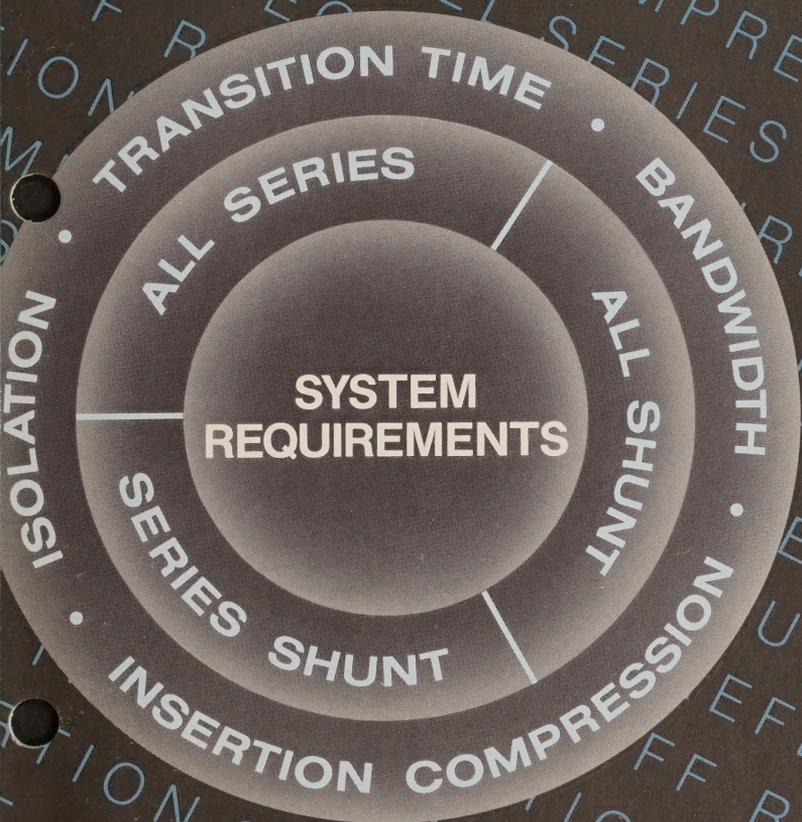


Microwave Switch Selection Techniques



WATKINS-JOHNSON COMPANY

Tech-notes

Pin-diode switches provide state-of-the-art switching performance in most present-day microwave systems, such as channelized receivers and electronic warfare systems. Yet, optimum system performance is not always realized, often because exact switching requirements are poorly communicated between the user and designer. Some parameters needed to specify pin-diode switches have several definitions in use within the control-products industry, and the interrelationships between these parameters are not always understood by the system designer. Microwave switches can be optimized for specific applications, but performance tradeoffs inherent in their design require the user to decide what parameters are most important for his needs. The purpose of this article, therefore, is twofold: to clearly define a set of parameters that characterize a pin-diode switch, and to discuss key performance tradeoffs, so as to develop a simple guide that will aid the switch user in selecting pin-diode switches.

Isolation

Although many parameters are used to describe pin-diode switch performance, four are of fundamental importance to the designer because of their strong interdependence: isolation, insertion loss, switching time, and power handling. Isolation is usually the first parameter of interest; the desired isolation determines how many diodes must be used in the switch circuit. Conceptually, isolation is a measure of how effectively a switch is turned off. It is calculated by taking the difference between the power measured at the switch input and the power measured at the switch output, with the switch off.

$$\text{Isolation [dB]} = P_{\text{in}}(\text{dBm}) - P_{\text{out,off}}(\text{dBm})$$

Note that isolation is a measure of the total power lost (reflected and atten-

uated) through the device when the switch is turned off. Since part of this isolation is due to transmission loss that is present within the device, whether the switch is turned on or off, it is often more meaningful for the switch user to specify isolation relative to the transmission loss. This normalized isolation is more commonly referred to as the *on/off ratio*, which can be calculated by taking the difference between the power measured at the switch output when the device is turned on, and the power measured at the switch output when the device is turned off. As can be seen, on/off ratio is actually the difference between isolation and transmission loss.

$$\begin{aligned} \text{On/Off ratio [dB]} &= P_{\text{out,on}} - P_{\text{out,off}} \\ &= (P_{\text{in}} - T_{\text{loss}}) - P_{\text{out,off}} \\ &= (P_{\text{in}} - P_{\text{out,off}}) - T_{\text{loss}} \\ &= \text{Isolation} - T_{\text{loss}} \end{aligned}$$

Insertion Loss

The transmission loss term used in the last equation is measured and calculated in exactly the same manner as isolation, with the exception that the switch is turned on rather than off. A more common term used to denote transmission loss is insertion loss. The insertion loss of a pin-diode switch is often the most critical parameter for the system designer, since this loss may add directly to the noise figure of the system.

