# **CHAPTER -2**

# **PIN DIODE RF SWITCHES**

NOTES

## **CHAPTER 2 PIN DIODE SWITCHES**

## **INTRODUCTION**

A switch is an electrical component for opening and closing the connection of a circuit or for changing the connection of a circuit device [1]. An "Ideal Switch" exhibits zero resistance to current flow in the "ON" state and infinite resistance to current flow in the "OFF" state. A practical switch design exhibits a certain amount of resistance in the "ON" state and a finite resistance in the "OFF" state.

The use of PIN diodes as the switching element in microwave circuits is based on the difference between the PIN diode reverse and forward bias characteristics [Chapter One]. At lower microwave frequencies, f < 2 GHz), the PIN diode (including package parasitics) appears to be a very small impedance under forward bias and a very large impedance under reverse bias. It is the difference in performance between forward and reverse bias states upon which switch operation relies.

Most switch designs to be considered use a difference in reflection, rather than dissipation, to obtain switch performance. Very little power is dissipated by the diode itself, thus permitting small devices to control relatively large amounts of microwave power. Thus, PIN diode switches are reactive networks, where losses are a second order effect. In subsequent sections, we will see that switch circuits resemble filter circuits in many ways.

## FUNDAMENTAL PARAMETERS THAT DESCRIBE PIN DIODE SWITCH PERFORMANCE

## **ISOLATION:**

Physically, Isolation is a measure of the microwave power through the switch, that is not transferred to the load, both from Attenuation Loss and Reflection Loss, when the switch is OFF.

As a practical matter, Isolation is a measure of how effectively a PIN Diode Switch is turned OFF. It is determined by calculating the difference between the power measured at the switch output port with the switch biased ON and the power measured at the switch output port with the switch biased OFF.

Isolation (dB) =  $(P_{out})$ on (dBm) -  $(P_{out})$ off (dBm) Equation 2.1

This equation avoids the problem of accounting for the Transmission Loss through the physical structure of the PIN Diode Switch (all switches have some finite Transmission Loss). Transmission Loss is present whether the switch is ON or OFF.

#### **INSERTION LOSS:**

Insertion Loss  $(I_L)$  is the Transmission Loss through the physical structure of a PIN diode switch. In the forward biased case (the ON state), large values of bias current plus microwave current may flow through the switch structure, causing significant Ohmic Loss. In the reverse bias case (the OFF or Isolation state), only small values of leakage current flow through the switch, so the reverse bias loss is small.

If the switch is mechanically and thermally designed properly, Ohmic Losses and Thermal Dissipation are minimized and Insertion Loss is relatively low ( $I_L < 0.25 \text{ dB}$ ).

Insertion Loss is a particularly critical parameter for the Communications System designer. Insertion Loss absorbs signal power, causing the system's Noise Figure to increase by the amount of the Insertion Loss.

#### PIN DIODE POWER HANDLING LIMITATIONS

The RF System Requirement that usually determines the choice of the particular PIN Diode to be used is the RF power that the switch must handle. The PIN Diode characteristically has relatively wide I-region and can therefore withstand larger RF Voltages than Varactors or microwave Schottky diodes. In Chapter One (Large Signal PIN Diode Operation) the forward and reverse bias conditions, necessary to insure safe high power switch operations were discussed.

In this Chapter, the switch's Power Dissipation is considered as another limiting factor in determining the maximum RF power level that the PIN diode switch can control without overheating. Power Dissipation depends on  $R_s$  (which is a function of the forward bias current) relative to  $Z_o$ , on the input power to the switch,  $P_a$ , as well as on the switch connection chosen.  $P_d$  is a very important rating for a PIN switching diode and is given by all manufacturers.

Finally, the maximum RF power that the PIN diode is <u>capable</u> of switching depends on the incident power,  $P_a$ ,  $Z_o$ , the switch connection type, average Dissipated Power ( $P_d$ ), and on the Reverse Breakdown Voltage (VBR) rating. This parameter is also supplied by most manufacturers, with the stipulation that  $Z_o = 50$  Ohms and that the switch circuit is series-connected.

#### RF AND MICROWAVE SWITCH DESIGN CONFIGURATIONS

In this and subsequent sections, circuit diagrams of simple and compound switches are given, as well as additional performance information needed to design a switch. We assume in this development, that the individual switch structure is a symmetrical linear two port network and that the characteristic impedance ( $Z_o$ ) of the input power source, the switch structure, the load impedance, and any transmission lines connecting these components are 50 Ohms. For the more general case, where the input  $Z_o$  is not equal to the output  $Z_o$ , the reader is referred to reference [2] or any general text on general network theory.

