Design Guide
Microwave Switches & RF Coaxial Relays

There is no substitute for experience

Dow Key Microwave Corporation
A Dover Technologies Company
SECTION 1

GLOSSARY OF BASIC MICROWAVES
Glossary of Basic Microwaves

MICROWAVES: A DEFINITION

The spectrum of electromagnetic radiation may be divided into two parts that differ primarily in the principal methods for detection of the radiation. The first of these regions, the optical region, extends from the shortest gamma rays, up through the ultraviolet and visual wavelengths, to some indefinite wavelength in the far infrared. In this region the elementary processes are discontinuous and must be described by quantum theory. The methods of detection involve quantum effects; such as the photoelectric effect or photochemical processes.

In the second region, electromagnetic phenomena are more directly associated with the electrical effects. Radiation is detected by the transformation of the radiant energy into some mechanical motion; the deflection of a meter, the sound from a loudspeaker, or the motion of an electron beam upon the screen of a cathode ray tube. This region can be further subdivided into four subregions, based on the frequency or free space (vacuum) wavelength of the radiation, as follows:

The Sub-Audio through Ultrasonic region: The frequency range from below one Hertz to approximately 100 KHz, with wavelengths ranging from many thousands of miles to 3,000 meters long;

The Radio Frequency region: The frequency range from approximately 100 KHz through 1 GHz, with wavelengths ranging from 3,000 meters to 30 centimeters long;

The Microwave region: The frequency range from approximately 1 GHz through 30 GHz, with wavelengths ranging from 30 centimeters to 1 centimeter long; and

The Millimeter Wave region: The frequency range from approximately 30 GHz through 300 GHz, with wavelengths ranging from 1 centimeter to 1 millimeter long.

The region in which the electromagnetic wavelength is between approximately 30 centimeters and 1 millimeter long, commonly called the microwave and millimeter wave frequency regions, are the subject of this discussion.

The aspect that sets the microwave and millimeter wave regions apart from the lower frequency regions is that at these frequencies, most of the characteristics of typical circuits are determined by the wave character of high frequency currents and fields, rather than voltage or current related effects. The physical size of most components or transmission lines range from an appreciable fraction of a wavelength to many wavelengths long. Therefore, electrical phase and transit time effects within individual circuit elements cannot be ignored, as in lower frequency electronics.

LUMPED VERSUS DISTRIBUTED PARAMETERS

In the previous definition, the various frequency ranges were described in terms of both their frequency range and the signal wavelength. The concept of signal wavelength is important in separating the frequency ranges because at low frequencies and long wavelengths, resistors, capacitors, and inductors are combined with transistors, integrated circuits, and other active devices to form electronic circuits. The size of the individual components is small compared with the signal wavelength, and each can be treated as a single, "lumped" device having a well defined parameter at a specific location in the circuit. Circuits can be mathematically modeled based on the individual values of the components and the circuit topology chosen. If an attempt is made to extend these techniques to the microwave region, component parts of the same electrical size (in wavelengths) would be too small for practical application; therefore, new circuit design and analysis techniques must be employed.

At high frequencies and short wavelengths, circuits made up of transmission lines and distributed elements must be used instead of circuits with lumped constants. Trying to separate a microwave circuit into lumped component elements is a process that must be applied with extreme care, and often should be avoided altogether. Circuit elements in the microwave region take the form of obstacles placed within a transmission line. For instance, the low frequency resonant combination of an inductor and a capacitor is replaced by a resonant cavity (waveguide), or a pattern of shunt or meander transmission lines (stripline). Conventional resistors, capacitors, active devices, and circuit construction techniques cannot be used in the microwave region because component lead wires are too long and the time of transit of the electrons in the components is no longer short compared to the period of the signal wave.

Mathematical modeling of short wavelength circuits is not as easy to perform as in the low frequency region. The resulting models are invariably based on the scattering parameters of an N-port network, rather than the characteristics of discrete resistances, capacitances, and inductances excited by a current or voltage source.

TRANSMISSION LINES

Technically described, a transmission line is a system of material boundaries forming a continuous path from one place to another that is capable of directing the transmission of electromagnetic energy.

At the higher frequency, short wavelength regions of the electromagnetic spectrum, the inductances of short lengths of conductors and the capacitances between short conductors and their surroundings cannot be neglected. These inductances and capacitances are distributed along the length of a conductor,
The concept of signal wavelength is an important aid in conceptually understanding microwave circuits. The primary use of transmission lines is to transmit signals or power between points which are separated by a distance that is significant when compared with the signal wavelength. At short wavelengths, they also find important use as reactive circuit elements, resonant circuits, impedance transformers, and many other similar applications.

The time lag between the sending and receiving ends of a transmission line is important whenever the line is so long or the frequency so high that it takes an appreciable portion of a cycle for the wave to travel the full length of the line. This is expressed more conveniently in terms of wavelength; transmission line theory should be used when the length of a line is greater than approximately one-tenth of a wavelength.

TRAVELING WAVES

Electromagnetic energy is carried along a transmission line in the form of guided electric and magnetic fields that comprise an electromagnetic wave. These waves travel simultaneously in both directions on the transmission line, and are composed of electric and magnetic fields that interact while periodically varying with time. These travelling fields and waves adjust their configuration to fit the material boundaries of the transmission medium in a manner that satisfies Maxwell’s equations.

When electric charges are set into motion, the magnetic field caused by the current of moving charges and the electric field caused by the presence of charges are not established throughout space instantaneously, but travel down a transmission line at a finite velocity. The voltage impressed by a generator on one end of a transmission line does not reach the load connected to the far end of that transmission line instantaneously, but travels down the transmission line at a finite velocity and reaches the load somewhat later. The velocity of propagation depends upon the medium comprising the transmission line, in which the electric and magnetic fields exist. For air-insulated transmission lines, the velocity is nearly equal to that of light in free space. The velocity is somewhat lower in transmission lines that use a solid dielectric insulation.
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Non-TEM Transmission Lines
- Waveguide
- Dielectric Waveguide
- Image Line
- Microguide
- Slot Line
- Fin Line

TEM & Quasi TEM Transmission Lines
- Coaxial Line
- Dielectric Loaded Stripline
- Suspended Substrate
- Microstrip
- Trapped Inverted Microstrip
- Coplanar Waveguide
- Suspended Stripline

FIGURE 1-1. Microwave transmission line cross-sections.

<table>
<thead>
<tr>
<th></th>
<th>4 - Excellent</th>
<th>3 - Good</th>
<th>2 - Fair</th>
<th>1 - Poor</th>
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<tr>
<td>Coaxial Line</td>
<td>4 4 1 1 1</td>
<td>3 1 2 1 2</td>
<td>Very Low</td>
<td></td>
</tr>
<tr>
<td>Metal Waveguide</td>
<td>3,000</td>
<td>4 4 1 1 1</td>
<td>4 3 4</td>
<td>Very Low</td>
</tr>
<tr>
<td>Image Line</td>
<td>2,500</td>
<td>3 1 2 1 1</td>
<td>1 1 2 1</td>
<td>High</td>
</tr>
<tr>
<td>Suspended Stripline</td>
<td>600</td>
<td>3 0 2 2 1</td>
<td>3 4 1</td>
<td>Low</td>
</tr>
<tr>
<td>Fin Line (Durod)</td>
<td>500</td>
<td>4 4 1 2 2</td>
<td>3 4 1</td>
<td>Low</td>
</tr>
<tr>
<td>Microstrip (Durod)</td>
<td>350</td>
<td>3 2 3 4 2</td>
<td>3 4 2</td>
<td>Moderate</td>
</tr>
<tr>
<td>TMM Line (Alumina)</td>
<td>300</td>
<td>1 2 2 3 4</td>
<td>2 3 4 2</td>
<td>Moderate</td>
</tr>
<tr>
<td>Coplanar Line</td>
<td>150</td>
<td>1 2 1 1 4</td>
<td>1 1 2 1</td>
<td>Moderate</td>
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<tr>
<td>Slot Line</td>
<td>100</td>
<td>1 1 1 3 1</td>
<td>3 3 2</td>
<td>High</td>
</tr>
</tbody>
</table>

FIGURE 1-2. Comparison of transmission line media.

Figure 1-3 shows the physical configuration and commonly accepted terminology for a coaxial transmission line.

Impedance

The characteristic impedance of a coaxial transmission line is dependent upon the dielectric constant of the insulating medium and the ratio of the two conductor diameters. This impedance can be calculated from the diameters of the two conductors and the dielectric constant of the insulating material. Mathematically, this is as follows:

$$Z_{(0)} = \frac{138}{\sqrt{\varepsilon_r}} \log \frac{D}{d}$$

Where:

- $Z_{(0)}$ = Characteristic impedance, in ohms
- $\varepsilon_r$ = Dielectric constant of the medium
- $D$ = Inside diameter of the outer conductor, in inches
- $d$ = Outside diameter of the inner conductor, in inches

Insertion Loss

An important consideration in the application of coaxial transmission lines is the attenuation, or insertion loss. This attenuation is the sum of the following components:

- A - Conductor loss
- B - Dielectric loss
- C - Reflection loss

A - The conductor loss is a function of the materials used for the transmission line, and the dimensions chosen, and can be calculated from the formula:
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\[ \alpha_{(\text{ref})} = 20 \log \left( \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \right) \]

Where:
- \( \alpha_{(\text{ref})} \) = Reflection loss, in dB
- VSWR = Voltage Standing Wave Ratio

Examining the equations for conductor and dielectric losses shows that the attenuation in the conductors increases proportional to the square root of the frequency, while the dielectric losses increase directly with the frequency. At some point towards the high end of the microwave frequency range, or the low end of the millimeter wave frequency range, the dielectric losses for most known solid materials become the parameter causing most of the attenuation, and low loss applications typically will use a center conductor supported in air dielectric by widely spaced bead supports. These dielectric beads are very short in comparison to the electrical wavelength. This form of construction is also used at lower frequencies to provide coaxial transmission lines capable of propagating very high power levels with low loss. Most of the low frequency applications of the bead supported center conductor are by nature specialized, narrow band, and not considered in this discussion.

Surface Loss

Microwave signals travel primarily along the surface (skin) of the coaxial conductors. The depth to which these microwave signals penetrate the conductor material, usually referred to as the "skin depth," is inversely proportional to frequency, and is given by the equation:

\[ \delta = 0.0144 \cdot \frac{\lambda}{\mu_{(c)}} \]

Where:
- \( \delta \) = Skin penetration, in inches
- \( \lambda \) = Wavelength, in inches
- \( \rho_{(c)} \) = Resistivity of conductor, in ohm-inches
- \( \mu_{(c)} \) = Relative permeability of conductor

At the high end of the microwave frequency region, this skin depth is on the order of one-one hundred thousands of an inch, or smaller. Therefore, surface finish and resistivity becomes increasingly more important at these higher frequencies. For satisfactory performance at frequencies through the lower ranges of the millimeter wave frequency range, surface finish of the conductors and mating contacts of switches and connectors becomes critical. Plating these conductors and contact surfaces
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with noble metals having very low resistivity can be very beneficial in maintaining low insertion loss. Plating thickness is normally selected to exceed twice the skin depth, as a minimum.

Frequency Limits

Coaxial transmission lines have an upper frequency limit that is determined by the physical dimensions of the line relative to the wavelength of the signal. Coaxial transmission lines (or any two-wire system) have the property of being able to propagate energy in a mode having neither electric or magnetic field components orientated in the direction of propagation. This mode is commonly referred to as the TEM (or Transverse Electromagnetic) mode. The TEM mode is the only transmission mode described by electromagnetic field theory that has a low frequency cut-off of zero hertz, and can transmit all frequencies down to DC. This TEM electric and magnetic field configuration for a coaxial transmission line is shown in figure 1-4.

Modeing Frequency

The dominant TEM transmission mode for coaxial transmission lines begins to "mode" (propagate energy in a set or sets of electrical and magnetic fields other than the dominant mode for which the transmission line was designed to handle) at a frequency given by:

\[ F_{(\text{Cutoff})} = \frac{7.52}{\sqrt{\varepsilon_r \times (D + d)}} \text{ GHz} \]

Where:

- \( F_{(\text{Cutoff})} \) = Cut off frequency (in GHz)
- \( \varepsilon_r \) = Dielectric constant of medium
- \( D \) = Inner diameter of outer conductor, in inches
- \( d \) = Outer diameter of inner conductor, in inches

A safety factor of 5 to 10 percent should be used with the maximum frequency of operation calculated with this equation. Frequencies above this "modeing" frequency are capable of being transmitted in modes other than the dominant TEM mode. This is undesirable since it significantly reduces the efficiency of transmission; these "modeing" signals are not detected or transferred to other circuit elements in the same manner as the dominant TEM mode signals.

Waveguide Transmission Lines

Definition: Waveguide was the original transmission line configuration for the microwave frequency range, and in spite of its bulky and unwieldy configuration, still is the most practical for uses at the extremely high frequency portions of this frequency range and for the transmission of high power signals. The term waveguide connotes a hollow conducting tube used for the transmission of electromagnetic waves. The basic difference between coaxial and waveguide transmission lines is the mode in which they propagate electromagnetic energy. There are an infinite number of electrical and magnetic field combinations, known as modes, that will propagate energy in a waveguide transmission system. These various modes are all characterized by having a cutoff frequency below which they cannot propagate energy. This cutoff frequency is proportionally higher based on the order of the mode.

