Microwave Circulators & Isolators

Both microwave circulators and microwave isolators are nonreciprocal transmission devices that use the property of Faraday rotation in the ferrite material. In order to understand the operating principles of circulators and isolators, let us describe the behaviors of ferrites in the nonreciprocal phase shifter.

A nonreciprocal phase shifter consists of a thin slab of ferrite placed in a rectangular waveguide at a point where a dc magnetic field of the incident wave mode are circularly polarized. Ferrite is a family of MeO. Fe_2O_3, where Me is a divalent iron metal. When a piece of ferrite is affected by a dc magnetic, the ferrite exhibits Faraday rotation. It does so because the ferrite is nonlinear material and its permeability is an asymmetric tensor,

Expressed by,

$$\mathbf{B} = \hat{\boldsymbol{\mu}}\mathbf{H}$$

Where

$$\hat{\mu} = \mu_0(1 + \hat{\chi}_m)$$

$$\hat{\chi}_m = \begin{bmatrix} \chi_m & j\kappa & 0 \\ j\kappa & \chi_m & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

This is the tensor magnetic susceptibility. Here x is the diagonal susceptibility and k is the off diagonal susceptibility.

When a dc magnetic field is applied to a ferrite, the unpaired electrons in the ferrite material tend to line up with the dc field because of their magnetic dipole moment. However, the nonreciprocal precession of unpaired electrons in the ferrite causes their relative permabilities to be unequal and the wave in the ferrite is then circularly polarized. The propagation constant for a linearly polarized wave inside the ferrite can be expressed as (μ_r^+, μ_r^-)

Where

$$\gamma^{\pm} = j\omega\sqrt{\epsilon\mu_0(\mu + \kappa)}$$

$$\mu = 1 + \hat{\chi}_m$$

$$\mu_r^+ = \mu + \kappa$$

$$\mu_r^- = \mu - \kappa$$

The relative permeability μ_r changes with the applied dc magnetic field as given by

$$\mu_r^{\pm} = 1 + \frac{\gamma_e M_e}{|\gamma_e| H_{dc} \mp \omega}$$

where γ_e = gyromagnetic ratio of an electron
M_e = saturation magnetization
ω = angular frequency of a microwave field
H_{dc} = dc magnetic field
μ_r^+ = relative permeability in the clockwise direction (right or positive circular polarization)
μ_r^- = relative permeability in the counterclockwise direction (left or negative circular polarization)

It can be seen that from the last equation, that if $\omega = |\gamma_e| H_{dc}$ then μ_r^+ is infinite. This phenomenon is called the gyromagnetic resonance of the ferrite. A graph of μ_r is plotted as a function of H_{dc} for longitudinal propagation in the figure below,

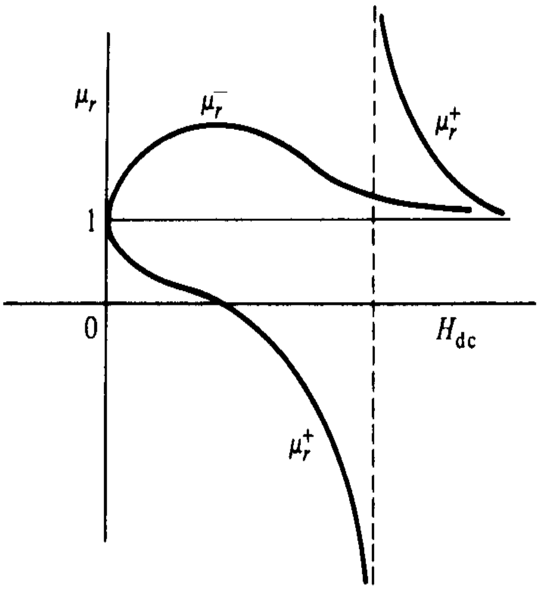

Figure 4-6-1 Curves of μ_r versus H_{dc} for axial propagation.

The clockwise direction. Consequently, the propagation phase constant β^+ for the forward direction differs from the propagation phase constant β^-

for the backward direction. By choosing the length of ferrite slab and dc magnetic field so that

$$\omega = (\beta^+ - \beta^-)\ell = \frac{\pi}{2}$$

a differential phase shift of 90° for the two directions of propagation can be obtained.

4-6-1 Microwave Circulators

A *microwave circulator* is a multiport waveguide junction in which the wave can flow only from the *n*th port to the $(n + 1)$th port in one direction (see Fig. 4-6-2). Although there is no restriction on the number of ports, the four-port microwave circulator is the most common. One type of four-port microwave circulator is a combination of two 3-dB side-hole directional couplers and a rectangular waveguide with two nonreciprocal phase shifters as shown in Fig. 4-6-3.

