MICROWAVE SWITCHES

Modern microwave systems often require the routing of microwave signals to different locations or subsystems. This signal routing is frequently controlled electronically and strict system requirements often require rapid signal routing. The system component used to control this flow of microwave energy is the *microwave switch.* Depending on the application, these devices must be able to rapidly switch microwave signals whose power levels range from the microwatt range in receiver applications to hundreds of kilowatts in high power radar applications.

A common use of a microwave switch is to connect a single antenna to either a receiver or a transmitter. Figure 1 shows a schematic diagram of a *transmit-receive switch* or TR switch. When switch SW_A is closed (connected) and switch SW_B is open (disconnected), the receiver is directly connected to the antenna. The transmitter is connected to the antenna when SW_B is closed and SW_A is open.

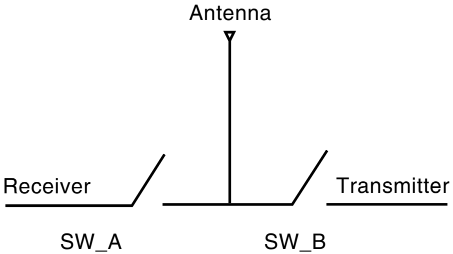

Figure 1. Schematic diagram of a microwave TR Switch.

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering.*

MICROWAVE SWITCH: TERMINOLOGY AND TYPES

An ideal microwave switch in the connected or on-state should exhibit no losses. The ideal microwave switch in the disconnected or off-state will not allow transmission of energy. In reality, losses do occur in the on-state switch, and these losses must be minimized through careful selection and design of the switch element. These losses will absorb the microwave energy as it flows through the switch. The term microwave engineers use to describe these on-state switch losses is the switch *insertion loss*. In the off-state switch, some transmission of energy does occur, but can be minimized by careful selection and design. For the off-state switch, the measure of the level of signal transmission is termed the switch *isolation.* The microwave engineer attempts to design microwave switches with low insertion loss and high isolation over the entire frequency and power range of operation. Often the engineer finds that by improving one switch property another one is adversely affected, so engineering tradeoffs are always a part of the design process. Several design passes using computer aided design tools and construction of actual switch prototype circuits are usually needed before the optimum microwave switch configuration is determined.

Modern microwave switch applications require the actual switching action be done electronically rather than mechanically (as in a light switch), allowing a digital computer system, for example, to control the switching operation. The utility of electronically controlled microwave switches can be shown by an example based on the TR switch shown in Fig. 1. Consider a radar transmitter sending out pulses of energy that will be reflected back to the receiver if an object is encountered. If the object is 25 km away from the radar site, the travel time for a single radar pulse to go from the transmitter to the object and back to the receiver is approximately 160 μs. The microwave switch must switch the radar antenna between the high power radar transmitter and the receiver in this short time period (or shorter if the object is closer), and the switch must be capable of repeating this action hundreds of times each second.

Two classes of electronically controllable microwave switching elements are widely used: *solid-state switch* elements based on specialized diode and transistor elements; and, *ferrite switch* elements based on magnetic material that controls the direction of microwave energy flow. Solid-state devices are used in applications such as battery operated radio systems, nuclear magnetic resonance imaging systems, and electronically steered antenna arrays. Ferrite switches are usually only found in applications such as high power radar systems where hundreds of kilowatts of power must be controlled.

Solid-state switching devices are further divided into two types: those based on two terminal switch elements such as *p-i-n* diodes (fabricated using silicon or gallium arsenide semiconductors) or three terminal switch elements such as gallium arsenide metal semiconductor field effect transistors (MESFET). Both types of solid-state switching elements are physically small. Microwave *p-i-n* diodes that are used for low power but very high frequency may be as small as 10 μm in diameter and 25 μm in length. Higher power diodes can be 100 μm in diameter and 250 μm thick to aid in handling the additional power requirements. FET switch elements may reside on squares of semiconductor material no larger than 1000 μm on a side. The bulk of a microwave switch module can be taken up by the package used to contain the solid-state switch element, allowing the switch module to be handled by skilled circuit fabrication technicians or automated electronic fabrication machines. Ferrite switches are physically larger than solid-state counterparts because of both the physical operation of the switch as well as the high power that the switch must handle.

Table 1. Characteristics of Common Microwave Switch Elements

Switch Type	Switching Energy	Switching Time	Power Handling
FET Elements	very low	very fast (3–4 μs)	watts
p-i-n Diodes	medium	fast (10–50 μs)	kilowatts
Ferrite Switch	high	slow (100 μs and up)	megawatts

The amount of energy used to activate the microwave switch is also an important design specification. Ferrite and some *p-i-n* diode switch elements can control much higher powers than FET-based switches, but FET switches require very little energy to activate. The switching energy is unusually high in some ferrite switches because of the relatively high current required to generate the necessary magnetic field that governs ferrite operation. Table 1 provides a summary of some important microwave switch characteristics. The table shows that selection of switch type is strongly dependent on the application. The designer must balance these specifications with other design specifications such as physical size, insertion loss, isolation, and cost.