The mode of a waveguide transmission system is commonly described as a TE (Transverse Electric field) or TM (Transverse Magnetic field) mode. The TE modes have no electrical field components orientated in the direction of signal propagation; these electrical fields are all orientated in the transverse directions. Correspondingly, the TM modes have no magnetic field components orientated in the direction of propagation. The most commonly employed transmission mode in rectangular waveguide is the TE\(_{1,0}\) mode. The electric and magnetic fields for this transmission mode are shown graphically in figure 1-5.

Cutoff Frequency

One of the major differences between waveguide transmission lines and transmission methods that employ solid conductors to form the two transmission paths (transmission and return) is the existence of a cutoff frequency in the waveguide, below which energy cannot propagate. The cutoff frequency for the commonly used rectangular waveguide operating in the TE\(_{1,0}\) mode is given by the formula:
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FIGURE 1-5. TE_{1,0} electric and magnetic fields in a rectangular waveguide.

\[ \lambda_{(c)} = 2 \times a \]
\[ \lambda_{(c)} = \frac{V_{(c)}}{f_{(c)}} \]

Where:

- \( \lambda_{(c)} \) = Cutoff wavelength
- \( f_{(c)} \) = Cutoff frequency
- \( a \) = The waveguide broadwall dimension
- \( V_{(c)} \) = Velocity of light in a vacuum

Velocity of Propagation

For a TEM (or coaxial) transmission system, the velocity of propagation is constant at all frequencies. In a waveguide transmission system, the velocity of propagation and other transmission parameters change with frequency, and the transmission system is dispersive. For a normal waveguide (with an air or vacuum dielectric) the velocity of propagation is given by the equation:

\[ v = \frac{V_{(c)}}{\sqrt{1 - \left( \frac{f_{(c)}}{f_{(o)}} \right)^2}} \]

Where:

- \( v \) = Velocity of propagation
- \( V_{(c)} \) = Free space velocity for frequency of operation (speed of light)
- \( f_{(c)} \) = Cutoff frequency
- \( f_{(o)} \) = Frequency of operation

Guide Wavelength

Similarly, the wavelength of the signal propagating down the waveguide, termed the guide wavelength, is shown by the equation:

\[ \lambda_{(o)} = \frac{\lambda_{(c)}}{\sqrt{1 - \left( \frac{f_{(c)}}{f_{(o)}} \right)^2}} \]

Where:

- \( \lambda_{(o)} \) = Guide wavelength
- \( \lambda_{(c)} \) = Free space wavelength for frequency of operation
- \( f_{(c)} \) = Cutoff frequency
- \( f_{(o)} \) = Frequency of operation

As the frequency of a signal propagating in a waveguide system is decreased from the center of the normal operating band towards this cutoff frequency, the rate of change of the guide parameters (such as velocity of propagation, phase or group velocity, guide wavelength, and impedance) increases as the operating frequency comes closer to the cutoff frequency. Since the transmission parameters are not constant with frequency, waveguide transmission systems are termed "dispersive" in nature.

Impedance

The characteristic impedance of this type of dispersive transmission media cannot be determined as easily as for a coaxial transmission line, because transmission is by electric and magnetic fields, and there are no unique currents and voltages present. This is not really a stumbling block in the application of waveguide transmission systems; all of the important transmission parameters can be normalized to the characteristic impedance of the system, and scattering parameters can be used to describe the system (or component) characteristics relative to this characteristic impedance. The basic quantities that are used in analyzing waveguide systems are reflection coefficient, stand-
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Operating Frequency

In all types of transmission lines, it is desirable to select the size of the transmission line so that only one mode of propagation is possible. In other words, the physical size of the waveguide is related to the frequency band over which it operates. Because of the existence of the higher order modes of propagation, it is common to operate a waveguide transmission system over a frequency range of only approximately 1.5 to 1. By properly selecting this operating frequency range, it is possible to operate far enough from the cutoff frequency so that the waveguide parameters do not vary too rapidly, and to avoid the frequency regions where transmission in other modes is possible.

TRANSMISSION LINE IMPEDANCE

Many circuit concepts apply to the microwave frequency region in essentially the same manner as they do in low-frequency applications. One of the most important of these concepts is Characteristic Impedance. The characteristic impedance of a transmission line is normally considered to be the input impedance of an infinitely long section of that line.

An infinitely long transmission line, though never actually encountered in practice, may be used to develop an understanding of the basic concepts of microwave transmission lines and circuits. Current flowing in the conductors of an infinitely long line sets up a magnetic field encircling the conductors. Therefore, the transmission line has inductance. The conductors making up this transmission line will have a specific resistance per unit length associated with them. There will also be a voltage between the conductors, and charges will exist on these conductors, so there will be a capacitance between these conductors. Additionally, in the usual configurations, the conductors may be embedded in a lossy dielectric material, so that a conductive element must be assumed to exist between the conductors to account for losses in this dielectric material.

If all of these factors are assumed to be distributed equally over the infinite length of the transmission line, then a certain amount of these resistances, capacitances, and inductances can be assumed to exist over a specific (shorter) length of transmission line, and the infinitely long line can be assumed to be made up of many sections (actually an infinite number of sections) of shorter transmission lines connected in series. Figure 1-6 shown above is a schematic representation of such an equivalent circuit.

The characteristic impedance of a real (finite length) transmission line can be calculated from the assumptions made regarding the infinitely long transmission line. This calculation of the microwave impedance of a transmission line is made in the same manner that impedances are calculated at the lower frequencies. Mathematically, the characteristic impedance of an infinitely long transmission line is given by the equation:

\[ Z_{(o)} = \sqrt{\frac{R + jL}{G + jC}} \]

Where:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z_{(o)}</td>
<td>Characteristic impedance</td>
</tr>
<tr>
<td>R</td>
<td>&quot;Real&quot; resistive component</td>
</tr>
<tr>
<td>G</td>
<td>&quot;Real&quot; conductive component</td>
</tr>
<tr>
<td>jL</td>
<td>&quot;Imaginary&quot; inductive component</td>
</tr>
<tr>
<td>jC</td>
<td>&quot;Imaginary&quot; capacitive component</td>
</tr>
</tbody>
</table>

DISCONTINUITIES

In an infinite transmission line, the electrical properties are very much like the mechanical properties of a stretched string; electromagnetic waves and fields can be transmitted down the transmission line in either direction. If the transmission line possesses resistance, these waves will be attenuated as they travel down the line. If this transmission line is terminated, rather than being infinitely long, a portion of the travelling wave will be reflected from this termination. Therefore, the electromagnetic fields in the transmission line will be travelling in both directions, and will consist of an incident wave and a reflected wave.
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If the geometrical dimensions and material constants are identical in all transverse sections of a transmission line, the line is said to be uniform. If the material properties or transverse dimensions of a transmission line are not uniform over its entire length, but change gradually from one configuration to another, and if these changes are evenly distributed and occupying a length of many wavelengths, then there will be very little reflection from this change; it will behave as a simple transformer, changing the characteristic impedance of the transmission line. If there is an abrupt change in these dimensions and/or constants, there will be a reflection from this "discontinuity." When a discontinuity is placed across a transmission line, a portion of the incident wave is absorbed by the discontinuity, a portion is transmitted into the transmission line beyond, and a portion of the incident electromagnetic energy is reflected back toward the source.

STANDING WAVES

Any load other than the characteristic impedance that is connected to the cut end of this infinitely long transmission line will not absorb all of the power travelling down the line. The power which is not absorbed by the load is reflected by it and travels back along the line towards the generator. Because of the reflection, a standing wave will be set up on the incident side of the discontinuity. The field strengths of the incident wave and reflected wave will add vectorially at all points in the transmission line to form the instantaneous electrical and magnetic fields present at any point in the transmission line. These field strengths will periodically vary from a minimum to a maximum and then back to another minimum over a length that is equal to the wavelength of the signal propagated down the transmission line.

The extent to which a load is matched to the transmission line is usually expressed as either the Reflection Coefficient. The Voltage Standing Wave Ratio (VSWR) caused by the load, or the Return Loss of the load. A few other characteristics of the transmission system that are important are the amount of the incident power that is transmitted to the load and the amount of this power that is reflected back toward the source by the load.

REFLECTION COEFFICIENT

The Reflection Coefficient is the ratio of the reflected wave voltage or current to the incident wave voltage or current. The best possible match, given by a load impedance exactly equal to the transmission line's characteristic impedance, will produce a reflection coefficient of zero. The worst possible match, given by a loss-free load (an ideal open circuit, short circuit, inductor, or capacitor) will produce a reflection coefficient of unity. The mathematical expression for Reflection Coefficient is:

\[ \Gamma = \frac{E_r}{E_i} = \frac{I_r}{I_i} \]

Where:
\[ \Gamma \] = Reflection coefficient
\[ E_r \] = Incident wave voltage
\[ E_i \] = Reflected wave voltage
\[ I_r \] = Incident wave current
\[ I_i \] = Reflected wave current

VOLTAGE STANDING WAVE RATIO

The Voltage Standing Wave Ratio (VSWR) is the ratio between the voltage at the maximum point of the standing wave and the voltage at an adjacent minimum of the standing wave. In the early days of the microwave industry, the electrical potential at any point on a microwave transmission line was virtually the only quantity that could be measured directly. Determining the VSWR and the phase of the reflected wave from a component with a slotted line became the primary methods of determining the characteristics of a microwave device. A transmission line which has no reflected wave present has \[ E_{(max)} = E_{(min)} \] and a VSWR of unity. This ratio becomes larger without limit as complete reflection of the incident power by the load is approached. VSWR is expressed by the equation:

\[ VSWR = \frac{E_{(max)}}{E_{(min)}} \]

Where:
\[ E_{(max)} \] = RMS value of the maximum electrical potential on the line
\[ E_{(min)} \] = RMS value of the minimum electrical potential on the line

VSWR is related to the Reflection Coefficient by the two equations:

\[ VSWR = \frac{1 - \Gamma}{1 + \Gamma} \]

RETURN LOSS

The Return Loss is the ratio, in dB, of the incident power on a transmission line to the reflected power. Return Loss is infinite for a transmission line that has no reflected wave present, and becomes smaller with a limit of zero as complete reflection of the incident power by the load is approached. The return loss of a transmission system is given by:
\[ \Gamma = \frac{VSWR - 1}{VSWR + 1} \]

\[ \text{Return Loss} = \frac{P(0)}{P(1)} \]

Where:

- \( P(0) \): Incident Power
- \( P(1) \): Reflected Power
- \( \Gamma \): Reflection Coefficient

Return Loss is related to the reflection coefficient by the equation:

\[ \text{Return Loss} = 20 \log_{10} |\text{Reflection Coefficient}| \]

**SCATTERING PARAMETERS**

If a two port device or network is embedded into a transmission line, and the transmission line is terminated in its characteristic impedance, the stimulus signal can be thought of as a traveling wave incident upon the device, and the response signals as another wave reflected from the device or transmitted through the device. A set of equations can be established relating these incident and "scattered" waves which will completely characterize the device or network. In the microwave frequency region the most commonly used set of such equations are the "S-Parameters."

Referring to figure 1-7, \( E(1) \) and \( E(2) \) are the voltages reflected from the first and second ports of the network when it is excited by the voltages \( E(1) \) and \( E(2) \). From these measurable quantities, a set of network equations can be developed, as follows:

\[ E(1) = S(11) \times E(1) + S(12) \times E(2) \]
\[ E(2) = S(21) \times E(1) + S(22) \times E(2) \]

Dividing through by the square root of the characteristic impedance to convert the excitations to their equivalent power levels, the following can be developed:

- \( A(1) \): power incident upon the first port,
- \( A(2) \): power incident upon the second port,
- \( B(1) \): power reflected from the first port, and
- \( B(2) \): power reflected from the second port

From this, the "S-Parameters" of the two port network can be developed, as follows:

\[ B(1) = S(11) \times A(1) + S(12) \times A(2) \]
\[ B(2) = S(21) \times A(1) + S(22) \times A(2) \]

Therefore:

\[ S(11) = \frac{B(1)}{A(1)} \quad \text{when} \quad A(2) = 0 \]
\[ S(12) = \frac{B(1)}{A(2)} \quad \text{when} \quad A(1) = 0 \]
\[ S(21) = \frac{B(2)}{A(1)} \quad \text{when} \quad A(2) = 0 \]
\[ S(22) = \frac{B(2)}{A(2)} \quad \text{when} \quad A(1) = 0 \]

The microwave "S-Parameters" of a two port network can be summarized as follows:

- \( S(11) \): Input reflection coefficient with the output matched.
- \( S(21) \): Forward transmission coefficient with the output matched. This is the gain or attenuation of the network.
- \( S(22) \): Output reflection coefficient with the input matched.
- \( S(12) \): Reverse transmission coefficient with the input matched.

**FIGURE 1-7.** Scattering Parameters of a 2 port network.
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Scattering Parameters are important in the microwave frequency domain because:

A S-Parameters are determined with resistive terminations. This avoids the difficulties involved in obtaining broadband open and short circuit conditions required for measuring the H, Y, and Z parameters used in lower frequency device measurements.

