

RF Switches

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In the transmission path, **RF Switches** can efficiently convey paths.

Four basic electrical parameters can be used to describe the function of this sort of RF switch. Despite the fact that numerous parameters affect the performance of RF switches, the following four are crucial due to their significant correlation:

1. Isolation

Isolation is an index that measures the effectiveness of the RF switch cut-off by attenuating the signal between the input and output of the circuit.

2. Insertion loss

When the RF switch is turned ON, insertion loss (also known as transmission loss) is the total power loss. Because insertion loss can immediately contribute in system noise figure, it is the most important metric for the RF designers.

3. Switching time

The time it takes for the RF switch to convert from ON state to the OFF state, and vice versa is referred to as switching time. For high-power switching, this time can be measured in microseconds, and for low-power high-speed switching, it can be measured in nanoseconds. The most typical definition of switching time is the amount of time it takes for the input control voltage to go from 50% to 90% of its ultimate power.

4. Power handling capacity

The power handling capability of a switch is defined as the maximum RF input power that the switch can withstand without deteriorating its electrical performance permanently.

Electromechanical RF switches

First **RF Switches** that were used in wireless applications were mechanical switches (keys, aerial switches, and electro-mechanical relays).

Those mechanical or electro-mechanical switches generally switch DC and low frequencies, and relative high voltage and currents.

They require having good electrical contacts and to use high isolation materials.

- There are two types of electromechanical RF switches: terminated and non-terminated.

- When all ports of an RF switch are terminated with a 50 ohms load, the selected port is closed, cutting off or isolating all currents. The incident signal energy will be absorbed by the termination resistor and will not be reflected back, to the RF source in this way.
- In a non-terminated RF switch, the system must accomplish external impedance matching to reduce energy reflection. The non-terminated RF switch has the advantage of having a low insertion loss.
- Electro-mechanical (EM) RF switches provides:
 - low insertion loss (<0.1dB)
 - high isolation (>100dB)
 - high power handling
 - no video leakage
 - very high ESD immunity
 - their frequency range starts from DC

Electro-mechanical RF switches have lower operating lifetime than Solid-State switches.

- The operating life of an electro-mechanical switch can be defined as the number of cycles the switch will complete while meeting all the RF and repeatability specifications.
- The operating life refers to the electrical life and RF properties of the switch, and not to the mechanical life (which is much longer than the electrical life).

There are some high-quality coaxial relays that use electro-mechanical switches referred as “frictionless switching” (since there is no friction produced between the jumper contact and center conductor), and this configuration produces switches that can mechanically actuate for tens of millions of cycles.

The drawback is, they might not fail mechanical, but their insertion loss gets higher due to increasing in time the resistance of the contacts.

Solid-State RF Switches

Solid-State RF switches have smaller package thickness and physical dimension than Electromechanical RF switches since their circuit assembly is relatively flat and does not contain big components.

- High speed silicon PIN diodes or Field-Effect Transistors (FET), or integrated silicon or FET monolithic microwave integrate circuits, are switching elements used in solid-state RF switches.
Other chip components like capacitors, inductors, and resistors are independently integrated on the same circuit board as these switching parts.
- PIN diode-based switches have higher power handling capabilities, but FET-based switch devices have faster switching speeds.

- Solid-state switches, have an infinite service life since they do not contain moving parts. The solid-state RF switch has high isolation (60>80dB), a quick switching speed (100 nanoseconds), and is stress and vibration resistant.
- In terms of insertion loss, solid-state RF switches are inferior of electromechanical switches.
- Solid-state RF switches have limits in low-frequency applications, the lowest limit of its operating frequency is merely kilohertz, not DC, due to the semiconductor diode's inherent carrier lifetime characteristics.
- Solid-state RF switches are also more susceptible to electrostatic discharge, and their power handling capabilities are influenced by the connector type, operating frequency, and ambient temperature. Certain PIN diode RF switch topologies can withstand peak power of several kilowatts, but this comes to the cost of slower switching rates.
- There are two types of solid-state RF switches: absorptive and reflecting.
- In order to obtain a lower voltage standing wave ratio (VSWR) in both ON and OFF states, the absorption switch has a 50-ohm terminal matching resistance at each output port, which can absorb the incident signal energy, but the port that is not linked to the terminating matching resistor will reflect it. Absorptive switches are ideal for applications where the RF source's echo reflection must be minimized.
- The reflecting RF switch does not have a terminal resistor to reduce the insertion loss of the open port, and is ideal for applications where reflections does not affect the system performance.
- Emerging **micro-electromechanical systems (MEMS)** switch technology attempts to deliver the advantages of traditional electro-mechanical switches, but in a small form factor.
MEMS switches employ micro-miniaturized mechanical contacts controlled by electrostatic forces to make RF connections.

Selecting Optimal RF Switch

A perfect RF switch has no resistance when biased ON and infinite resistance when biased OFF. It switches instantly, requires no power to change states or to remain ON, passes electrical signals from DC to light at any power level, is very small, lasts forever and costs nothing.

However, this device does not exist, so switch advantages must be balanced against disadvantages to get as close as possible to the ideal switch.

There are two main types of switching technologies used for high frequency applications: solid-state and electromechanical. There are options for each type:

- Solid-state:
 - Silicon-on-insulator (SOI)
 - PIN diode
 - GaAs Field-Effect Transistor (FET)
 - GaN FET
- Electromechanical:
 - Relays
 - Micro-electromechanical systems (MEMS)

- For solid-state switches, PIN diodes are current-controlled and FETs are voltage-controlled. Both can be implemented in different semiconductor processes like GaAs, AlGaAs, GaN and silicon. For FETbased switches, SOI and silicon-on-sapphire are also commonly used.

Using PIN diodes comes with a complex set of tradeoffs. Some of the key advantages are moderate RF power handling of several watts, switching speeds in the nanosecond to microsecond range, high isolation and IP3 values that can be greater than 45 dBm. Those advantages must be weighed against the disadvantages of DC power consumption that may exceed 100mW per switch, low frequency operation that may not go below 50 MHz, larger overall circuit area and increased insertion loss created by additional passive bias components.

