much lower impedance than the I region, and the I region dominates the PIN diode impedance. The capacitance of the diode will be less at the higher frequencies by a factor of 10 to 100. The AC resistance also changes. By an accident of nature it has approximately the same dependence on current at high frequencies as

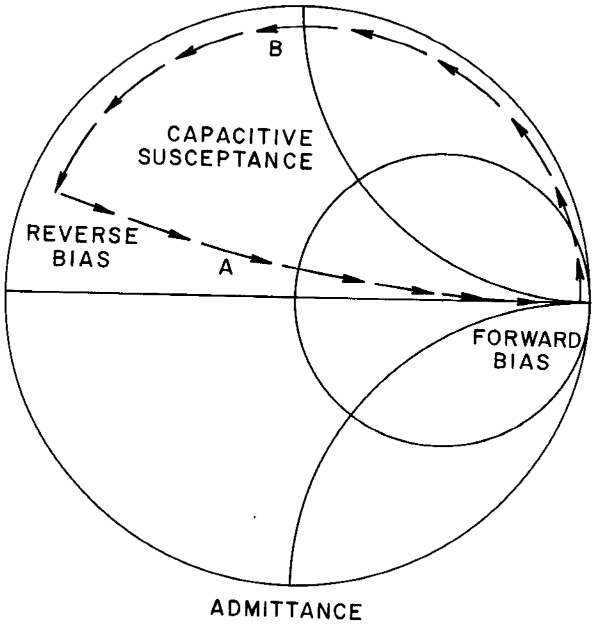

FIG. 3 PIN Diode Switching Admittance

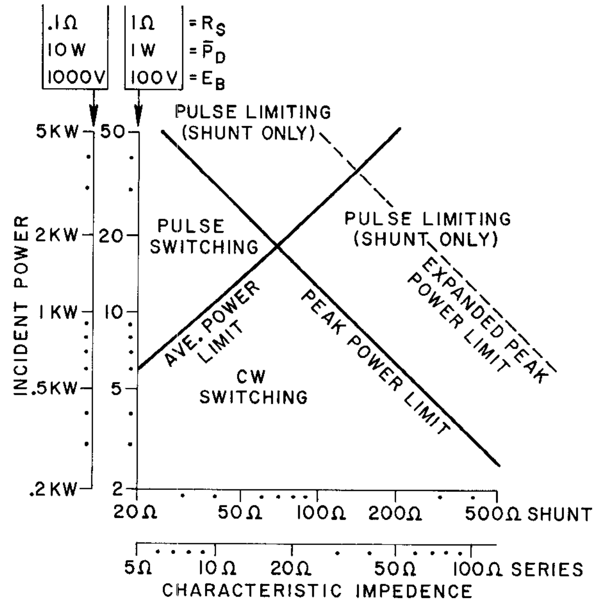

FIG. 4 Switching Diode Power Limits

it does at the low frequencies with the exception that the constant of proportionality is different.

The AC resistance R at low frequencies is obtained from equation 1.

$$\frac{1}{R} = g = \frac{\partial I}{\partial V} = \alpha\, I_o\, e^{\alpha V} \simeq \alpha I \qquad \text{eq. 2}$$

Since $\alpha \simeq 20$, then R = 1Ω should be given by 50 mA for all PIN diodes. The RF resistance is given by

$$R = \frac{1}{\alpha_{RF}\, I_{DC}} \qquad \text{eq. 3}$$

in which α_{RF} will range from 10 to 80 depending on I region height d, mobility μ, and lifetime τ as indicated on figure 2.