MICROWAVE SWITCH MODELING

The primary design specification that a microwave switch designer considers is the switch circuit's insertion loss and isolation. Insertion loss (IL) and isolation (ISO) are defined as the level of microwave power present at the load after the switch is installed with respect to that present at the load before the switch is installed. This definition can be written mathematically as (1):

$$IL/ISO = 10 \log \frac{P_{\mathrm{La}}}{P_{\mathrm{Lb}}}\, dB \tag{1}$$

where $P_{\mathrm{La(Lb)}}$ is the power available at the load after (before) the switch module is inserted into the system. Typical values of switch insertion loss range from 0.2 dB to 1.0 dB, with the higher values of insertion loss typical for microwave switch elements used at X-band (8 GHz to 12 GHz) and above. A good microwave switch will exhibit isolation greater than 20 dB. At low frequencies, microwave switch isolation can be greater than 80 dB depending on the actual switch configuration. Because of the nature of microwave switch elements, isolation and insertion loss often exhibit marked variations with frequency.

The microwave switch designer's task is simplified by use of *lumped element switch modeling.* These switch models replace the actual switch with simple circuit elements that can be quickly and easily analyzed. Insertion loss and isolation for the various switch elements is computed by modeling each individual switch element as a parallel combination of an

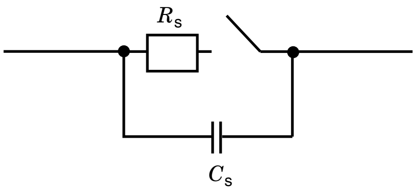

Figure 2. Simplified model for a microwave switch element, showing the on-state resistance R_S and the off-state capacitance C_S.

ideal switch and a resistance R_S and a capacitance C_S. This simple microwave switch element model is shown in Fig. 2. The utility of this model can be seen by studying the simplest microwave switch topology, the single pole-single throw (SPST) switch. The switching elements in the SPST circuit can be placed either in series or shunt. Figure 3 shows a series connected switch element (with switch model in place), and Fig. 4 shows the shunt connected switch element. Z_0 is the source and load impedance (so-called matched load condition). Using the circuit diagrams shown in Figs. 3 and 4, relationships for insertion loss and isolation can be developed. For the series switch, insertion loss and isolation can be written in terms of R_S. C_S, and the operating radian frequency ω as:

$$\mathrm{IL} = 20\log\left[1 + \frac{R_S}{2Z_0}\right] \tag{2}$$

and

$$\mathrm{ISO} = 10\log\left[1 + \left(\frac{1}{2\omega C_S Z_0}\right)^2\right] \tag{3}$$

whereas for the shunt switch, insertion loss and isolation can be written as:

$$\mathrm{IL} = 10\log[1 + (0.5\omega C_S Z_0)^2] \tag{4}$$

and

$$\mathrm{ISO} = 20\log\left[1 + \frac{Z_0}{2R_S}\right] \tag{5}$$

Insertion loss for the shunt switch is frequency dependent due to the reactance of the shunt capacitance, whereas isolation for the series switch is the frequency dependent parameter. Figure 5 shows the insertion loss (isolation) for the series (shunt) SPST switch as a function of resistance R_S. The data shown in Fig. 5 indicate that low insertion loss (less than 0.5 dB) occurs for resistance values of less than approximately 5 Ω for the series switch. Isolation greater than 20 dB occurs for resistance values of approximately 2 Ω or less for the shunt switch. Figures 6 and 7 illustrate the isolation (insertion loss) for the shunt (series) SPST 50 Ω switch as a function of frequency using the switch capacitance C_S as a parameter. Figure 6 shows that isolation of the series switch is greater than 25 dB at 1000 MHz using capacitance values less than 0.1 pF. Figure 7 indicates that a shunt switch with capacitance of 1.0 pF or less exhibits less than 0.5 dB insertion loss at 1000 MHz.

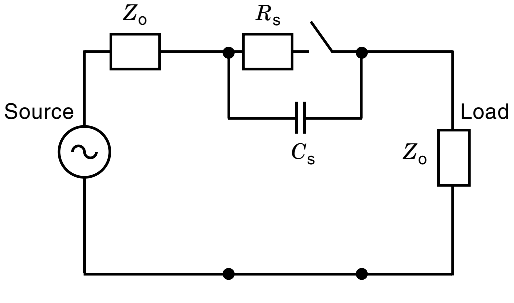

Figure 3. Series connected SPST microwave switch showing source, load, and equivalent circuit for the switch element.