- GaAs FET-based switches easily cover the desired frequency range and are widely used. GaAs FETs have switching speeds in the nanosecond range for 10% to 90% settling. That is sufficient for many systems, but gate lag can amount to several milliseconds. This decreases the usefulness of GaAs devices in precision test and measurement applications requiring signal stability and complete settling.

GaAs switches suffer from lower RF power handling, typically in the 0.5W range with higher insertion loss, especially for high throw count switches.

The linearity is mediocre with IP3 values around 35 dBm and low P1dB performance.

- GaN switch performance is similar to GaAs switch, but these devices can typically handle much higher RF power levels.

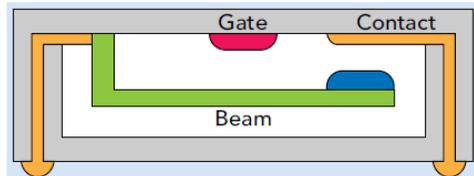
GaN switches need control voltages in the 40V to 60 V range. Most GaN switches are also limited, in general, to a maximum operating frequency of 18 GHz.

They also have similar switching characteristics to GaAs switches, in fundamental including gate lag and they are generally more expensive.

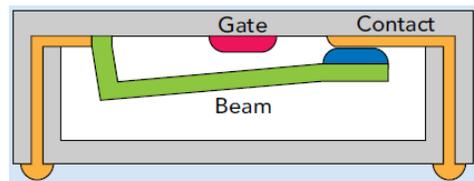
- Electromechanical (EM) relays work from DC to 50 GHz and beyond with minimal insertion loss, good return loss and high isolation.

They can handle hundreds of watts and have extremely high linearity. However, EM switches consume hundreds of milliwatts of DC power when actuating, have switching speeds in the tens of milliseconds and are physically large, heavy and expensive. They also have comparatively short lifespans.

- MEMS switches combine the performance advantages of EM switches with the miniature size, low cost, long life and scalability of solid-state switches. Ohmic MEMS switches operate by applying a DC voltage to the gate electrode. With no gate voltage, the beam is in its resting position as shown in figure below.



When the voltage applied to the gate reaches the pull-in voltage, the beam or cantilever bends toward the contact due to electrostatic force and connects the input to the output, as shown in figure below.



When the DC voltage falls below a pull-off level, the beam returns to its original position under its spring force. It is important to mention that while the pull-in voltage is in the tens of volts (DC), no power is consumed by the switch during actuation.

Types and Architectures of Solid-State RF Switches

There are few main types of Solid-State RF switches:

- High-Speed Silicon diodes RF switches
- PIN diodes RF switches
- Field Effect Transistors (FET) RF switches
- Hybrid (FET and PIN diode) RF switches

Two basic switch architectures that describe the behavior of the unused switch port are classified as Absorptive or Reflective.

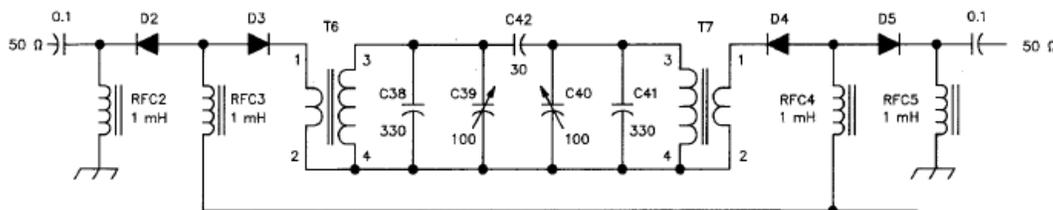
- Absorptive switches present a termination (most commonly 50Ω) to the unselected arm typically at the expense of increased insertion loss. Absorptive switch will have a good VSWR on each port regardless the switch mode.
- Reflective switches leave the unused port un-terminated. In a reflective switch, the impedance of the port that is OFF will not be 50Ω and will have a very high VSWR.

Reflective switches can be further categorized as: either reflective-open or reflective-short.

- Reflective-open architectures do not have a shunt path to ground in the OFF state; as a result, the loading on the unused port will be minimized. For example, LNA bypass switches are reflective-open in order not to disturb the LNA's functionality when the switch is in the OFF state.
- Reflective-short architectures use a shunt path to ground. This low impedance renders attached circuitry effectively useless.
- The rule is to use an absorptive switch when you need a good VSWR looking into the port that is not switched to the common port, and to use a reflective switch when high OFF port VSWR does not matter, and when the switch has some other desired performance feature.
- In most cases, an absorptive switch can be used instead of a reflective, but not vice-versa.

High-Speed Silicon diodes RF switches

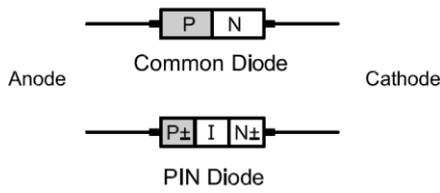
- The silicon switching diode is the most basic function of almost every electronic application.
- Switching diodes are also used in high-speed rectifying applications, such as in radio receivers. Applications also include general-purpose switching and reverse polarity protection in telecommunication industry.
- The low power (<100mW) high-speed silicon diode RF switches can provide switching speeds down to 1ns, and ON resistances less than 0.5 Ω .
- The DC current flow through the high-speed silicon diodes have to assure that they are completely turned ON, because too little junction current cause them to conduct partially resulting in high signal loss through the switch. Usually the DC bias current for ON operation is about few mA and not exceeding 20mA.
- A single silicon switching diode can provide up to 20dB of isolation, and two back-to-back silicon diodes can provide up to 30dB of isolation.



Band Pass Filter switching using silicon diodes

PIN diode RF switches

The PIN diode is constructed with a layer of intrinsic (undoped) semiconductor material between very highly doped P type and N type material called P+ and N+. This contrasts with a normal high-speed switching diode such as the common 1N914 which has a simple PN junction.



