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PIN Diodes for High Power T/R Switches

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Introduction

In military radios, private land mobile radios and cellular base station failsafe switch systems, high power RF switching has been the province of ceramic-packaged PIN diodes for decades. Recently, new miniature plastic packages with excellent thermal properties have been introduced which enable circuit designers to design switches which safely handle tens of watts of continuous wave (CW) RF power while reducing cost and footprint of the switch. This paper discusses some basic operation theory of PIN diodes in switches, introduces these new PIN diodes and describes their performance in single-pole double-throw switch designs at frequencies up to 1 GHz and CW power levels up to 35 W.

PIN Diode Basics

The PIN diode is a 3-layer, 2-terminal device comprised of an intrinsically-doped (i.e., undoped) layer of semiconductor material, sandwiched between a layer highly doped with acceptor (p-type) atoms and another layer which is highly doped with donor (n-type) atoms. The layer doped with the p-type atoms is known as the P layer, the intrinsically doped layer is known as the I layer, and likewise the layer doped with n-type atoms is known as the N layer.

The I layer of the device presents a large impedance. If the PIN diode is subjected to forward bias, charge carriers are injected into the I layer from the N and P layers, which increases the number of free charge carriers in the I layer. As long as these free charge carriers exist in the I layer, the resistance of the I layer is reduced in proportion to the number of the free charge carriers present.

The holes injected from the P layer and the electrons injected from the I layer will recombine when they encounter each other in the I layer. The mean time free charge carriers exist in the I layer is known as the minority carrier lifetime, t_L. As long as the forward bias is maintained, the free charge carriers lost to recombination are continually replaced in the I layer.

If the PIN diode is subjected to zero or reverse bias, the I layer is evacuated of free charges so its resistance increases to its maximum value.