B Parasitic oscillations in active devices are minimized when these devices are terminated in resistive loads. This avoids the measurement difficulties that can be involved in measuring un-terminated active devices.

C Since only incident and reflected voltage measurements are required to determine S-Parameters, practical test equipment is readily available for directly determining these values at frequencies up to approximately 100 GHz.
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Scattering Parameter Testing

Many Dow-Key Microwave electromechanical switch specifications are based on S-Parameter test data obtained by using a Hewlett-Packard Model 8510A Automatic Network Analyzer system, both during the design phase and also during in-process and final production acceptance testing. This HP 8510 ANA system is capable of making extremely rapid, fully error corrected magnitude, phase, and group delay measurements over the the frequency range from 45 MHz to 26.5 GHz, and can present these measurement results in either the time domain, the frequency domain, or both domains simultaneously. Measurement data can be stored for use in Statistical Quality Control or Cost of Quality analysis, both routine aspects of Dow-Key Microwave's Quality Assurance system.

The low loss, high isolation electromechanical switch is a difficult component to accurately test, since insertion losses are frequently less than 0.1 dB while isolation is often greater than 70 or 80 dB. The extremely wide frequency and dynamic range of the HP 8510A ANA has been shown to be important in repeatedly testing high performance electromechanical switches to difficult specifications. When required, Dow-Key Microwave can provide (at extra cost) full frequency range X-Y plots of both Insertion Loss and Isolation for selected switch models. Please consult the Dow-Key Microwave factory Applications and Sales Engineers for further information regarding these services.
SECTION II

TYPES OF MICROWAVE SWITCHES
Types of Microwave Switches

**INTRODUCTION**
No one switch, or even one basic type of switch, can best fit all applications. The relative advantages and disadvantages of the different types of microwave switches tend to suit them to a particular use. Even among switches of the same basic type there is a variety of switching speeds, frequency ranges, functions, and power handling capabilities available. In this section the various types of microwave switches that are commonly available will be briefly examined, a general indication of their performance capabilities will be presented, and basic information that will assist the design engineer in selecting the most appropriate switch type for a given application will be outlined.

**TYPES OF SWITCHES**
The three basic RF and microwave switching technologies are electromechanical, diode, and ferrite. These three basic technologies can be further categorized in several ways: for instance, by frequency range, transmission line interface (waveguide/coax/strip), power handling capability, etc. Of these basic technologies, the electromechanical switch was the first to be commercially available, and still represents over one-third of the dollars spent on the microwave switching function. Approximately one-half of the current switch applications (measured in dollars spent) are satisfied by PIN diode based switching technology. Ferrite switching devices represent a

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<th>Type</th>
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<th>EM Coax High Power 100 W</th>
<th>EM W/G High Power 10 MHz</th>
<th>Ferrite W/G High Power</th>
<th>Diode Coax Low Power 100 W</th>
<th>Diode W/G High Power 100 W</th>
<th>GaAs Monolithic Low Power 1 W</th>
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<tr>
<td>Switching Speed</td>
<td>1-20 mS</td>
<td>1-20 mS</td>
<td>50-250 mS</td>
<td>1-5,000 mS</td>
<td>1-200 mS</td>
<td>1-200 mS</td>
<td>20-500 mS</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>DC - 40 GHz</td>
<td>DC - 26 GHz</td>
<td>6% - 50%</td>
<td>6% - 50%</td>
<td>6% - 50%</td>
<td>6% - 50%</td>
<td>6% - 50%</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>.05-8 dB</td>
<td>.05-8 dB</td>
<td>.05-7 dB</td>
<td>.05-7 dB</td>
<td>.5-1.5 dB</td>
<td>.8-2 dB</td>
<td>1-3 dB</td>
</tr>
<tr>
<td>Isolation</td>
<td>80-110 dB</td>
<td>60-100 dB</td>
<td>40-80 dB</td>
<td>40-80 dB</td>
<td>20-30 dB</td>
<td>20-30 dB</td>
<td>20-30 dB</td>
</tr>
<tr>
<td>VSWR</td>
<td>1.1 - 1.5</td>
<td>1.1 - 1.5</td>
<td>1.1 - 1.3</td>
<td>1.1 - 1.3</td>
<td>1.5 - 2.0</td>
<td>1.5 - 2.0</td>
<td>1.5 - 2.0</td>
</tr>
<tr>
<td>Power Handling</td>
<td>100-5,000 W</td>
<td>200 kW</td>
<td>20 kW</td>
<td>1-5,000 W</td>
<td>.01-1 W</td>
<td>100-500 W</td>
<td>5-100 W</td>
</tr>
<tr>
<td>Typical Size</td>
<td>0.2x1.0x0.2</td>
<td>Very Large</td>
<td>2.0x2.0x4.0</td>
<td>Large</td>
<td>0.5x1.0x2.0</td>
<td>1.0x1.0x2.0</td>
<td>0.5x0.7x0.01</td>
</tr>
<tr>
<td>Typical Cost</td>
<td>10X</td>
<td>2X-3X</td>
<td>2X-5X</td>
<td>10X</td>
<td>10X-20X</td>
<td>10X-10X</td>
<td>10X-50X</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>3.0 W</td>
<td>10 W - 50 W</td>
<td>5 W - 80 w</td>
<td>5 W - 250 W</td>
<td>1 W - 5 W</td>
<td>3 W - 15 W</td>
<td>1 W - 5 W</td>
</tr>
<tr>
<td>Multithrow: Capability</td>
<td>SPST-SP1ST</td>
<td>SPST-SP10T</td>
<td>No</td>
<td>No</td>
<td>SP4T</td>
<td>SP10T</td>
<td>No</td>
</tr>
<tr>
<td>Multithrow: Cost per Throw</td>
<td>1X</td>
<td>2X</td>
<td>--</td>
<td>--</td>
<td>5X</td>
<td>10X</td>
<td>--</td>
</tr>
<tr>
<td>Switch Matrix: Capability</td>
<td>100x100</td>
<td>100x100</td>
<td>No</td>
<td>No</td>
<td>8x6</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**FIGURE 2-1.** Characteristics of various types of microwave switches.

**NOTES:**
1. "On" condition with matched load. Electromechanical switches can be matched or reflective in the off state. Ferrite switches are normally matched in the off state. Diode switches are normally reflective in the off state, matched switches are available.
2. Cold Switching.
3. SP2T configuration.
4. Latching electromechanical and ferrite switches consume power only when switching. Fail-safe electromechanical switches consume power continuously in the "On" (non-failsafe) state(s). Diode switches and cold saturated ferrite switches consume power continuously.
Types of Microwave Switches

small, but important segment of current applications due to their high power handling capability, and the ability to switch this high power under "hot" (power on) conditions without damage.

ELECTROMECHANICAL MICROWAVE SWITCHES

Electromechanical microwave switches can be further subdivided into four groups: rotary waveguide switches, shuttle or vane type waveguide switches, rotary coaxial switches, and moving contact relay or stripline types of coaxial switches.

Rotary Waveguide Switches

No center contact is involved in waveguide transmission lines, and switches can be designed with the mechanical simplicity and strength of rotary stop-cocks or three-way valves. These switches have an unbroken transmission path and excellent RF characteristics. Waveguide continuity is maintained with VSWR and insertion loss typically no greater than obtained from a good waveguide right angle bend. With proper mechanical design and precision manufacturing of the body and rotor, 60 dB or greater isolation is easily obtainable over complete waveguide bands up through the millimeter wave frequency ranges. VSWR's of 1.1:1 or better, and insertion loss of less than 0.1 dB are common. Life ratings up to 100,000 switching cycles are possible with proper mechanical design and construction.

Rotary waveguide switches are normally rated to carry the full waveguide power levels (both peak and average). Hot switching at high power levels is not practical with these switches, as the abrupt RF discontinuities that occur while the rotor is moving between positions can cause arcing. Hot switching can be accomplished at lower power levels, provided that the circuits with which they are used can withstand working into an infinite VSWR during the switching period. Switching speed can only be described as slow, being as long as 250 milliseconds in the larger waveguide sizes and never faster than a few tens of milliseconds. At high average power levels, where considerable heating can be involved, forced cooling methods have been developed using techniques such as circulating water jackets, etc. Pressurization can be used to improve peak power handling capability. The frequency range of most waveguide switches is generally identical to the waveguide size with which they are used.

Although some special switches with five and six ports (single channel, four or five position) have been made, the rotary waveguide switch is generally available in a single channel, two position or two channel, two position (transfer switch) configuration. Electrical actuation is by rotary solenoids or motor drive, and auxiliary contacts are easily implemented.

Shuttle and Vane Waveguide Switches

These types of waveguide switches are characterized by the ability to hot switch relatively high power levels. The vane type of switch has the output waveguide ports displaced at 120 degree angles to each other. A vane (or door) is pivoted at the intersection of the two channels, arranged so that the input channel is directed alternately to one or the other of the output ports. During switching, power division between the output channels takes place as the vane swings between positions. VSWR and insertion loss capabilities are fairly good, although the isolation between output channels is generally limited to approximately 40 dB. Power handling capability is generally limited by the small contact area between the thin vane and the switch body. Electromechanical actuation is generally by a rotary solenoid with a spring return, and the mechanism is generally less rugged than the rotating waveguide switch configuration. Switching times are relatively slow, typically ranging from the tens of milliseconds to low hundreds of milliseconds.

The shuttle type of waveguide switch is normally furnished in a "T" configuration where the input port is switched to either of two output ports by means of a sliding shuttle or gate. This sliding component moves in a linear fashion, making firm contact at either end of its travel. With proper design of the sliding component, these switches are capable of "Hot" switching substantial power levels. Good microwave characteristics are readily obtainable and the power handling capability is high for both peak and average conditions. Actuation is normally by a geared motor drive, and switching speeds are generally very slow.

Rotary Coaxial Switches

The first commercial coaxial microwave switches were of the rotary electromechanical design, with optional motor driven remote control capability and good electrical performance up to approximately 10 GHz. Some configurations provide input and output connectors protruding parallel to each other from a single surface of the switch. Other configurations provide a central axial input connector with radiating output connectors.

Rotary coaxial switches are supplied for connector sizes between SMA and HN, with up to ten or twelve positions commonly available, as well as the transfer switch (four-port, dual channel) configuration. The practical upper frequency limit for rotating coaxial switches is that frequency at which interfering secondary modes are propagated along the particular transmission line used, offering the potential of operation up to the
Types of Microwave Switches

lower regions of the millimeter frequency range. Power handling capability is moderate, with switches using the type "N" connector capable of handling 2 to 3 kW peak, or 100 watts average, at X-Band. VSWR is typically 1.5:1 maximum up to approximately 12 GHz, with an insertion loss of approximately 0.3 dB and an isolation specification of 60 dB being typical.

Moving Contact or Stripline Coaxial Switches

Plunger type, or relay type, microwave coaxial switches have been available in many configurations since the 1940's. They are small and lightweight, and available in configurations ranging from SPST to SP12T, including the transfer switch and bypass switch configurations. Actuation is usually accomplished by small linear solenoids, one solenoid being provided for each output position. Transition from the coaxial input and output transmission lines to a well matched stripline contact assembly, operating in a microwave cavity that has the characteristics of a waveguide beyond cutoff, occurs at the connectors.

With careful design and fabrication, coaxial switches with stripline contact assemblies can provide acceptable performance up to 40 GHz or 50 GHz. Excellent values of isolation can be obtained within the practical limits of cavity cross section and length, with values often exceeding 100 dB. These values of isolation prove to be substantially in conformance with the theoretical values, and exhibit virtually complete absence of resonant spikes or any of the various forms of leakage which tend to spoil the performance of other switch designs. Switching times of 20 milliseconds or less are practical. VSWR ratings below 1.5:1 up to a frequency of 16 GHz are common, with values below 1.1:1 possible. Insertion loss approaches the theoretical minimums at the lower frequencies, and almost never exceeds one-half dB, except at the millimeter wave frequency ranges. Power handling ability is modest, normally in the range of watts to hundreds of watts. Designs that have been optimized for power handling capability are capable of handling 3 to 5 kW average power at the lower frequencies, and up to 200 to 300 watts average power at X-Band.

FERRITE SWITCHES

The application of ferrite materials and technology has resulted in a long list of devices: isolators, circulators, phase shifters, limiters, filters, amplitude modulators, and switches, to name a few. Many common ferrite devices can be used as switches. These switches are used in many systems applications because they can generally handle much greater peak and average power levels than diode or electromechanical switches. Most ferrite switches are implemented in waveguide and are of the SPST configuration. It is possible to provide multipole switches, with a practical upper limit of about SP4T or SP6T, using three-port junction circulators as the switching elements.

Ferrite switches are generally waveguide devices, and, as such, have limited frequency ranges. There are three basic categories of ferrite switching devices. The first is the coil actuated absorptive switch, which consists of two ferrite slabs centrally located in a section of waveguide. The ferrite elements are generally tapered in order to provide a good impedance match to the waveguide transmission line. A thin resistance card is inserted between the ferrite slabs, perpendicular to the input RF field. This absorptive switch configuration uses an external coil or solenoid to establish a steady state longitudinal magnetic field around the ferrite material. In the absence of the magnetic field, RF energy is transmitted without loss through the waveguide section. When a magnetic field is applied to the ferrite material by the external coil, the incident RF energy is coupled into the resistance card, where it is attenuated. While this configuration of ferrite switch is capable of handling very high power levels, it requires the application of continuous power to maintain the "off" state. Switching speed is dependent upon the characteristics of the external magnetic coil, and can range from microseconds to several milliseconds at the lower frequencies. Insertion loss is typically 1 to 1.5 dB, with isolation approaching 60 dB in the higher frequency ranges.