Switching Time

Switching time is another parameter of special interest to the solid-state switch user; it is a measure of the time required for the switch to change state (i.e., on to off or off to on), and can range from several microseconds in high-power switches to a few nanoseconds in low-power, high-speed devices. The most common definition of switching time is

the time measured from 50% of the input control voltage (usually TTL¹) to 90% of the final rf power output (see Figure 1).

Notice in Figure 1 that two separate time intervals comprise the total switching time. The first period, from 50% TTL to 10% rf, denoted, t_{db} , is referred to as *delay time*, and is a function of both the propagation delay of the particular switch driver being used and the charge storage characteristics of the pin diodes in the switch circuit.² The second time interval, from 10% rf to 90% rf, denoted, t_r , is called *transition time* (or rise time), and is solely a function of the electrical characteristics of the pin diodes. As shown in Figure 1, delay time is usually the major factor contributing to switching time. Unfortunately, the transition time is frequently given as a device's switching time (which is especially common if the unit is supplied without a driver). Hence, when specifying switching time,

a good practice is to preface the switching time specification with the desired interval over which it will be measured (e.g., 50% TTL to 90% rf or 10% rf to 90% rf, etc.) One other important point about switching time is that although it is defined relative to the rf power, several techniques exist for measuring switching time that detect rf voltage. If rf voltage is used, the equivalent 50% TTL to 90% rf power switching time would be measured from 50% TTL to 95% rf voltage.

Power Handling

Several definitions of the term, power handling, are used in the control-products industry today. One definition is the maximum RF input power that the switch can withstand without *any* degradation in electrical performance. Another definition sometimes used is the rf input power below which no *permanent* degradation in switch performance will occur. The reason for the

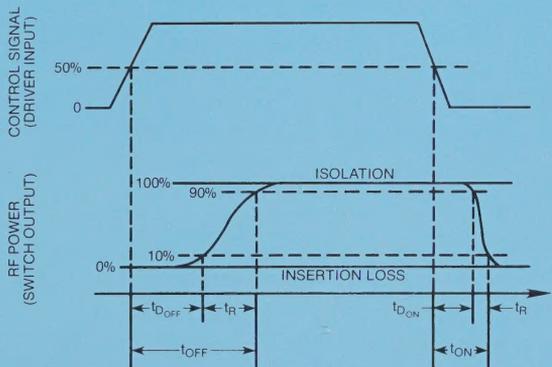


Figure 1. Switching time.

1. Standard TTL logic is defined as follows:

Logic Low ("0"): $0V \leq V_c \leq 0.4V$ at 10 mA max.

Logic High ("1"): $2.4V \leq V_c \leq 5.5V$ at 250 μA max.

where, V_c is the control voltage.

2. Many commercially available switch drivers employ output current waveshaping ("current spiking") to compensate for the delay due to diode storage charge.

multiplicity of definitions is simple: Power handling, in a qualitative sense, specifies a limit to the amount of power that a switch can withstand; yet no standard criteria for that limit has ever been established. The confusion is eliminated by redesignating power handling in terms of two different parameters, each of which is consistent with the parameters already used to describe other passive components. The first is, *maximum rf power*, which is defined as the maximum rf input power that a switch (or any other device) can withstand with no permanent degradation in electrical performance. The second term is, *insertion compression point*, which is defined as the rf input power at which the insertion loss increases by 1 dB above the loss measured with the switch operating in its linear state. As can be seen, insertion compression point is exactly analogous to the 1-dB compression point, which is generally considered to be the upper limit of a device's dynamic range.

A summary of definitions of microwave switch parameters appears in Table 1.

Categorizing Microwave Switches

To understand the basis for the trade-offs between key switching parameters, such as isolation and power handling, it is helpful to categorize microwave switches according to class, function, and diode configuration. All microwave switches fall into one of two distinct classes: *reflective* and *nonreflective*. Reflective switches reflect incident power back to the source when in the isolated state; nonreflective switches (or "matched switches," as they are sometimes called) are those devices which are designed to terminate any incident power when in the isolated state. Either type of switch will connect a source to a load when in the insertion-loss state.