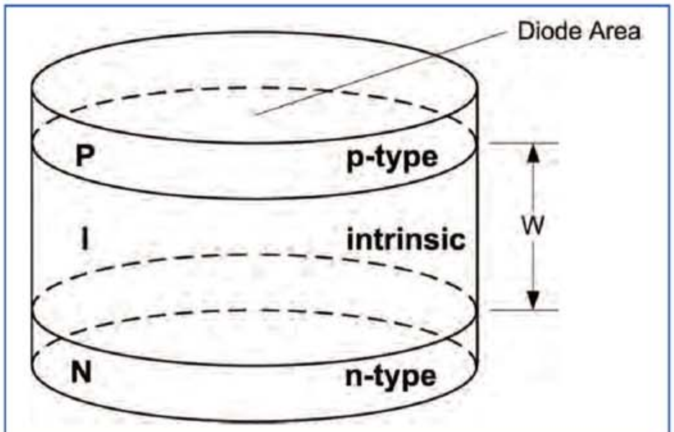

Figure 1: Layers of the PIN Diode

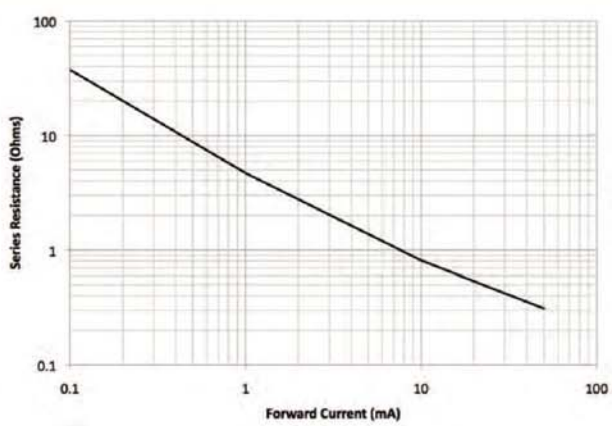

Figure 2: The RF Series Resistance vs. DC Forward Bias, SMP1324-087LF

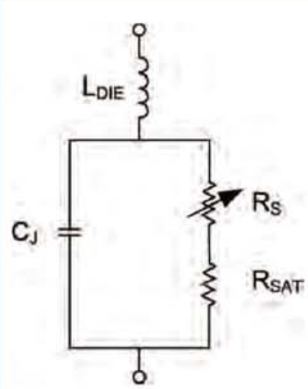

Figure 3: PIN Diode Die Equivalent Circuit

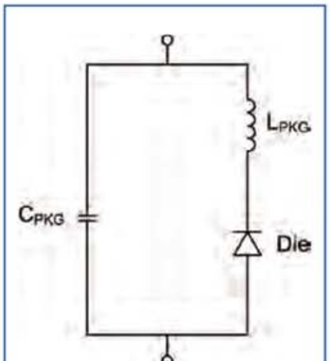

Figure 4: Packaged PIN Diode Die Equivalent Circuit

For a DC signal the PIN diode acts as a rectifier: current can flow when the diode is forward biased and current is blocked when the diode is reverse biased. Very low frequency AC signals, defined as signals whose periods are much less than t_L, will also be rectified since the duration of the AC alternation which reverse biases the diode is longer than the time required to conduct the free charge carriers out of the I layer.

For AC signals whose periods are significantly less than t_L, such as RF and microwave signals, the reverse-bias alternation is not present long enough to significantly reduce the population of free charge carriers in the I layer. Consequently, the resistance of the diode is not altered by such signals but is substantially controlled by the magnitude of the forward bias direct current and the characteristics of the diode. The PIN diode can be considered to be a direct-current-controlled, variable RF resistor. A typical series resistance vs. bias current curve for a representative PIN diode, SMP1324-087LF, is shown in Figure 2. The series resistance depicted was measured at a signal frequency whose period is much smaller than t_L.

The resistance of a typical PIN diode can be varied over three or more orders of magnitude by varying the DC bias current over several orders of magnitude. When the diode is biased in its nonconducting state, its very high impedance approximates an open circuit, and in its heavily-forward-biased state its very low resistance approximates a short, so it is often used as a solid state switching device for RF signals.

PIN Diode Equivalent Circuit

The PIN diode die can be represented by the simplified equivalent circuit shown in Figure 3. When the diode is packaged,

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its equivalent circuit must also include the parasitic reactances of the package, as shown in Figure 4.

The variable resistance in Figure 3 represents the variable I layer resistance. The fixed resistance, R_{SAT}, represents the total resistance of the saturated I layer in series with the resistances of the P and the N layers. For most PIN diodes, this resistance is of the order of tenths of an ohm. C_J is the junction capacitance of the diode, which depends upon the design of the die. L_{DIE} is the series inductance of the diode. For most chips, L_{DIE} is very small, typically of the order of 150 pH, so it is often omitted from analysis.

When the diode chip is packaged, its equivalent circuit must also include the parasitic reactances of the package, as shown in Figure 4. C_{PKG} is the shunt capacitance between the terminals of the package and L_{PKG} is the inductance produced by the conduction path through the package, including internal bond wires, lead frames, etc. For surface mount plastic packages, C_{PKG} is typically of the order of 100 fF to 200 fF and L_{PKG} may be as small as 350 pH and as large as 3 nH, depending upon the design of the package.

