CHAPTER ONE

Architecture of Symmetrical Stripline Junction Circulators

1.1 INTRODUCTION

The three-port circulator is a unique nonreciprocal symmetrical junction having one typical input port, one output port, and one decoupled port. The fundamental definition of the junction circulator has its origin in energy conservation. It states that the only matched symmetrical three-port junction corresponds to the definition of the circulator. A wave incident in such a junction at port 1 is emergent at port 2, one incident at port 2 is emergent at port 3, and so on in a cyclic manner. One possible model of a circulator is a magnetized ferrite or garnet gyromagnetic resonator having three-fold symmetry connected or coupled to three transmission lines or waveguides. The purpose of this introductory chapter is to provide one phenomenological description of the operation of this sort of device, to summarize some of the more common resonator geometries met in its construction, and to indicate some of its uses. The introduction of any such resonator at the junction of three striplines produces a degree-1 circulation solution. In practice, the gyromagnetic resonator is embedded in a filter circuit in order to produce a degree-2 or degree-3 frequency response. The possibility of realizing a single junction circulator with more than three ports is understood.

1.2 PHENOMENOLOGICAL DESCRIPTION OF STRIPLINE CIRCULATOR

The geometry of the stripline circulator geometry is depicted in Fig. 1.1. It consists of two ferrite planar disk resonators separated by a disk center conductor symmetrically coupled by three transmission lines. The gyromagnetic material is magnetized perpendicularly to the plane of the device by a static magnetic field. An important property of

The Stripline Circulator: Theory and Practice. By J. Helszajn

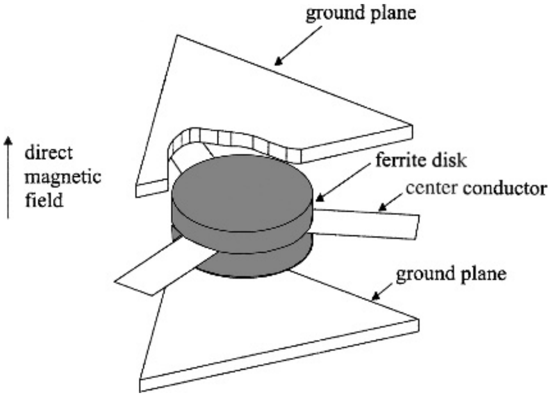


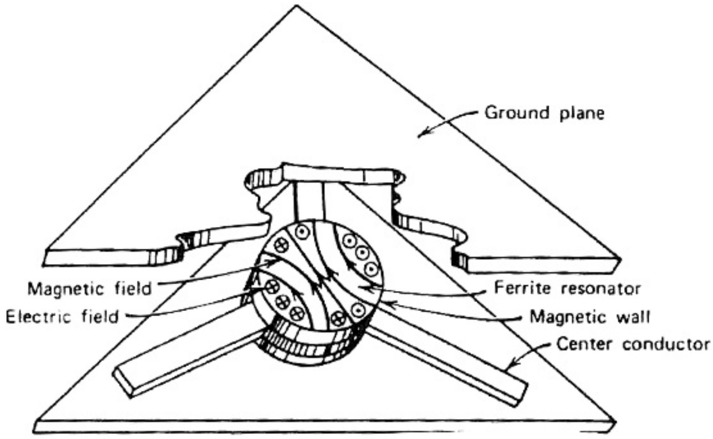
FIGURE 1.1 Schematic diagram of three-port stripline circulator.

this device is that a circulator condition is met whenever all three ports are matched. For a three-port junction this requires two independent variables. Under certain simplifying conditions its adjustment can be described in terms of a figure-eight standing wave pattern within the disk due to the interference of a pair of degenerate field patterns rotating in opposite directions. When the gyromagnetic junction is unmagnetized, the resonant frequencies of the two field patterns are identical. When it is magnetized, the degeneracy is removed, and the standing wave pattern within the resonator is rotated. One circulation condition is established by operating between the two split frequencies. This requirement essentially fixes the radius of the gyromagnetic resonator. The second condition is met by adjusting the splitting, until the standing wave pattern is rotated through 30°. From symmetry, port 3 is then situated at a null of the standing wave pattern and is therefore isolated and the junction displays properties akin to that of a two-port transmission line resonator between the other two ports. This condition fixes the magnitude of the gyrotropy or the direct magnetic field. Figure 1.2 depicts the two standing wave patterns under discussion. A third, in-phase mode, also strictly speaking enters into the description of this type of junction. It has, however, an electric wall at the periphery of the resonator so that it does not affect the total field pattern there.

