APPLICATION NOTE
ANV001

# CIRCULATOR

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A Circulator is defined as a non-reciprocal, passive three ports, ferromagnetic device in which power is transferred from one port to the next adjacent port in a prescribed order.

Circulators are non-reciprocal devices, meaning their behavior in one direction is very different from that in the other direction.

## Working Principle:

A Circulator utilizes a transversely magnetized ferrite junction to circulate incoming microwave energy from port 1 to port 2, port 2 to port 3, and port 3 to port 1. The arrows represent the direction of the magnetic fields and the signal when applied to any port of these devices. An RF signal experiences a low loss in the direction of arrow and high loss in reverse direction while propagating through the Circulator (*see Figure1*).

For example, a signal is placed at port 1 and port 2 is well matched, the signal will exit at port 2 with very little loss (typically *0.4 dB*). If there is a mismatch at port 2, then some signal power will be reflected towards port 3.

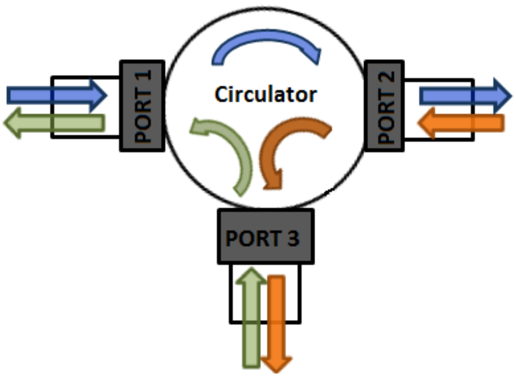


*Figure 1: Circulator Working Principle*

To have a better idea how the applied magnetic field controls the RF signal flow in Circulator, consider a glass filled with water. Now, stir water in a clockwise direction using a spoon. If we put small thermacol balls in water and continue to stir, it is observed that thermacol balls easily follow the circular motion of the water. Also it would be impossible for the thermacol balls to move in a counterclockwise (opposite) direction because the water motion is too strong.

The ferrite discs and permanent magnets inside the Circulator create very strong rotary magnetic fields similar to the water motion in glass. This leads to follow the magnetic flow by any RF/microwave signals in the desired frequency band from one port towards the next adjacent port and not in the opposite direction.

## Construction:

Typical junction Circulator consists of a Y- junction stripline circuit sandwiched between two ferrite discs, an upper and lower magnetically biased permanent magnets and ground planes. The ferrite materials, magnets are selected according to the frequency of operation, input power ratings and intended application. In a Circulator, the magnetic field is applied through the vertical axis of this assembly, results into a circulation of the RF energy from one port to the adjacent port, depending on from which port the energy is coming from.

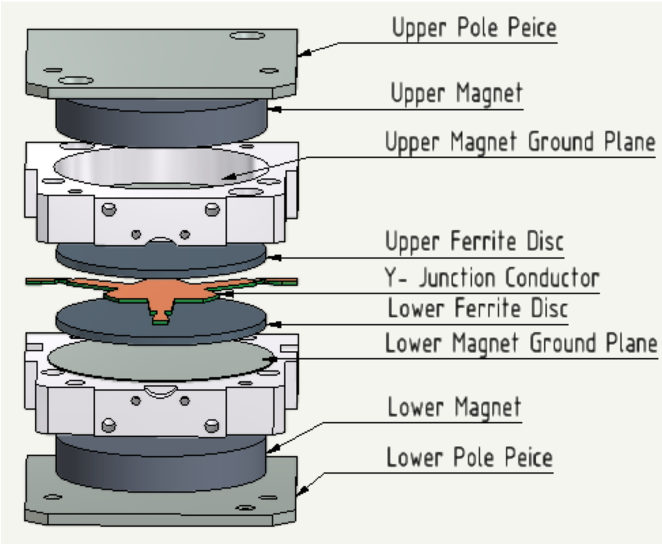


*Figure 2: Circulator Construction Elements*

As shown in the *Figure 2*, two relatively large planes of ferrite material are arranged either in thin triangular, circular or hexagonal shapes. A Y-shaped conductor called as 'inner conductor' having three arms is interposed between these ferrite plates. This conductor junction connects to port connectors. Outside the ferrite discs flat permanent magnets are arranged with mild steel ground planes and pole pieces. This arrangement allows concentrating magnetic flux through the assembly, magnetically biasing the ferrite discs. This whole arrangement is then enclosed in plated steel casing which provides a high immunity to outside magnetic influences and protection from any mechanical damages.