#### SINGLE POLE SINGLE THROW SWITCHES

#### SERIES SPST SWITCH

The PIN diode SPST can be used in broadband designs. The maximum isolation ( $I_{SO}$ )obtainable depends on the diode's Capacitance ( $C_t$ ). The Insertion Loss ( $I_L$ ) and Power Dissipation ( $P_d$ ) depend on the diode's forward biased Series Resistance ( $R_s$ ). The equations for  $I_{SO}$  &  $I_L$  and the performance characteristics are given below.



Figure 2.1 Series SPST Switch

For Series SPST Switches:

$$I_{L} = 20 \log \{ 1 + R_{s} / 2 Z_{o} \}$$

$$I_{SO} = 10 \log \{1 + 1 / (4 \pi f C_t Z_o)^2 \}$$

Power Dissipation (P<sub>d</sub>) :

$$P_{d} = \{ 4 R_{s} Z_{o} / (2Z_{o} + R_{s}) \}^{2} P_{av}$$
 Watts

where  $P_{av}$  is the maximum available power,  $V_g{}^2\!/\,4\,Z_o$  (Watts).

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These equations pertain only to matched SPST switches. For VSWR ( $\sigma$ ) > 1.0, multiply these equations by the factor [  $2\sigma / \sigma + 1$ ], designated "sigma", to calculate P<sub>d</sub>.

Peak RF Current (SPST)	Peak RF Voltage (SPST)		
$I_p = \sqrt{2 P_{av} / Z_o} Amps$	$V_p = \sqrt{8 Z_o P_{av}}$ Volts		

If the series SPST switch is not matched, multiply the above equations by the factor "sigma".

## SHUNT SPST SWITCH

The Shunt SPST Switch (Figure 2.2) offers high isolation over a broad frequency range (approximately 20 dB for a singled diode switch). Insertion Loss is low because there are no switch elements in series with the transmission line. The diode is electrically and thermally grounded to one side of the transmission line and has higher  $P_d$  capability than the SPST circuit.  $I_{SO}$  and  $P_d$  are functions of  $R_s$ .  $I_L$  primarily depends on  $C_t$ . The design equations are given below.

For Shunt SPST Switches:

 $I_L = 10 \log \{1 + (\pi f C_t Z_o)^2\} dB$ 

Power Dissipation (Forward Bias):

 $P_{d} = 4 R_{s} Z_{o} / (Z_{o} + 2 R_{s})^{2} P_{av}$  atts

(where P<sub>av</sub> is the maximum available power)

Peak RF Current (Shunt Switch)

 $I_p = \bigvee 8P_{av} / Z_o Amps$ 

If the shunt switch circuit is not matched, multiply the above equations by the "sigma" factor.



Figure 2.2 Shunt SPST Switch

Power Dissipation (Reverse Bias)

 $I_{SO} = 20 \log \{1 + Z_o / 2 R_s\} dB$ 

 $P_d = \{Z_o / R_p\} P_{av}$  Watts

$$V_p = \sqrt{2 Z_o P_{av}}$$
 Volts

#### SINGLE POLE DOUBLE THROW SWITCHES



Figure 2.3 Series SPDT Switch



The simplest example of the more general Single Pole Multi-throw Switch structure is the Single Pole Double Throw Switch, in which the signal power in a single input transmission line can be connected to either of two output transmission lines.

If the SPDT switch is symmetrical, each switch branch performs like the SPST equivalent; but the Isolation of multi -throw switches is increased by 6 dB. This effect occurs because the OFF branch is shunted by the ON branch and its 50 Ohm termination, causing the RF Voltage across the OFF diode to be 50% less than would be the case for the equivalent SPST switch.

The Shunt SPDT Switch design in Figure 2.4 enhances the electrical performance of this switch by inserting quarter-wavelength transmission lines between the signal power source and the PIN diodes. The isolation of this design is approximately double (ie, 3 dB) that of the Shunt SPST Switch plus 6 dB due to the effect of the multi-throw switch junction. However, the bandwidth is now constrained to less than an octave.

#### **MULTI-THROW SWITCHES**

Multi-throw switches are difficult to realize using only shunt diodes. A band-limited shunt multi-throw switch (less than one octave) as shown in Figure 2.5, uses two cascaded quarter-wavelength sections, each terminated by a shunt diode. This configuration gives the OFF branch a high input impedance at the common (signal source) port to prevent impedance "loading" of the ON arm that would otherwise occur.