The rotation of the standing wave pattern in a gyromagnetic resonator under the application of a direct magnetic field may be understood by decomposing the linearly polarized radiofrequency (rf) magnetic field on its axis into counterrotating ones, which are then split by its gyrotropy. The direction in which the pattern in such a resonator is rotated is fixed by that of the direct magnetic field so that it may be utilized to realize an electrically actuated waveguide switch.

1.3 ADJUSTMENT OF JUNCTION CIRCULATOR

The operation of any junction may be understood by having recourse to superposition. It starts by decomposing a single input wave at port 1 (say) into a linear



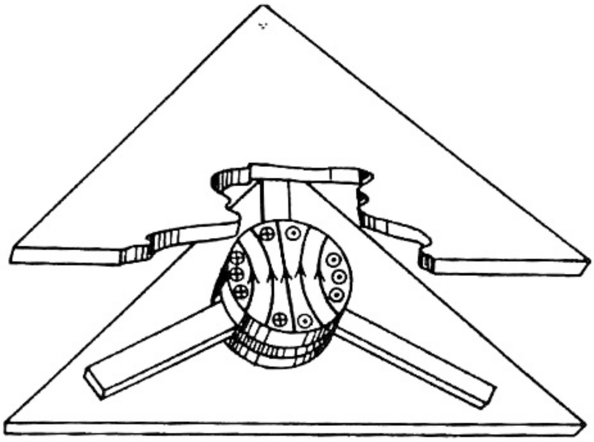


FIGURE 1.2 (a) Standing wave patterns in (a) demagnetized stripline junction and (b) magnetized stripline junction. (Reproduced with permission from C. E. Fay and R. L. Comstock, Operation of the ferrite junction circulator, *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-13, pp. 15–27, January 1965.)

combination of voltage settings at each port:

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + \frac{1}{3}\begin{bmatrix} 1 \\ \alpha \\ \alpha^2 \end{bmatrix} + \frac{1}{3}\begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix} \tag{1.1}$$

where

$$\alpha = \exp(j120) \quad \text{and} \quad \alpha^2 = \exp(j240)$$

A scrutiny of the first, so-called in-phase generator settings indicates that it produces an electric field along the axis of the junction. The reflected waves at the three ports of the junction are therefore in this instance unaffected by the details of the gyrotropy. A scrutiny of the second and third, so-called counterrotating generator settings indicates, however, that these establish counterrotating circularly polarized alternating magnetic fields in the plane of the junction. A characteristic of a suitably magnetized gyromagnetic insulator is that it has different scalar permeabilities under the two arrangements. It therefore provides one practical means of removing the degeneracy between the reflected waves associated with these two generator settings. The fields produced at the axis of the junction by each of these three possible generator settings are illustrated in Fig. 1.3.

A typical reflected wave at any port is constructed by adding the individual ones due to each possible generator setting. A typical term is realized by taking the product of a typical incident wave and a typical reflection coefficient.

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \frac{\rho_0}{3}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + \frac{\rho_-}{3}\begin{bmatrix} 1 \\ \alpha \\ \alpha^2 \end{bmatrix} + \frac{\rho_+}{3}\begin{bmatrix} 1 \\ \alpha^2 \\ \alpha \end{bmatrix} \tag{1.2}$$

An ideal circulator is now defined as

$$\frac{\rho_0 + \rho_- + \rho_+}{3} = 0 \tag{1.3a}$$

$$\frac{\rho_0 + \rho_-\alpha + \rho_+\alpha^2}{3} = -1 \tag{1.3b}$$

$$\frac{\rho_0 + \rho_-\alpha^2 + \rho_+\alpha}{3} = 0 \tag{1.3c}$$

To adjust this, and other circulators, requires a 120° phase difference between the reflection coefficients of the three different ways in which it is possible to excite the three ports of the junction. One solution is