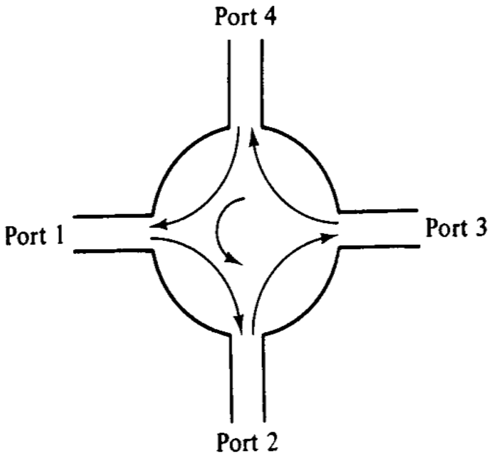

Figure 4-6-2 The symbol of a circulator.

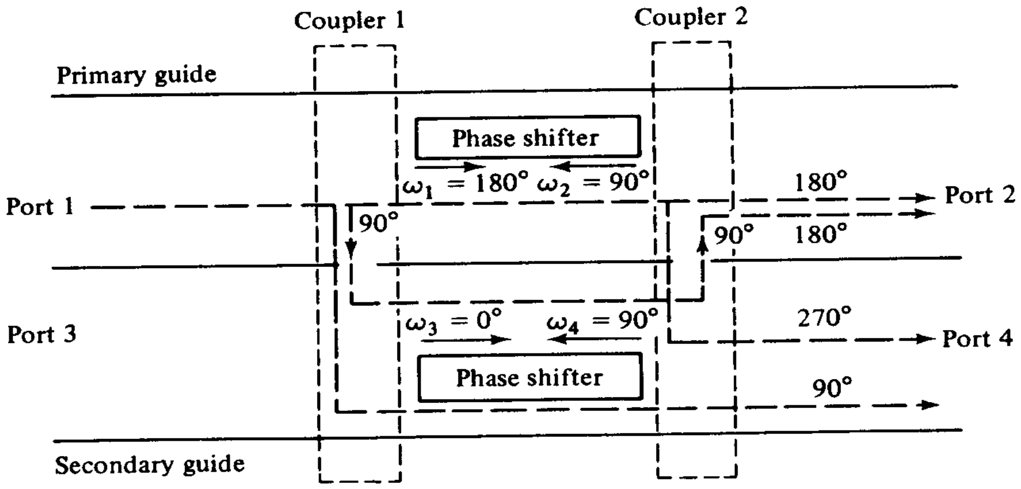

Figure 4-6-3 Schematic diagram of four-port circulator.

The operating principle of a typical microwave circulator can be analyzed with the aid of Fig. 4-6-3. Each of the two 3-dB couplers in the circulator introduces a phase shift of 90°, and each of the two phase shifters produces a certain amount of phase change in a certain direction as indicated. When a wave is incident to port 1, the wave is split into two components by coupler 1. The wave in the primary guide arrives at port 2 with a relative phase change of 180°. The second wave propagates through the two couplers and the secondary guide and arrives at port 2 with a relative phase shift of 180°. Since the two waves reaching port 2 are in phase, the power transmission is obtained from port 1 to port 2. However, the wave propagates through the primary guide, phase shifter, and coupler 2 and arrives at port 4 with a phase change of 270°. The wave travels through coupler 1 and the secondary guide, and it arrives at port 4 with a phase shift of 90°. Since the two waves reaching port 4 are out of phase by 180°, the power transmission from port 1 to port 4 is zero. In general, the differential propagation constants in the two directions of propagation in a waveguide containing ferrite phase shifters should be

$$\omega_1 - \omega_3 = (2m + 1)\pi \qquad \text{rad/s} \tag{4-6-10}$$

$$\omega_2 - \omega_4 = 2n\pi \qquad \text{rad/s} \tag{4-6-11}$$

where m and n are any integers, including zeros. A similar analysis shows that a wave incident to port 2 emerges at port 3 and so on. As a result, the sequence of power flow is designated as $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1$.

Many types of microwave circulators are in use today. However, their principles of operation remain the same. Figure 4-6-4 shows a four-port circulator constructed of two magic tees and a phase shifter. The phase shifter produces a phase shift of 180°. The explanation of how this circulator works is left as an exercise for the reader.

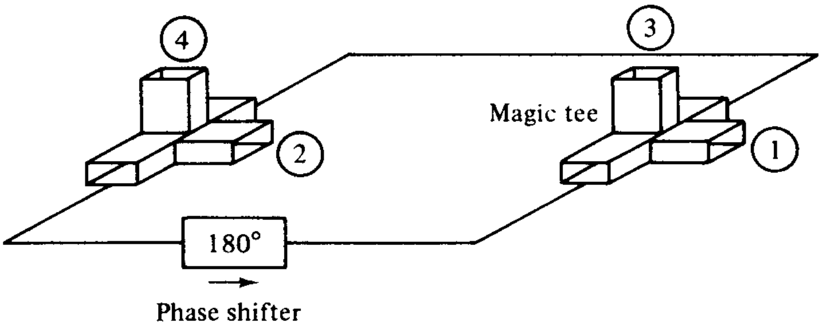

Figure 4-6-4 A four-port circulator.