An ordinary PN junction diode can be used to switch RF currents ON and OFF.

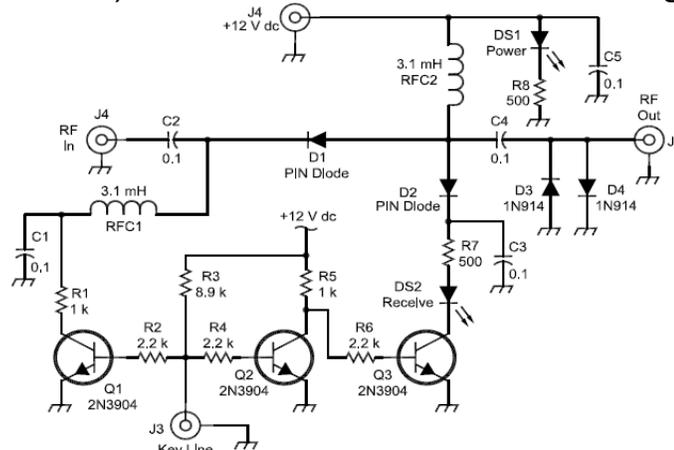
- In order to completely close OFF the current, the common diode must be reverse biased with a voltage equal to the peak RF voltage to be blocked.
- For example, to block an RF signal of 10 V p-p, the diode anode must be 10 V DC more negative than the cathode. If the diode is to remain turned ON for the complete RF cycle, the DC bias current must exceed the RF current. For example, if the diode is expected to pass 0.1 A of peak RF, it must have a forward bias of at least 0.1 A DC.

The behavior of the PIN diode is notably different. Because of the intrinsic layer, the RF takes a significant time to travel between the P+ and N+ regions.

The delay characteristic is important for RF switching.

- The PIN diode is normally OFF for RF and only requires a bias to turn ON. If the length of an RF cycle is shorter than this delay and the diode is not forward biased, the current flow will be negligible and the diode will appear to be OFF. If a forward bias current is applied, some RF current will flow and the diode switch will be ON.
- Over a limited range, the diode acts like a current controlled resistor to RF.
- Resistance decreases with increasing bias current. Used in conjunction with a fixed resistor, the PIN diode can be used to construct an electronically controlled RF attenuator.
- The capacitance of the diode itself and the diode package will permit some RF feedthrough current in the OFF condition. Feedthrough in the OFF condition will always be greater than zero, so a switch intended to provide high levels of isolation will frequently have two PIN diode elements.

A series element (D1 in figure below) disconnects the switch from the source, and a shunt element (D2 in figure below) shorts out most of the feedthrough signal.

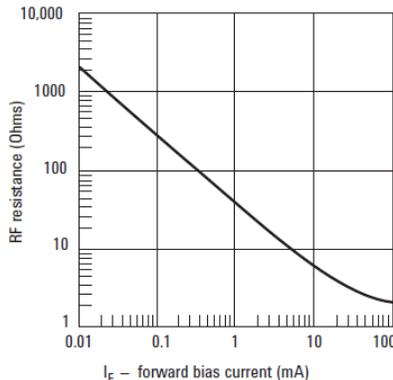


TX/RX Switch using PIN diodes

When the switch is ON, the series element will be biased ON and the shunt element will be unbiased and OFF. Conversely, when the switch is OFF, the series element will be unbiased and OFF and the shunt element will be biased ON to short out the feedthrough signal.

However, a PIN diode is a semiconductor device that operates as a variable resistor at RF and microwave frequencies.

- Its resistance value varies from less than 1 Ω (ON-state) to more than 10 k Ω (OFF-state) depending on the amount of current flowing through it. As a current-controlled device, the resistance is determined only by the forward biased DC current. When the control current is switched ON and OFF, the PIN diode can be used for switching.
- Compared to high-speed silicon diode, an important feature of the PIN diode in switching applications is its ability to control large RF signals while using much smaller levels of DC excitation.
- The resistance of the PIN diode under forward bias is inversely proportional to the total forward bias current, making the PIN diode perfect for achieving excellent isolation at high frequencies.



PIN diode characteristics, such as: high switching speed, low package parasitic reactance and small physical size compared to a signal wavelength, make them ideal for use in broadband switch design.

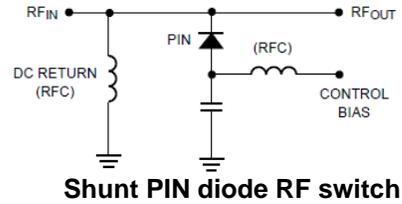
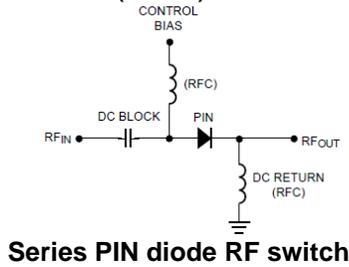
- The drawback of PIN diodes is that they cannot be used at lower frequencies. One of the properties of the PIN diodes is the transit time frequency of the I-region defined as:

$$f_{\text{transit}} [\text{MHz}] = 1300 / W^2$$

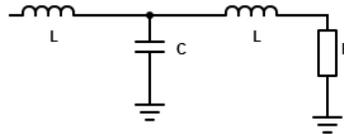
where W is the width of the I-region in microns.

- The PIN diode works properly if the frequencies are higher than f_{transit} .
- At frequencies less than f_{transit} , the PIN diode acts like a PN-junction diode and rectify the RF signal, making the PIN diode unsuitable for use at these frequencies. The frequency f_{transit} typically ranges from a few kHz to 1MHz.
- In reverse biased mode, at lower frequencies, the capacitance characteristic of the PIN diode resembles a varactor diode. Changes and variations of this capacitance affect the utility of PIN diode as a switch at lower frequencies, the same as in forward biased mode.

PIN diodes are often used to design a switch that controls the path of the RF signals. The attenuation (isolation) in the series type PIN circuit is decreased as the resistance of the PIN is reduced by increasing the forward current. The opposite occurs for the shunt configuration. If the control bias is switched rapidly between high and low (zero) values, then the circuit acts simply as a switch.



