UNDERSTANDING COAXIAL AND DROP-IN CIRCULATORS AND ISOLATORS

This article describes the basic operating principles of the stripline junction circulator. The following information has been compiled from many technical papers to present a simplified non-mathematical description that is used to highlight the operating characteristics of the various circulator and isolator types. Although this paper is not intended to be a design guide it is hoped that the information presented will be useful to both the buyer and system engineer.

**Figure 1**

Figure 1 provides a schematic construction of a typical circulator, in which only one of the three stripline ports is shown. In practice there are no air gaps inside the case. The magnetic field is axial through the ferrite disks, and returns through the steel case. Larger circulators may use an aluminum case for the core, and steel cladding to complete the magnetic return path.

Consideration of the following is necessary to understand the operation of a junction circulator:

- **FERRITE REGION**
- **MAGNETIC CIRCUIT**
- **IMPEEDANCE TRANSFORMATION**
- **TRANSMISSION LINE GEOMETRY**
- **CONNECTORS**

**FERRITE REGION**

A ferrite disk and the intersection of 3 transmission lines form the Y-junction where the actual circulation occurs. In order to have a better understanding of this region it is necessary to briefly discuss the concept of circulation and ferrimagnetic resonance.

A simple model can be used to explain how a junction circulator operates as shown in figure 2. For a more comprehensive explanation refer to the bibliography.

The ferrite material is essentially enclosed in a metal cavity, forming a cylindrical cavity resonator. When power is applied from any of the three transmission lines, a standing wave pattern is established. This electromagnetic field pattern is due to a pair of mathematically identical counter-rotating waves, with a maximum at the input port, and nulls at 90° from the input port. The standing wave pattern is symmetrical with respect to the input port if there is no applied magnetic field, and energy is transferred equally into the other two ports, as shown in figure 2a. Coupling and isolation from the resonator are determined by the relative position of a given port and the standing wave pattern. For example, if a port were situated at a null in the standing wave, there would be no power transfer to that port.

The presence of an axial magnetic field across the ferrite material changes the effective permeability seen by the rotating waves, but in a direction that depends on the sense of rotation. The result is the pair of waves are no longer identical, and are split into two mathematical solutions having different radial velocities. This causes the standing wave pattern to be rotated from its symmetrical position. The desired power transfer and isolation properties are obtained by designing the circulator so that the standing wave pattern is rotated 30°. With power applied to port 1, the next port in the direction of rotation (port 3) is isolated from the resonator, whereas port 2 is fully coupled to the resonator, as shown in figure 2b. In practice, circuit tuning can be used for some adjustment to the amount of rotation of the standing wave pattern.

**Figure 2a**

Electric field shown by gray intensity

**Figure 2b**

Magnetic field shown by ↓
When a ferrite material is magnetized the magnetic moments of the electrons precess (wobble like a spinning top) at a frequency proportional to the biasing magnetic field. Ferrimagnetic resonance occurs when a rotating RF magnetic field has the same direction and frequency as the precessing electrons in the ferrite material. The maximum coupling of the energy from the RF signal to the ferrite material will occur at ferrimagnetic resonance. If the direction of rotation or the frequency of the RF signal is changed, minimum coupling will occur. A simplistic analogy can be used to explain this phenomena. It is easier for a person to pass items to an individual riding on a merry-go-round if he is running in the same direction and at the same speed while it is more difficult to pass them if both are moving in opposite directions.

However, biasing the junction circulator at ferrimagnetic resonance is not desirable because the device would be extremely lossy. High insertion loss can also occur at very low biasing magnetic fields. This low field loss region arises from the fact that the applied magnetic field is not sufficient to fully saturate or align the individual magnetic domains of the ferrite material. Although high loss occurs in both the low field and ferrimagnetic resonance areas low loss operation can still be obtained in the below and above resonance regions as shown in figure 3.

**COMPARISON OF ABOVE AND BELOW RESONANCE CIRCULATOR DESIGNS**

It should be noted that the following comparison applies principally to stripline junction circulators and is intended as a guide only.

Also the meaning of above or below resonance is with respect to the magnetic field and not the operating frequency.

**OPERATING FREQUENCY**

Above resonance (A/R) circulators can be designed to operate from 50 MHz to approximately 2.5 GHz. Although operation above this frequency can be achieved, impractical magnetic circuits are required in order to bias the ferrite material. Operation at frequencies below 50 MHz is difficult because the magnetic field and the demagnetizing factors of the ferrite geometry do not allow proper biasing of the junction.