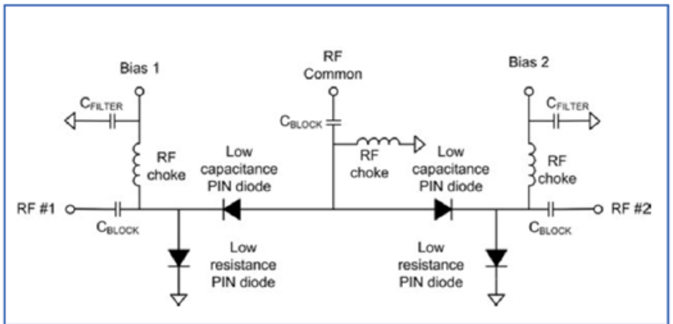

Figure 5: A Typical Symmetric SPDT T/R Switch

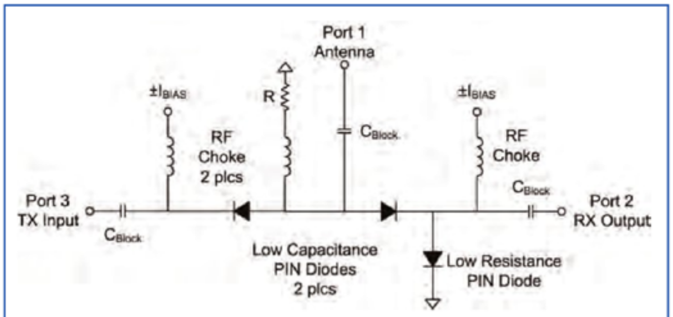

Figure 6: A Typical Asymmetrical SPDT T/R Switch

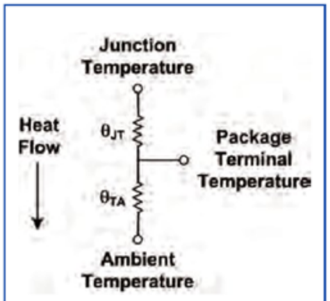

Figure 7: Thermal Schematic for the Diode-PCB Assembly

High Power Switching

In many wireless communications systems, the radio transceiver must have the ability to alternately connect the transmitter and the receiver to a common antenna. Primarily as a result of path loss, the receiver must be designed to process very weak receive signals and the transmitter must produce very large output power. The sensitive receiver could easily be damaged if the transmitter output signal is permitted to be incident on its input. Also, insertion loss between the transmitter amplifier and the antenna represents wasted energy as well as a possible source of internal heating, both undesirable effects. The performance of high isolation, high power handling, low loss transmit receive (T/R) switches is a very important part of the transceiver system design.

A representative single pole double throw (SPDT) symmetric T/R switch circuit is shown in Figure 5. This circuit comprises PIN diodes utilized as switching elements and some passive components used to decouple the RF and DC bias signal paths from each other.

In this circuit, the RF Common port is connected to the system antenna. Port RF #1 could be connected to the system transmitter output and Port RF #2 would then be connected to the system receiver input. Since this switch is symmetric, the connections RF #1 and RF #2 could be interchanged with no change in performance.

An alternative SPDT topology is shown in Figure 6. This circuit is very similar to that shown in Figure 5, with the main exception that the shunt diode on the transmit side of the switch is omitted. The primary motivations for this reduction are to reduce the insertion loss between the transmit input port and the RF common port, reduce the component count for the circuit, reduce the area which it occupies on a printed circuit board and to simplify the DC bias requirements for the switch. These benefits come at the cost of reduced isolation between the RF common port and the transmitter input port, which is generally of less importance than the factors described above, since in many systems the transmitter's power amplifier is turned off when the system is in receive mode.

In both of these SPDT circuits, the capacitance of the series diodes and the series resistance of the shunt diode(s) must be minimized in order to get high isolation. The need for low capacitance in the series diodes can be problematic, since low capacitance is achieved by reducing the junction area of the diodes, which in turn increases their thermal resistance.

In most transceiver systems the structures which act as electrical ground also comprise the main thermal path to the system heat sink. The series diodes must be isolated from electrical ground in order to perform their intended function, which makes it difficult at best to provide a low thermal resistance path from the series diodes' junctions to the system heat sink. The simplified thermal schematic for this diode is shown in Figure 7. Since the system designer has limited ability to minimize the portion of the thermal impedance between package terminal and heat sink (θ_{TA}), the series PIN diodes must have minimal thermal resistance between their junctions and their package terminals (θ_{JT}). The thermal resistance of the series diodes, especially the series diode on the Tx side of the switch, is of great importance in T/R switch designs.

Even if θ_{TA} is minimized through careful selection of PCB materials and design, its value can still be substantial, since there are practical limitations on how low the thermal resistance of the PCB can be.

Skyworks package style -087LF was designed to minimize θ_{JT} while accommodating PIN diode chips which are sufficiently robust to reliably withstand tens of watts of incident RF power. This package has a large exposed paddle to which the cathode of the PIN diode die is attached inside the package. The external surface of this exposed paddle is the cathode terminal of the package, which is soldered onto the PCB. This path produces minimal thermal resistance due to the metallic composition of the paddle and its physical dimensions. For example, θ_{JT} for SMP1324-087LF is 40°C/W

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typical, which is a factor of two or more lower than that of other surface mount, plastic packaged PIN diodes.