Both switch categories can be divided into three groups, according to switch

Term	Definition
Isolation	Total power lost through the switch in the off state.
Insertion Loss	Total power lost through the switch in the on state.
On/Off Ratio	Isolation referenced to (less) the insertion loss.
Switching Time	Total time elapsed from 50% of the input control voltage to 90% of the final rf output power.
Transition Time	Time elapsed from 10% of the final rf output power to 90% of the final rf output power.
Delay Time	Time elapsed from 50% of the input control voltage to 10% of the final rf output power.
Insertion Compression Point	rf input power at which the insertion loss increases by 1 dB.
Maximum rf Power	Maximum rf input power that the switch can withstand with no permanent degradation in electrical performance.

Table 1. Summary of definitions.

3. Other configurations, such as double-pole, double-throw are merely combinations of switches from one or more of these groups.

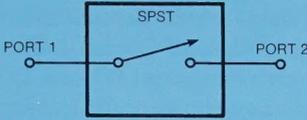


Figure 2. Single-pole, single-throw switch.

function: Single-pole single-throw (SPST), single-pole multithrow (SPMT), and transfer.³ An SPST switch is a two-port device which either connects the source to the load (in the insertion-loss state) or isolates the source from the load (as shown in Figure 2). An SPMT switch is a multiport device which can connect (or isolate) a source and any one of a number of different loads. Figure 3 shows an SP4T switch connecting a generator, G1, to a load, L2.

Loads L1, L3 and L4 are isolated from each other and the generator. Transfer switches are four-port devices that have two states; the truth table in Figure 4

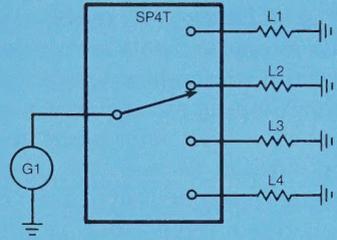
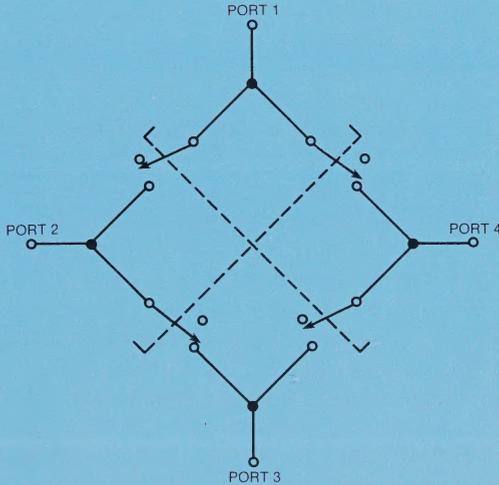


Figure 3. Single-pole, multithrow switch.

shows which pair of ports are connected and which are isolated in each state. Note that the insertion-loss port pair in state 1 is “transferred” to the isolated port pair in state 2.

There are three principle diode configurations which can produce the SPST, SPMT and transfer functions: All shunt, all series, and series/shunt. Consider the reflective SP2T switch using the all-shunt diode configuration



State	Insertion Loss Port Pairs	Isolation Port Pairs
1	1-4 2-3	1-2 3-4
2	1-2 3-4	1-4 2-3

Figure 4. Transfer switch.

of Figure 5. The input is connected to output 1 when diode D2 is biased into the low-impedance state and diode D1 is biased into the high-impedance state. The low impedance at D2 is transformed to a high impedance at the center junction through the quarter-wavelength transmission line. This transformed impedance is much greater than the impedance between the center junction and output 1. Hence, the signal will flow to output 1, and output 2 will be isolated from the input.

A schematic for an SP2T switch employing the all-series diode configuration is shown in Figure 6. When D1 is biased into the low-impedance state and D2 is biased into the high-impedance state, the input is connected to output 1. Output 2 is isolated from the input because of the high impedance at D2.

The SP2T switch in Figure 7 uses the series/shunt diode configuration. By biasing D1 and D4 into the low-impedance state, and D2 and D3 into the high-impedance state, the input is connected to output 1. The amount of isolation from the input to output 2 is directly proportional to the impedance ratio between D3 and D4. These three diode configurations can each produce any of the three switch functions, but with markedly different electrical performance.