Below resonance (B/R) circulators are generally limited to operation above 500 MHz. Operation below this frequency is possible but generally more limited in performance. As the frequency is reduced, the B/R region of operation diminishes as shown in figure 4. The lower magnetic field required for operation of the B/R junction is not sufficient to fully saturate the ferrite material, resulting in the low field loss region.

The low field loss and ferrimagnetic resonance regions merge together, thereby reducing or eliminating entirely the B/R region for ferrite operation. The B/R junction can operate at frequencies up to approximately 30 GHz. Operation above this frequency is limited mainly by the stripline geometry. Waveguide circulators can be designed to operate at frequencies greater than 100 GHz.

**BANDWIDTH**

B/R junction characteristics allow broad bandwidth operation up to 100%. The A/R junction, is generally limited to 40% maximum bandwidth.

![Figure 3](image1.png)

**Figure 3**

Resonance curve shows basic regions of circular operation.

![Figure 4](image2.png)

**Figure 4**

Regions of Operation vary with frequency.
TEMPERATURE
The A/R circulator can be temperature compensated using special magnetic materials. The magnetic properties of these materials change with temperature and are used to compensate for the ferrite junction temperature characteristics. Above 1 GHz, operation over a temperature range of -54 to +95°C is common.

The B/R junction is virtually limited to room temperature operation below 1 GHz. The magnetic properties of the ferrite materials available to build devices at these frequencies are extremely temperature sensitive. Available materials have Curie temperatures less than 100°C. The Curie temperature is defined as the temperature at which the ferrite material's magnetic characteristics are reduced to zero. Circulation of the input signal can not occur at this temperature. In general, ferrite materials used for the higher operating frequencies have greater temperature stability. Operation above 4 GHz, and from -54 to +85°C can be obtained depending on the bandwidth and the level of performance desired.

The temperature performance of the B/R and A/R circulators can be improved by the use of temperature compensating materials in the magnetic circuit.

JUNCTION SIZE
The ferrite disk diameter is a function of the effective permeability, dielectric constant, and frequency of operation of the ferrite junction. The A/R junction has a greater effective permeability than the B/R junction because of the higher internal magnetic biasing field and ferrite saturation magnetization value. The ferrite disk in the A/R junction will therefore be smaller than the B/R junction for the same operating frequency. For narrow bandwidths in the 1.0 GHz to 2.5 GHz range the A/R junction circulator is usually smaller.

MAGNETIC CIRCUIT
High energy product magnets which are now used to bias the ferrite junction have minimized the problem of irreversible change in the magnetic field due to temperature. Extensive temperature cycling is no longer required to stabilize the magnetic field against further permanent change. As previously discussed, the magnetic circuit will also include materials to compensate for the reversible changes with temperature. However optimization of the magnetic circuit can be done to provide additional magnetic shielding for critical applications where units are mounted in very close proximity. A steel case provides a return path for the magnetic field as shown in Figure 5. The magnetic field is largely contained so that adjacent units do not interfere.

Magnetic Field in Circulator

**Figure 5**

Figure 5 shows the steel case around the circulator providing a return path for the magnetic field.

IMPEDANCE TRANSFORMATION
Multiple quarter-wavelength sections of transmission line are commonly used to match the lower impedance of the ferrite disk to the 50 Ohm impedance of the connectors. The VSWR and bandwidth specifications determine the number of transformer sections required. A typical VSWR specification for a circulator is 1.25:1.

For narrow bandwidths (less than 5%) the ferrite junction impedance can be designed to be 50 Ohms. Matching transformers are not required for this type of design which allows a small package size to be obtained. The impedance characteristic of this junction is shown in figure 6A.

Moderate bandwidths (less than 40%) can be obtained for both the A/R and B/R junctions by using a single section transformer external to the ferrite disk. The transformer length can be shortened by using high dielectric materials and meandering the circuit. The single section transformer can also be designed to be included within the ferrite region. Although a more compact size can be obtained, the bandwidth using this technique will be on the order of 25%. The impedance characteristic of the single section design can be seen in figure 6B.

Bandwidths greater than an octave can be obtained for the B/R junction by using two or...
three external transformer sections. Using more than three transformer sections provides little improvement in performance due to the limitations of the ferrite junction. The A/R ferrite characteristics limit its operation to the previously discussed 40%. The typical two section transformer impedance characteristic is shown in figure 6C.

![Figure 6A](image1)

![Figure 6B](image2)

![Figure 6C](image3)

**Figure 6**

**Circulator Impedance Characteristics**

Lumped element circulator designs replace the quarter-wavelength transformer sections with discrete capacitors and inductors to achieve small package sizes in the frequency range of 50 MHz to 1.0 GHz. These devices are temperature sensitive and operate over narrow bandwidths at low power levels.