$$\rho_+ = \exp\left[-j2\left(\phi_1 + \phi_+ + \pi/2\right)\right] \tag{1.4a}$$

$$\rho_{-1} = \exp[-j2(\phi_1 + \phi_- + \pi/2)] \tag{1.4b}$$

$$\rho_0 = \exp[-j(2\phi_0)] \tag{1.4c}$$

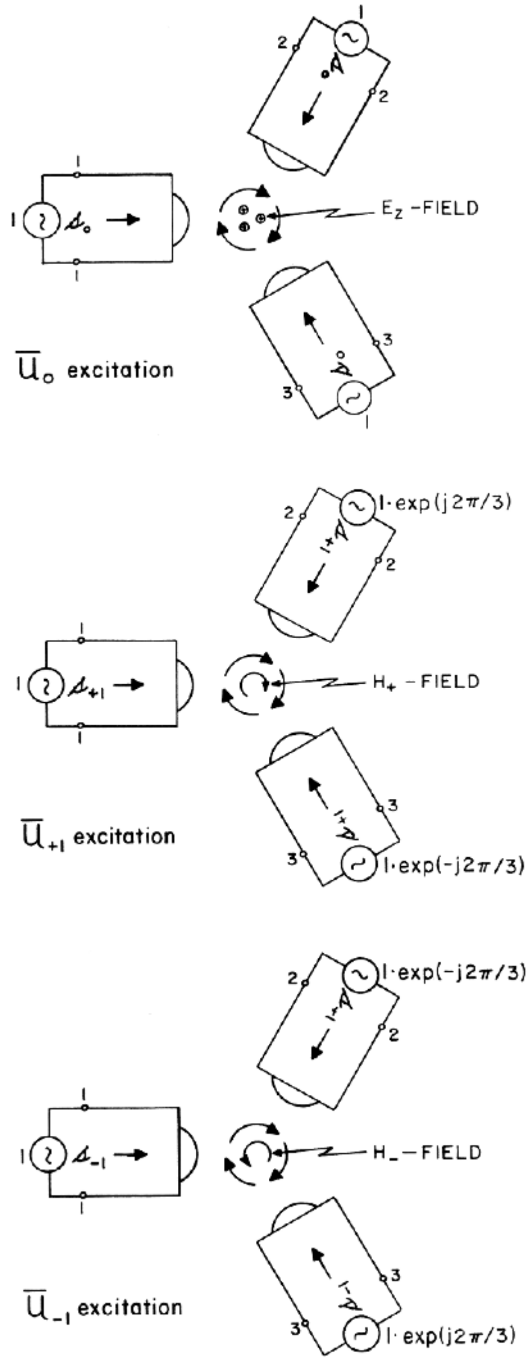


FIGURE 1.3 Voltage settings on three-port circulator.

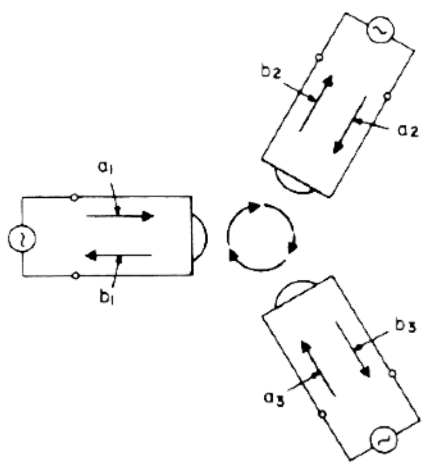
provided that

$$\phi_1 = \phi_0 = \pi/2 \tag{1.5a}$$

$$\phi_+ = -\phi_- = -\pi/6 \tag{1.5b}$$

The in-phase and degenerate counterrotating reflection angles are established by adjusting the details of the corresponding one-port eigen-networks of the demagnetized ferrite section so that the angle between the two is initially 180°. The degenerate phase angles of the counterrotating reflection coefficients are thereafter separated by 120° by the gyrotropy of the gyromagnetic region, thereby producing the ideal phase angles of the circulator. These two steps represent the necessary and sufficient conditions for the adjustment of this class of circulator.

The relationship between the incident and reflected waves at the terminals of a network or junction is often described in terms of a scattering matrix. It is therefore appropriate to reduce the result established here to that notation. The nomenclature entering into the definition of this matrix is indicated in Fig. 1.4. Its entries relate



$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{31} & S_{11} & S_{21} \\ S_{21} & S_{31} & S_{11} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

FIGURE 1.4 Scattering variables in three-port junction.

incident and reflected waves at suitable terminal planes of the circuit:

$$S_{11} = \frac{b_1}{a_1}\bigg|_{a_2 = a_3 = 0} \tag{1.6a}$$

$$S_{21} = \frac{b_2}{a_1}\bigg|_{a_2 = a_3 = 0} \tag{1.6b}$$

$$S_{31} = \frac{b_3}{a_1}\bigg|_{a_2 = a_3 = 0} \tag{1.6c}$$

A scrutiny of these definitions indicates that the entries of the scattering matrix may readily be evaluated once the reflected waves at all the ports due to an incident wave at a typical port are established. Taking a_1 as unity and making use of the results for b_1, b_2, and b_3 gives the required parameters without ado.