In general, determining the class and function of a pin-diode switch is fairly straightforward. For example, a system may have 4 sources which must be selected and connected to a single output, as in a multioctave sweeper. An SP4T switch would perform this function if the common arm was connected

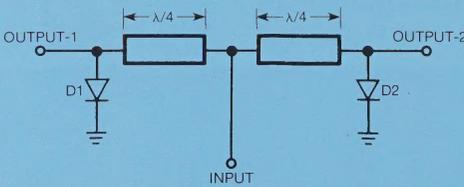


Figure 5. All-shunt diode, SP2T switch.

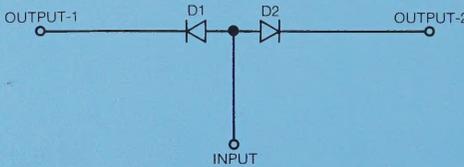


Figure 6. All-series diode, SP2T switch.

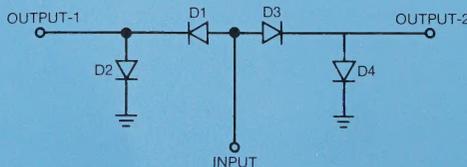


Figure 7. Series/shunt diode, SP2T switch.

to the output of the sweeper, and each source was connected to one of the other switch arms. The class of the switch needed is determined by the sensitivity of the load and sources to reflection. A reflective switch, such as the WJ MS401, can be used if the sources can withstand operation into a poor match when they are isolated from the sweeper output. Selecting the diode configuration, however, is considerably more difficult than choosing the class and function, because it involves numerous tradeoffs between isolation, transition time, power handling and bandwidth.⁴

Reflective Switches

Let's consider the all-shunt diode configuration for each of the three switch functions (see Figures 8, 9 and 10). In general, the all-shunt approach limits itself to octave bandwidths in the SPMT and transfer functions, because insertion loss changes drastically with frequency. The SPST function is not characterized by this same drastic change of insertion loss, and is, therefore, multioctave. Isolation in all three functions is high, but due to the electrical spacing between the diodes, it degrades as the frequency moves away from the quarter-wavelength frequency. In the insertion-loss state, a reverse dc voltage can be applied across the diodes that is limited only by their breakdown voltage. Thus, proper diode selection can provide insertion compression points of up to 10 watts, CW. However, a tradeoff exists between insertion compression point and transition time: Short to medium transition times can be realized for insertion compression points up to 2 watts, CW; for compression points up to 10 watts,

diode lifetime must be increased, causing transition time to exceed 200 nanoseconds. A summary of these switching parameter tradeoffs is given in Table 2, along with term definitions in Table 3.

Schematic diagrams of each switch function using the all-series diode configuration are shown in Figures 11, 12 and 13.

Bandwidth for all three functions is multioctave, and the insertion compression point is low. In the insertion-loss state, the diodes are on, and absorb rf energy as it passes through the switch. This absorbed power is the major factor limiting the maximum power capability. Also, due to the physical spacing of the diodes, isolation is frequency dependent. However, this frequency dependence is less severe than with the all-shunt diode configuration. The lowest isolation for the all-series approach usually occurs at the upper limit of the frequency range. Slow transition time is the major drawback of this diode configuration. When two or more diodes are in series, each cannot be connected directly to a low impedance dc source. Hence, for the diodes to be turned off, the stored charge in the I-layer of the pin diodes must recombine through another diode rather than directly through a dc source. This diode-to-diode recombination results in a net transition time that is much longer than that of either diode alone, and generally causes the transition time to fall into the "long" category. Since there is no stored charge in a diode that is turned off, the transition time from isolation (diodes off) to insertion loss (diodes on) can still be short. Once again, a summary of these performance tradeoffs is given in Table 2.

4. Insertion loss is also dependent on diode configuration, but to a much lesser degree. Generally, the greater the complexity of a solid-state switch (i.e., the number of components) the higher the insertion loss.

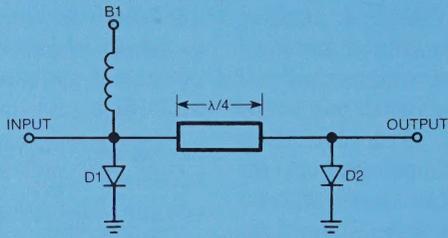


Figure 8. All-shunt diode, reflective SPST switch.