The second type of ferrite switch is the latching configuration that exploits the remnant states of a closed ferrite toroid. In this mode of operation, switching is achieved with a single pulse of current, and no holding current is required. Switching speeds of less than one-half microsecond are possible. This type of switch is generally limited to lower power levels than the absorptive ferrite switch, typically 10 watts CW at X-Band. Insertion loss and isolation specifications are moderate, with insertion loss of approximately 1 dB and isolation of approximately 40 dB readily achievable.

Another ferrite switching configuration is the differential phase shift circulator, which provides a SPDT switching function. This is actually an assembly of several components, and consists of a folded waveguide magic T and a 3 dB sidewall hybrid, between which is placed a dual section of waveguide containing non-reciprocal 45° latching ferrite phase shifters. The phase shifters in each waveguide are oppositely magnetized, providing a total phase difference between the two transmission paths of 90°. When these two phase shifted waves combine at the output ports of the hybrid, they will be in phase (add) at one of the ports and out of phase (cancel) at the other port. Reversing the phase states of the phase shifters
causes the resulting power output to switch to the other port. Power handling capability of this type of ferrite switch can be as high as 5 KW CW and 1 MW Peak at X-Band, although 200 to 300 W CW and 30 KW peak ratings are more typical. Switching times ranging from 1 microsecond to 5 milliseconds, depending on the power handling capability. The frequency range of this type of ferrite switch is generally narrow, sometimes as narrow as only a few percent bandwidth. VSWR performance is typically good, with values between 1.2:1 and 1.5:1 possible through Ku Band. Acceptable isolation can be obtained, but is normally on the order of only about 40 dB maximum. Insertion loss characteristics are reasonable, but not outstanding, and generally run approximately 1 dB.

DIODE SWITCHES

The diode switch is one of the many solid-state control devices to evolve from the discovery that junction diodes could control the flow of power in RF transmission lines. First introduced commercially in the late 1950's, diode switches are capable of extremely fast switching speeds, and are available in very compact packages. Diode switches are available in both waveguide and TEM transmission media, with frequency ranges covering from the UHF band to the upper regions of the millimeter frequency range. Switching speeds can be as fast as one nanosecond (transition time), and power handling capability ranges from the low milliwatt level through as much as 10 KW average power at the low microwave frequencies. Diode switches are also available in multithrow configurations. SPDT through SP10T switches have been manufactured.

Diode switches generally employ a semiconductor device called a PIN (Positive - Intrinsic - Negative) diode as the active element in a stripline circuit. A PIN diode has the properties of a variable resistor, rather than a rectifying device, at high frequencies. Although not commonly used at this time, variable capacitance varactor diodes have occasionally been used to provide extremely fast switching (transition) times, but with very low power handling capability. These diodes are normally mounted in either a series or shunt configuration across a microwave transmission line, usually implemented in a microstrip configuration. Waveguide configurations normally employ some form of suspended substrate construction. The power required for bias and drive circuits generally runs from approximately 100 mW up, depending on the circuit configuration, the type of driver used, and the characteristics of the individual diodes.

Single element diode switches using a shunt stub configuration can operate over narrow bands to frequencies as high as 40 GHz, with insertion losses of approximately 1 dB, and isolation of approximately 25 dB. By cascading these elements, isolation can be increased to as great as 120 dB at X-Band frequencies. Ultra broadband (greater than 1 decade bandwidth) switches are available, with trade-offs made in other specification areas to achieve the required bandwidth. Diode switches are normally designed to be reflective in the "off" state, although configurations that are absorptive and present a good match to the source in the "off" state are available.

In general, the performance limitations of diode switches are set by the characteristics of the semiconductors used. For example, power handling capability is established primarily by the heat dissipating characteristics of the diode when conducting RF. Similarly power handling is normally limited by the voltage breakdown capability of the semiconductor material under open circuit conditions. In a like manner, switching speed is determined by the minority carrier lifetime in the intrinsic region of the diode chosen for a given switch. In general, with proper design techniques the operating life and reliability of a diode switch can be extremely high, an inherent property of the semiconductor devices used.

FET AND GaAs MONOLITHIC SWITCHES

RF and Microwave FET and GaAs monolithic switching technology is in the infant stage, but is rapidly making progress with respect to increased bandwidth and faster switching speeds. Application of monolithic and FET switching technology at the microwave frequency ranges is most appropriate in the monolithic and MIC construction methods. For microwave FET switches, the switching principles used are an extension of techniques used at the lower (audio through VHF) frequency ranges. For GaAs monolithic switches, the techniques used are an application of either FET switching techniques or monolithic PIN diodes fabricated on a Gallium Arsenide wafer. The monolithic and FET technologies offer the potential of very high quality switches, with low loss, high switching speed, and respectable power handling capability in a very small package. Dow-Key Microwave recognizes the importance of these technologies, but since the monolithic components that have been reported were essentially built in a research environment and no known production microwave FET or monolithic switches are available, additional data will not be presented in this Design Guide.
Types of Microwave Switches

SWITCH SELECTION CRITERIA

As stated above, there is no one, single type of microwave switch that is suitable for all applications. To help in selecting a particular switch technology for an application, some simple guidelines and comparisons between the available switch types will be presented, and the performance advantages of each type will be discussed.

Waveguide versus Coaxial Switches

The selection between coaxial and waveguide switches is usually based on the transmission line in the system where the switches will be used, and on power level. Coaxial transmission lines are substantially smaller, more flexible, and have much broader bandwidths than waveguide, but also have higher loss, less effective shielding (leakage) performance, and lower power handling capability. Waveguide systems have the advantages of substantially lower loss, higher power handling capability, better VSWR, higher frequency (millimeter wave) capability, and lower leakage when compared to coax, but are bulky and inflexible by nature. It is generally not practical to use switches designed for one type of transmission line with the other type.

Coaxial Switching Applications

In typical coaxial transmission line applications, the microwave electromechanical switch and the stripline microwave PIN diode switch are selected for the majority of applications. Ferrite switches with coaxial input and output connections are possible, but generally involve a transition from coax (TEM mode) to a waveguide (TE mode) transmission media, and therefore assume all of the disadvantages of waveguide systems. The microwave electromechanical switch is generally selected because of low insertion loss, good impedance match, and high isolation. Diode switches are normally selected where the requirement calls for very fast switching times or semiconductor levels of reliability. Figure 2-2 shows the comparative advantages and disadvantages of the microwave coaxial electromechanical switch and the microwave stripline PIN diode switch.

<table>
<thead>
<tr>
<th>Electromechanical Coaxial Switches</th>
<th>PIN Diode Coaxial Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADVANTAGES</strong></td>
<td><strong>ADVANTAGES</strong></td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>Switching Speed</td>
</tr>
<tr>
<td>Isolation</td>
<td>1 - 500 nanoseconds</td>
</tr>
<tr>
<td>Power Handling</td>
<td>Size</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Small</td>
</tr>
<tr>
<td>VSWR</td>
<td>Reliability</td>
</tr>
<tr>
<td>Cost</td>
<td>Semiconductor Levels</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>Life</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Semiconductor Levels</td>
</tr>
<tr>
<td>Multithrow Capability</td>
<td></td>
</tr>
<tr>
<td>Matrix Capability</td>
<td></td>
</tr>
<tr>
<td><strong>DISADVANTAGES</strong></td>
<td><strong>DISADVANTAGES</strong></td>
</tr>
<tr>
<td>Switching Speed</td>
<td>Power Handling</td>
</tr>
<tr>
<td>Size</td>
<td>0.1 to 1,000 WCW</td>
</tr>
<tr>
<td>Life</td>
<td>1 to 100 WCW</td>
</tr>
<tr>
<td></td>
<td>0.5 to 3 dB</td>
</tr>
<tr>
<td></td>
<td>15-30 dB per Stage</td>
</tr>
<tr>
<td></td>
<td>&gt;1.5:1</td>
</tr>
<tr>
<td></td>
<td>Octave to Decade</td>
</tr>
<tr>
<td></td>
<td>Continuous Required</td>
</tr>
<tr>
<td></td>
<td>Medium to High</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
</tr>
</tbody>
</table>

FIGURE 2-2. Coaxial microwave switch advantages and disadvantages.
Types of Microwave Switches

Waveguide Switching Applications

The predominant application of waveguide transmission systems is either at very high frequencies (above 40 GHz) or high power levels. This is primarily due to the high quality transmission characteristics (e.g., low loss, low VSWR, low leakage) that can be obtained with precision mechanical assemblies. One of the objectives of switch selection in these types of systems is often the preservation of the high quality (e.g., low loss or low VSWR) that is available with the waveguide transmission line. The electromechanical, ferrite, and PIN diode switches are available for waveguide systems, and the selection is often based on the required switching speed, "hot" switching requirements, and cost. PIN diode switches offer the fastest switching speeds, with acceptable isolation (about 25 dB per stage) but relatively limited power handling capability and VSWR performance. Figure 2-3 shows the comparative advantages and disadvantages of the microwave waveguide electromechanical switch, the waveguide ferrite switch, and the waveguide PIN diode switch.

High Power PIN Switching Applications

Stripline or Finline PIN diode switch power handling capability is limited primarily by the ability to remove internally dissipated heat from the diode structure. Current PIN diode switch power handling capabilities are as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Power Handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide</td>
<td>15 KW peak and 1.5 KW average</td>
</tr>
<tr>
<td></td>
<td>at 16 GHz (narrow band)</td>
</tr>
<tr>
<td>Coaxial</td>
<td>1,000 W CW at 1 GHz (narrow band)</td>
</tr>
<tr>
<td></td>
<td>400 W CW over 2 to 9 GHz</td>
</tr>
<tr>
<td></td>
<td>100 W CW over 6 to 18 GHz</td>
</tr>
</tbody>
</table>

One of the primary applications of fast, high power microwave switches is in EW jamming systems. Further development of ECM capabilities will require the development of broadband (multi-octave) coaxial PIN diode switches with the ability to handle power levels up to 1 KW peak power and 300 W average power over the frequency range from 6 GHz to 18 GHz, and switching times on the order of 100 to 1,000 nanoseconds.

<table>
<thead>
<tr>
<th>Electromechanical Waveguide Switches</th>
<th>PIN Diode Waveguide Switches</th>
<th>Ferrite Waveguide Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADVANTAGES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>&lt; 0.1 dB</td>
<td>Full W/G Rating</td>
</tr>
<tr>
<td>Isolation</td>
<td>60 - 100 dB</td>
<td></td>
</tr>
<tr>
<td>Power Handling</td>
<td>Full W/G Rating</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Full W/G Band</td>
<td></td>
</tr>
<tr>
<td>VSWR</td>
<td>&lt; 1:1:1</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>2x2x4 Typical</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Lowest</td>
<td></td>
</tr>
<tr>
<td>Frequency Range</td>
<td>To 100 + GHz</td>
<td></td>
</tr>
<tr>
<td>Drive Power</td>
<td>Lower</td>
<td></td>
</tr>
<tr>
<td><strong>DISADVANTAGES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switching Speed</td>
<td>1 to 200 milliseconds</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>1 x 10^6 cycles</td>
<td></td>
</tr>
<tr>
<td>Life</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ADVANTAGES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switching Speed</td>
<td>1 - 100 nanoseconds</td>
<td>Full W/G Rating</td>
</tr>
<tr>
<td>Size</td>
<td>Small</td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>Semi Levels</td>
<td></td>
</tr>
<tr>
<td>Life</td>
<td>Semi Levels</td>
<td></td>
</tr>
<tr>
<td><strong>DISADVANTAGES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Handling</td>
<td>100 to 1,000 WCW</td>
<td></td>
</tr>
<tr>
<td>Hot Switching</td>
<td>1 to 100 WCW</td>
<td></td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>&gt;1.0 dB</td>
<td></td>
</tr>
<tr>
<td>Isolation</td>
<td>30 dB per Stage</td>
<td></td>
</tr>
<tr>
<td>VSWR</td>
<td>&gt;1:1:1</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 - 10 % (High Power)</td>
<td></td>
</tr>
<tr>
<td>Drive Power</td>
<td>Continuous Required</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Medium to High</td>
<td></td>
</tr>
<tr>
<td>Harmonic Distortion</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Intermod. Distortion</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>DISADVANTAGES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>Heavy</td>
<td></td>
</tr>
<tr>
<td>Drive Power</td>
<td>Continuous, or high power pulse</td>
<td></td>
</tr>
<tr>
<td>Isolation</td>
<td>20 to 50 dB</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 - 10 % (High Power)</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>
SECTION III

ELECTROMECHANICAL
SWITCH BASICS
Electromechanical Switch Basics

INTRODUCTION

This section will discuss the various characteristics, advantages, and limitations of coaxial RF and microwave electromechanical relays. The subjects that are covered will include discussions of power handling capability, determining the maximum power limits of a relay, the derating of power handling capability required for circuit VSWR, hot switching applications, contact resistance effects, actuator coil considerations, and other factors that affect the use of RF and microwave coaxial relays.