The internal anode connection is composed of a wire, bonded at one end to the anode contact of the die and at the other to a smaller metal terminal which is also exposed to the outside surface of the package, in the same plane as that of the cathode terminal.

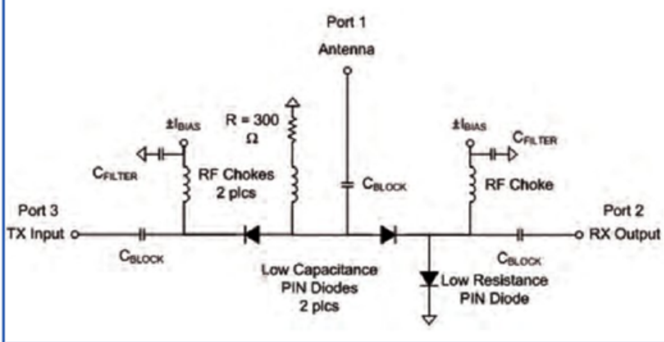

Figure 8: High Power T/R SPDT Switch Evaluation Circuit

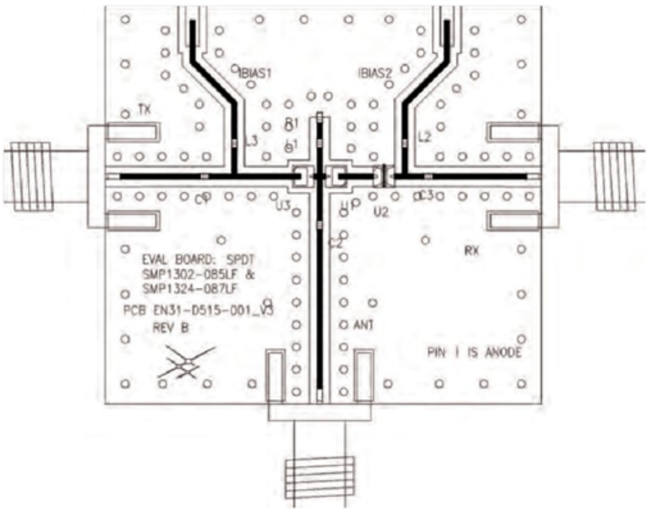

Figure 9: High Power T/R SPDT Switch PCB

Performance in SPDT T/R Switch Circuits

Transmit receive SPDT switches were designed and fabricated comprising three different PIN diodes, as shown in the schematic diagram in Figure 8. The first circuit utilized SMP1324-087LF as the series diodes in the asymmetric SPDT, with the SMP1302-085LF as the shunt diode on the receive side of the switch. The other circuit contains a pair of SMP1371-087LF PIN diodes in the series diode positions, again with SMP1302-085LF as the receive-side shunt diode. These circuits were evaluated for power handling capability as well as for small signal insertion loss and isolation for the transmit and receive states.

The SMP1324-087LF has very low series resistance (0.75 Ω maximum at forward current, I_F, of 50 mA), low capacitance (1.5 pF maximum at reverse voltage, V_R, of 30 V) and I layer thickness of 100 microns nominal for the high reverse breakdown voltage capability required to handle high power RF signals.

The SMP1371-087LF has very low series resistance (0.5 Ω maximum at forward current, I_F = 10 mA), low capacitance (1.2 pF maximum at reverse voltage, V_R = 20 V) and I layer thickness of 12 microns nominal for very fast switching time, with a slightly lower maximum RF power handling capability compared to that of the SMP1324-087LF.

The SMP1302-085LF is a 50 micron, 0.35 pF maximum, 1.5 Ω maximum, PIN diode packaged in a QFN package with three terminals which is optimized for low thermal resistance and shunt electrical connection. (For more details on all three of these diodes, including detailed data sheets, please visit www.skyworksinc.com)

The switches were designed for use in the HF (3 MHz to 30 MHz), VHF (30 MHz – 300 MHz) and lower UHF (300 MHz to 950 MHz) bands. The circuits were built using two different PCB materials: the ubiquitous and relatively inexpensive FR4; and, Rogers 5880, which has better thermal conductivity but somewhat higher cost than that of FR4. Significant attention was paid to providing adequate heatsinking by adding metal blocks to the undersides of the evaluation PCBs in order to dissipate heat. The topside view of the evaluation PCB is shown in Figure 9.