**TRANSMISSION LINE GEOMETRY**

Balanced stripline is the most common transmission line geometry in use for the circulator junction, and is used for coaxial and drop-in form factors.

**CONNECTORS**

Various connector types can be supplied on circulators. SMA male or female connectors are the most popular and in general the easiest to install. TYPE N, TNC, and right angle connectors of various types can also be used. Some connectors however cause limitations in the electrical performance of the high frequency and broad bandwidth circulators.

The package size may have to be increased to accommodate certain connector types. For example a 0.50 inch thickness package will not accommodate a TYPE N connector without an increase to at least 0.63 inch. Circulators requiring the use of high voltage connectors such as HN or the larger EIA 7/8, 1-5/8 or 3-1/8 types use an intermediate adapter so that they can be installed on the circulator.

Another connector configuration can be obtained by mounting the circulator on a waveguide adapter. The large waveguide section provides a rigid base for the usually smaller coaxial circulator. These units are particularly useful when both waveguide and coaxial connectors are required. For example, the waveguide port can accept a signal directly from a waveguide antenna, while the output from a SMA connector port can be fed directly into a solid state amplifier.

Circulators can be supplied with removable connectors. The connector shell can be removed to allow the center conductor to be directly soldered to a circuit board. High temperature solder is used for the internal solder joint so the pin will not move while being soldered.

The use of tabs in place of connectors is increasing as they allow stripline Drop-in circulators to be mounted directly into a microstrip assembly. Careful consideration must be given to the grounding of the circulator housing as well as the geometry of the mating substrate. It is essential that the circulator manufacturer be supplied with as much information as possible on how the unit will be integrated into the final assembly. The manufacture's test fixture should be used to improve the correlation of measured data.

**DESCRIPTION OF OPERATING PARAMETERS**

**VSWR:** This parameter specifies to what degree the input signal will be reflected back toward the source. For critical applications the magnitude and phase of the reflected signal can be provided as an impedance plot recorded on a Smith Chart.
**INSERTION LOSS:** When a signal is applied in the low loss direction to the circulator the insertion loss will be the ratio of the output signal to the input signal, expressed in dB.

**ISOLATION:** An isolator is a two port device made by internally terminating one port of a circulator as shown in figure 7. When a signal is applied in the high loss direction to the isolator, the isolation will be the ratio of the signal applied to the output port (2) to the signal measured at the input port (1), expressed in dB. It should also be noted that in the case of a circulator this parameter is not applicable.

**Figure 7**

Adding a termination at port 3 results in an isolator

The parameters of isolation, VSWR, and insertion loss are required to specify an isolator, whereas a circulator is completely defined by only the VSWR of the three ports and its insertion loss. Although a circulator can be made into an isolator by terminating one port, it does not have an intrinsic isolation value. The isolation measured is dependent on the VSWR of both the termination and the circulator port.

**Example:** A circulator has a measured VSWR of 1.22 for all three ports. If a perfect test termination with a VSWR equal to 1.00 were available to place on Port 3, the resulting isolation from Port 2 to Port 1 would be 20 dB. If a test termination with a VSWR equal to 1.05 were placed on Port 3, the resulting isolation from Port 2 to Port 1 would vary between 18.2 and 22.5 dB depending on the phasing between the two VSWR’s. The resulting isolation value is a function of the VSWR of the test termination and how it phases with the VSWR of the circulator port.

**PERCENTAGE BANDWIDTH:** Expressed as the difference between the high and low operating frequencies divided by the center frequency multiplied by 100, this parameter is useful when comparing the relative performance of various devices.

**TEMPERATURE RANGE:**

**OPERATING:** The temperature range at which a circulator must meet all specifications.

**STORAGE:** The temperature range at which a circulator must survive without permanent degradation in specifications. Storage temperatures from -60 to +125°C can usually be accommodated.

**PHASE TRACKING:** Phase tracking is a measurement of the variation of the electrical length between the input and the output ports of two or more circulators. The insertion phase of the A/R circulator is very sensitive to changes in the magnetic biasing field. This effect can be used to magnetically trim the phase. Some degradation in VSWR or isolation may be required to allow this method of trimming to be used. The insertion phase of the B/R circulator cannot be easily adjusted.

**PHASE LINEARITY:** This parameter is defined as the deviation from a best fit straight line of insertion phase versus frequency. For A/R and B/R circulators with less than 20% bandwidth, the phase linearity will generally be within 2 degrees.