## Performance Parameters:

An important consideration when selecting a Circulator is to ensure the device has adequate performance specifications for the given application. Insertion loss, VSWR & Isolation are the basic and most important performance parameters for Circulators. These parameters have a direct trade off with bandwidth; with increase in the operating bandwidth there is degradation in their values.

### Isolation:

A measure of the separation of signal levels on adjacent ports of a Circulator is called as Isolation. It is measured in *dB* .The greater the isolation value, the lesser will be the interference from a signal on one port relative to an adjacent port.

This isolation is due to a matched termination attached to one of the three ports of the Circulator. The isolation of a Circulator is mainly dependent on following two parameters:

- Termination match level
- VSWR of terminated port

In case of the poor match on terminated port, expected isolation is below *10 dB*. When terminated port match is improved to VSWR of *1.10:1* by using a good termination, then the isolation would improve to over *20 dB*. For the same quality of termination and VSWR values (*1.05:1* or better) comparatively better isolation (around *25 dB*) can be achieved for narrowband units than that for broadband units (around *15-20 dB*). In some applications greater isolation is required (*30* to *40 dB*). In such situations a dual junction Circulator is used, by the combination two Circulators (see *Figure 5*).

The VSWR value on terminated Circulator port represents the absolute maximum amount of energy that will reflect off from the port when a *50Ω* load is connected on it. In order to dissipate this reflected energy safely, Circulator isolation values must be equal to or higher than VSWR values for a given bandwidth.

## Insertion Loss (I.L.):

Transmission path insertion loss is another important parameter when selecting a Circulator. The total amount of energy lost while transmitting the RF signal from one port to another port of the Circulator is called as Insertion Loss.

As stated above, Circulator is a passive RF component, so a signal traveling through it will undergo some attenuation. Insertion loss is the ratio of the output signal to the input signal & it is measured in decibels (d*B*).

$$I.L. = 10\, log_{10}[\frac{Pout}{Pin}] \quad [dB]$$

The insertion loss is frequency dependent, it increases with operating frequency. Hence, insertion loss of a Circulator becomes more significant at higher frequencies due to more power being dissipated as a heat. Typical values of Circulator insertion loss are of the order *0.2* to *0.4 dB*.

For the same quality of load terminations and VSWR values narrowband Circulators comparatively have less insertion loss (around *0.3 dB*) than that for broadband Circulators (up to *1.5 dB*).

## VSWR:

VSWR stands for voltage standing wave ratio. The ratio of the reflected power to the incident power of standing waves created due to impedance mismatch between RF source and load.

These standing waves are unwanted as the transmitted energy gets reflected and travels back to the source. It may damage the RF signal source.

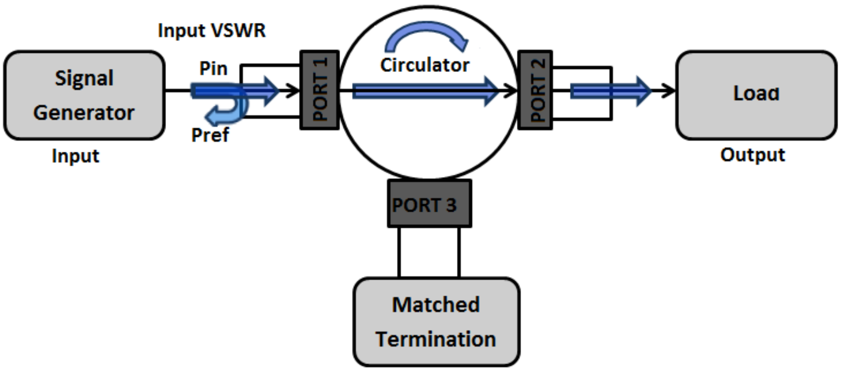


*Figure 3: Circulator VSWR*

The reflective property of each Circulator port is characterized by the reflection coefficient magnitude | *Γ* |.