$$S_{11} = \frac{\rho_0 + \rho_+ + \rho_-}{3} \tag{1.7a}$$

$$S_{21} = \frac{\rho_0 + \alpha\rho_+ + \alpha^2\rho_-}{3} \tag{1.7b}$$

$$S_{31} = \frac{\rho_0 + \alpha^2\rho_+ + \alpha\rho_-}{3} \tag{1.7c}$$

The entries of the scattering matrix are therefore linear combinations of the reflection variables at any port associated with each possible family of generator settings. One definition of an ideal circulator, which is on keeping with the description of the junction circulator, is therefore

$$S_{11} = 0 \tag{1.8a}$$

$$S_{21} = -1 \tag{1.8b}$$

$$S_{31} = 0 \tag{1.8c}$$

This solution may be established separately by having recourse to the unitary condition and may therefore be taken as a universal definition of a three-port lossless junction circulator.

1.4 GYROTROPY IN MAGNETIC INSULATORS

One means of removing the degeneracy between a pair of counterrotating field patterns is by having resource to a suitably magnetized magnetic insulator. The

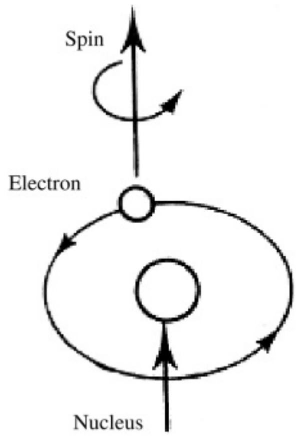


FIGURE 1.5 Atomic orbit.

origins of the magnetic effects or magnetization in magnetic insulators are due to the effective current loops of electrons in atomic orbits and the effects of electron spin and atomic nuclei (Fig. 1.5). Each of these features produces a magnetic field that is equivalent to that arising from a magnetic dipole—the total magnetic moment being the vector sum of the individual moments. In ferromagnetic insulators the predominant effect is due to the electron spin. A property of this sort of medium is that while it has, in general, a tensor permeability, it displays scalar permeabilities under one of three specific arrangements. One solution is a circularly polarized magnetic field in the plane transverse to the direct magnetic field, which rotates in the same sense as that of the electron spin; another is one that rotates in the opposite direction. The scalar permeabilities ($\mu \pm \kappa$) displayed by the medium under these two situations are simple linear combinations of the diagonal (μ) and off-diagonal (κ) entries of the tensor permeability. The absolute values of these quantities are essentially fixed by the frequency of the alternating radio magnetic field and the direct magnetization of the magnetic insulator and its direct magnetic field. The third normal mode coincides with a linearly polarized alternating magnetic field along the axis of the electron spin. It involves no gyromagnetic interaction.

1.5 PLANAR RESONATORS

In the design of any directly or transformer coupled planar circulator, it is essential to simultaneously reconcile physical, magnetic, and network conditions. It is necessary in order to do so with acceptable microwave characteristics to adjust either the substrate thickness or the resonator shape of the junction. The substrate thickness is often specified by the system rather than by the junction design, so that an ideal synthesis procedure is one where the resonator shape can be varied. If this is the case, a quarter-wave coupled triangular resonator coupled at its corners is best at low frequencies, a disk resonator is best at intermediate frequencies, and a triangular