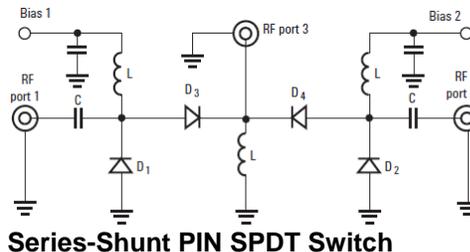
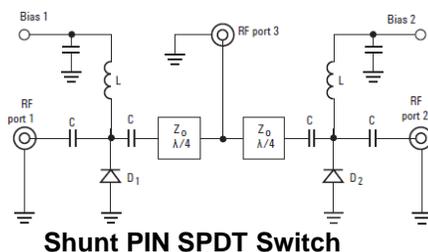
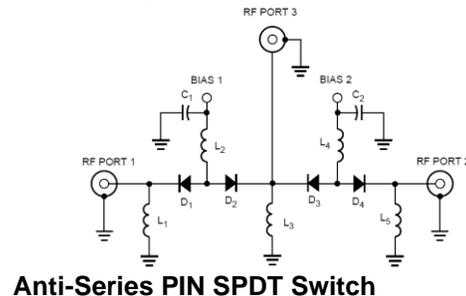
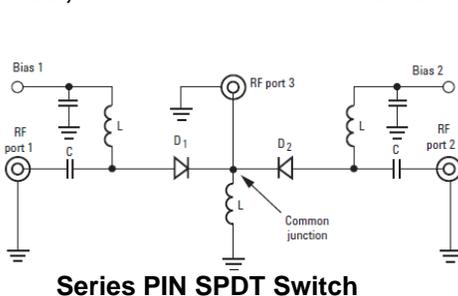
- Isolation of a SPST (single-pole-single-throw) PIN diode switch is about 50dB at 10MHz and about 15dB at 1GHz.
- As the bias on the diode is varied, the load resistance as seen by the source also varies; consequently, the isolation (attenuation) is achieved primarily by reflection and partly by dissipation in the PIN diode.
- The upper frequency limitation in a shunt PIN diode switch is determined by the increase in insertion loss as the diode parasitic capacitance starts to short out the load. However, can be used a symmetrical matching circuit that extends this frequency limitation by incorporating the diode capacitance C , into a low pass filter.



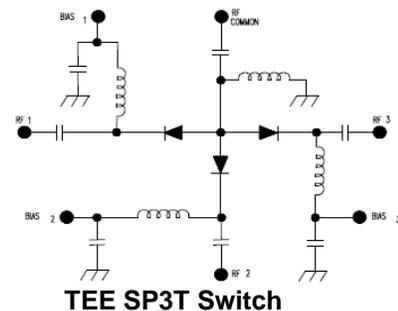
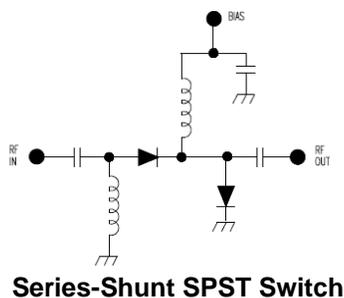
The inductance value L , is chosen to form a Chebyshev equal ripple filter. The upper frequency is determined by the diode capacitance C , by ripple value, and by R .

- Higher upper frequencies or lower ripple may be obtained by lowering the diode capacitance C using reverse bias.

Depending on the performance requirements, the switch can consist of all series diodes, all shunt diodes, or a combination of series and shunt diodes.



- Series PIN diode switches are capable of functioning within a wide bandwidth, which is limited by the biasing inductors and DC blocking capacitors. In reverse biased mode the parasitic capacitance of PIN diodes gives rise to poor isolation at microwave frequencies, with a 6dB per octave roll-off versus frequency. In some applications these parasitic elements can be either “tuned-out” by additional external reactance (parallel inductor) which actually is utilized by forming a resonant circuit around the diode. The bandwidth of such structures is, however, limited.
- Shunt PIN diode switches feature high isolation relatively independent of frequency. To turn a switch on, PIN diodes are reversed, and this means a dominant reverse biased capacitance exists. Commonly, designers use a circuit transmission line to create series lumped inductance to achieve a low pass filter effect which enables the switch to work up to the desired frequency. Shunt diodes RF switches have limited frequency bandwidth, arising from the use of the $\lambda/4$ transmission lines between the common junction and each shunt diode. At frequency f_0 , where the transmission lines are $\lambda/4$ in length, when diode D1 is forward biased and diode D2 is reverse biased, the RF signal flows from port 3 to port 2, and the RF port 1 will be isolated. The $\lambda/4$ line will transform the short circuit at D1 into an open circuit at the common junction, eliminating any reactive loading at that point. As the frequency is changed from f_0 , the transmission lines will change in electrical length, creating a mismatch at the common junction.
- There are PIN switch designs that use combination of series and shunt diodes (compound switches), and switches that use resonant structures (tuned switches) to improve isolation and insertion loss performance. These switches are more complicated to design and consume higher biasing current compared to series or shunt PIN diode switches.



In a PIN diode RF switch design, the biasing path is connected to the RF path of the switch and DC blocking capacitors are needed at the RF ports.

- The DC blocking capacitors will degrade the insertion loss performance of the PIN diode switch:
 - at low frequencies due to the high pass filter effect of the capacitor.
 - at high frequencies due to SRF (self-resonant frequency), and due to transmission loss through the capacitor.

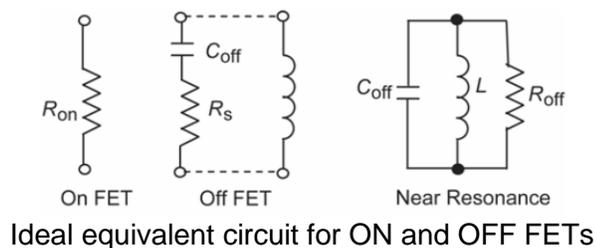
RF chokes (inductors) are used along the biasing paths to avoid RF signal leakage.