In this circuit, U3 is the series PIN diode on the transmit side of the switch, U1 is the series PIN diode and U2 is the shunt

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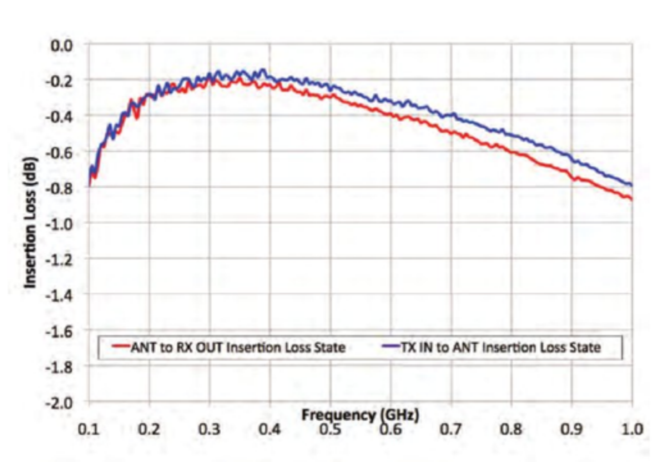

Figure 10: High Power T/R Asymmetric SPDT Switch Insertion Loss on Rogers 5880 PCB.

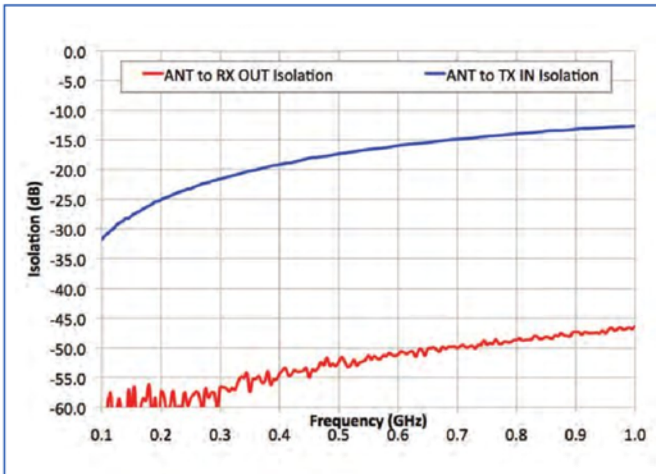

Figure 11: High Power T/R Asymmetric SPDT Switch Isolation on Rogers 5880 PCB.

Table 1

IBIAS1	IBIAS1	Tx to Antenna Path	Antenna to Rx Path
-50 mA	50 mA	Low loss	Isolation
28 V	-50 mA	Isolation	Low loss

Table 2

Series Diode Part No.	Max. CW Input Power on Rogers 5880 PCB	Max. CW Input Power on FR4 PCB
SMP1324-087LF	35 W	30 W
SMP1371-087LF	23 W	20 W

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diode on the receive side of the switch.

The circuits were controlled by applying ±50 mA bias currents from a 28 V supply to the IBIAS1 and IBIAS2 ports. The truth table for the switch circuit is shown in Table 1.

Power Handling

The lower thermal resistance of the Rogers 5880 material allowed the switches to safely handle higher input power than was the case for the circuit made with the FR4 PCB. The results for the combinations of PCB material and series diode types are shown below. The shunt diode on the RX side of the switches was SMP1302-085LF in all cases.

SMP1324-087LF/SMP1302-085LF T/R Switch Performance

The small signal insertion loss and isolation performance for the Tx and the Rx paths of the switch comprising SMP1324-087LF as the series diodes and SMP1302-085LF as the shunt diode, mounted on the Rogers 5880 PCB are shown in Figures 10 and 11.

The small signal performance of the other switches, built with FR4 and with SMP1371-087LF, are very similar to that shown in Figures 10 and 11.

[redacted]

Conclusion

New PIN diodes with thermally optimized, surface mount, low cost plastic packages permit high power handling as high as 35 W CW in T/R SPDT switch circuits in the HF, VHF and lower UHF frequency bands. These devices produce excellent small signal performance in addition to very robust large signal performance.

For more information, please visit www.skyworksinc.com.

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