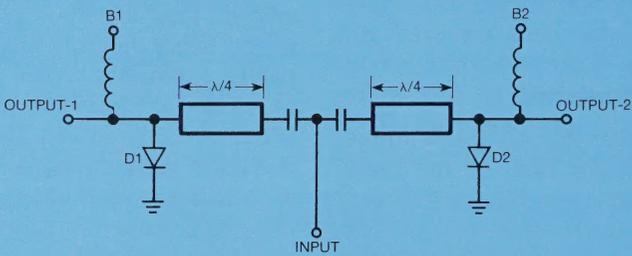


Figure 9. All-shunt diode, reflective SPMT switch.

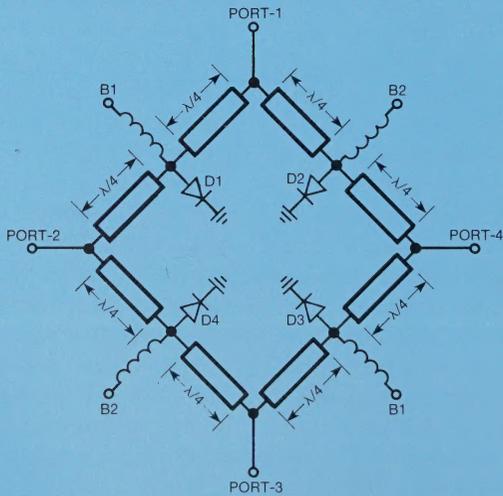


Figure 10. All-shunt diode, transfer switch.

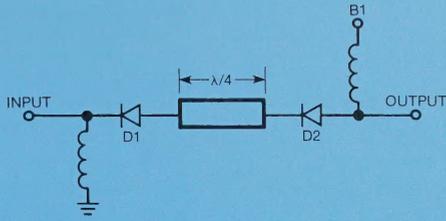


Figure 11. All-series diode, reflective SPST switch.

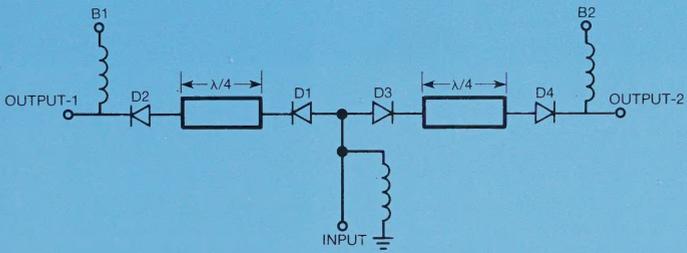


Figure 12. All-series diode, reflective SPMT switch.

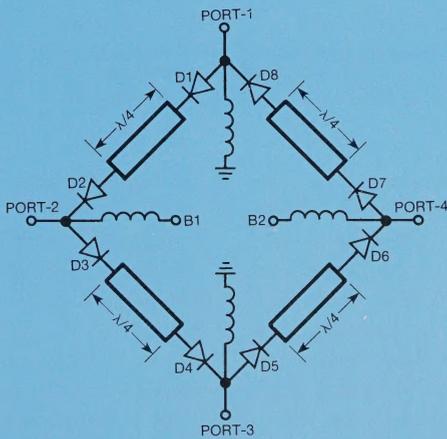


Figure 13. All-series diode, transfer switch.

Function	Tradeoff Parameters					
	Diode Configuration	Isolation	Transition Time	Insertion Compression Point	Bandwidth	Figure
SPST	All Shunt	High (freq. dependent)	Short	High	Multi-octave	8
	All Series	High (freq. dependent)	Long	Low	Multi-octave	11
	Series/Shunt	High	Short	Low	Multi-octave	14
SPMT	All Shunt	High	Short	High	Octave	9
	All Series	High (freq. dependent)	Long	Low	Multi-octave	12
	Series/Shunt	High	Short	Low	Multi-octave	15
TRANSFER*	All Shunt	High	Short	High	Octave	10
	All Series	High (freq. dependent)	Long	Low	Multi-octave	13
	Series/Shunt	High	Short	Low	Multi-octave	16

*Transfer switches are actually nonreflective due to the nature of their function.

Table 2. Tradeoff chart for reflective switches.

Term	Tradeoff Parameters		
	Isolation	Transition Time	Insertion Compression Point
Low (Long)	20 dB to 30 dB	($t \geq 200$ ns)	100 mW max.
Medium	30 dB to 45 dB	$50 \text{ ns} \leq t < 200$ ns	100 mW to 2 Watts
High (Short)	45 dB to 60 dB	($5 \text{ ns} \leq t < 50$ ns)	2 Watts to 10 Watts

Table 3. Term definition table.