$$|\Gamma| = \sqrt{Pref\ /\ Pin} = \ V - /V +$$

Where
$P_{ref}$ : reflected power [*W*]
$P_{in}$ : incident power [*W*]
*V-* : reflected wave [*V*]
*V+* : incident wave. [*V*]

The resulting VSWR is given by:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

The effective input VSWR of a Circulator will vary as a function of the load VSWR. If the output load mismatch is increased, more energy is reflected towards the terminated port. After attenuated by the isolation it is then reflected back to the input. Due to which there is increase in total VSWR observed at the input.

Therefore, a low VSWR specification is always desirable. VSWR is expressed in ratio form relative to 1 (example *1.25:1*). Following are two special cases of VSWR:

- VSWR of *∞:1* is obtained when the load is an open circuit
- VSWR of *1:1* is obtained when the load is perfectly matched to source impedance.

## Power Ratings:

Power ratings are a measure of maximum RF signal handling capacity of a Circulator, without degradation in performance, signal distortion and / or attenuation. Exceeding these absolute ratings can cause malfunctioning of the Circulator. Depending on the nature of applied RF signal, a Circulator can have following different power ratings:

**Average Power Ratings:** The Average power represents the maximum power that the Circulator can handle when power is applied continuously. This can be the average power of a continuous wave (CW) signal or the temporal average of the power of a pulsed signal. In the case of a CW signal, the average power rating of the Circulator must be greater than the average power of the applied RF signal. Whereas for pulse signal, the Circulator average power rating must be greater than the product of temporal peak and duty cycle of the applied RF signal.

**Peak Power Ratings:** The capability of the Circulator to handle applied pulsed RF signal with certain peak level. The temporal peak level of applied RF signal must not exceed the peak power rating of the Circulator.

**Reflective Power Ratings:** Circulators do not have reflective power ratings because they do not have an internal termination attached to them. But when using a Circulator as an Isolator an external termination is connected to the one of the three ports of the Circulator. In that case only, the capability of the Circulator terminated port (e.g. port 3) to handle and dissipate the reflected RF signal from output port (e.g. port 2) is known as reflective power ratings.

The maximum reflective power rating depends upon the quality of termination and termination power handling capacity which will be the same as peak power ratings of the terminations. In case when the termination receives too much power for long period, it will be damaged. The power ratings of the Circulator are determined by the following primary factors:

- Voltage levels: Voltage levels are ultimately determined by the incident and reflected signal levels and the effective VSWR of the Circulator.

- Heat dissipation: Heat is generated in the Circulator because of insertion losses and reflections. This heat is nothing but unwanted form of power. Hence, it should be dissipated otherwise it can cause following adverse effects on the Circulator operation:
  - Degaussing of the permanent magnets that bias the ferrites
  - Once the magnets are degaussed completely, the dielectric will melt which eventually destroys the Circulator
  - Thermal expansion of the internal circuit to distort geometric parameters and thereby degrading quoted specifications


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Heat dissipation is mainly determined by the impedance match quality and power ratings of Circulator. Hence, sometimes it is beneficial to operate the Circulator with heat sink, to handle power levels which are much closer to the maximum power levels of the Circulator.

### Group Delay:

The time taken by the applied RF signal to travel from input port towards the output port of the Circulator is called as Group delay. It is typically expressed in picoseconds or nanoseconds; it indicates the phase linearity of the Circulator.

Circulator group delay measurement is done using frequency domain method. This involves considering the vector S-parameter data over desired frequency range for the Circulator. From this S-parameter data set group delay is evaluated as a function of frequency.