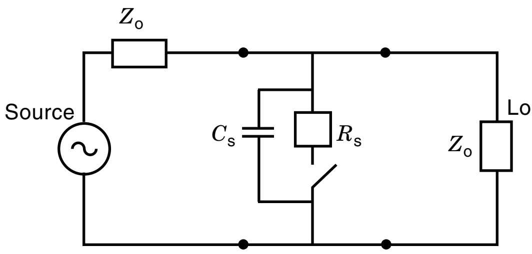

Figure 4. Shunt connected SPST microwave switch showing source, load, and equivalent circuit for the switch element.

Multithrow microwave switches are designed using combinations of series and shunt elements to implement the desired switching function. The operation of a single pole-double throw (SPDT) TR switch illustrated in Fig. 1, for example, can be predicted by replacing the two switches SW_A and SW_B by the switch element model in Fig. 2. Various applications often require more complex switch topologies, but the insertion loss and isolation of these circuits can still be estimated using the lumped element switch model in Fig. 2. It should be noted that Fig. 2 represents the simplest of switch element models. Switch packaging and circuit connections introduce their own undesired properties that must be included by the microwave engineer as part of the design process. Some of these undesired or *parasitic elements* are package capacitance, contact resistance, and bond wire inductance. The

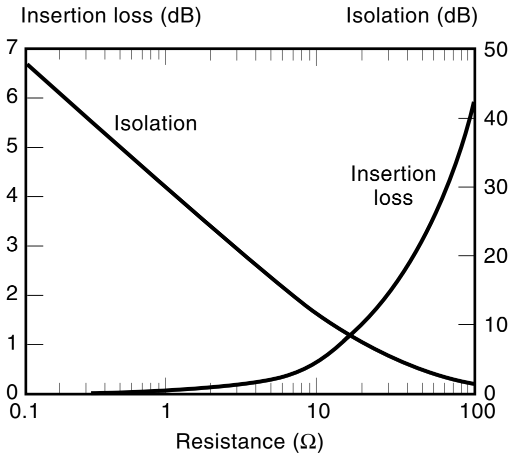

Figure 5. Insertion loss and isolation for the series and shunt SPST 50 Ω switch as a function of series resistance R_S.

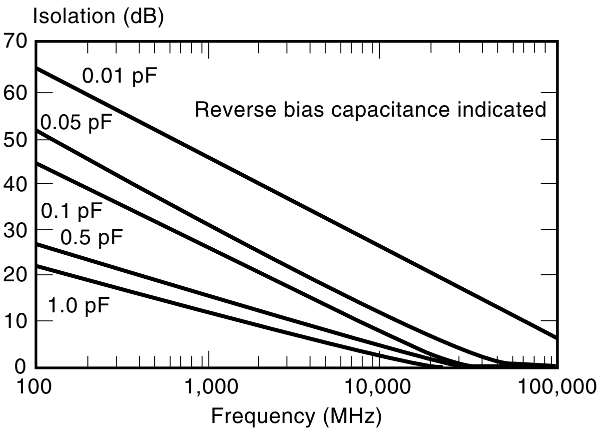

Figure 6. Isolation for the series SPST 50 Ω switch as a function of frequency using the switch capacitance C_S as a parameter.

parasitic elements influence both microwave switch insertion loss and isolation.

When a microwave switch is in its high impedance state, the majority of the signal voltage is dropped across the switching element. In the low impedance state, the current flow through the switch element can be large. These maximum voltages and currents, and the corresponding peak power, must be known at the time of the design so that suitable switch elements can be selected. These specifications can vary widely depending on the application, from low power, low voltage requirements for receive-only applications to high voltage, high power switching devices for radar or other transmitter applications. A wide variety of switching elements have been developed over the decades in response to these differing system requirements. The choices facing the microwave switch designer are detailed in the next section.

MICROWAVE SWITCH ELEMENTS

P-i-n diodes and FETs are the primary solid-state switch elements used in modern microwave switches. *P-i-n* diodes fabricated using either silicon or gallium arsenide are used in switching applications from frequencies below 1 MHz to 50 GHz and beyond, and can switch peak microwave power into the tens of kilowatts range. *P-i-n* diode switching elements exhibit on and off state characteristics that are modeled using parameters illustrated in Fig. 2.