Dow-Key Microwave is actively applying currently available microcomputers in both the design and production groups. Many of the items illustrated in this section have been implemented using this technology, and simplified versions of several microcomputer programs used by Dow-Key Microwave engineers are presented in the "REFERENCE DATA" section of this Design Guide to illustrate these concepts.

ELECTROMECHANICAL SWITCH POWER HANDLING CAPABILITY

Power handling capability is often a key specification in the design, selection, and application of microwave components. In fact, designing a component for a specific power handling capability often causes substantial changes in the mechanical design and all of the other specifications. In this section we will examine some of the factors that affect the CW, closed contact power handling capability of a microwave electromechanical switch, operating from a matched source and into a matched load.

The power handling capability of a microwave switch is primarily determined by two factors, both of which are dependent on the mechanical design and the materials used in the construction of the switch. These factors are voltage breakdown and internal self-heating. These power handling limitations are further dependent upon several external factors (such as the frequency of operation, ambient temperature, heat sinking of the switch, VSWR, etc.), which will be covered in other sections.

Maximum Voltage Limits

When the Internal voltage breakdown limits of an electromechanical switch are exceeded, the air surrounding the internal transmission path ionizes, and arcing in the form of electrical discharges (or miniature lightning bolts) occurs within the switch causing damage to the internal parts. The maximum voltage limits of a switch are determined by the length of the air gap between the internal parts in the transmission path and the body of the switch, and by the voltage breakdown ratings of the RF connectors. The air gap distance in Dow-Key Microwave electromechanical switches varies with each model, and voltage breakdown information is available from our factory Sales and Applications Engineers, if required. Voltage breakdown and power ratings for some of the more popular connectors used with Dow-Key Microwave electromechanical switches are shown in Figure 3-1 and 3-2.

![Image of a chart showing connector voltage breakdown and power ratings.](chart)

**FIGURE 3-1.** Connector voltage breakdown and power ratings, showing the improvement in power handling capability using proprietary high temperature dielectric materials.

![Image of a chart showing connector power ratings versus frequency.](chart)

**FIGURE 3-2.** Connector power ratings versus frequency.
Electromechanical Switch Basics

![Diagram of Electromechanical Switch](image)

**FIGURE 3-3.** Simplified cutaway view of a Microwave electromechanical stripline switch cavity configuration, showing heat dissipation paths.

**Maximum Current Limits**

In most applications at the microwave frequencies, localized heating due to current flow is the limiting factor in the power handling capability of an electromechanical switch. The sources of this internal heating in a typical electromechanical switch are as follows:

A. Power dissipation due to skin effect losses in the switch contact assembly, and

B. Skin effect and dielectric losses in the RF connectors.

The primary dissipation path for this internally generated heat is by conduction through the RF connectors, with a small amount of the heat being dissipated by conduction out the dielectric actuator pushrod. Figure 3-3 shows these dissipation paths for a typical microwave electromechanical switch.

The materials chosen for the contacts, dielectric pushrod, and connector insulators in an electromechanical switch play a very important role in determining the temperature limits that the component will satisfactorily handle, and thus the power handling capability of the device. The following section will describe the power handling limitations, the trade-offs that are available with the various material choices, and how they effect the power handling capability of the switch.

An electromechanical switch’s current handling limits have been reached when the internally dissipated power raises the temperature of the switch cavity high enough to soften or damage the dielectric materials. This internal heat rise is primarily due to skin effect and resistive losses in the contact assembly. Typically, the dielectric pushrod used to move the contacts begins to soften, and proper contact pressure can no longer be maintained. This lower contact pressure increases the contact resistance, which further increases the internal dissipation. If an effective barrier metal has not been used in the plating of the contact assembly, this elevated internal temperature also causes the gold plating on the contact to migrate (or diffuse) into the beryllium copper blade material, destroying the contact surface, and further increasing the contact resistance.

The contact assemblies used in a majority of Dow-Key Microwave’s electromechanical switches are fabricated from beryllium copper, with various cross sections depending upon the frequency range and required power handling capability. Contact finish and plating materials are very important in achieving high power handling capability; contact finish because it affects the series resistance of a pair of closed contacts, and plating materials because of the effect on both the contact resistance and thermal conductivity of the assembly.

Movable electrical contacts used in the electronic and microwave industry are often fabricated from a beryllium copper alloy, and normally employ some form of gold finish on the contact surfaces. A beryllium copper alloy is used for the basic contact material. Pure copper, which has all of the desirable electrical and thermal characteristics, lacks the mechanical toughness, corrosion resistance, and spring qualities required to provide a good pressure contact and long life. A gold finish is often used on the contact assembly because it has good corrosion resistance, low contact resistance, good solderability, good RF characteristics, and acceptable wear characteristics. This gold plating has one undesirable characteristic; if it is plated directly on the copper base material, over time it will migrate or diffuse into the copper. This migration is also accelerated by heat. At temperatures greater than 100 °C, the life of a gold layer plated directly over a copper base metal will be measured in hours, not in thousands or millions of switch cycles. Therefore some form of barrier material must be plated between the beryllium copper switch blade and the gold contact surface. Some of the potential barrier metals are nickel, silver, rhodium, palladium, and alloys of these metals.

Contact assemblies used by some manufacturers of electromechanical switches are fabricated from a beryllium copper...
Electromechanical Switch Basics

![Diagram of electromechanical switch](image)

**FIGURE 3-4.** Electromechanical switch contact configuration, showing microscopic wiping, or microbrushing. Vertical scale greatly enlarged.

The beryllium copper contact assemblies used in all Dow-Key Microwave electromechanical switches are plated with a thick layer (100 microinches minimum) of a proprietary barrier alloy consisting of silver and a noble metal. This barrier alloy is then covered with a minimum of 100 microinches of pure gold in order to obtain a contact assembly with the best possible environmental, microwave, and thermal characteristics.

Flat contact surfaces are avoided; Dow-Key Microwave contacts are designed with a spherical mating surface having a one-half inch radius. The movable contact blade does not extend to the center of this mating contact, but ends a few thousandths of an inch short. The mating of the movable contact to a slightly curved surface provides a slight downward force, and a small movement between these surfaces. The result is a slight microscopic "wiping" between the surfaces. This microbrushing action continuously cleans the contact area. This contact configuration also provides room for more than one blade to mate with the contact (for multi-pole and transfer switch applications). Figure 3-4 shows this contact configuration in greater detail, and figure 3-5 provides some additional information regarding the physical properties of several materials commonly used in electromechanical switch contacts.

The dielectric materials used for the connector insulators also has a major influence on the power handling capability of a microwave electromechanical switch. As can be seen in figure 3-3, the primary dissipation path for the internally generated heat in a microwave electromechanical switch is through the RF connectors. Therefore, the thermal conductivity of the insulating material used in these connectors will determine the amount of power that can be removed from the microwave cavity. Teflon, often used as the material for this insulator in low power switches, has a relatively low thermal conductivity of 1.7 BTU/hr./sq. ft./°F/inch. For high power applications, Dow-Key Microwave uses a proprietary Teflon based dielectric material with an inorganic reinforcing additive which has a thermal conductivity of approximately 8.5 BTU/hr./sq. ft./°F/Inch, which will conduct approximately five times as much heat out of the cavity area as a pure Teflon insulator.

The actuator pushrod that provides the pressure to mate the contact blade assembly with the stationary contacts is the final critical component in determining the power handling capability of a microwave electromechanical switch. This actuator pushrod is under a constant compressive pressure, applied by the magnetic actuating solenoid, and resisted by the spring action of the contact blade. As the contact assembly heats up from skin effect and resistive losses, this heat is transmitted to the pushrod. As the temperature of this pushrod increases, it softens. Eventually a temperature is reached where the pushrod deforms, and can no longer apply the proper pressure to the contacts. Reduction in the pressure applied between the contact surfaces increases the contact resistance, further increasing the power dissipation. Under extreme condi-

---

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical Resistance (microhm-cm)</th>
<th>Thermal Conductivity (W/cm²K)</th>
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</thead>
<tbody>
<tr>
<td>Copper (pure)</td>
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<td>0.934</td>
</tr>
<tr>
<td>Beryllium Copper</td>
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</tr>
<tr>
<td>Dow-Key Silver Alloy</td>
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<td>0.980</td>
</tr>
</tbody>
</table>

**FIGURE 3-5.** Thermal and resistive properties of various switch contact materials.
Electromechanical Switch Basics

Sections, permanent deformation of the pushrod can take place, possibly causing the contacts to go out of alignment or other internal damage. Therefore the plastic deformation temperature of this pushrod is critical.

Many low power microwave electromechanical switches use a Teflon, Kel-F, or similar low deformation temperature plastic for the actuator pushrod. While Teflon is electrically stable under temperature to approximately 300 °C, it has a mechanical softening point of approximately 60 °C, and under some circumstances, Teflon will even "cold flow" at room temperatures. Kel-F has a similar low deformation temperature, but is free from the "cold flow" problem experienced with Teflon. For high power and high temperature applications, Dow-Key Microwave uses a proprietary Polyamide type of dielectric material for the pushrod that has a deformation temperature of approximately 360 °C.

As an illustration of the importance of the choice of dielectric insulating materials, figure 3-5 shows the power handling capability of two standard Dow-Key Microwave electromechanical switch models, along with the power handling capability of similar switches using high temperature dielectric materials.

Power handling specifications for each of the standard Dow-Key Microwave electromechanical switches is shown in the data sheet section of this Design Guide. A convenient selection matrix that shows the power handling capabilities of all of the standard models is shown at the front of this Design Guide.

Determining Maximum Power Limits

Directly determining the maximum power that a microwave component can carry is difficult and expensive. Difficult because of the many effects that are frequency dependent, such as skin effects and dielectric losses. Expensive because this has traditionally been accomplished by testing the device at high power levels for extended periods of time. Generating the necessary high power test signals at microwave frequencies requires specialized test equipment that is both expensive and has high operating costs.

Because of the small geometries involved, traditional methods of calculating the heat transferred out of the switch cavity are extremely difficult to perform, and often do not provide realistic values. Dow-Key Microwave engineers have developed a computer approximation that will determine the maximum power handling capability of a particular electromechanical switch, within reasonable limits. Suitable safety margins and derating factors are applied to the values calculated by this method. This approximation is easily made with a few basic assumptions, and a few simple measurements that can be made with the equipment available in most microwave laboratories.

FIGURE 3-6. Comparative improvement in power handling capability due to the use of high temperature dielectric materials.

The basic assumptions are as follows:

Assumption: The power will be dissipated in the switch contact assembly and connectors.

Assumption: The lost power will not be radiated, but will be converted into heat.

Assumption: The losses are constant and unrelated to applied power.

Assumption: There are no unusually high microwave losses due to poor dielectric materials within the component.

Assumption: The microwave losses will be primarily due to skin effect losses.

Assumption: The internal microwave power dissipation at a particular frequency will be proportional to the microwave insertion loss at that frequency.

Assumption: The power dissipation caused by passing a DC current through the switch will be proportional to the microwave power dissipation.
Electromechanical Switch Basics

Assumption: The internal heating produced by a DC power dissipation will be proportional to the internal heating produced by a microwave power dissipation.

The simple measurements are as follows:

Measurement: Measure the low power microwave insertion loss over the frequency range of interest. This measurement should be made with well matched test equipment and at the ambient temperature of interest. Plot or otherwise record this insertion loss data.

Measurement: Instrument the electromechanical switch with miniature thermocouples at the critical internal points (usually the contact assembly), and pass a DC current through the switch. Monitoring the DC current through the switch and the voltage drop across the switch, increase the DC current until the desired temperature limit is reached. This measurement should be made at the ambient temperature of interest, and with proper heat sinking.

Using the experimental data developed in the steps above, the computer program "POWER.BAS" shown in the "REFERENCE DATA" section of this Design Guide calculates the amount of microwave power that will cause the same amount of power to be dissipated in the switch as the DC power required to heat the switch to the chosen temperature limit. This calculation is based on the measured insertion loss at the frequency of interest. Since, in properly constructed microwave components, the majority of the losses are related to skin effect phenomenon, it is assumed that this procedure provides results that are within 3 dB of the actual microwave dissipation. Suitable derating factors should be used in applying data developed by this method.

DERATING POWER HANDLING CAPABILITY FOR CIRCUIT VSWR

Both of these limiting factors can be calculated from the circuit VSWR.