- The RF choke must have high impedance at low frequencies so that the RF signal will not leak through the biasing path leading to higher insertion loss. A good rule is the reactance X_L of the inductor at working frequency should be at least ten times higher than port impedance. If port impedance is 50Ω the $X_L > 500\Omega$. At the same time, the RF choke should have a high SRF (self-resonant frequency) to enable broadband switch design.

FET switches

Field-Effect transistor (FET) it is a semiconductor device which depends on an electric field to control the conductivity of a channel in the semiconductor material.

- The current between source and drain connections is controlled by a voltage applied between the gate and source.
- FET switches are stable and repeatable due to good control of the drain-to-source resistance (R_{DS}).
- The application of a reverse-biasing voltage between gate and source causes the depletion region at that junction to expand, thereby “pinching-off” the channel between source and drain through which the controlled current travels.
- In the OFF state, the conduction channel is depleted (pinched-off), which causes the FET to exhibit very high resistance (R_{OFF}), mechanism which provides good isolation at low frequencies.
- A FET is basically a gate voltage-controlled resistor. Insertion loss is largely dictated by channel resistance, and gate-to-source capacitance determines isolation. To increase isolation (high impedance OFF state), a short (inductive) section of a transmission line is connected between the source and drain to resonate out the pinch-off capacitance C_{off} .



The inductor L is a short section of a transmission line used to parallel resonate the RC combination in order to enhance the high impedance state.

The resistor R_s is the total series resistance at pinch-off (un-depleted channel resistance plus source and drain contact resistance).

A high figure of merit (Q) requires small R_{on} , R_s , and C_{off} . A good approximation is:

$$Q^2 = (R_{on}R_s)^{-1}(\omega C_{off})^{-2}R_{off} / R_{on}$$

Scaling the gate width allows a tradeoff between isolation and insertion loss.

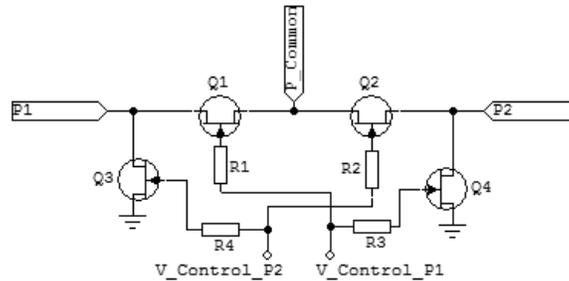
If the gate width is doubled, R_{on} and R_s are halved, C_{off} is doubled, and Q is invariant. Typical values of Q^2 at 10 GHz and 30 GHz are about 1000 and 100,

respectively. In normal operation, no bias is applied to the drain. A negative bias on the gate (relative to the source) pinches-off the channel. Zero or positive gate bias turns the channel on.

- The isolation of FET switches degrades at higher frequencies due to the effect of drain-to-source capacitance (C_{DS}).

For example, a GaAs FET has the reactance X_C of the C_{DS} at 10GHz about 320Ω which can give an equivalent of about 10dB drain-to-source isolation, which is not sufficient to satisfy the isolation performance.

A simplified schematic of a SPDT switch (single-pole-double-throw) using FETs is shown below:



To switch the RF from the common port to port 2, Q1 and Q4 are reversed biased so that the channels between source and drain are pinched-off; while Q2 and Q3 are forward biased so that low channel resistance exists between drain and source.

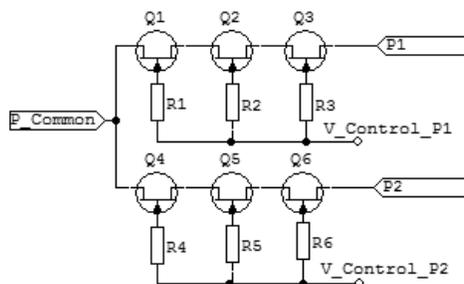
Q1 and Q3 act as a series device to switch the RF ON and OFF, while for better isolation, Q3 and Q4 are used to shunt to the ground the RF that leaks to the OFF port.

- To increase the isolation and linearity in a FET switch more FETs can be added in series on each arm.

Power handling in the OFF state can be increased by "stacking" FETs in series. If done properly the RF voltage will divide among the gates.

Thus, a double-stack of FETs with 12 volt breakdown can achieve comparable power handling to a PIN diode switch with 24 volts breakdown.

- For stacked-FET switches, the power handling ideally goes up as the square of the number of FETs in the stack. A double-stack structure (two FETs in series) has four times the power handling of a single FET structure. Adequate isolation is needed between the adjacent gates so that the voltage divides equally. Resistive gate feeds are one way to accomplish this.



- In the FET switch shown above if adding drain-to-source bypass resistors (few $k\Omega$) on each FET, can improve the overall insertion loss and the linearity of the switch.

- A down side to stacking FETs to improve power handling in the OFF state is that the series resistance (insertion loss) in the ON state is multiplied.

In the FET type switch design the biasing path (V control) is not connected to the RF path of the switch, as in the PIN switch case.

This gives to the FET switch a simpler DC biasing path, eliminating the need for an expensive high-performance RF chokes, avoiding the insertion loss that results from the biasing path being connected to the RF path as in case of PIN diode switches.

- The ON resistance of a FET is typically higher than a PIN diode, resulting in inferior insertion loss performance for FET switches compared to PIN diode switches.
- As voltage-controlled devices, FET switches consume much less current than PIN diode switches.

Hybrid RF Switches

As we see both PIN diodes and FETs provide distinctive advantages. However, neither exhibits superior bandwidth and isolation requirements at the same time.

So, hybrid switches using FET and PIN diode technology were created to provide wide bandwidth and high-performance switching.