**IMPEDANCE CHARACTERISTIC:** This parameter describes both the magnitude and phase of the reflected signal recorded as an impedance plot on a Smith Chart. Applications such as amplifiers and VCOs may require the reflected signal to have a minimum phase variation with frequency. The basic input impedance characteristic of a circulator will be one of the three types as shown in figure 6. The phase change is proportional to the number of transformer sections used to obtain a given bandwidth. For moderate bandwidths it is possible to restrict the phase change to less than 360 degrees.

**PEAK POWER:**

**BREAKDOWN:** The peak power breakdown value of a circulator is reduced by an increase in
load mismatch, altitude, temperature, or pulse width. A mismatch on the output port will reflect a percentage of the signal back into the circulator causing a higher internal voltage level which will reduce the power rating of the circulator. The peak power rating can be increased by filling the internal volume of a circulator with a high dielectric strength material. Hermetically sealed modules can be used to maintain pressurization for operation at high altitudes.

LIMITING: Another effect related to the peak power rating of a circulator is known as the non-linearity or peak power threshold of the device. As the peak power level increases beyond a critical value, the loss versus magnetic field curve will show considerable changes in the region below the main resonance as shown in figure 6. The A/R region will remain essentially unaffected.

![Figure 8](peak_power_effects_on_resonance Curve)

The peak power threshold is dependent on the junction geometry, bandwidth, and ferrite material properties. The threshold level can be improved by doping the ferrite material with elements such as holmium, which will cause a slight increase in the insertion loss at low powers.

HARMONICS: At high peak power levels the nonlinearity of the circulator generates harmonic and intermodulation products within the ferrite junction. Because of design limitations imposed by other parameters it is difficult to eliminate this effect.

AVERAGE POWER: The power dissipated in the circulator is in proportion to the insertion loss. If the average power level is significant, the dissipated power will cause heating of the ferrite junction and a degradation in performance. Conduction, convection or liquid cooling can increase the average power rating of a circulator. The connector type is also important when the average power is significant. Captured SMA and hermetic seal connectors are limited in power rating because of their internal losses. The average power rating of a circulator will also depend on the resultant mismatch at the output port. For example if a signal of 100 W average power were applied at the input of a circulator terminated with a 6.00:1 mismatch, 51 Watts would be reflected, requiring the circulator to handle 151 watts total.

ISOLATOR TERMINATION RATING: The power rating required for the termination of an isolator depends on the mismatch on the output port as shown below.

<table>
<thead>
<tr>
<th>Mismatch on output port</th>
<th>% Power reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 (perfect match)</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>2.0</td>
<td>11</td>
</tr>
<tr>
<td>6.0</td>
<td>51</td>
</tr>
<tr>
<td>Short or open circuit</td>
<td>100</td>
</tr>
</tbody>
</table>

RFI: RFI leakage values of 30 dB or less are easily obtainable in a standard package. Internal plates bonded using conductive epoxy can be used so that values up to 60 dB can be obtained. Additional RFI shielding can be provided by utilizing special packaging techniques.

BIBLIOGRAPHY:


HOW TO SPECIFY CIRCULATORS AND ISOLATORS

GENERAL
This catalog lists the specifications for M2 GLOBAL’S isolator and circulator product line. Standard and high power isolator and circulator products are available in Coax, Waveguide, Stripline, Microstrip, Drop-in, Puck and Dual Junction form factors, over the frequency range 300 MHz to 50 MHz. All models have been optimized to meet the following parameters for most popular applications: bandwidth, VSWR, isolation, insertion loss, temperature, and size. These and other parameters can be selectively optimized for your specific application. The following is a brief description of the various parameters and options available.

VSWR
The reflective property of each port of an isolator or circulator is usually specified in terms of VSWR. For critical applications a Smith Chart, with an impedance plot recorded at a specified reference plane, can be provided. A typical specification for VSWR is 1.25; however, a value of 1.10 can be provided for narrowband applications.

ISOLATION
This parameter is used to specify the reverse loss characteristic of an isolator. All isolators described in this catalog consist of a circulator with an internal termination. The parameters of isolation, VSWR, and insertion loss are required to specify an isolator, whereas a circulator is completely defined by only the VSWR of the three ports and its insertion loss. Although a circulator can be made into an isolator by terminating one port, it does not have an intrinsic isolation value. The isolation measured would be dependent on the VSWR of both the termination and the circulator port. Most isolators are specified at 20 dB but values of 26 dB can be obtained for narrow band applications.

Example: A circulator has a measured VSWR of 1.2 for all three ports. If a perfect test termination with a VSWR equal to 1.00 were available to place on Port 3, the resulting isolation from Port 2 to Port 1 would be 20 dB. If a test termination with a VSWR equal to 1.05 were placed on Port 3, the resulting isolation from Port 2 to Port 1 would vary between 18.2 and 22.5 dB depending on the phasing between the two VSWR’s. The resulting isolation value is a function of the VSWR of the test termination and how it may phase with the VSWR of the circulator port.