Mathematically, it is the negative of the rate of change of phase with angular frequency.

$$\tau_g = -\,(\partial\phi / \partial\omega)$$

Where,

| | |
|---|---|
| $\phi$: *total* phase shift | [*Radians*] |
| $\omega$: angular frequency | [*Radians/Seconds*] |
| $f$: frequency | [*Hertz*]. |

It is desirable to have a group delay value that is constant relative to all frequencies in the band of interest. A constant group delay represents a linear phase over the desired frequency band. On the other hand large fluctuations in group delay represent phase nonlinearities caused by the Circulator. These nonlinearities in a transmission path of RF signal are undesirable, as they indicate the signal degradation by the Circulator.

### Spin Waves:

Spin waves are associated with Circulator ferrite discs and there measurement is important to determine the power handling of ferrites. Power handling capability of Circulator in turn depends on the power threshold of ferrites. Above the threshold power level, there is an abrupt rise in the peak power. At certain critical RF power level, spin waves excitation starts.

Spin wave instability disrupts the RF signal driven uniform mode. The excited spine waves are out of the phase with uniform mode and have same or harmonics frequencies of the uniform mode. These forms a wave’s pattern causing the saturation of the main resonance line width. As saturation level begins to increase absorption within the ferrite increases nonlinearly.

These spin waves eventually increase the heat and Circulator insertion loss than the specified values.

## Applications:

### RF Duplexer:

Circulator can be used as an RF duplexer to share the same antenna between transmitter and receiver, which are tuned to different frequencies. This configuration allows bidirectional communications over a single channel. Using a Circulator for branching, only one inexpensive filter is necessary at the input of the receiver. This helps to reduce the number of components and operating costs.

As shown in the *Figure 4*, by attaching a transmitter to port 1, an antenna to port 2, and a receiver to port 3, one antenna is used perform two tasks. The transmitted signal goes directly to the antenna port and is isolated from the receiver. All received signals from the antenna go straight to the receiver and not towards the transmitter because of the non-reciprocal nature of the Circulator.

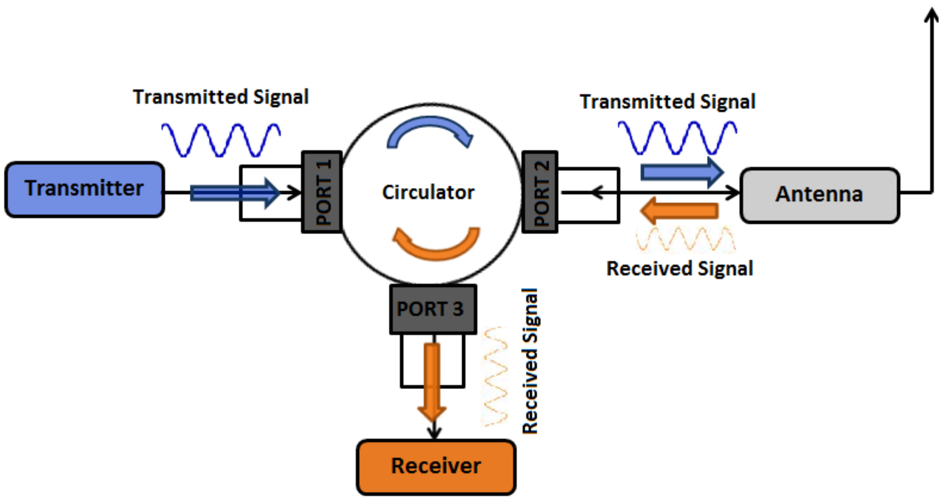


*Figure 4: Circulator as RF Duplexer*

Depending upon the antenna impedance, the power of the transmitter at the input of the receiver branch is reduced by more than *10 dB* by the circulator. There by protecting the receiver from high power transmitter signals.

## High Isolation:

For applications where higher isolation and much better directivity are needed, a dual junction Circulator is used. A dual junction Circulator is a series combination two Circulators integrated in a single package.