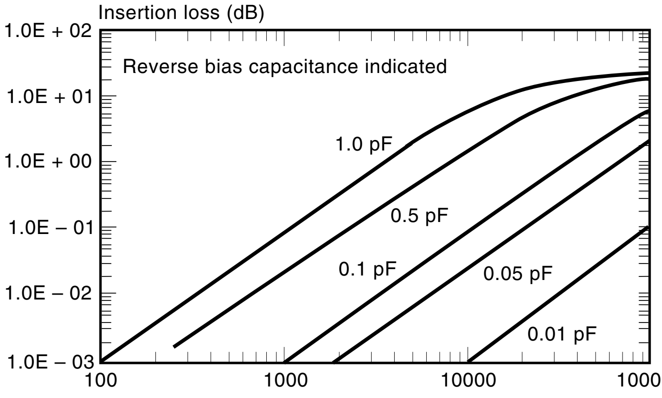

Figure 7. Insertion loss for the shunt SPST 50 Ω switch as a function of frequency using the switch capacitance C_S as a parameter.

A *p-i-n* diode consists of a nearly intrinsic or pure semiconductor region (*I*-region) sandwiched between heavily doped *n* and *p* type regions. The on-state or forward bias resistance R_S of the *p-i-n* diode is a function of the *I*-region width W as well as the *I*-region carrier lifetime τ and the dc bias current flowing through the device, I_0. In its simplest form, the on-state resistance can be written as (2):

$$R_S = \frac{W^2}{2\mu I_0 \tau} \tag{6}$$

where μ is the ambipolar carrier mobility. The *I*-region carrier lifetime τ is the average time a carrier exists in the *I*-region of the device, and can vary from one nanosecond in thin gallium arsenide *p-i-n* diodes to ten microseconds or longer in thick silicon diodes. The *I*-region thickness W can vary from 1 μm or less in low power *p-i-n* diodes to 200 μm and higher in *p-i-n* diodes designed for high power, high voltage applications. Under reverse bias conditions, a capacitance is developed across the *p-i-n* diode's *I*-region. Beyond a certain reverse bias voltage termed the *punch-through voltage,* the off-state or *punch-through capacitance* is constant and is modeled as C_S. Gallium arsenide *p-i-n* diodes and some thin silicon *p-i-n* diodes typically exhibit punch-through with no voltage applied (*zero bias punch-through*).

P-i-n diode switch elements are available either as discrete devices or as multithrow switching modules. Switch modules provide the microwave switch designer ease of design whereas discrete devices provide more design flexibility. Discrete devices are usually used in very high power operation. A wide variety of discrete *p-i-n* switching diodes of different electrical and physical properties are commercially available. Manufacturer's data sheets often specify their *p-i-n* diode products in terms of W, τ, R_S at certain bias currents (1 mA or 10 mA) and frequencies (usually 100 MHz), C_S at a certain reverse bias voltage (typically 6 V) and a frequency of 1 MHz, and the diode's maximum voltage rating. *P-i-n* diode switching modules are specified by their multi-throw switch operation, operating frequency range, minimum isolation, maximum insertion loss, diode voltage rating, and maximum power handling.

A common misconception involved in specifying *p-i-n* diodes is the relationship between carrier lifetime τ and *p-i-n* diode *switching time.* These two parameters are only weakly related, with the switching time more a function of the external driver circuitry. This driver circuit must remove the I-region *stored charge* ($Q = I_0\tau$) to completely turn the diode off or inject the necessary charge to turn the diode on. The *p-i-n* diode driver circuit is usually not included in switch circuit diagrams, but is fundamental to proper switch operation. Silicon *p-i-n* diodes can not be driven directly from digital TTL-compatible signals, so a driver circuit is used to translate these digital signals into voltages and currents needed to turn the *p-i-n* diode on and off quickly. The driver circuit must also be ac decoupled from the microwave switch circuit. Zero bias punch-through dodes such as gallium arsenide *p-i-n* diodes can be driven directly by digital TTL-compatible signals without the need for complex driver circuitry, although ac decou-

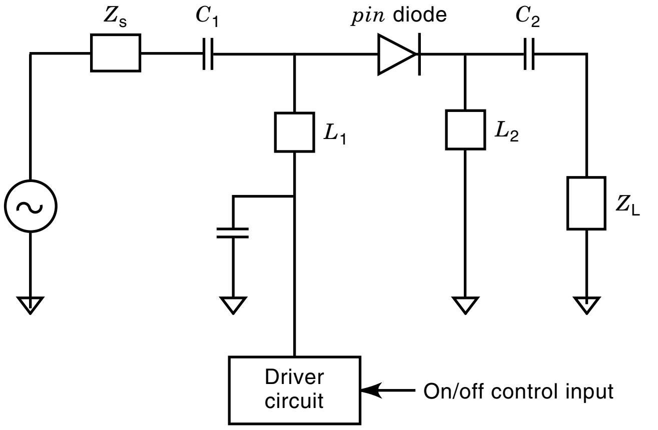

Figure 8. SPST *p-i-n* diode switch with driver circuit dc decoupling elements shown.

pling is still required. The circuit elements used in this decoupling circuit frequency limit the usable bandwidth and switching speed of the *p-i-n* diode switch. Figure 8 shows an example of an SPST *p-i-n* diode switch circuit with driver circuit and ac decoupling elements included. Capacitors C_1 and C_2 act as dc blocks preventing dc from reaching either the source or the load. Inductor L_1 isolates the driver circuit from the ac signal path and inductor L_2 provides a dc return path. L_2 and C_2 may be eliminated if the load Z_L can act as the dc return path.