INSERTION LOSS
This parameter is used to specify the forward loss characteristics of an isolator or circulator. Most catalog models have an insertion loss specification between 0.2 to 0.4 dB. Many low noise systems require an isolator with as low an insertion loss as possible. For these applications the insertion loss can be minimized by using low loss ferrite and dielectric materials. Losses as low as .10 dB have been provided in large production quantities.

TEMPERATURE RANGE
The operating temperature range of an isolator or circulator is limited by the ferrite materials available. In general the lower the operating frequency, the greater the temperature sensitivity an isolator will have. Temperature compensation can be used at some operating frequencies. Catalog units make use of temperature compensation where possible. Operating temperatures from -20 to +65°C or from -40°C to 100°C are common although some models are limited to 0 to 50°C. Special temperature compensation can be provided for most units to operate from -55 to +125°C.

MAGNETIC SHIELDING
Catalog units all have sufficient magnetic shielding for general handling and mounting. These units can usually be mounted to within 1/2 inch of one another or from other magnetic materials without degrading electrical performance. For more stringent applications (mounting in direct contact with a magnetic plate) additional shielding may be required and necessitate a larger package size.

RFI SHIELDING
Standard Models have an RFI leakage measured at close proximity of 40 dB. Special packaging and sealing methods can improve the RFI shielding. Leakage values up to 100dB can be provided at a nominal cost. RFI leakage is usually not specified for Puck form factors.
TERMINATION RATING
The termination rating must be sufficient to safely dissipate the reverse power that is expected to occur under normal or anticipated fault conditions. The reverse power will be determined by the power applied to the input port of the isolator and the mismatch on the output port. This reverse power will be dissipated by the internal termination.

Isolators are rated at reverse power levels of typically 5, 10, 30 or 70 watts average, depending on termination capabilities. If frequency, bandwidth, and size permit, higher average power values can be specified. High power levels require the termination to be mounted directly to a heat sink.

POWER RATING
The input power to an isolator or circulator can be supplied from a CW or a pulsed source. In the case of a pulsed source both the peak and average power components of the pulse train should be specified in order to determine an adequate safety margin for a particular model.

Standard models are rated for 100 CW forward power. Higher power levels can be obtained at the lower frequencies, while drop-in units generally operate at lower power levels. The peak power should not be at a high enough level to cause breakdown or arcing, which generally results in permanent degradation of performance. Proper connector selection and an optimized internal geometry are required to maximize the peak power capability of a particular model. Peak power levels exceeding 1 KW are possibe on certain models. Contingent on the peak power level and other parameters, units can be provided that will operate to altitudes in excess of 100,000 feet.

The peak power level can also cause an increase in the insertion loss in a below resonance design, due to nonlinearity effects of the ferrite material. This increase can occur at peak power levels considerably lower than that required for breakdown or arcing. The increased insertion loss will cause more power to be dissipated in the ferrite region of the device which may result in overheating. Higher peak power levels can be obtained by using special ferrite materials.

Non-linearity effects of the insertion loss do not occur in the above resonance models. The average power rating of an isolator or circulator is determined by the insertion loss, the internal geometry of the ferrite region, and the type of cooling available. The insertion loss of an isolator or circulator will cause some of the average power to be absorbed and dissipated in the ferrite region as heat. Adequate cooling is necessary to insure the ferrite material does not reach an excessive temperature. Mounting to a heat sink for cooling is sufficient in many cases if the average power is moderate.

In high power applications, a component with a high VSWR connected to the output port of an isolator will reflect a substantial amount of power. The temperature of the ferrite region as well as the internal voltage will increase causing the performance to deteriorate or arcing to occur before full rated input power can be realized.

Isolators and circulators that must meet stringent peak and average power levels require design considerations of many parameters. The normal and worst case load VSWR conditions and the available cooling must be specified when ordering high power models.

CONNECTORS
The connectors used on Coaxial Models are N-Type or SMA female. Other connectors can be provided based on operating frequency and package size, however certain types may cause electrical degradation.

INSERTION PHASE
Many applications require isolators and circulators to be supplied as phase matched sets. Although the catalog models are not phase matched, this feature can be provided on a specified basis. The tolerance in phase matching will depend on the particular model and size of the lot to be matched. Phase matched pairs can usually be provided to within ± 5 degrees.

Linearity of the insertion phase can also be specified. It is usually defined as a deviation from a best fit straight line of insertion phase versus frequency.