As shown in the *Figure 5* a constructed dual Circulator has 4 ports with following possible configurations:

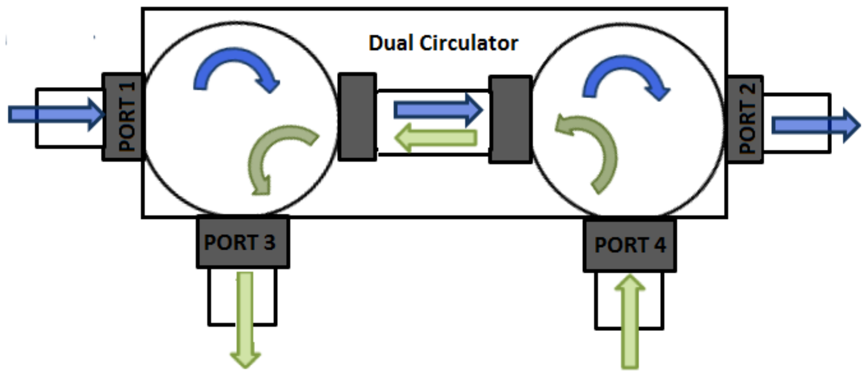


*Figure 5: Dual Circulator*

| Port Number | Configuration 1 | Configuration 2 |
|---|---|---|
| Port 1 | Input | Terminated |
| Port 2 | Output | Terminated |
| Port 3 | Terminated | Output |
| Port 4 | Terminated | Input |

*Table 1: Dual Circulator Port Configurations*

Applied RF signal is forced to flow either from (port 1 to port 2) or (port 3 to port 4); while (ports 3 and 4) or (ports 1 and 2) are terminated with external matched loads respectively. When travelling from (port 1 to port 2) or (port 3 to port 4) transmitted signal cross two ferrite junctions. In this way very high isolation is achieved between the input and output. Typical isolation obtained with a dual Circulator is in the range of *40* to *50 dB*.

## Radio Link Combiner:

A Circulator can be used as an RF signal combiner for multiple transmitters and receivers in the VHF/UHF bands. For radio links operating at *2 GHz* and higher frequencies the conventional combining technique using an array of sharp filters, results in relatively high losses especially for transmitter TX1 and receiver RX1. These losses are due to difficulties in sharp tuning of the filters.

When some of the filters in conventional combiner are replaced by Circulators following combiner topology is obtained (see *Figure 6*). The combining losses are reduced by reducing the filter tuning influences. To meet the stringent requirements for intermodulation the Circulator used only in waveguide systems.

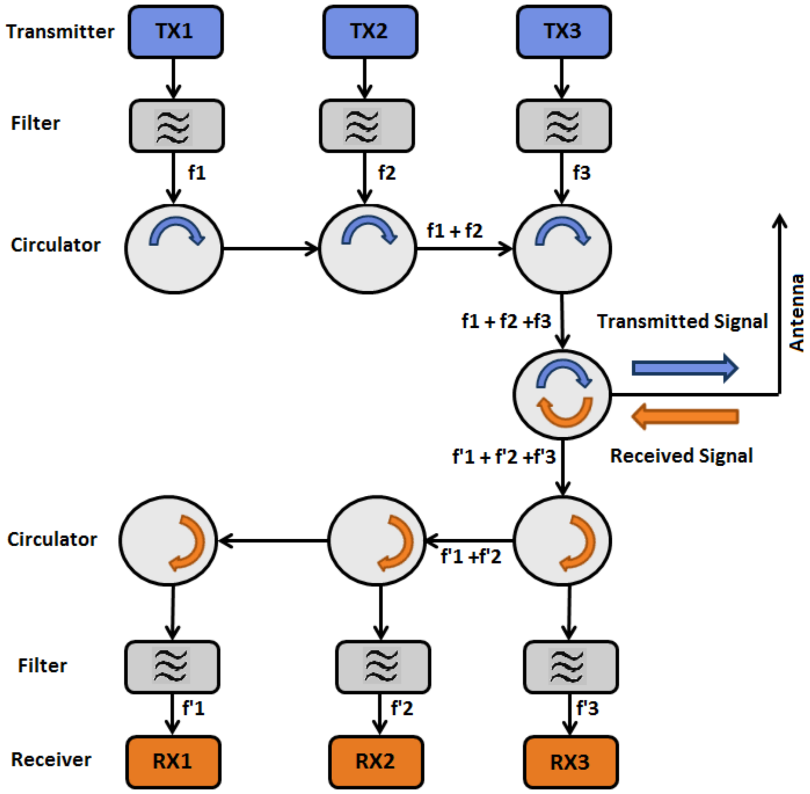


*Figure 6: Circulator Radio Link*

Using the above principle RF amplifier stage combiner can be designed with the help of Circulators.