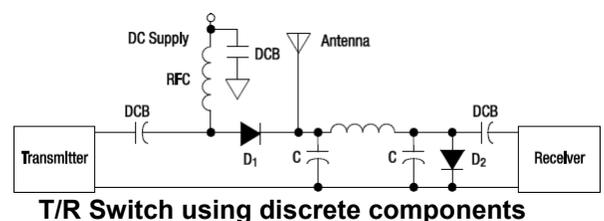
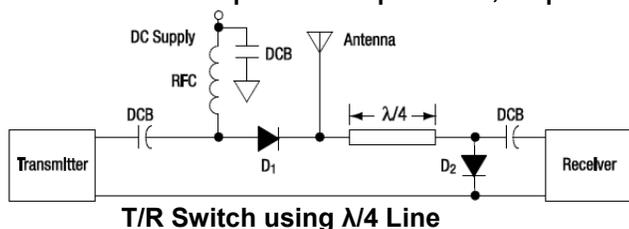
- Hybrid RF switches use series FETs to extend the frequency response down to DC with excellent isolation, and shunt PIN diodes at $\lambda/4$ spacing to provide good isolation at high frequencies. Utilization of series FETs instead of PIN diodes also provides better repeatability performance due to the well-controlled $R_{DS\ ON}$.
- Hybrid RF switches contains shunt PIN diodes and thus draws a certain amount of current.
- The RF path and biasing path should not converge; that might lead to RF leakage in the DC biasing path as in PIN diode switch case.

Transmit / Receive Antenna Switches

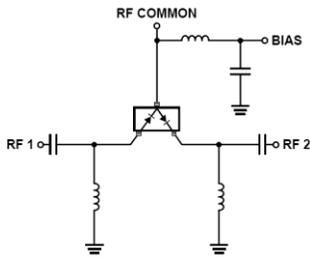
There is a class of RF switches used in transceiver applications whose function is to connect the antenna to the transmitter (exciter) in the transmit state, and to the receiver during the receiver state.

- When PIN diodes are used as elements in these T/R switches, they offer higher reliability, better mechanical ruggedness, and faster switching speed than electro-mechanical designs.

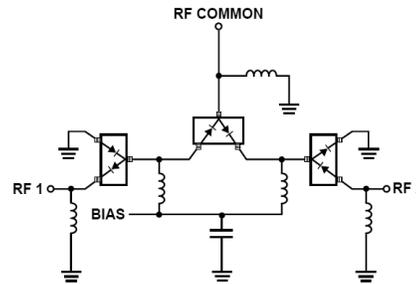
The basic circuit for a T/R switch consists of a PIN diode connected in series with the transmitter, and a shunt diode connected a quarter wavelength away from the antenna node. An LC lumped-component, equivalent of a $\lambda/4$ transmission line, can also be used.



When switched into the transmit state, each diode becomes forward biased. The series diode appears as low impedance to the signal heading toward the antenna, and the shunt diode effectively shorts the antenna terminals of the receiver to prevent overloading. This type of T/R switch is narrowband (due to using the $\lambda/4$ element), and its isolation is mainly given by the resonance of the circuit instead of the ON/OFF behavior. Broadband T/R switches don't use resonant elements.



Broadband T/R Switch with dual (+/-) bias



Very high isolation broadband T/R Switch dual (+/-) bias

Detailed Characteristics and Properties of RF Switches

Frequency Coverage

Operating frequency is often one of the first considerations when selecting an RF switch for a given application.

Low-frequency performance is another consideration that is equally important as maximum operating frequency.

- The frequency response of the FET and PIN diode switches is also influenced by the external components, such as RF bias chokes and DC-blocking capacitors.

Even though a switch may be specified to operate at very low frequencies, the frequency response of DC-blocking capacitors may limit its ability to do so. Careful selection of these external components is necessary to preserve switch performance.

Isolation

Isolation is defined as the ratio of the power level when the switch's path is OFF to the power level when the switch is ON. In other words, it is the suppression of a signal in excess of the insertion loss at the OFF port.

High isolation in switches is crucial in most measurement applications.

Good isolation prevents stray signals from leaking into the desired signal path.

High isolation is especially critical in measurement systems where signals are consistently being routed to and from a variety of sources and receivers through various switch test ports. If these stray signals are allowed to get through, measurement integrity is severely compromised.

- An electro-mechanical (EM) switch or MEMS-based switch achieves isolation by physically disconnecting the metal-to-metal contact of the conduction path. The non-conducting states of these devices are not perfect, such as parasitic capacitances that degrade the ability to impede signal flow.
- PIN diode switches typically offer better isolation performance at high frequencies than FET switches due to the FETs' drain-source capacitance when the FET is

turned OFF. However, this disadvantage can be resolved with the hybrid design by using shunt PIN diodes for isolation.

- PIN diode switch isolation is poorer than FET switches at lower frequencies, around tens of MHz, due to the low frequency limitations of the PIN diodes. This isolation can be improved by proper selection of the PIN diodes, for optimum I-region thickness of the diode used in the switch design.

Insertion Loss

Insertion loss of an RF switch, expressed in decibels (dB) is determined by measuring the power loss (difference) of a signal that is sent in through the common port, and the output signal from the port that is in the ON state.

In receiver applications, the effective sensitivity and dynamic range of the system is lowered by the insertion loss of the front-end switch.

In transmitter applications where the additional RF power needed to compensate for the loss is not available (RF power amplifiers in particular), insertion loss will be a critical specification of a switch.

Insertion loss in Solid-State switches is generally attributed to the following factors:

- Resistance losses due to the finite resistance of series connected components, particularly PIN diodes and finite Q-factor of capacitors.
- Mismatch loss (VSWR losses) at the terminals of the switch, or within the switch. With proper matching compensation techniques, mismatches can be reduced.
- Signal leakage through any OFF path device capacitance.
- Conductor or transmission line loss within the switch itself due to the presence of microstrip, coaxial line, or wave-guide inter-connection lines.
- Solid-State RF switches get more insertion loss as the number of arms (or throws) of the switch increases.
- Extra insertion loss includes off-arm terminations and video filters.
- PIN diode RF switches typically have higher insertion loss at low frequencies due to the sharing of DC biasing and RF paths, while FET switches have higher insertion loss performance at higher frequencies due to the higher ON resistance of FETs.
- To achieve broadband insertion loss performance at high frequencies, the challenge is in managing the OFF device capacitance. This is commonly done by reducing device size while accepting degradation in the minimum insertion loss at low frequencies.
- Narrowband tuning techniques can be used to minimize capacitive effects and recover much of the insertion loss degradation over a 10% to 20% bandwidth.