The instantaneous electric field or current present at a point in a component or transmission line is determined by the vector sum of the field strengths of the power in both the forward wave and the reflected wave present at that point. Because of the complex nature of high frequency currents, voltages, and impedances, the magnitude of these instantaneous fields and currents can exceed the simple Ohm's law (e.g., \(E = I \times R\) and \(P = E \times I\)) relationships by several times in a system with a high VSWR. At the maximum and minimum impedance points, the maximum and minimum current and voltage present can be evaluated from the standing wave ratio, characteristic impedance, and forward (transmitted) power as follows:

\[
I_{\text{(min)}} = \sqrt{\frac{P}{\text{VSWR} \times Z_0}}
\]

\[
I_{\text{(max)}} = \sqrt{\frac{P \times Z_0}{\text{VSWR}}}
\]

\[
E_{\text{(min)}} = \sqrt{\frac{P}{\text{VSWR} \times Z_0}}
\]

\[
E_{\text{(max)}} = \sqrt{\frac{P \times \text{VSWR} \times Z_0}{\text{VSWR}}}
\]

Where:

- \(Z_0\) = Characteristic Impedance in Ohms
- \(P\) = Power in watts
- \(\text{VSWR}\) = Voltage standing wave ratio expressed as a number greater than unity
- \(I_{\text{(min)}}\) = Current at maximum impedance points
- \(I_{\text{(max)}}\) = Current at minimum impedance points
- \(E_{\text{(max)}}\) = Voltage at maximum impedance points
- \(E_{\text{(min)}}\) = Voltage at minimum impedance points

The amount of power derating required for systems with a VSWR greater than unity may be computed from two points of view, depending upon whether the component or system is being described is based on:

A. The net power delivered to the load (forward power less power reflected from the load)

B. The power carried only by the forward component of the standing wave (the input power to the component)

A. In the first case, where the net power delivered to the load is the known quantity, as the value of VSWR increases, the derating factor that is required is equal to:

\[
\frac{P_{\text{(i)}}}{P_{\text{(m)}}} = \frac{1}{\text{VSWR}}
\]

Where:

- \(P_{\text{(i)}}\) = Power Delivered to the Load
- \(P_{\text{(m)}}\) = Power Breakdown Rating
- \(\text{VSWR}\) = Load VSWR
Electromechanical Switch Basics

This relationship is shown in the lower curve of figure 3-7. A continuous decrease in power handling capability occurs because the breakdown is determined by the sum of the field strengths in the forward and reflected waves. The transferred power, on the other hand, is determined by the difference in the square of the field strengths which continues to decrease with increasing VSWR.

B. In the second case, where the input power is the known quantity, the derating factor decreases to a lower limit of only 0.25, as shown by the upper curve of figure 3-7. Mathematically, this can be expressed as:

\[
\frac{P_{in}}{P_{in}} = \sqrt{\frac{2 \times VSWR}{1 + VSWR}}
\]

Where:
- \( P_{in} \) = Power in Forward Wave
- \( P_{in} \) = Power Breakdown Rating
- VSWR = Load VSWR

For microwave switches and relays, Dow-Key Microwave defines the power handling specification as a component's capability to handle CW power through closed contacts at a specific frequency. These specifications assume unity VSWR (matched load) conditions, an ambient temperature of 20 °C, and sea level atmospheric pressure.

Figure 3-7 shows the derating that is required to the power handling specification of an electromechanical switch when circuit VSWR is greater than unity. Power should be removed during switching (cold switching), or suitable additional derating should be applied for hot switching applications. Please contact Dow-Key Microwave Sales Representatives or Sales and Applications Engineers for additional information regarding derating and power handling specifications for hot switching, high ambient temperature, high altitude, or pulse power applications not covered by the above.

**HOT SWITCHING AND PULSE APPLICATIONS**

The power handling specifications shown for all Dow-Key Microwave Corporation electromechanical switches are based on the CW power carrying capability of the switch with the contacts closed, unless otherwise noted. Switch actuation with the rated power applied (hot switching) and operation with pulsed power signals is specifically not included in these specifications. Developing meaningful specifications for hot switching or pulsed power requirements involves many factors, many of which are external to the switch itself. These factors include external source and load VSWR, signal modulation, expected switch life, ambient temperature, atmospheric pressure, etc.

**Hot Switching**

Switching with RF power applied to the contacts during the switching period can be performed with all Dow-Key Microwave electromechanical switches at power levels significantly below their maximum power handling ratings. As a general rule of thumb, satisfactory life for most switches, in most applications, should be obtained at power levels between 1 % and 10 % of the maximum ratings before arcing damage occurs to the contact areas.

**Pulsed Power Operation**

High peak power levels can also cause contact damage due to localized heating of the contact surfaces, damaging the surface plating. Another source of damage when electromechanical switches are used in pulse applications is from internal arcing from the contact assembly to the switch housing or voltage breakdown of the RF connectors. As a general rule of thumb, all Dow-Key Microwave electromechanical switches will operate satisfactorily in pulse power applications where:

A. The duty factor is not less than 10 percent,
B. The pulse length is shorter than 25 microseconds,
C. The load VSWR is less than 1.25:1,
D. Cold switching conditions exist, and
E. The average power does not exceed the maximum power rating of the switch.

![Graph](image)

**FIGURE 3-7.** Power derating required for circuit VSWR.
Electromechanical Switch Basics

Please contact Dow-Key Microwave factory Sales and Applications Engineers for additional information and special switch configurations for specific hot switching and pulsed power applications.

INSERTION LOSS AND CONTACT RESISTANCE

A very important specification in microwave switch applications is insertion loss, or the loss in signal power that will be experienced in going through the closed contacts of the switch. Electromechanical switches have excellent, low insertion loss characteristics over their full bandwidth, which can be as broad as from DC to 40 GHz. The insertion loss of a typical microwave electromechanical switch consists of the following components:

A Loss in the input and output connectors
B Dielectric losses within the insulators in the switch
C Contact resistance losses
D Radiation losses

In most well-designed electromechanical switches, operating at relatively low levels, the primary cause of insertion loss is the contact resistance. Accurately measuring these loss characteristics, which are frequently less that 0.1 dB, requires some fairly sophisticated and expensive microwave test equipment, and a substantial amount of time.

Dow-Key Microwave Engineering, Production, and Quality Assurance groups have developed procedures to improve in-process testing of certain switch products, and to make the continuous monitoring of insertion loss possible during long-term environmental or life tests. In order to accomplish this with relatively low cost and simple test equipment, Dow-Key Microwave engineers have developed methods of approximating the expected microwave insertion loss from values of DC contact resistance. These DC resistance methods have proven to be highly accurate and repeatable, and are routinely used for monitoring and screening purposes during production operations. These methods do not replace the 100 percent final inspection, made at microwave frequencies on computerized Network Analyzers, performed on all production hardware.

Using conventional transmission line theory, the insertion loss due to contact resistance (or any other series resistance) can be calculated from the equivalent circuit shown in figure 3-8. The mathematical equation is:

\[
\text{Insertion Loss} = 10 \log_{10} \left( \frac{Z(0) + Z(L)}{Z(0) + R + Z(L)} \right)
\]

Where:

- \( Z(0) \) = Characteristic impedance of the source and transmission line
- \( Z(L) \) = Impedance of the load
- \( R \) = Series contact resistance

This approximation is valid over the frequency range where the assembly being tested provides a good match to both the source and the load, and becomes invalid when discontinuities, parasitic and resonance effects become significant. A graph of the predicted insertion loss versus contact resistance is shown in figure 3-9.

The Dow-Key Microwave Model DK-688 Electromechanical Switch and Relay Tester can be used with a simple multimeter to provide a low cost method of measuring DC contact resistance. This instrument uses an active, four wire milliammeter to simulate the low contact potentials and currents typical in "dry" signal relay and low signal level microwave switch or connector applications. A listing of the computer program "I-LOSS.BAS" that allows calculating either the expected insertion loss for a given contact resistance, or the value of contact resistance that is expected from a given microwave insertion loss, is shown in the "REFERENCE DATA" section of this Design Guide.

ACTUATOR COILS

The actuator coil used in an electromagnetic switch or relay provides the magnetic force that causes the switch contacts to close. This coil is usually bobbin wound with insulating copper "magnet" wire. The resistance of this coil, and thus the current that will flow in the coil for a particular energizing voltage, is determined by the size and length of wire wound in the coil. The coil's magnetomotive force (the force that moves the switch's armature) is proportional to the current flowing through the coil, times the number of turns of wire on the coil. This magnetomotive force is usually expressed in "ampere-turns." As more turns are put in the actuator coil, less current is needed to provide the required amount of force to operate the relay.

Winding the actuating coil with a few turns of heavy gauge wire results in a low-resistance, low-voltage electromechanical switch that requires a relatively large current to operate. The opposite case is using many turns of fine wire, which results in a high-resistance winding that can operate from a high-voltage supply, and that will draw little current to operate the switch.

For constant electrical input power and constant magnetomotive force, the current or voltage required to develop the magnetomotive force required for switch operation is not a linear function of coil resistance, but varies as the square of the actuating coil resistance. If the number of turns of wire on the
Electromechanical Switch Basics

**FIGURE 3-8.** Microwave equivalent circuit for an electromechanical switch contact resistance.

The actuating coil is doubled, only half as much current is needed to operate the electromechanical switch, provided the other factors are the same. In other words, a big coil on a large switch will require less electrical power for operation than a tiny coil on a miniature switch.

**FIGURE 3-9.** Insertion Loss versus contact resistance for a coaxial microwave electromechanical switch.

**Operate and Release Time**

The time interval between the instant the actuator coil circuit of an electromechanical switch is energized and the closing of the switch contacts is called the operating, or switching time. This time includes the following:

1. Driver Delay (if switch has an internal driver)
2. Inductive delay in the actuator coil
3. Mechanical transfer time of the RF contacts
4. Contact Bounce time.

The operating time of any coil actuated switch is determined essentially by the following:

A. Resistance and inductance of the actuating coil,
B. Physical design and adjustment of the relay,
C. Effective source voltage and source impedance,
D. Final steady-state coil current.

The resistance and inductance of the actuating coil is the limiting parameter in most electromechanical switch designs, since in excess of fifty percent of the operating time of an electromechanical switch is spent in building up the current through the coil's inductive windings, and the resulting magnetic field in the actuating coil, sufficiently to initiate switching action.

Operating time can be reduced with voltage or current overdrive, or a combination of both, during the switching period. Voltage overdrive and current overdrive are equivalent if there is no series resistance in the circuit, and the voltage source has sufficiently low internal resistance. Series resistance will limit current overdrive, without affecting voltage overdrive. Additionally, actuating coils energized in parallel from the same source will interact through the source impedance of the drive circuit, and slow each other down. Applying a steady-state bias current or voltage (at a level below the minimum drop out voltage) to the actuating coil is another technique that can be used to reduce electromechanical switch operating time. However, this may have the undesirable side effect of increasing the release time.

The release time is normally less than the switching time. Both switching time and release time are affected by transient suppression networks placed across the actuating coil. A transient suppression diode across the actuating coil can increase the release time of an electromechanical switch by as much as 100 times. Resistor and capacitor networks placed across the coil for transient suppression can also increase both the operating time and release time by as much as ten times. If operate and release times are important parameters in a circuit application, they should be checked in the prototype stage, and adjustments should be made to the power supply source impedance and transient suppression circuitry if required.
Electromechanical Switch Basics

Please see SECTION IV "SWITCH APPLICATIONS," and "Switch Applications Tips and Traps" page in the "REFERENCE DATA" section of this Design Guide for further information. Dow-Key specifies switching time at 20 °C, and at the nominal actuator coil voltage supplied from a low impedance power source.

Coil Wire Size

Electromechanical switches and relays differ in the amount of voltage and current required for operation. Also, the DC resistance of the actuating coils may vary from a few ohms to several tens of thousands ohms. These characteristics are determined by (among other considerations) the type, size, and amount of wire wound on the actuating coil. Copper "magnet" wire is available in sizes such that there are three steps for doubling (or halving) the cross-sectional area. With twice the cross-sectional area, only half the original length will fit on a given coil bobbin. With half the length and twice the cross-sectional area, the resulting coil will have only one-fourth of the original coil’s resistance, and thus will be suitable for operation at half of the original coil's operating voltage. Figure 3-10 shows the relationship between wire size and other actuator coil characteristics in more detail.

The relationships shown in figure 3-10 are for a general case only. In practice, factors such as bobbin filling factor, insulation of relatively constant thickness for all sizes of magnet wire, the ability to physically wind a particular wire size on a given bobbin size, and other factors all have their effect upon the final choice of actuator coil wire and bobbin size for a given application. For instance: for the same size of bobbin, a 10,000 ohm coil is more difficult to manufacture than a 500 ohm coil; it takes a longer piece of wire, more time on the winding machine, and there is more chance of breaking the wire or damaging the insulation.

Coil Resistance Variation With Temperature

A well established phenomenon in electrical circuits is the increase in resistance of a metallic current path as temperature is increased. The temperature rise may be caused either by current flow through the wire, or by changes in the ambient temperature. In electromagnetic switch applications, this can become a significant factor in the successful specification and application of a particular relay actuating coil.