Figure 2.5 Band-Limited Shunt Multi-throw Switch

These configurations can achieve very high isolation (70 to 90 dB) with additional shunt diodes and transmission line sections. These designs would be even more constrained in bandwidth and Insertion Loss increases as sections are added. In the microwave bands, isolation is limited by cross coupling between switch components, causing some direct signal feed-through between input and output ports.

# **COMPOUND SWITCHES**

Compound Switches differ from multi-throw switches in that series-shunt switches are used in combinations to improve overall switch performance. The broad band Insertion Loss of the series switch is combined with the broad band Isolation of the shunt switch in a number of combinations to follow.

## SERIES-SHUNT COMPOUND SWITCHES



Figure 2.6 Series-Shunt SPST Switch

# **TEE COMPOUND SWITCHES**



Figure 2.7 TEE SP3T Switch

The simplest compound switches are the Series-Shunt Switch (Figure 2.6) and the TEE Switch (Figure 2.7). These circuits offer improved overall performance but the added circuit complexity degrades the VSWR and the Insertion Loss. Since all diodes are not simultaneously biased in one state or the other, there is an increase in bias circuit complexity. A summary of overall performance parameters for the Series and Shunt SPSTs and for the

Series-Shunt and TEE Compound Switches is shown for comparison in Table I. Performance parameter trade-off is inevitable in any practical switch design.

ТҮРЕ	ISOLATION (dB)*	INSERTION LOSS (dB)
SERIES	$10\log\left[1+\frac{1}{\left(4\boldsymbol{p}fC_{T}Z_{0}\right)^{2}}\right]$	$20\log\left(1+\frac{R_s}{2Z_0}\right)$
SHUNT	$20\log\left(1+\frac{Z_0}{2R_s}\right)$	$10\log\left[1+\left(\boldsymbol{p}fC_{T}Z_{0}\right)^{2}\right]$
SERIES-SHUNT	$10\log\left[\left(1+\frac{Z_0}{2R_s}\right)^2 + \frac{1}{4\mathbf{p}fC_TZ_0}\left(1+\frac{Z_0}{R_s}\right)^2\right]$	$10\log\left[\left(1+\frac{R_s}{2Z_0}\right)+\left(\boldsymbol{p}fC_T\right)^2\left(Z_0+R_s\right)^2\right]$
TEE	$10\log\left[1 + \left(\frac{1}{2\boldsymbol{p} fC_T Z_0}\right)^2\right]$ $+10\log\left[\left(1 + \frac{Z_0}{2R_s}\right)^2 + \left(\frac{1}{4\boldsymbol{p} fC_T R_s}\right)^2\right]$	$20\log\left(1+\frac{R_s}{2Z_0}\right)$ $+10\log\left[1+\left(\boldsymbol{p}fC_T\right)^2\left(Z_0+R_s\right)^2\right]$

## TABLE I. SUMMARY OF FORMULAS FOR SPST SWITCHES

\* For SPNT Switch, Add 6 dB

# **TUNED SWITCHES**

A simple tuned shunt SPDT switch was shown in Figure 2.4. The presence of quarter-wavelength transmission lines constrain the overall bandwidth but enhance the switch's performance over that bandwidth. Similarly, many RF switch applications operate over a limited frequency band. Distributed lines can be used to improve switch performance as the following examples show.



Figure 2.8 Tuned Series SPST Switch



Figure 2.9 Tuned Shunt SPST Switch

The Insertion Loss and Isolation for the circuits in Figures 2.8 & 2.9 can be calculated from the formulas in Table I. The total diode resistance,  $R_s$ , used in these calculations is twice that of a single diode SPST switch, unless the bias current is increased to off-set this effect. The maximum Isolation obtainable, using multiple diodes spaced a quarter-wavelength, is twice the dB value obtainable with a single diode switch.

A further increase in Isolation can be obtained by adding more quarter-wavelength sections to these designs. Such tuned switches have band widths less than 10 %, which is quite adequate for wireless radio applications (reference Chapter 6).

# TUNED SERIES SPST SWITCHES

Quarter-wavelength spacing reduces the maximum RF voltage across each diode to half of that which would appear across a single diode switch.

Even if the series diode had no quarter-wavelength spacing, the Isolation would increase by 6 dB, because the effective Capacitance is half of that of a single diode.