The switching properties of a PIN diode may be understood with the aid of figure 3. When the diode is driven into the conduction state very fast or very slow, it follows the resistive curve A. When it is driven into reverse bias very quickly, it follows curve B[3]. As it is driven into reverse bias more and more slowly, the characteristic approaches curve A. Referring to Figure 2 the strange behavior can be explained as follows:

Initially the I region is free of mobile carriers (nonconduction state). When the PIN diode is forward biased, injected carriers diffuse rapidly into the I region, meeting with no resistance. A uniformly conductive I region is resistive. Now assume the I region is heavily populated with injected carriers--both holes and electrons (conduction state). When reverse bias is suddenly applied, the I region continues to be conductive but the voltage is dropped at the two junctions. For example during conduction, electrons at the P-I junction are flowing from the I region into the P region and there recombine. When the voltage is reversed, these electrons turn around and begin heading back toward the N region. Now because the P-I junction does not inject electrons into the I region, all of the electrons are moving back to the N region as a block. At the same time a similar action is taking place with the holes at the I-N junction. The PIN diode continues to conduct very heavily in the reverse direction until all of the carriers have gone back to their planes of origin. Then the current suddenly drops to zero giving the sharp pulse well known in step recovery diodes. When these two walls of carriers meet a depleted I region begins to grow between them. The blocks of carriers are fully conductive back to their planes of origin so the growing depletion region looks like a capacitor with separating plates and thus a variable capacitance.

In order to have hot switching, either the diode must be able to dissipate the incident power in its most absorptive state or it must move through it so fast that no significant heating occurs as previously indicated. Heating accelerates the switching transient shown as curve A on figure 3 since higher temperature induces higher conductivity in a semiconductor. During the transient shown as B the PIN diode is a varactor and can "lock up" into harmonic interactional modes and never reach the reverse bias admittance point. The driving voltage may force the diode to an admittance point where it will absorb power and burn out. Theoretical and experimental work is needed to determine the limitations of hot switching and to find techniques to improve performance.

Another area in PIN junction theory that needs work is in the theory of rectification efficiency for self-limiting. A long I region and lifetime make for a PIN diode with high breakdown voltage and low forward resistance, but these two parameters contribute to poor rectification efficiency. Of course a limiter diode need not have a high breakdown voltage since it is in the conduction state whenever it has high RF power incident on it. It would be useful to know how the lifetime, I-region depth, and frequency combine to determine rectification efficiency. Then special self-limiting diodes could be made taking passive duplexers up to their maximum power and frequency capabilities.

High Power

The power rating of a typical diode is given in figure 4. Under both curves the diode is able to control both the peak power and average power. In the area of pulse switching it can control the peak power but not the average power; thus, the peak power can go up to the peak line, and the average power must remain below the average power limit line. Normally the peak power curve can be exceeded by a factor of 4 at the expense of inducing a slight amount of harmonic generation and intermodulation distortion. The only device that can exceed the peak power curve is the shunt diode operated as a limiter (including keyed limiters). Whenever the shunt limiter is subjected to high power, it is in the conduction state so it never has to hold off high voltages.

Figure 4 can be useful for estimating the power limitations for all other diodes. For example suppose a $R_S = 0.1\Omega$ $\overline{P_D} = 10$ W diode is used as a pulse limiter (in a duplexer) in $Z_o = 50$ transmission line. The $\overline{P}$ of 13.5 W is raised by one factor of 10 by $\overline{P_D}$ and by another factor of 10 by R_S. Thus the average power rating becomes 1350 W. Now suppose a duplexer is needed for a 1-MW transmitter at .01 duty ratio. Using a pair of 3-dB couplers with the limiters between them, each diode limiter would be exposed to 5-kW average power. Two of the above diodes in parallel would have twice the $\overline{P_D}$ of one and 1/2 the R_S of one; thus, the 1350-W limit would be increased by a factor of 4 to 5.4 kW. (As a practical matter, lower power limiters would follow the high power ones to clean up power leaking past them.)

It might seem that in biasing a PIN diode to 0.1-Ω resistance the high bias current would cause so much bias power to be dissipated in the diode that there would be no dissipation left for the RF power. But such is not normally the case. It is interesting that the DC bias voltage is dropped half across the PI junction and half across the IN junction. On the other hand RF voltage is dropped across the I region: thus, RF power is dissipated there. The heat is generated in different volumes, but it all must be conducted away via the P and N ends of the junction, so that the dissipation rating $\overline{P_D}$ of the diode is not altered but must include both sources of heat.