It is good practice in a new PIN switch design to first evaluate the circuit loss by substituting, alternatively, a wire short or open in place of the PIN diode.

This simulates the circuit performance with “ideal PIN diodes.” Any deficiency in the external circuit may then be corrected before inserting the PIN diodes.

Ports Return Loss and VSWR

Return loss, expressed in decibels (dB), is a measure of voltage standing wave ratio (VSWR) and is caused by impedance mismatch between circuits.

At microwave frequencies, the material properties as well as the dimensions of a network element play an important role in determining the impedance match or mismatch caused by the distributed effect.

- VSWR is an indicator of reflected waves bouncing back and forth within the transmission line, which increases the RF losses.
- Mismatched impedances increase VSWR and reduce power transfer. If VSWR is high, higher power in the transmission line also leaks back into the source, which might potentially cause it to heat up or make the circuit oscillate.

In Solid-State RF switch design, there will be a finite ON resistance whether we choose to use FET or PIN diode as the series ON-OFF mechanism.

This causes an impedance mismatch which results in poor return loss.

- Proper design can use matching circuits to improve the VSWR or return loss of the switch without sacrificing the other specifications of a switch.

Switching Speed

Fast switching speed is important in RF applications especially in applications that require the stacking of multiple switches in series, or where high-frequency transmitting and receiving rates need to be used.

- Switching speed is defined as the time needed to change the state of a switch port from ON to OFF or from OFF to ON.
- Switching speed is often characterized in two ways: Rise/Fall time, and ON/OFF time.
- Rise time is the time it takes for the detected RF output to raise from 10% to 90% of the final value, when a switch arm is changed from an OFF state to an ON state.
- Fall time is the time it takes for the detected RF output to drop from 90% to 10% of the initial value, when a switch arm is changed from an ON state to an OFF state.
- Rise and fall times do not include the switch driver delay time.
- ON time is the time period from 50% of the transition of the control signal to 90% of the detected RF output when the switch arm is changed from an OFF state (isolation) to an ON state (insertion loss).
- OFF time is the time period from 50% of the transition of the control signal to 10% of the detected RF output when the switch arm is changed from an ON state (insertion loss) to an OFF state (isolation).
- The ON and OFF times include the switch driver propagation delay.

Switching time of an RF switch can be measured by using an RF signal generator, a square law RF detector (e.g. Schottky diode), a fast Rising/Falling edge (~10nsec) square wave function (pulse) generator for switch control, and an oscilloscope.

Settling Time

The widely used margin to final value of settling time is 0.01dB (99.77% of the final value) and 0.05dB (98.86% of the final value).

- The above specification is commonly used for GaAs FET switches because they have a gate-lag effect caused by electrons becoming trapped on the surface of the GaAs.
- PIN diode switches have excellent rise time and settling time performance, in the nanosecond range compared to FET or hybrid switches.

There are two common ways to measure the settling time of a FET switch:

- First is the measurement with an oscilloscope, but this method always has some uncertainties due to the resolution of the oscilloscope as well as the linearity and response time of the square law detector.
- A faster and more accurate measurement can be made using a Network Analyzer with an external trigger output. The two ports of the Network Analyzer are connected to the switch input and output ports. The trigger signal from the function or pulse generator is used to synchronize the switch control input with the Network Analyzer external trigger.

In systems where RF switches with a slow settling time are used, designers have to idle the test program for few milliseconds (or more) before each switching cycle in order to allow the switches to fully settle.

Video Leakage

The word “video” was adopted from television, and refers to signal spectrum starting from very low frequencies up to few or even hundreds of MHz range.

- Video leakage refers to the spurious signals present at the RF ports of the switch when it is switched without an RF signal present.

These signals arise from the waveforms generated by the switch driver and, in particular, from the leading-edge voltage spike required for high speed switching of PIN diodes.

- Most switches contain video leakage, which can damage sensitive devices.

The magnitude can be as low as a few mV to as high as few Volts in a 50Ω system.

FETs or hybrid switches generally offer lower video leakage (< 10mV), while PIN diode switches have higher video leakage (~1V), because in PIN diode switches, the RF and DC biasing share the same path. When control voltage is applied to turn the switch ON and OFF, a current surge will be generated. The DC block capacitor used on the RF path causes the current to surge along the RF path when the switch is turned ON and OFF. The current surge level depends on how fast the control voltage changes as well as the voltage level and the capacitor's value.

- If the load's DC input impedance is much higher than 50 ohms, the load will suffer higher video leakage than a load with lower input resistance.

Off-Port Termination

- An RF switch can be reflective or absorptive.
- With reflective RF switches, the RF signal at the OFF port is reflected back to the source due to the load mismatch.
These switches have a simpler design, a slightly lower cost, and can handle higher power than absorptive switches.
- Absorptive RF switches provide a matched termination at the inactive ports. Because they absorb the RF signal, they are limited by the power-handling capability of the terminations. These switches are slightly more complex in their design.

Phase Tracking

- Phase tracking is the ability of a system with multiple parts, or a component with multiple paths, to closely reproduce their phase relative to each other.

A phase tracking requirement is best achieved by first equalizing the time delay between arms of a multi-throw switch. This requires a tightly controlled physical length of the arms from the input port to the output port.

The difference in phase from one unit to another within a product line should be minimized. Since the switch is made up internally of many elements, (diodes, capacitors, and chokes) with their accompanying mounting parasitic reactance and losses, it is necessary to control the uniformity of parts and assembly techniques to achieve the best phase tracking possible.

A good multi throw RF switch features a phase difference of less than 10 degrees, in a frequency range from very low frequencies up to microwave frequencies.