If this reduction in Capacitance is not primary to the design objectives, diodes with increased Capacitance could be used to increase the power handling capability of the switch

# TUNED SHUNT SPST SWITCHES

The maximum isolation obtainable using a Tuned Shunt SPST Switch is twice the dB value obtainable using only a single diode switch. Figure 2.4 shows a Double-throw Tuned Shunt Switch. In this circuit, the Capacitive Reactance of one diode is transformed by the quarter-wavelength line (into an Inductive Reactance) and resonates with the Capacitive Reactance of the second diode. This effect lowers the switch Insertion Loss by about 50%, but narrows the operating bandwidth. As with the Tuned Series SPSTs, quarter-wave spacing can be use higher power diodes with larger values of Capacitance ( $C_t$ ), but the effective bandwidth of the switch is lowered considerably.

# LUMPED CIRCUIT EQUIVALENT OF QUARTER-WAVELENGTH TRANSMISSION LINE

Quarter-wavelength techniques, using distributed line elements, are impractical at frequencies below UHF because of their physical size. Quarter-wavelength lines can be simulated with lumped circuit elements in a network such as that shown in Figure 2.10. The equations for calculating the equivalent L & C values are also shown.





#### **TRANSMIT - RECEIVE SWITCHES**

Transmit-Receive Switches are a class of Tuned Series-Shunt SPDT Switch, used by designers of Communications Transceivers to alternately connect the transceiver's antenna to either the Transmitter or to the Receiver. Figure 2.11 shows the typical T/R quarter line switch and its lumped circuit equivalent.



Figure 2.11 Quarter-Wavelength Antenna Switches

The quarter -wavelength line T/R Switch uses the unique property of the quarter-wavelength impedance transformer [3]. Ordinarily, the quarter-wavelength line is used to match two network elements of unequal impedance over a narrow band. If  $Z_1$  and  $Z_2$  are the unequal impedances, then they will be matched if the characteristic impedance of the transformer,  $Z_0$ , is related to  $Z_1 \& Z_2$  by the equation:

$$Z_0^2 = Z_1 \times Z_2$$

A 25 Ohm signal source can be matched to a 100 Ohm load if they are connected by a quarter wave line of characteristic impedance  $Z_0 = 50$  Ohms.

The T/R Switch uses this property to protect the Receiver.  $Z_o$  is fixed (usually 50 Ohms) and  $Z_1$  is either the low  $R_s$  of a forward biased diode or the isolation state (nearly open circuit) of the reversed biased diode. If  $Z_1$  is nearly a short circuit, the input impedance ( $Z_2$ ) to the quarter wave line is nearly an open circuit. The transmitter and antenna are disconnected from the receiver. Similarly, when  $Z_1$  is nearly an open circuit (high Impedance), the transmitter is disconnected from the antenna and the receiver is connected to the antenna.

The quarter-wavelength T/R switch is a relatively narrow band SPDT used in many Wireless Telecommunication Transceiver designs. The quarter-wavelength line constrains the bandwidth to 5% to 10%, which is adequate for most communications applications. When both diodes  $(D_1 \& D_2)$  are forward biased, the transmitter is connected to the antenna and the receiver is protected by the low  $R_s$  of  $D_1$  terminating the quarter-wavelength line. When  $D_1 \& D_2$  are reverse biased, the transmitter port is isolated by the high reactance of  $D_1$  and the quarter-wavelength line (terminated in an open circuit), and the Receiver port is connected to the Antenna.

The biasing scheme is very simple, requiring only one RF Choke Coil and a few d-c Blocking Capacitors. Greater than 30 dB isolation and less than 0.25 dB insertion loss can be obtained with a UM9401, which has an  $R_s$  of 1 Ohm and a  $C_t$  of 0.75 pF.

The maximum power,  $P_{av}$ , that this T/R switch can handle depends on the power rating of the PIN diode, Pd, and the forward biased diode resistance,  $R_s$ . If the antenna has a mismatch (VSWR =  $\sigma$ ),  $P_{av}$ , is given by the equation:

$$P_{av} = P_d Z_o / R_s \{(\sigma + 1) / 2\sigma\}^2$$

If the antenna is totally mismatched (perhaps the connection is broken),  $P_{av}$  is given by:

$$P_{av} = P_d Z_o / 4 R_s$$

We may observe further, that the RF current flowing in both  $D_1 \& D_2$  are nearly the same and so, both diodes dissipate about the same amount of RF power.

# **BROADBAND ANTENNA SWITCHES**

If more than 10 % bandwidth is required, more complex switch structures are required. The simplest broad band antenna switch to construct uses two series diodes in a Compound Switch configuration (similar to Figure 2.7) and is shown here as Figure 2.12.