A decade increase in bias current on a PIN diode increases the voltage drop across the diode by .115 V. Therefore increasing bias current from 100 mA to 1 A to lower the resistance from 1 to 0.1Ω does not increase the dissipated bias power by 100 as might happen with a resistor but by 10, since the voltage across the forward-biased diode changes very little. The optimum bias current for maximum average power can be easily calculated. Since the forward-bias voltage drop across the PIN diode will be practically constant at 1 V, the bias power $\overline{P}_{Bias}$ is given by I_{DC}. The diode dissipation $\overline{P_D}$ permitted by the equations given in figure 1 is reduced by the bias power, the term becoming $(\overline{P_D} - I_{DC})$. Assuming R_s is dominated by the I-region resistance given in figure 2, the incident average power for a shunt diode becomes

$$\overline{P} \simeq \frac{Z_o}{4} (\alpha_{RF} I_{DC}) (\overline{P_D} - I_{DC}) \qquad \text{eq. 4}$$

$\overline{P}$ has its maximum value when $I_{DC} = \overline{P_D}/2$. Half of $\overline{P_D}$ is used in bias dissipation, and half, in RF dissipation. Thus using 1 W to bias a 10-W diode to 0.1 Ω could be considered conservative.

Filter Theory

The theoretical limit of bandwidth into which a given capacitance can be matched to a given resistor R for a constant reflection coefficient Γ is given by the Bode matching integral as

$$\ln \left| \frac{1}{\Gamma} \right| = \frac{\pi}{\omega CR} \qquad \text{eq. 5}$$

This is translated to insertion loss δ

$$\delta = -10 \log (1 - e^{-1/fCZ_o}) \qquad \text{eq. 6}$$

which gives the curves shown in figure 5. The degree to which this bandwidth can be realized is indicated by the cross marks on the same figure. They correspond to 5 pF in the middle of a five-element low-pass filter which is as good as can be obtained with a

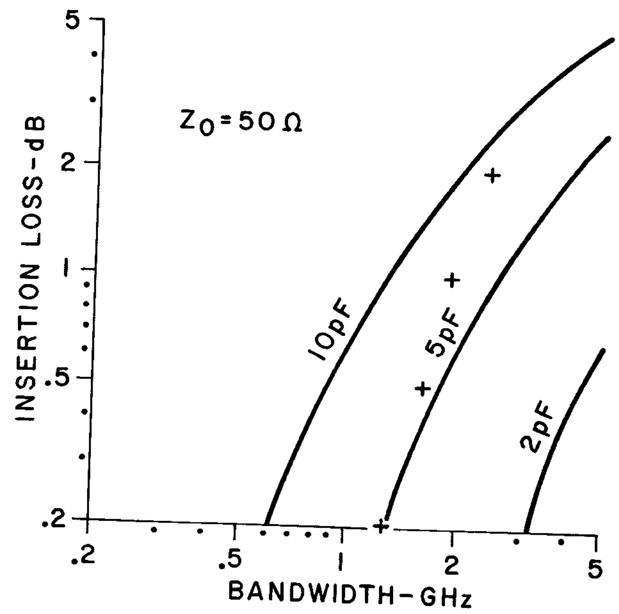

FIG. 5 Insertion Loss Bandwidth

lumped element IC filter structure in which the diodes (5 pF) are the middle elements. Thus even though typical high power diodes may have 2 pF each, they can be combined in a filter structure to give low insertion loss over a modest bandwidth.

Conclusion

Although the basic diode switch today is useful in making small, fast, broadband solid-state control devices it will be even more useful in the future with a little investment in understanding its basic operation. It will be able to control very high power levels over modest bandwidths.

References

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