Table 2 also indicates how the series/shunt diode configuration affects the four tradeoff parameters for each of the three switch functions shown in Figures 14, 15 and 16. This diode configuration, which is used in many high performance W-J switches, such as the 2 to 18 GHz MS202, provides high isolation and short transition times over multi-octave bandwidths. The only real drawback to the series/shunt configuration is its low power-handling capability. In the insertion-loss state,

the shunt diodes are exposed to the peak rf voltage, yet the reverse dc voltage across these same diodes is limited to only one volt, because of the forward voltage of the series diode. This small reverse bias allows the shunt diodes to be forward biased by a much smaller rf voltage than would be possible if the reverse voltage were high, and results in a lower insertion compression point. Despite its lower compression point, the series/shunt configuration provides the best overall

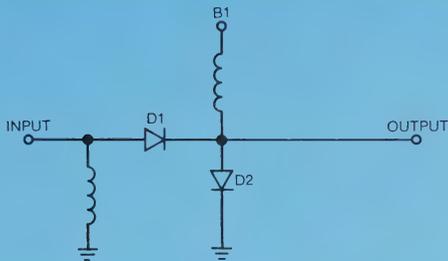


Figure 14. Series/shunt diode, reflective SPST switch.

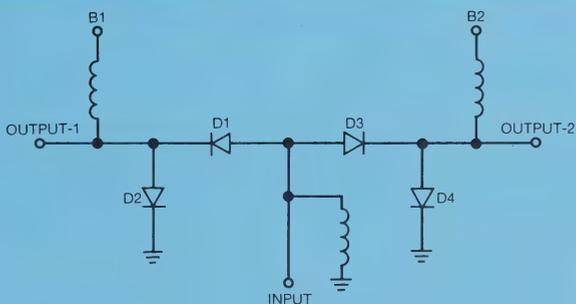


Figure 15. Series/shunt diode, reflective SPMT switch.

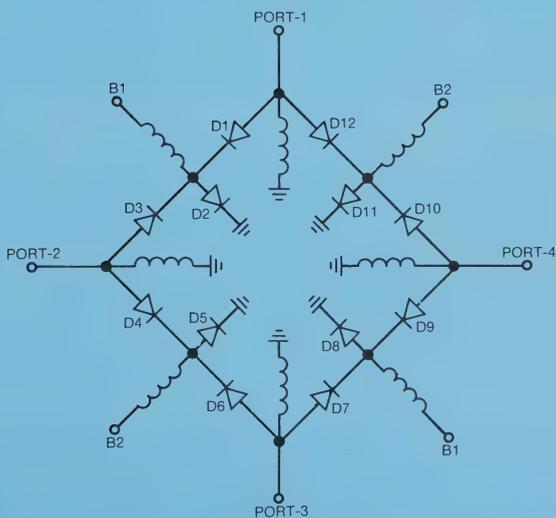


Figure 16. Series/shunt diode, transfer switch.

performance for a given number of diodes, and is the most commonly used design approach for reflective switches.

Nonreflective Switches

Any SPST⁵ or SPMT reflective switch can be made nonreflective by adding a shunt diode in series with a resistor at the input to each arm (compare Figures 8, 9, 11, 12 and 15 with Figures 17, 18, 19, 20 and 21, respectively). This diode-resistor combination is designed to provide a 50-ohm load impedance to the system to absorb the rf energy when the switch is in the isolated state. Although diode configuration affects

the four tradeoff parameters in exactly the same way as for reflective switches, the 50-ohm load has an additional effect on power handling and bandwidth. First, for any diode configuration or switch function, maximum rf power is limited to the power dissipation capabilities of the resistor, which usually limits the maximum rf power of the switch to the "medium" category. Second, due to the quarter-wavelength spacing between the diode-resistor pair and any adjacent shunt diode, the bandwidth for both the all-shunt and series/shunt diode configurations will be reduced to an octave. A summary of the tradeoffs between isolation, transi-

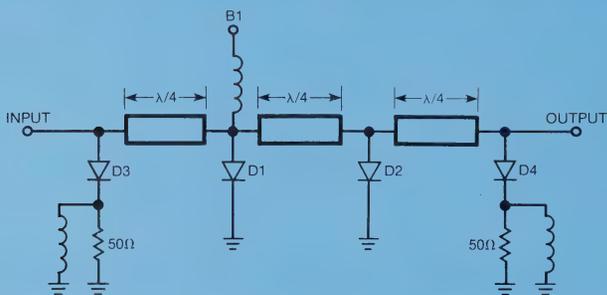


Figure 17. All-shunt diode, nonreflective SPST switch.