Figure 2.12 Broadband Antenna Switch

Figure 2.12 is a more broad band SPDT switch, but the biasing scheme is more complex, requiring two bias tees and a d-c return coil, because  $D_1 \& D_2$  are alternately biased forward or reverse now. When the Transmitter is ON (and the Receiver is OFF),  $D_1$  is forward biased and  $D_2$  is reverse biased.  $D_1$  is reverse biased and  $D_2$  is forward biased when the Receiver is ON and the transmitter is OFF.

The Transmit / Receive isolation state depends solely on the reverse bias Capacitance of  $D_2$ , and this becomes the upper frequency limitation of the switch. The Isolation can be increased by using one of the techniques discussed in the "Tuned Switches" section. If  $D_2$  is replaced by two similar PIN diodes is series, the Isolation increases by 6 dB, without reducing the bandwidth significantly. Of course, two diodes will represent an increase in Insertion Loss unless the bias current is increased to off-set the increase in  $R_8$ .

Although PIN diode parasitic reactances somewhat limit the bandwidth over which low Insertion Loss and high Isolation can be achieved, the operating bandwidth can also be limited by the bias network, which is a filter network that isolates the d-c bias current from the RF circuit components. The frequency response of this bias network should be measured with the PIN diodes removed from the switch circuit.

 $D_1$  is selected primarily based on its power handling capability. The UM2101 series is recommended for HF Band and the UM4001 or UM4901 for VHF, UHF, and L-Band applications, either in the axial leaded (B package) or insulated stud (D package) because of their excellent thermal properties. For SMT circuit construction, the UPP9401 is recommended for  $D_1$ .  $D_2$  is not exposed to high RF currents and therefore should be selected for low Capacitance and low distortion. The 1N5767, the UM7301B, and the UPP1002 (SMT) are recommended for  $D_2$ .

As an example, if the UM9401 is used as  $D_1$  and the 1N5767 is used as  $D_2$ , the receiver isolation at 50 MHz will be greater than 40 dB, and at 500 MHz, greater than 20 dB.

## HIGH POWER BROADBAND ANTENNA SWITCH

An example of a high power broad-band antenna switch, designed to operate over the 10 to 100 MHz band, is shown in Figure 2.13.



Figure 2.13 High Power Broadband Antenna Switch

This switch can control 1 KW transmitter power with excellent distortion performance (IM3 < -80 dBc). The forward bias into Bias Terminal 1 is 1 Ampere, for low power dissipation in the transmitter diode and reverse bias of 500 Volts (at Bias Terminal 2) so that excessive RF current does not flow in the OFF state. HF Band (2 to 30 MHz) switches should use the UM2010 series and MF Band (0.3 to 3 MHz) switches should use the UM2310 series of PIN diodes.

# MUPTIPLE POLE-MULTIPLE THROW SWITCHES (M x N SWITCHES)

So far, we have only discussed single pole, single or multiple throw switches. A Switch Matrix is a generalization of the concept of the M x N Switch, in which any one of M inputs can be connected to any one of N outputs by means of the network of interconnecting switches. Reference [2] discusses this generalized case.



2.14 Double Pole - Double Throw Switch

The simplest case is the Double Pole-Double Throw Switch or Transfer Switch, which is quite important to RF circuit designers. The DPDT Switch allows a pair of input terminals to be connected to either of two pairs of output terminals as in Figure 2.14. The performance of each pair of connections can be analyzed as a SPST Switch. The DPDT Switch will be discussed in detail in Chapter 7, when it is used as a Transfer Switch for an Amateur Radio Transmitter Antenna. The application is to replace relays in RF Power Amplifiers.

DEVICE	HIGH VOLTAGE >2000 V	HIGH AVERAGE POWER >100 W	HIGH PEAK POWER >10 KW	HIGH POWER CW DUPLEXERS >100 W	ANTENNA SWITCHING >100 W	HIGH FREQUENCY > 1GHz	LOW FREQUENCY <10 MHz	ULTRA LOW FREQUENCY <1 MHz	L C
									к <
HUM2020	х	х	х	Х	Х		Х		
UM2100		Х	х	Х	Х		Х	Х	
UM2300		х	х	Х	Х		Х	Х	
UM4000		х	х	Х	Х		Х		
HUM4020	х	х	х	Х	Х		Х		
UM4300		х	х	Х	Х		Х		
UM7000		х	х	Х					
UM7100		х	х	Х					
UM7200									
UM7300		х	х	Х	Х		Х		
UM7500		х	х	х					
UM9401		х	х	х					
UM9415					Х				
UMM5050	х		х	х	Х				
UPP9401		х		Х					
UPP1004		Х		Х					

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