Linearity, Harmonic and Intermodulation Distortion

- Linearity assesses the ability of the RF switch to faithfully transfer a signal without distortion.

Harmonics and intermodulation distortions are strongly influenced by the RF power which is applied to the diode or to the FET, and by the lifetime of a PIN diode.

- Harmonic distortion is a single-tone (single-frequency) distortion product caused by device nonlinearity.

When a non-linear device is stimulated by a signal at a single frequency f_1 , spurious output signals are generated at the harmonic frequencies $2f_1, 3f_1, 4f_1, \dots, nf_1$.

Harmonics are usually measured in dBc, (dB below the carrier or fundamental signal).

- In PIN diode RF switches if use anti-series diodes topology can substantially reduce even order harmonic distortion products.
- Intermodulation distortion appear when the nonlinearity of a device or a system with multiple input frequencies, causes undesired outputs at other frequencies, causing the signals in one channel to interfere with adjacent channels.

It is common practice to limit the analysis to two tones (two fundamental frequencies), f_1 and f_2 , which are normally separated by a small offset frequency of about 1MHz.

For example the 3rd order intermodulation products (IP3) of the two signals, f_1 and f_2 , would be: $2f_1 + f_2$, $2f_1 - f_2$, $2f_2 + f_1$, and $2f_2 - f_1$.

The amplitude in dBm of the intermodulation products will increase in power three times faster than the carrier signal.

- To improve linearity in a FET switch the transistor should be biased to maximize saturated power. Increasing the FET's gate width also improves linearity.

P1dB Compression Point

Another nonlinearity of a system or device (RF switch in our case) is measured by the compression point.

In the linear region, a 1dB increase in input power to the RF switch will correspond to 1dB increase in the output power of the switch.

- When an RF switch is driven into compression it will generate harmonics and insertion loss will increase.
- P1dB is the RF input power level at which the switch insertion loss increases by 1dB over its low-level value (linear region). P1dB is a measure of how much power the on switch can handle before it will distort or compress the signal.

The nonlinearity effect becomes apparent when the output power starts to increase less than the input power.

Power compression in switching FETs has separate mechanisms in the ON-case and the OFF-case.

- For the ON-case FET is about the peak RF current (I_{pk}) flowing through the device which causes compression.
Once the RF current swing is high enough ($I_{pk} > I_{dss}$) to cause the RF voltage-drop across the FET to exceed the knee voltage, the switch starts to compress.
 - Increasing the size of the FET increases the I_{dss} and so increases its compression point and power handling ability.
- In the OFF case, the switch FET is high impedance and there is little current flow through it. Compression occurs when the RF voltage swing causes the gate-drain breakdown voltage to be exceeded on the positive half cycle, or when it moves the FET out of pinch-off on the negative half cycle.
 - A simple rule of improving the compression performance of OFF-case switching FETs is to use higher gate control voltages.
- The mechanisms determining IP3 and P1dB of RF switches are different. IP3 is measured at low input power levels, while P1dB is measured at high input power levels.

Maximum Power Handling

Maximum power handling for RF switches is the power level that will correspond to the onset of gain compression. Once you exceed the calculated power handling, the insertion loss of your switch starts to go up.

- PIN diode RF switches are inherently higher power, lower distortion devices than FET switches. In pulse mode some PIN diodes can switch kilowatts of RF power.
- The maximum RF power that a PIN diode switch can handle is limited by either the diode's breakdown voltage, or by its power dissipation capability. In a 50Ω system, the power dissipation is usually the limiting factor.
- The power handling capability of FET switches tends to be reduced for low frequency operation. This reduction occurs gradually with decreasing frequency.
- Power handling for FET switches in the ON state is calculated using the maximum current the device can pass. The maximum current is proportional to the periphery of the device. Thus a 1mm periphery device will have four times the power handling of a 0.5mm device.
- The maximum power handling for FET switches in the OFF state is mainly a function of FET breakdown voltage. The greater the difference between FET pinch-off and breakdown, the higher is the maximum power handling.
- In both, PIN diode and FET switches, the RF voltage shall not exceed the breakdown voltage limit with turned OFF switching elements.

Reliability, Lifetime, and Hot-Switching

Reliability and lifetime are critical when selecting switches for applications that require repeated switching or expose the device to harsh or uncontrolled environments.

- Electro-mechanical switches have limited lifetimes due to their mechanical switching mechanisms.

Normal wear and tear over time will cause these mechanical structures to degrade. Solid-state switches provide the unique advantage of never wearing out by simply being switched under normal operating conditions, since no moving parts are used.

For these switches, life expectancy is determined by overall time in operation, not the number of switching cycles.

- When used within specifications, Solid-State switches can exceed 500 million cycles, whereas EM switches typically endure less than 10 million operations.

Switch lifetime can degrade when the RF switch is operated under conditions that introduce additional stresses, such as high operating temperature, thermal fluctuations, or exposure to excessive RF signal power.

Another potential stress is hot-switching, which occurs when the device is switched while an RF signal is being applied.

- Although switches are specified for a maximum power handling, this can degrade when hot-switched.

- PIN diode switches are typically more robust when switched at high powers, whereas switched FETs transition through a region during which high amounts of signal power may be dissipated.
- MEMS switches are typically more sensitive to hot-switching, as micro-welding between contacts can occur, resulting in reduced lifetime. Micro-welding could be eliminated (or reduced) in MEMS switches if there is a circuit to block (or limit) the input signals during the switching transition period.

Electrostatic Discharge – ESD

RF switches can be susceptible to electrostatic discharge (ESD), which occurs when static charge is suddenly transferred between surfaces with differing voltage potentials. This can subsequently damage sensitive devices.

- Electro-mechanical switches are almost immune to ESD.
- PIN diode switches have a moderate sensitivity to ESD.
- GaAs switches are generally more sensitive to ESD, with typical ratings of 200V.
- MEMS switches are similarly sensitive to ESD as GaAs switches.

Noise Figure

- Noise Figure of an RF switch (in dB) is considered equal to its insertion loss (in dB).

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