For actuator coils made from copper magnet wire, the resistance \( R(0) \) after a specific temperature change can be calculated using the formula:

\[
R(T) = R(20) \left[ 1 + 0.00393 \left( T - 20 \degree C \right) \right]
\]

Where:

- \( R(0) \) = Resistance at temperature
- \( R(20) \) = Resistance at 20 °C
- \( T \) = Temperature of interest

For example, if a Dow-Key Series 60 electromechanical switch's actuating coil has a resistance of 245 ohms at 20 °C, what resistance will it have at 85 °C?

\[
T(2) - T(0) = 85 - 20 = 65 \text{ Degrees}
\]

\[
R(245) = 245 \times \left[ 1 + 0.00393 \times 65 \right]
\]

\[
R(85) = 245 \times 1.25555
\]

\[
R(85) = 208 \text{ ohms}
\]

Relay Pick-Up Voltage Variation With Temperature

An electromechanical switch will close when a specific amount of current is applied to the actuating coil, as shown in figure 3-11. Thus, switch pick-up voltage varies directly with coil resistance, and therefore directly with temperature. This is based on the basic Ohm's Law equations:

\[
E = I \times R
\]

\[
R = \frac{E}{I}
\]

\[
I = \frac{E}{R}
\]

Where:

- \( E \) = Voltage
- \( I \) = Current
- \( R \) = Resistance
- \( P \) = Power

Substituting in the equation shown above for coil resistance gives the following equation for pick-up voltage vs. temperature:

\[
V(T) = V(20) \times \left[ 1 + 0.00393 \times (T - 20 \degree C) \right]
\]

Where:

- \( V(T) \) = Coil pick-up voltage for a given temperature
- \( V(20) \) = Coil pick-up voltage at 20 °C
- \( T \) = Temperature of interest

For example, assume that an electromechanical switch with a pick-up voltage of 17 VDC (the catalog specification for most...
Electromechanical Switch Basics

<table>
<thead>
<tr>
<th>Wire Gauge Number</th>
<th>X - 4</th>
<th>X - 3</th>
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<th>X</th>
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<th>X + 2</th>
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<td>1.587</td>
<td>1.260</td>
<td>1.000</td>
<td>0.794</td>
<td>0.630</td>
<td>0.500</td>
<td>0.397</td>
</tr>
<tr>
<td>Coil Current</td>
<td>0.157</td>
<td>0.250</td>
<td>0.397</td>
<td>0.630</td>
<td>1.000</td>
<td>1.587</td>
<td>2.520</td>
<td>4.000</td>
<td>6.350</td>
</tr>
<tr>
<td>Full Bobbin Resistance</td>
<td>6.350</td>
<td>4.000</td>
<td>2.520</td>
<td>1.587</td>
<td>1.000</td>
<td>0.630</td>
<td>0.397</td>
<td>0.250</td>
<td>0.157</td>
</tr>
<tr>
<td>Full Bobbin Turns</td>
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<td>2.000</td>
<td>1.587</td>
<td>1.260</td>
<td>1.000</td>
<td>0.794</td>
<td>0.630</td>
<td>0.500</td>
<td>0.397</td>
</tr>
<tr>
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<td>2.000</td>
<td>1.587</td>
<td>1.260</td>
<td>1.000</td>
<td>0.794</td>
<td>0.630</td>
<td>0.500</td>
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</tr>
<tr>
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<td>1.000</td>
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<td>1.587</td>
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<td>2.520</td>
</tr>
<tr>
<td>Larger Diameter Wire Sizes</td>
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<td></td>
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</tr>
</tbody>
</table>

**FIGURE 3-10.** Theoretical actuator coil wire size ratios.

Dow-Key Microwave electromechanical switches is being considered for a particular circuit design.  If a 20 VDC supply is being used, this switch will operate reliably at room temperature, but will it operate reliably at 85 °C and 125 °C? Solving the equation shown above gives:

At 85 °C

\[ V_{(85)} = 17.0 \text{ VDC} \times [1 + .00393 \times (85 - 20)] \]

\[ = 21.3 \text{ VDC} \]

At 125 °C

\[ V_{(125)} = 17.0 \times [1 + .00393 \times (125 - 20)] \]

\[ = 24.02 \text{ VDC} \]

Therefore, unreliable operation at the elevated temperatures is predicted with the supply voltage chosen.  Either a 24 VDC power source, or an electromechanical switch with a lower pick-up voltage, should be selected for satisfactory operation at the maximum required temperature.

**FIGURE 3-11.** Coil temperature factors.
Copper wire resistance, and therefore switch actuator coil resistance changes linearly with temperature over the temperature range where most electronic systems operate, so this equation works identically with a decrease in temperature. As an example, let’s determine the 20 °C pick-up voltage that would be required for the above electromechanical switch to operate reliably from a 20 VDC power source at 125 °C:

\[
V_{(20)} = \frac{20.0 \text{ VDC}}{[1 + 0.0393 \times (125 - 20)]}
\]

\[
= 14.2 \text{ VDC}
\]

Now let’s determine the -20 °C pick-up voltage for a standard Dow-Key electromechanical switch actuator coil. This coil is rated at 17 VDC maximum pick-up voltage at 20 °C. The decrease in temperature is 40 °C, so:

\[
V_{(-20)} = 17.0 \text{ VDC} \times [1 + (0.0393 \times -40)]
\]

\[
= 14.3 \text{ VDC}
\]

A graph of the approximate multiplication factor to apply to a specified 20 °C actuator pick-up voltage to obtain the pick-up voltage at various temperatures is shown in figure 3-12.

Most electromechanical switches with actuator coils designed for direct current will operate satisfactorily from an alternating current source if the AC drive voltage is rectified with a diode bridge rectifier. Due to the filtering caused by the actuator coil inductance, additional filtering of the rectified drive voltage is not usually required. Figure 3-13 shows the required circuit. Since the actuating coil is sensitive only to the magnitude of the actuating current, the diode bridge may be connected to the relay without respect to polarity. Switching time for this type of AC actuation can be no faster than one-half cycle of the applied AC voltage, and switching is often completed in the first half cycle. The voltage applied to the coil can be assumed to be equal to the AC supply voltage, less the diode voltage drop (approximately 0.6 volts RMS with a low resistance bridge rectifier). Care should be taken to ensure that this voltage is sufficient to pick up the electromechanical switch over the full temperature range of interest.
SECTION IV

SWITCH

APPLICATIONS
Switch Applications

SWITCH OR RELAY?

There is sometimes confusion over these two terms, they are often used interchangeably. In practice, RF engineers (those who are primarily involved with systems operating below approximately 1 GHz) have differentiated relays from switches by the classical definition; a relay is a remotely actuated device, and a switch is a manually activated device.

Designers in the microwave field tend to think of the function being accomplished (i.e., switching), and relays designed for the microwave frequency ranges are almost universally called switches. Manually operated microwave switches, in both waveguide and coaxial configurations, are occasionally used, but the only sure way to distinguish a manually operated switch from a remotely actuated switch is to ask specifically for it.

In this Design Guide, we have attempted to follow the prevailing conventions by using the terms "relay" when discussing products which are limited to RF applications, and "switch" for those products which are designated for microwave applications. In most cases, the reader may consider the terms switch and relay to be interchangeable. There is a growing trend toward the use of microwave switches for lower frequency applications, and the distinction in terms may eventually disappear.

POWER RATINGS

CW Power: Catalog power ratings are for continuous power carry at the specified frequency and power level for each product. The specified power levels are guaranteed when the following conditions are met:

1:1 VSWR system;

Signal is terminated in a 50 ohm load;

Relays are not switched when power is applied to RF contacts.

A graph for showing the derating required for specified CW power handling capacity due to SWR mismatch is shown in the "REFERENCE DATA" Section, and additional technical discussion is presented in Section III, "Electromechanical Switch Basics," of this Design Guide. The catalog power rating of all Dow-Key Microwave electromechanical switches should be multiplied by the derating factor shown (or calculate) to determine the RF power handling capacity for a known (or estimated) load mismatch.

Peak Power: Peak power capacity depends primarily on pulse duration. Most Dow-Key products have the ability to carry power spikes which are two to four times the published CW power rating. Many variables affect peak power capacity, however successful handling of low nanosecond duration pulses up to 10 to 20 times the CW power rating of the switch is possible, under select conditions.

Switching Under Load: Dow-Key relays are not designed for switching while power is applied to the RF, contacts (hot switching). Using a Dow-Key Microwave coaxial relay for power switching will void the product warranty. However some generalizations may be made regarding the probable effects of hot switching. Switching with low power (< 0 dBm) through the RF contacts will normally accelerate a build-up of oxide corrosion on the switches’ gold contacts. The movable contacts in a Dow-Key relay are designed with a slight over-travel, and the stationary contacts are designed so that a microscopic wiping action occurs during contact closure and release. This action is generally sufficient to maintain low contact resistance over the rated mechanical life of the relay. Additional information on contact configurations and microbrushing, contact materials, and power handling capabilities can be found in Section III of this Design Guide, titled "Electromechanical Switch Basics."

At higher power levels, contact pitting and/or material transfer occurs during hot switching. Example: a contact being switched at 20% of rated CW power for a given frequency may continue to operate with acceptable contact resistance for 10% to 20% of its normal mechanical life in many applications. Contact erosion is normally more rapid during contact "break" than contact "make" operation. Power switching at the maximum rated CW power level may cause internal voltage breakdown, extreme contact erosion, or contact welding within a few operations.

FIGURE 4-1. RC relay "speed-up" network.
Switch Applications

OPERATE TIME

Electromechanical switch operating time is primarily a function of the coil power and inductance. Since it requires in excess of 50% of the total switching time to build up the coil’s magnetic field, reducing this time or increasing the coil power could mean faster switch operating time. The following are several methods commonly used to reduce the operating time of a coaxial electromechanical switch:

1 - Increase the coil voltage. A voltage which is 20% greater than the nominal coil voltage may be applied continuously when the ambient temperature is 20 °C or below. A voltage which is 50% greater than the nominal coil voltage may be applied for a few seconds without damage to the coil. To avoid coil overheating, this method is not recommended for continuous duty operation.

2 - Apply a higher than normal voltage pulse to the coil during the switching period. A simple method of accomplishing this is to use a resistance-capacitance network in series with the coil (DC coils only). Figure 4-1 shows a schematic of a network commonly used for this type of relay "speed-up."

When coil drive voltage is applied, the capacitor acts as a short circuit, allowing a high pulse current through the relay’s actuator coil. When the capacitor becomes fully charged, it acts as an open circuit, dropping the coil voltage to its steady-state value.

3 - Apply a higher than normal voltage pulse to the coil, using the indicator contacts. Figure 4-2 shows a schematic commonly used for this type of coil "speed-up" network.

When coil drive voltage is applied, the indicator contacts short the series dropping resistor, applying the full power supply voltage to the coil winding. As the relay operates, the indicator contacts open and the coil actuating voltage drops to its steady-state voltage.

4 - Apply a "priming" current to the actuator coil. This approach improves relay turn-on, but often complicates turn-off. Often the priming current necessary to substantially improve turn-on time is the same as or greater than the relay’s holding current, and the relay might not drop out at all.

FIGURE 4-2. Relay auxiliary contact "speed-up" configuration.

SWITCHING APPLICATIONS

The simplest switching mechanism is an on-off (single pole single throw) type, used to open or close an RF signal path. It may be a fail-safe switch which is normally open (NO), or normally closed (NC), or it may have a latching mechanism which stays in the last position selected. Figure 4-3 shows a schematic diagram of a normally open (form A) SPST switch.

The smallest and least complex switching mechanism manufactured by Dow-Key Microwave is the single-pole-double-
Switch Applications

Communications Antenna Switching

A common application in communications systems is to select alternate antennas to be connected to a transmitter or receiver. In mobile applications, small, balanced actuator mechanisms (such as used in the Dow-Key Microwave 401 Series switches) are more tolerant of shock and vibration. These small switches can often be made to operate for several million cycles, with switching times of less than 10 milliseconds. Directional antennas in tactical aircraft often have this type of rapid switching requirement.

Transmit / Receive Switching

For transmit/receive switching applications, a high isolation switch is usually required to protect the receiver. For microwave applications, the Dow-Key Microwave 401 and 402 series switches are commonly used. For medium power (up to 1 kilowatt CW) HF through UHF applications, a cost-effective choice is the high isolation ("G") option for the Dow-Key Microwave 60 Series relay. Figure 4-6 shows a typical transmit/receive (or "T/R") application in greater detail.

Redundant Communications Systems

Communications transmitting station down time can be minimized by maintaining a constant low power "on" condition in a pair of transmitters, with only one of the transmitters connected to the antenna at a given time. The switch selects a dummy load or a test circuit when the antenna is disconnected.

Transfer and Bypass Switches

The small size and relatively high reliability of SPDT switches provides tremendous flexibility in more complex switching functions. For example: a transfer, by-pass, or DPDT relay is
Switch Applications

FIGURE 4-7. Circuit insertion using two SPDT switches in a transfer switch configuration.

shows how a bypass switch can be used to achieve circuit insertion without shorting the circuit element.

SPDT switches are often cascaded for multi-throw switching, when there is a significant difference between switching rates of the various RF paths. The system repair time and spare parts costs are reduced by part commonality and the ability to selectively replace high usage switch points. In cascaded switch configurations (sometimes termed a "tree" configuration) insertion loss may increase; however, isolation will also be increased. For example, in a switch-filter-switch application, the higher isolation offered by using two SPDT switches may be needed to further separate a desired signal from those passed by non-selected filters. This type of application is shown in figure 4-10.

Transfer switches may be used as SPDT switches, although it is seldom cost effective to do so unless the need exists to terminate the unused input signals. In this instance, a transfer switch offers several advantages over the SPDT configuration. Using internally terminated SPDT switches may limit the power or frequency range of a switch assembly, whereas the user controls the size and quality of the external termination used in a transfer switch configuration. The mechanical complexity of an internally terminated SPDT switch decreases its reliability when compared to most SPDT or transfer mechanisms. A transfer switch with external terminations usually costs about the same as or less than an internally terminated SPDT switch.