To improve isolation or insertion loss in *p-i-n* diode switch circuits, multiple diodes may be placed in series or parallel. If two shunt connected *p-i-n* diodes replace the one diode illustrated in Fig. 4, the effective series resistance R_S is halved, increasing the isolation by 6 dB. When two or more *p-i-n* diodes are used in shunt, improved switch performance can frequently be obtained by spacing the diodes a quarter wavelength ($\lambda/4$) apart. This spacing can be obtained physically by the use of transmission lines or a lumped element equivalent. This technique, however, can restrict the overall bandwidth of the switching module.

A significant achievement in switch module and monolithic microwave integrated circuit (MMIC) technology occurred with the development of metal-semiconductor FET (MESFET) switch elements in gallium arsenide. This technology allows switch elements not only to be available in modular form, but also allows entire systems, switching included, to be fully integrated onto a single gallium arsenide integrated circuit. Modern microwave FET switches can be directly connected to their driver circuitry without the need for complex driver or decoupling circuitry since the control port of the FET, a three terminal device, is inherently isolated from the signal ports. FETs switch faster than *p-i-n* diodes since the amount of charge that must be added or removed during switching is much less. Switching energy is lower for FET switches since only a few microamperes flow into the control line versus milliamperes in *p-i-n* diodes. The disadvantages of FET switches are that they are only available in switch modules and can only handle power levels in the tens of watts. Another disadvantage of FET over *p-i-n* diode switch modules occurs in unipolar power supply applications. Gallium arsenide FET switches require negative voltages to turn them off, so the microwave switch designer must float or dc isolate the switch to obtain the proper voltage polarity. These dc decoupling elements complicate the switch design and can limit the switch bandwidth.

FET switch modules can operate over wider bandwidths than *p-i-n* diode switches. Packaged FET modules exhibit good switch performance from dc to 2 GHz. Wider bandwidths of dc to 18 GHz can be obtained using unpackaged switch chips that are directly connected (wire bonding, for example) to the circuit to be controlled. Gallium arsenide MESFET switch modules are specified by their multithrow switch operation, packaging (packaged or chip form), operating frequency range, minimum isolation, maximum insertion loss, diode voltage rating, and maximum power handling. Insertion loss is usually higher and isolation usually lower for the wider bandwidth switch modules because of engineering tradeoffs that are needed to extend the bandwidth in these devices. Gallium arsenide FET switch insertion loss typically ranges from 0.2 dB to 1.0 dB, with the higher values of insertion loss typical for operation at 8 GHz and above. A good MESFET switch will exhibit isolation greater than 20 dB, although isolation at lower frequencies can be greater than 80 dB.

Ferrite switch modules have been largely replaced by semiconductor switches for all but high power applications. Ferrite switch modules are physically large and bulky. However, they are the only method of controlling microwave power into the megawatt levels. Peak powers of more than a megawatt can be easily switched at frequencies below 8 GHz with ferrite switches with low loss (less than 0.5 dB) and isolation greater than 20 dB. Ferrite switches based on switching circulators have been used as high as 220 GHz (3).

A common ferrite switch uses a switched *ferrite circulator* as the basic switching module (see FERRITE DEVICES). The arrow in Fig. 9 shows the direction of microwave energy flow. With one magnetic field orientation, microwave energy entering port 1 leaves port 2, and energy entering port 2 leaves port 3. By reversing the magnetic field orientation, the circulation pattern ($1 \rightarrow 2 \rightarrow 3 \rightarrow 1$) changes to ($1 \rightarrow 3 \rightarrow 2 \rightarrow 1$), and the circulator acts as a nonreciprocal SPDT switch. Because of the nonreciprocity of the switch, energy entering port 1 leaves port 2 but energy entering port 2 leaves port 3. A reciprocal version of this SPDT switch requires one nonreciprocal switching module and two fixed circulators (4). Ferrite switch modules are inherently narrow band. Figure 10 shows insertion loss, isolation, and VSWR of a 35 GHz latching ferrite switch module (5), illustrating the relatively narrow band properties of the module. Ferrite switches exhibit insertion losses of less than 0.5 dB at frequencies below 12 GHz, although higher losses (up to 1.0 dB) occur at higher operating frequencies. Isolation of 20 dB or greater is typical at frequencies of 94 GHz and beyond. The bandwidth of a ferrite switch can be extended using special matching techniques (6).