## Application Areas:

Following are some industrial fields served by Circulators:

- Television & Radio broadcasting
- Radio links & telecommunication networks
- Aviation & navigation industries
- Military equipment & Radar systems
- Laboratory measurement systems
- Industrial microwave heating


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## Operating Precautions:

Like other high frequency components Circulators have some kind of operating safety and handling precautions. In this section the Circulator protection measures have been considered.

## Operating Temperature:

The material properties of ferrites and magnets used in Circulators are temperature dependent. This can cause unstable performance characteristics over operating range. This mainly depends on the magnetic field, applied to saturate the ferrite material. Following techniques can extend the Circulator temperature performance range by a significant amount.

- Temperature compensated magnets and ferrites materials need to be used where wide temperature ranges are required.
- For proper thermal behavior Circulator is installed such that ambient temperature air must be allowed to circulate freely.
- External heat sinks and forced air cooling systems must be used under high heat dissipations and high ambient temperatures.

## External Magnetic Fields:

Circulators have permanently biased magnets that produce strong fields to control RF signal flow. When a Circulator is placed in close proximity to another magnet / magnetic fields the two magnetic fields interact with each other.

Circulators are normally semi-shielded for operation in close proximity of large ferrous objects or external magnetic fields to minimize magnetic interference.

Even if the Circulator is magnetically shielded, strong AC field can affect its characteristics and demagnetize the internal magnets, causing complete de-tuning. This mechanism is known as degaussing. At this stage the Circulator magnets are unable to control the RF signal flow. Hence, during storage it is recommended that Circulators should be separated by at least *3 inches* from other magnetic devices.

## On Site Mounting:

To ensure the satisfactory performance and avoid any mechanical damage to the Circulator following measures should be taken into account:

- With a proper assembly mount a Circulator in its specified operating conditions only
- Do not put too much stress on Circulator connectors
- If possible avoid mounting a Circulator near strong AC fields, magnetic fields and high power sources

## Packaging Types:

Depending on the application environment requirements various connector types can be supplied on Circulators such as:

- Drop-In Circulators
- N-Type Circulators
- SMA Coaxial Circulators
- Surface Mount Circulators

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. In general SMA male or female connectors are the most popular and easiest to install. Many times N-Type and right angle connectors of various types are used. Some connectors, however, cause limitations in the electrical performance of the high frequency and broad bandwidth Circulators.

Another connector configuration can be obtained by mounting the Circulator on a waveguide adapter. These devices are known as Isoadaptors. In such devices 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 to solid-state amplifier.

Circulators can also be supplied with removable connectors. The connector shell can be removed to allow the center conductor to be directly soldered to a circuit board. Normally a high temperature solder is used for the internal solder joint so the pin will not move while being soldered to the board. This type of component is known as drop in Circulator.


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# ABOUT VALVO

Valvo Bauelemente GmbH is a Germany based company specializing in design and developments of standard as well as special RF and microwave ferrite components. Valvo Bauelemente GmbH has more than 30 years of experience in providing well-rounded expertise solutions, technologies and design techniques.

The core of the company is a highly experienced team of respected technologists with developments of performance specific, high reliability complex products. The company has delivered excellent performance in several International R&D projects.

All products are controlled to the highest standards for guaranteed delivery and customer satisfaction.

# PRODUCTS

Valvo Bauelemente GmbH is focused on 50 MHz to 18 GHz Circulators, Isolators, Waveguides, and microwave ferrite devices. We offer narrow and broad band devices in coaxial, waveguide, drop-in constructions which are ideally suited for integration into compact systems.

Our highly skilled staff has a strong working knowledge and experience on a variety of ferrite devices with over 2,000 existing designs. This makes us possible to offer custom product solutions in addition to wide range standard product solutions.

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