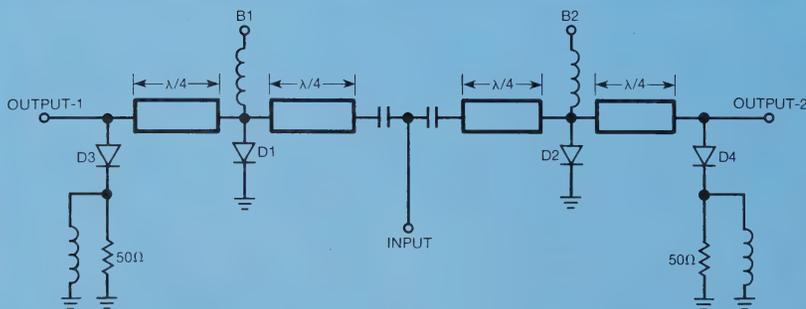


Figure 18. All-shunt diode, nonreflective SPMT switch.

5. The SPST series/shunt nonreflective switch cannot be practically realized.

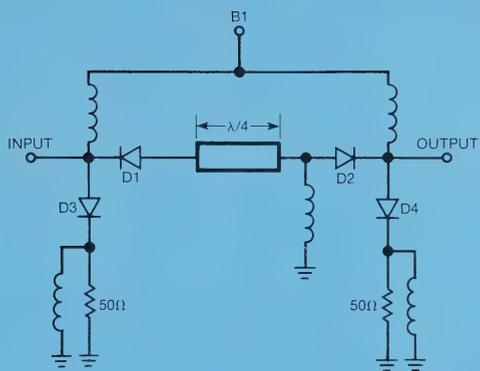


Figure 19. All-series diode, nonreflective SPST switch.

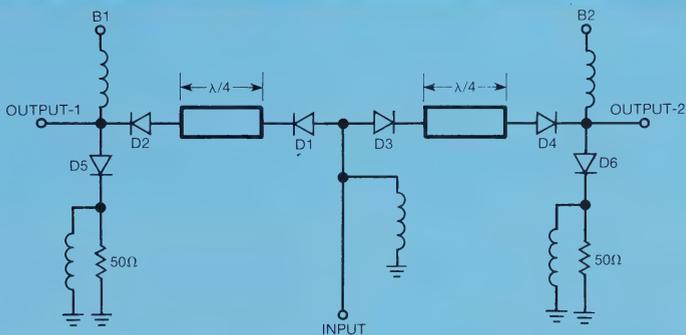


Figure 20. All-series diode, nonreflective SPMT switch.

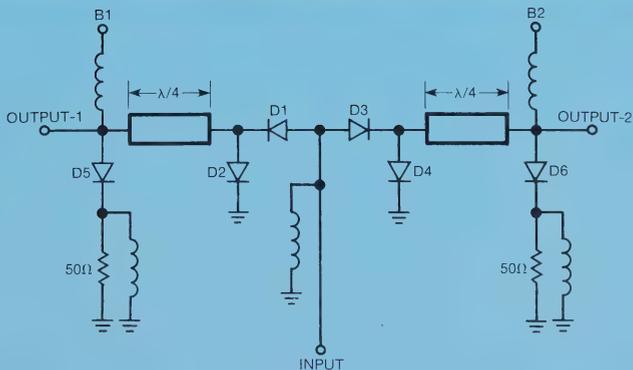


Figure 21. Series/shunt diode, nonreflective SPMT switch.

Function	Tradeoff Parameters					
	Diode Configuration	Isolation	Transition Time	Insertion Compression Point	Bandwidth	Figure
SPST	All Shunt	High	Short	Medium	Octave	17
	All Series	High	Short	Low	Multi-octave	19
	Series/Shunt	(See Note 5)				
SPMT	All Shunt	High	Short	Medium	Octave	18
	All Series	High	Long	Low	Multi-octave	20
	Series/Shunt	High	Short	Low	Octave	21

Table 4. Tradeoff chart for nonreflective switches.

tion time, insertion compression point, and bandwidth for nonreflective switches is given in Table 4.