Another drawback for the ferrite switch compared to the solid-state microwave switch is the ferrite switch's relatively slow switching speed. To change switch states, the magnetic field in the ferrite must be reversed, and phenomena such as material demagnitization and switching eddy currents combine to slow the switching speed. Switching speeds of several hundred nanoseconds have been achieved in some ferrite switch modules (5). Relatively large currents are needed to induce the ferrite switch action, making them unsuitable for most battery or portable applications.

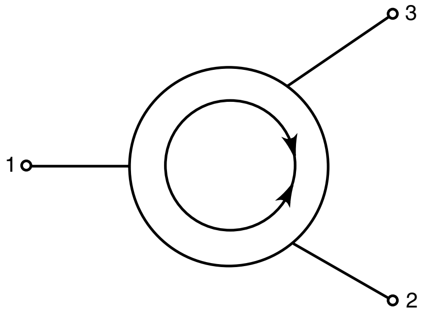

Figure 9. Microwave energy flow in a switching ferrite circulator (7) (© 1989, John Wiley and Sons. Reprinted by permission of John Wiley & Sons, Inc.).

NONIDEAL MICROWAVE SWITCH ELEMENT OPERATION

The insertion loss and isolation are measures of the microwave switch's impact on the fundamental microwave signal. A side effect of using active microwave switch elements is their generation of unwanted signals based on the level of microwave signal energy. These so-called *nonlinear effects* produce spurious signals that are harmonically related to the fundamental microwave signal, introducing *distortion* into the system. The two most widely specified microwave switch distortion products are second and third order *intermodulation distortion.* These distortion products are measured using the *two-tone test* where two signals of equal amplitude but slightly different frequency (F_1 and F_2) are incident on the microwave switch. The second order nonlinear effects in the microwave switch generate spurious signals at frequencies $2F_1$ and $2F_2$ (*harmonic distortion*) and at frequencies $F_1 \pm F_2$ (intermodulation distortion). The third order nonlinearity generates signals at frequencies $3F_1$ and $3F_2$ (harmonic distortion), and $2F_1 \pm F_2$ and $2F_2 \pm F_1$ (intermodulation distortion). The most difficult distortion terms to manage are the third order intermodulation products ($2F_1 - F_2$ and $2F_2 - F_1$) because these frequency components can be close to the fundamental frequencies F_1 and F_2, and hence are difficult to remove by filtering. Second and third order microwave switch intermodulation distortion is frequently specified using distortion intercept points IP2 and IP3. The intercept point is determined by measuring the distortion power with respect to the power in the fundamental (8):

$$IP2 = P_{\mathrm{F}} + R_{\mathrm{ab/a}} \tag{7}$$

$$IP3 = P_{\mathrm{F}} + 0.5R_{\mathrm{2ab/a}} \tag{8}$$

where P_{F} is the fundamental power (in dBm), and $R_{\mathrm{ab/a}}$ and $R_{\mathrm{2ab/a}}$ are the relative second and third order distortion powers (in dBc), respectively. Equations 7 and 8 also show that the distortion power can be computed given the distortion intercept point and fundamental power level. Less distortion is introduced into the system by using high intercept point switches or switching elements.

For a single series *p-i-n* diode switch, the on-state (forward biased *p-i-n* diode) *IP*2 and *IP*3 have been found to be a function of QF/R_{S} where $Q(I_0\tau)$ is the *I*-region stored charge, F is the operating frequency, and R_{S} is the series resistance. For a series connected *p-i-n* diode switch, *IP*2 and *IP*3 have been computed as (8):

$$IP2 = 34 + 20\log\left(\frac{Q_{\mathrm{nC}}F_{\mathrm{MHz}}}{R_{\mathrm{S}}}\right)\ dBm \tag{9}$$

$$IP3 = 24 + 15\log\left(\frac{Q_{\mathrm{nC}}F_{\mathrm{MHz}}}{R_{\mathrm{S}}}\right)\ dBm \tag{10}$$

where Q_{nC} is the *I*-region stored charge in nanocoulombs, F is the frequency in MHz, and R_{S} is the series resistance in ohms. This ratio can be increased by increasing the *I*-region stored charge (high dc bias current or large carrier lifetime) and/or lowering the series resistance. Distortion also improves as the frequency of operation increases. The underlying cause of forward biased *p-i-n* diode distortion is modulation of the *I*-region dc stored charge by the microwave signal.