If two transmitters are connected to the inputs (ports 2 and 4) of a transfer switch, and antennas are connected to outputs 1 and 3, it can be seen that terminations located on ports 2 and 4 will provide a load to either transmitter in any configuration. Figure 4-11 shows this type of application of a transfer switch used to connect a primary transmitter and a "hot standby" transmitter to a single antenna for a fully redundant communications channel.

FIGURE 4-8. Circuit insertion using a transfer switch.

FIGURE 4-9. Circuit insertion using a bypass switch.
Switch Applications

Transfer switches can also be used in combination with one or more SPDT switches to form simple switching matrices. Figure 4-12 shows a simple 2 x 4 single channel matrix made with this configuration.

A non-blocking matrix with all inputs and outputs terminated can be achieved using transfer switches. While this is not practical for large matrices, simple configurations (up to approximately 6 x 6) are cost effective with this circuit topology. Figure 4-13 shows how two transmitters can be connected to either of two antennas or two terminations, with all ports terminated in all transmission states, using a simple 4 x 4 transfer switch matrix.

SWITCH MATRICES

When a switch matrix with a complex network of RF signal paths is being designed, it can often be subdivided into smaller switching modules which are conceptually and mechanically easier to work with than the final product. There are several bases for subdividing a switch matrix, and a few key parameters will determine which options are practical in a given situation. These parameters are primarily related to:

1. Total number of inputs and outputs
2. Frequency range
3. Signal uniformity
4. Simultaneous signal processing requirements
Switch Applications

Total Number of Inputs and Outputs

The total number of inputs and outputs required determines overall system size. Note that when unused inputs are terminated into a dummy load, each termination is actually another output, as shown in the previous examples of a matrix using four transfer switches. However, when switches with internal terminations are used, the matrix is usually defined by the number of signals which can pass into and out of it without regard to the terminations. Various methods of subdividing a matrix based on number of inputs and outputs are discussed later.

Frequency Range

When a matrix can be subdivided by frequency range, it is possible to mix not only different switch configurations (i.e., SPDT, transfer, multithrow), but different types of switches. For example, a wide variety of inexpensive electromechanical relays exist which are not true coaxial elements, but which have adequate RF performance at frequencies below 300 MHz. "Crystal can" relays, for example, offer the advantages of low cost and small size. When they are mounted on pc boards, they offer a packaging density at least one order of magnitude greater than coaxial microwave switches. There are also a few small (pc board mountable) electromechanical relays which are sealed in plastic and are suitable for some applications up to 1 GHz. A schematic example of matrix subdivision based on frequency range is shown in figure 4-14. One of the primary disadvantages of using "crystal can" relays is isolation at RF frequencies (approximately 40 dB at 50 MHz). Solid state relays can also be used at low frequencies. Like the crystal can relays, they offer the advantages of low cost, small size, and long operating life. At microwave frequencies, however, solid state switching devices are quite expensive and few users can tolerate the cumulative insertion loss through a matrix which is inherent in solid state switches. In those instances where the switching speed or the high reliability of solid state switches are necessary, they must be optimized for a relatively narrow bandwidth. Please refer to Section II of this Design Guide, "Types of Microwave Switches" for a more detailed comparison of the characteristics and inherent trade-offs of the various types of solid state and electromechanical switches.

There is also a broad range of coaxial RF relays (such as the Dow-Key 46 Series through 260 Series) which operate very well over the frequency range from DC through 2 GHz. They are generally less expensive than microwave switches and offer RF performance superior to the smaller pc board relays.

**FIGURE 4-12.** A transfer switch used with two SPDT switches to form a simple 2 x 4 matrix.

**FIGURE 4-13.** A matrix with all unused inputs and outputs terminated can be achieved using all transfer switches. (Note: This is actually a matrix with four inputs and four outputs. Additional system components could be used in place of the resistive terminations.)
Switch Applications

**Figure 4-14.** Switch matrix subdivided according to the frequency range requirements of the individual paths.

**Signal Uniformity**

Some switch matrices, or portions of matrices, require uniform path lengths for phase matching, signal strength (loss) matching, or both. The difficulty of the task increases as signal frequency increases. Therefore it behooves the designer to minimize and group as a module the paths which really need to be matched. For example in a test set, signal uniformity can be achieved by using a multithrow switch with radial symmetry. Figure 4-15 shows a schematic of such an application.

Where higher isolation is required (such as between a signal generator and a network analyzer) signal uniformity can also be maintained using SPDT switches in place of multithrow switches.

**Simultaneous Signal Processing Requirements**

The need for simultaneous processing is the single most significant factor in determining switch matrix complexity (and cost). The two major uses of complex matrices are automatic test equipment (ATE) and communication systems. In ATE systems such as flight line or depot level test sets, the high cost of the test equipment, and of the devices under test, demand the efficiency of simultaneous processing. Some specialized communication systems require continuous use of multiple antennas and receivers or transmitters. In some cases, these requirements may also be modularized by any of the criteria noted above.

**Single Channel Matrices**

The simplest form of switch matrix is a single channel configuration. Regardless of the number of inputs or outputs, there can be only one signal path through the matrix at any given time. Figure 4-16 shows a single channel 12 x 12 matrix using

**Figure 4-15.** Application of a multithrow switch with radial symmetry.

**Figure 4-16.** A 12 x 12 single channel matrix.
Switch Applications

two Dow-Key® IN-LINE MULTITHROW Series 4X3- 430603C INTELLIGENT RELAYS. This arrangement can occupy less than 4" x 4" x 9" (or 2" x 4" x 18"). Although not shown in this illustration, all unused inputs and outputs can be internally terminated in 50 Ω loads, and both SP1T switches contain internal binary decoding CMOS logic circuits and MOSFET switch drivers.

FIGURE 4-17. A 3 x 3 non-blocking matrix using six SP3T switches.

Non-Blocking (Full Access) Coaxial Switching Matrices

A non-blocking switch matrix is defined as a multiple channel matrix which permits any input to be connected to any output. Normally, a matrix of this type does not permit more than one input to be connected simultaneously to an output. Thus, all paths in a non-blocking matrix are also non-intersecting, and simultaneous signal passage is permitted for any number of discrete signals. The size of the matrix determines the maximum number of simultaneous paths that are possible. For example, a matrix with five inputs and eight outputs (5 x 8) has five possible non-intersecting paths at any given time. Figure 4-17 shows a simple 3 x 3 non-blocking matrix. Depending on the switch positions selected, this matrix may have connections made in 1, 2, or 3 simultaneous transmission paths. In the illustration shown, there are two paths in use (input 3 and output 2 are not connected). This matrix is implemented using six SP3T switches.

Thought should be given to the mechanical layout of a switch matrix to minimize the length and number of connections which have to be made with the interconnecting cables. In larger matrices, component selection will have a major impact on the mechanical layout. A poorly designed matrix will have long cable lengths, many more bends then necessary, and can take days to assemble. Once assembled, trouble-shooting and repair of a poorly designed matrix assembly can be very difficult to perform without major disassembly.

Figure 4-18 shows a functional block diagram of an 8 x 10 coaxial switching matrix, using eight SP10T and ten SP8T Dow-Key® IN-LINE multithrow switches. A matrix of this size can be housed in a standard 19" rack enclosure approximately 5" high and 24" deep. Large matrices are easier to assemble first as smaller modules. For example, a 16 x 16 non-blocking matrix can be assembled from four 8 x 8 modules and 32 SPDT switches, as shown in figure 4-19.

In the Dow-Key® IN-LINE INTELLIGENT RELAY multithrow switch design, the insertion loss through any switch increases toward the output port which is located farthest from the common, or input, port (keep in mind that coaxial mechanical relays permit signals to pass in either direction). The optimum layout of a matrix will depend on the priority of signal uniformity, versus the frequency range required for each path. For example, if four outputs in the matrix will pass only UHF signals, while all other output ports are used for microwave signals, the insertion loss can be minimized by connecting the ports closest to the common connector on each switch to the paths which carry the highest frequency signals. Figure 4-20 shows the connections for a 3 x 3 matrix, optimized for minimum insertion loss based on frequency range. This configuration is also commonly employed in matrices which include filters.

Full Fan Out Matrix

A matrix with any input capable of being connected to all outputs at the same time is called a full fan out matrix. In some instances the number of simultaneous outputs will be limited (partial fan out). The fan out capability is achieved by placing a power divider at each input and a multiposition switch at each output, as shown in figure 4-21. Note that the multiposition switches permit selective use of the fan out capability. For example, all switches may select the same input channel power divider, or each may select a different input channel divider, with the result that there are any number of simultaneous, non-intersecting paths through the matrix. Normally, a full fan out matrix has the same capability as a non-blocking matrix, with the added fan out capability.

Full Fan Out Matrices have three significant characteristics which may limit their usefulness in some applications:
Switch Applications

FIGURE 4-18. Functional block diagram of an 8 x 10 coaxial switch matrix using SP8T and SP10T IN-LINE Series Dow-Key® INTELLIGENT RELAYS.

- High insertion loss
- Low Isolation
- High Cost

Amplifiers are often used at the outputs of a full fan out matrix to compensate for the signal lost in the power dividers, and also to improve the output channel to channel isolation. Isolation can be critical when sensitive receiving, monitoring, or test equipment is involved. For example, a bank of receivers scanning an array of incoming signals might feed a signal back into the matrix from the internal local oscillator in each receiver. The power dividers may provide only 25 dB or 30 dB isolation between channels, allowing a significant level of spurious noise into adjacent receivers. A way of countering this problem is to put an isolator at each switch matrix output, immediately in front of the receiver. This has the advantage of improving the interchannel isolation by an additional 30 dB to 40 dB per isolator used, but also has the disadvantages of reduced channel bandwidth, increased insertion loss, larger size, and higher cost per channel.

It is easy to see that the variety of possible switch matrix designs is primarily limited by the designer's imagination. The control wiring is also an important consideration in larger ma-
Switch Applications

trices. For this reason, Dow-Key Microwave has chosen to design multiposition switches with internal binary decoders so that in many instances a single control cable can be run from one switch to the next, each capable of decoding the control signal to achieve the desired combination of signal paths.

FIGURE 4-20. SP4T switch connections optimized for frequency range.

compatible signals and achieve selection and deselection of the desired inputs and outputs. The rectangular shape and "IN LINE" coaxial connectors make the instrument easy to mount and "plumb" with the coaxial cables. In many situations the rectangular form factor and IN LINE connectors allow a substantial reduction in lengths of coaxial interconnecting cables and the problems associated with them. A "rack and stack" approach allows extremely tight packaging configurations such

FIGURE 4-19. A two channel 16 x 16 matrix assembly using 1 x 2 power dividers and 8 x 8 sub matrices.

SWITCH MATRIX BUILDING BLOCKS:
THE IN-LINE SERIES MULTITHROW Dow-Key® INTELLIGENT RELAYS

The IN-LINE Series multithrow Dow-Key® INTELLIGENT RELAYS were designed specifically as switch matrix building blocks for complex switching functions or ATE applications. The primary advantages of the IN-LINE Series multithrow Dow-Key® INTELLIGENT RELAYS is the rectangular packaging configuration (with all of the input/output connectors "IN LINE") and the internal electronics provided to decode TTL

FIGURE 4-21. A full fan-out 4 x 4 switch matrix using four 1 x 4 power dividers and four SP4T IN-LINE Series Dow-Key® INTELLIGENT RELAYS.
Switch Applications

FIGURE 4-22. 9 x 18 non-blocking switch matrix assembly using model 491-101 IN-LINE Dow-Key® INTELLIGENT RELAYS. Picture courtesy of Electromechanical Systems, Inc., Anaheim, California.

as shown in the 9 x 18 non-blocking switch matrix shown in figure 4-22. A 16 x 16 full fan out, non-blocking (full access) microwave switch matrix system using IN-LINE Series Dow-Key® INTELLIGENT RELAY switch matrix building blocks is shown in figure 4-23.

The Dow-Key® INTELLIGENT RELAYS contain TTL compatible CMOS binary decoding circuits, solid state self-cutoff circuits, internal MOSFET actuator coil drivers, and internal 5 volt power regulation. Four data input lines, and a "latching enable" strobe line, are required for complete control of these switches. The other four pins available are used for redundant power and ground connections. This design makes it easy to provide electronic harnesses fabricated from flat ribbon cable with female "D" connectors. The connections to several switches can be "daisy chained" with the harness, and the latching enable command can be used to address individual switches within a matrix. The 4X3-430003E Series IN-LINE Multithrow Dow-Key® INTELLIGENT RELAYS have binary decoders, latching with self-cutoff actuators, and also contain internal 50 Ω terminations for all unused ports. This means the switches will latch into position and cut off the coil actuation power internally, so that switching power supplies are not required. The switch will stay in the selected position, even if the entire system power is disrupted. This is a critical criteria for most complex switch matrices, and when the system regains power the switches will not switch unless the latching enable strobe is presented to the switch to latch in a new binary code and trip the self cutoff timer circuit.

FIGURE 4-23. 16 x 16 non-blocking, full fan-out switch matrix assembly using model 493 Series IN-LINE Dow-Key® INTELLIGENT RELAYS. Picture courtesy of Electromechanical Systems, Inc., Anaheim, California.
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