Example

The use of the tradeoff charts is best illustrated with an example. Consider a system that has the following switch requirements:

Function:	SP3T
Frequency Range:	2.5 to 10.0 GHz
Isolation:	40 dB (min.)
Insertion Compression Point:	+17 dBm
Maximum rf Power:	+30 dBm
Insertion Loss:	3 dB (max.)
Switching Time:	40 nsec (max.) [50% TTL to 90% rf]
VSWR:	2.0:1 (max.) [Insertion Loss State]

To access the manufacturability of this switch, the first step is to convert the quantitative electrical specifications for isolation, transition time and insertion compression point to their corre-

sponding qualitative ranges via Table 3. For the switch in this example, the isolation requirement of 40 dB falls into the "medium" range, and the insertion compression point of +17 dBm is in the "low" range. Since the electrical specification calls for a switching time of 40 nsec, clearly, the transition time must be in the "short" category. Once these three numbers have been converted, the next step is to compare the desired switch performance with that of each of the 3 switch types from Table 2 or 4. The switch in our example is a reflective SPMT⁶; therefore, we will compare the specifications of our switch with those of the three SPMT switches in Table 2. The objective of this comparison is to determine if any of these three switches will meet (or exceed) the required performance specifications. If one or more do, it would be fairly certain that the specified switch performance could be readily achieved in practice.

Looking at Table 2, an all-shunt SPMT switch would meet or exceed all electrical specifications, with the exception that this design is effective only over octave bandwidths, and, thus, would not be useful for the 4:1 bandwidth

6. Since no maximum VSWR is specified for the isolation state, we assume that the system is not affected by the VSWR of the isolated arms; therefore, a reflective switch can be used.

switch in our example. The all-series SPMT switch is multioctave, and meets or exceeds both the isolation and the insertion compression point for our switch requirement. However, Table 2 also indicates that the transition time for this type of SPMT switch is long, which is not compatible with the short switching time needed. Comparing our switch specifications to those of the series/shunt SPMT switch in Table 2, we see that this design will meet or exceed all four switch requirements. Hence, we can conclude that our switch specifications are realizable.

If the switch in this example needed an insertion compression point of +30 dBm (which falls into the “medium” range), then none of the three SPMT switch configurations in Table 2 would meet all four performance requirements simultaneously. The system designer should then reevaluate his switch requirement. For instance, he may find that each arm of the SP3T switch need only operate over a portion of the 2.5 to 10-GHz frequency range originally specified. If the frequency range of each arm is an octave or less, then this switch requirement can be fulfilled by an all-shunt SPMT switch, and the

electrical specification should be rewritten to specify the frequency range of each arm.

Conclusion

Several switching parameters have been defined with the intent of standardizing the terminology used to describe pin-diode switches. By utilizing terms that are standard throughout the control products industry, the system designer can comfortably specify the pin-diode switch required for the system. Also, four parameters — isolation, transition time, insertion compression point and bandwidth — were selected as key tradeoff parameters, because of their strong interdependence. The interaction between these four parameters was shown to stem from the particular diode configuration used for the switch circuit, and, ultimately, allowed us to develop charts which qualitatively and quantitatively compared the three switch types for each of the three diode configurations. Finally, an example was given to illustrate how the tradeoff charts could be used by a system designer as an aid in determining the most practical switch for the system.

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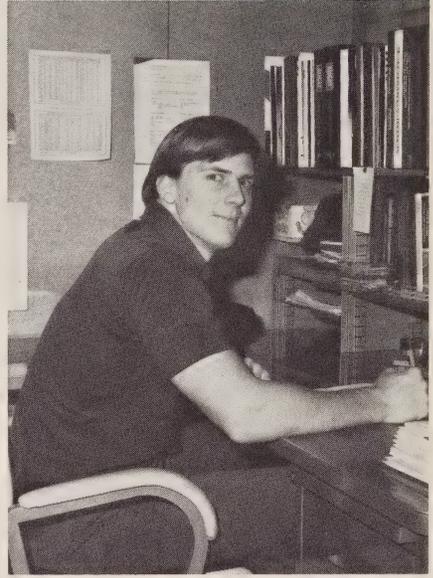


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Some of Mr. Algeri's previous responsibilities at Watkins-Johnson Company include design and development of microwave integrated circuit (MIC) FET amplifier gain modules, and design of subassemblies containing temperature compensation modules, protective limiters, and attenuators.

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Notes

Notes

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