The *p-i-n* diode also introduces distortion in its off state (reverse bias) due to modulation of the reverse bias capacitance C_{S} by the microwave signal. Second and third order distortion for the series connected *p-i-n* diode switch can be estimated from the reverse bias capacitance-voltage characteristic, specifically the first and second derivative (C'_{S} and C''_{S}, respectively) (9):

$$IP2 = \frac{1}{32(C'_{\mathrm{S}})^2 Z_0^3(\omega_1 + \omega_2)^2} \tag{11}$$

$$IP3 = \frac{1}{12(C''_{\mathrm{S}}) Z_0^2(2\omega_1 + \omega_2)} \tag{12}$$

Since multithrow switch circuits have combinations of on and off state *p-i-n* diodes for each switch state, all diode distortion contributions must be included for an accurate microwave switch distortion prediction. The on-state *p-i-n* diode usually contributes more distortion than *p-i-n* diodes in the off-state.

Gallium arsenide MESFET switches also introduce distortion (10). On-state MESFET switch distortion is caused by modulation of the conducting channel region by the applied microwave signal. In the off-state, distortion is generated by variations in the gate-drain and gate-source capacitance (C_{GD}

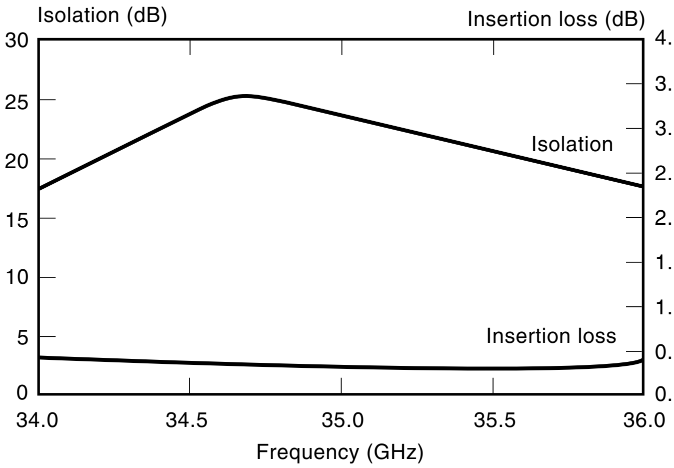

Figure 10. Insertion loss, isolation, and VSWR for a 35 GHz latching ferrite switch (5) (© 1966 IEEE).

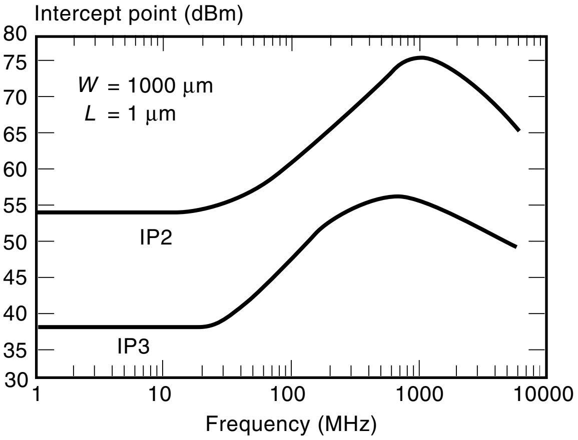

Figure 11. Simulated second and third order distortion intercept point (*IP*2 and *IP*3, respectively) for the on-state series connected GaAs MESFET SPST switch (Reprinted with permission from *Microwave Journal,* Sept. 1994).

and C_{GS}, respectively) by the applied signal. Figure 11 shows on-state *IP*2 and *IP*3 versus frequency for a typical 1000 μm by 1 μm series connected MESFET switch. The transition region for the distortion occurs in the vicinity of $R_B(C_{GS} + C_{GD})$ where R_B is the gate bias resistor. In the off-state, MESFET switch distortion increases with increasing frequency. Figure 12 shows *IP*2 and *IP*3 for a gallium arsenide MESFET SPST switch. Typical *IP*2 (*IP*3) values range from 80 dBm (50 dBm) for 2 GHz SPDT gallium arsenide MESFET switch modules to 65 dBm (40 dBm) for 18 GHz switch modules. Similar to *p-i-n* diodes, MESFET switch on-state distortion is usually much larger than distortion in the off-state. Since gallium arsenide MESFET switches are typically available only in module form, *IP*2 and *IP*3 are only specified for the on-state.

The ferrite circulator will generate intermodulation distortion as well. The two main sources of nonlinearities in the ferrite circulator are due to uniform precession of the ferrite magnetization and by the presence of spin waves (11). The third order intermodulation distortion has been shown to improve with increasing frequency, similar to the behavior of the *p-i-n* diode. However, the amount of distortion introduced by the ferrite is significantly lower than that introduced by either the *p-i-n* diode or MESFET switch element. Since the switching ferrite circulator is used at high power levels, the low distortion behavior of the ferrite device is an asset.