A perfectly matched, lossless, and nonreciprocal four-port circulator has an **S** matrix of the form

$$\mathbf{S} = \begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{21} & 0 & S_{23} & S_{24} \\ S_{31} & S_{32} & 0 & S_{34} \\ S_{41} & S_{42} & S_{43} & 0 \end{bmatrix} \tag{4-6-12}$$

Using the properties of S parameters as described previously, the **S** matrix in Eq. (4-6-12) can be simplified to

$$\mathbf{S} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{4-6-13}$$

4-6-2 Microwave Isolators

An *isolator* is a nonreciprocal transmission device that is used to isolate one component from reflections of other components in the transmission line. An ideal isolator completely absorbs the power for propagation in one direction and provides lossless transmission in the opposite direction. Thus the isolator is usually called *uniline*. Isolators are generally used to improve the frequency stability of microwave generators, such as klystrons and magnetrons, in which the reflection from the load affects the generating frequency. In such cases, the isolator placed between the generator and load prevents the reflected power from the unmatched load from returning to the generator. As a result, the isolator maintains the frequency stability of the generator.

Isolators can be constructed in many ways. They can be made by terminating ports 3 and 4 of a four-port circulator with matched loads. On the other hand, isolators can be made by inserting a ferrite rod along the axis of a rectangular waveguide as shown in Fig. 4-6-5. The isolator here is a Faraday-rotation isolator. Its operating principle can be explained as follows [5]. The input resistive card is in the y-z plane, and the output resistive card is displaced 45° with respect to the input card. The dc magnetic field, which is applied longitudinally to the ferrite rod, rotates the wave plane of polarization by 45°. The degrees of rotation depend on the length and diameter of the rod and on the applied dc magnetic field. An input TE_{10} dominant mode is incident to the left end of the isolator. Since the TE_{10} mode wave is perpendicular to the input resistive card, the wave passes through the ferrite rod without attenuation. The wave in the ferrite rod section is rotated clockwise by 45° and is normal to the output resistive card. As a result of rotation, the wave arrives at the output end without attenuation at all. On the contrary, a reflected wave from the output end is similarly rotated clockwise 45° by the ferrite rod. However, since the reflected wave is parallel to the input resistive card, the wave is thereby absorbed by the input card. The typical performance of these isolators is about 1-dB insertion loss in forward transmission and about 20- to 30-dB isolation in reverse attenuation.

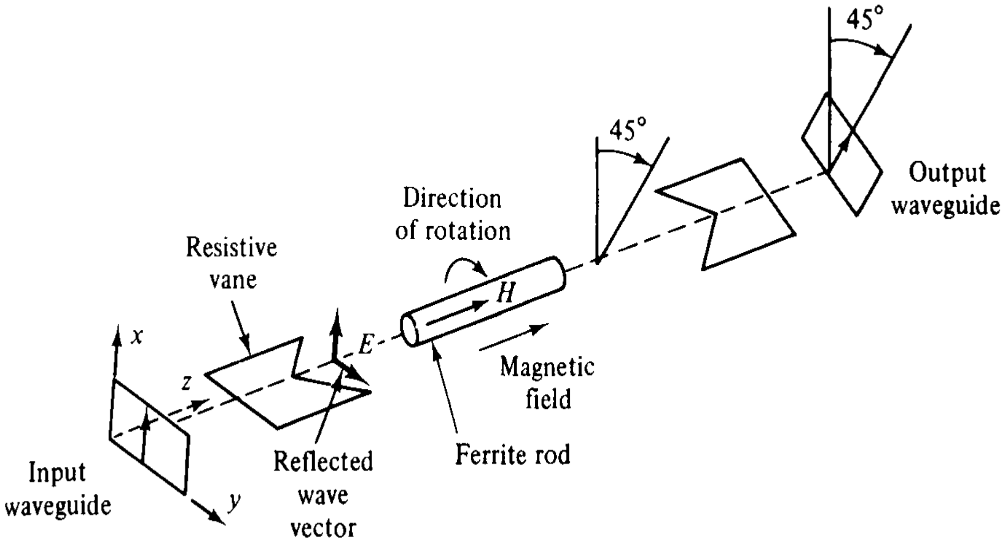

Figure 4-6-5 Faraday-rotation isolator.