OTHER MICROWAVE SWITCH ELEMENTS

Semiconductor and ferrite microwave switches require direct wired connections to control their switch state. Optical control of microwave switches has been investigated by a number of workers. The two most common types of optically-controlled switches use bulk semiconductor (12) and *p-i-n* diodes (13,14). Bulk semiconductor switches, or photoconductive semiconductor switches, use light energy (usually from a high power laser) to modulate the conductivity of the material. The most common optically controlled microwave switch circuit topology has a transmission line gap with the bulk semiconductor within the gap (Fig. 13). The transmission line gap can range from a few micrometers in low power applications to millimeters in high power or high voltage applications. During the off (dark) state, the high resistivity of the bulk semiconductor effectively isolates the two transmission lines. The switch is activated by an intense beam of photons directed on the semiconductor material, which quickly generates electron-hole pairs in the material, increasing the semiconductor's conductivity, and providing a low loss connection between the two transmission lines. When the light source is removed, the electron-hole pairs recombine, returning the switch to its off state. This turn-off process is dependent on the carrier lifetime of the electron-hole pairs in the semiconductor material. Various semiconductor processing techniques such as introducing a high density of recombination centers have been developed to lower the carrier lifetime to speed the switching action.

Optically controlled *p-i-n* diode switches also rely on electron-hole pair generation by an incident beam of photons as well. The off-state (high isolation) is accomplished with a reverse biased *p-i-n* diode bridging the transmission line gap instead of the bulk semiconductor material (Fig. 13). The switch is turned on with a beam of photons focused on the *I*-

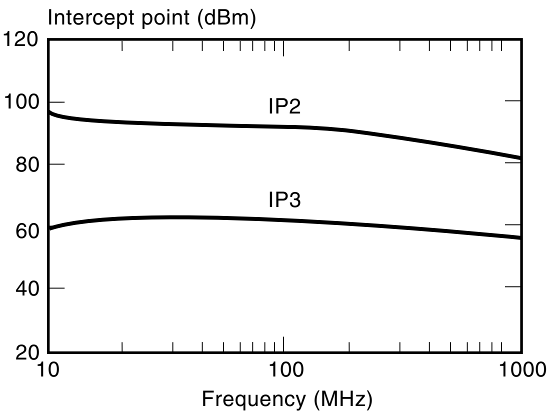

Figure 12. Simulated second and third order distortion intercept point (*IP*2 and *IP*3, respectively) for the off-state series connected GaAs MESFET SPST switch (Reprinted with permission from *Microwave Journal,* Sept. 1994).

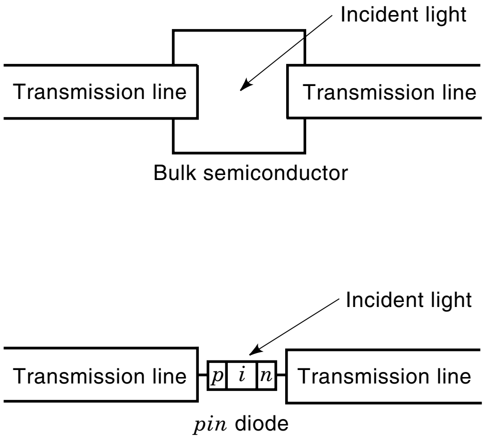

Figure 13. Optically controlled microwave switches: bulk semiconductor and reverse biased *p-i-n* diode physical layouts.

region causing the generation of electron-hole pairs. The *I*-region conductivity dramatically increases, thereby creating a low loss connection across the gap. Carriers swept out of the *I*-region by the electric field are continually replenished by the optically generated carriers. This same field quickly sweeps all the electron-hole pairs out of the I-region when the light source is removed, rapidly returning the microwave switch to its off-state. These switches can be activated in less than 100 ps, and turned off in several nanoseconds (13).

ADDITIONAL READING

Several excellent publications on microwave switches are available for further reading. The classic treatment of *p-i-n* diode switches can be found in Ref. 2. For gallium arsenide MESFET switches, the classic papers in the field are in Refs. 15–17. Since ferrite switches are usually based on circulator technology, the reader is encouraged to read the sections on ferrite devices elsewhere in the encyclopedia. The most widely used research publications containing information on microwave switches are the *IEEE Transactions on Microwave Theory and Techniques* and the *Microwave Journal*. The *Transactions on Microwave Theory and Techniques* has cumulative indices listing the Transactions' publications from 1950 to 1988 (18,19). Application notes from suppliers of microwave switch elements and modules are also good sources of design information.

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