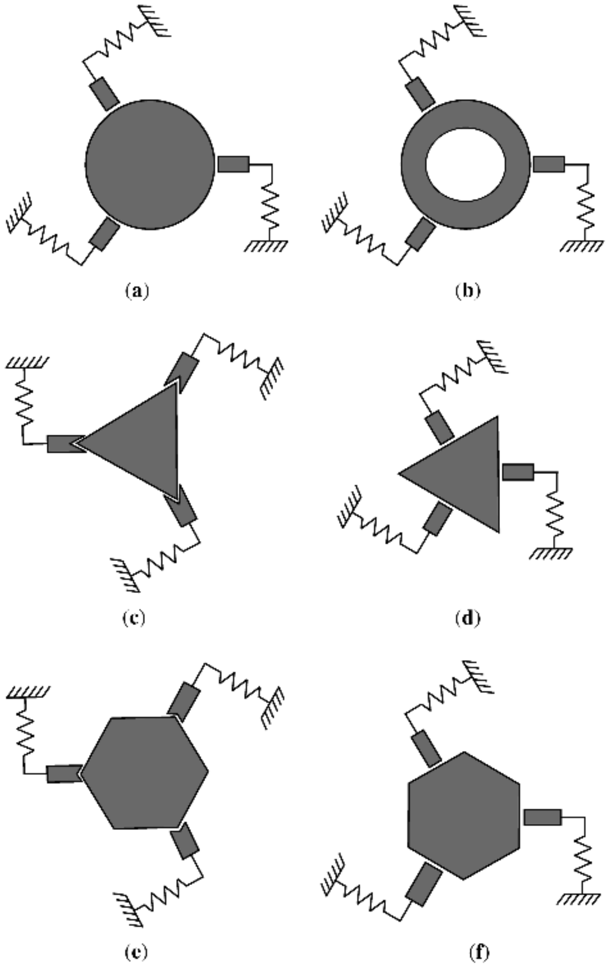


FIGURE 1.6 Some planar resonators that are suitable for the construction of three-port circulators.

resonator fed midway along its side is most suitable at high frequencies. Figure 1.6 depicts some possibilities. Figure 1.7 shows the construction of circulation solutions using triangular and wye resonators in terms of the field patterns of the demagnetized resonators.

1.6 PARALLEL PLATE WAVEGUIDE MODEL OF MICROSTRIP CIRCULATORS

The usual approach to the design of microstrip passive circuits and circulators using weakly magnetized resonators is to replace the problem region with imperfect

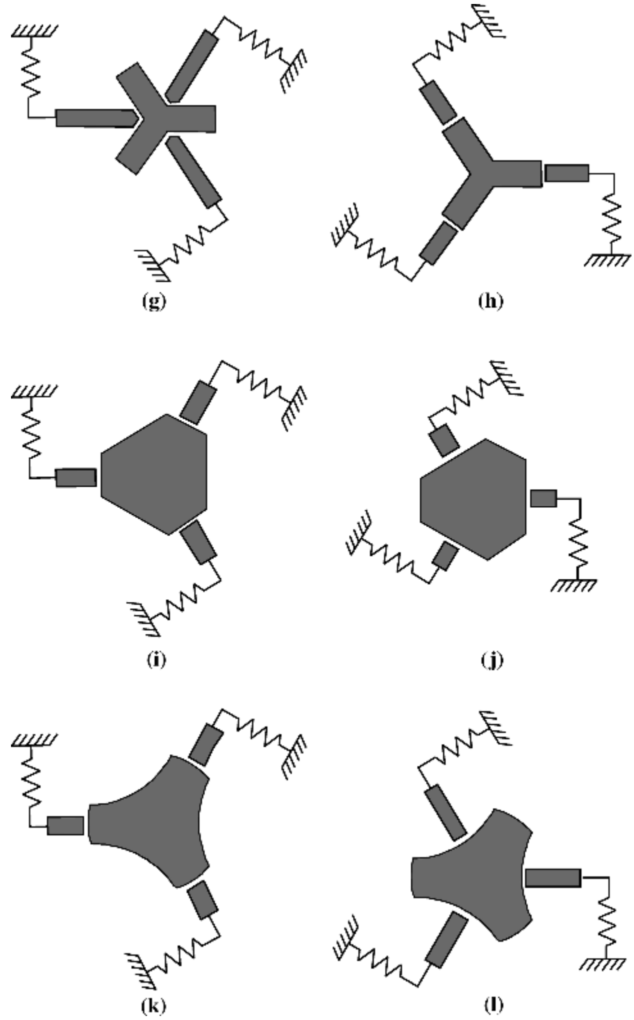


FIGURE 1.6 *Continued.*

magnetic side walls by an equivalent waveguide model. Figure 1.8 indicates a possible equivalence for a microstrip circulator using a circular resonator. The concepts entering into this sort of model are well established and need not be dwelt upon. Once any design is complete, in terms of the equivalent parallel plate waveguide approximation, it is necessary to invoke the relationship between the actual and effective parameters of the problem region. Another matter of concern in the design of such circuits is that if the fringing fields on a typical contour are excessive then it becomes difficult to preserve the definitions of both the coupling angle at the terminals of the resonator and its shape. One way to partially avoid both difficulties is to impose a lower bound on the aspect ratio (r/H) of the resonator.

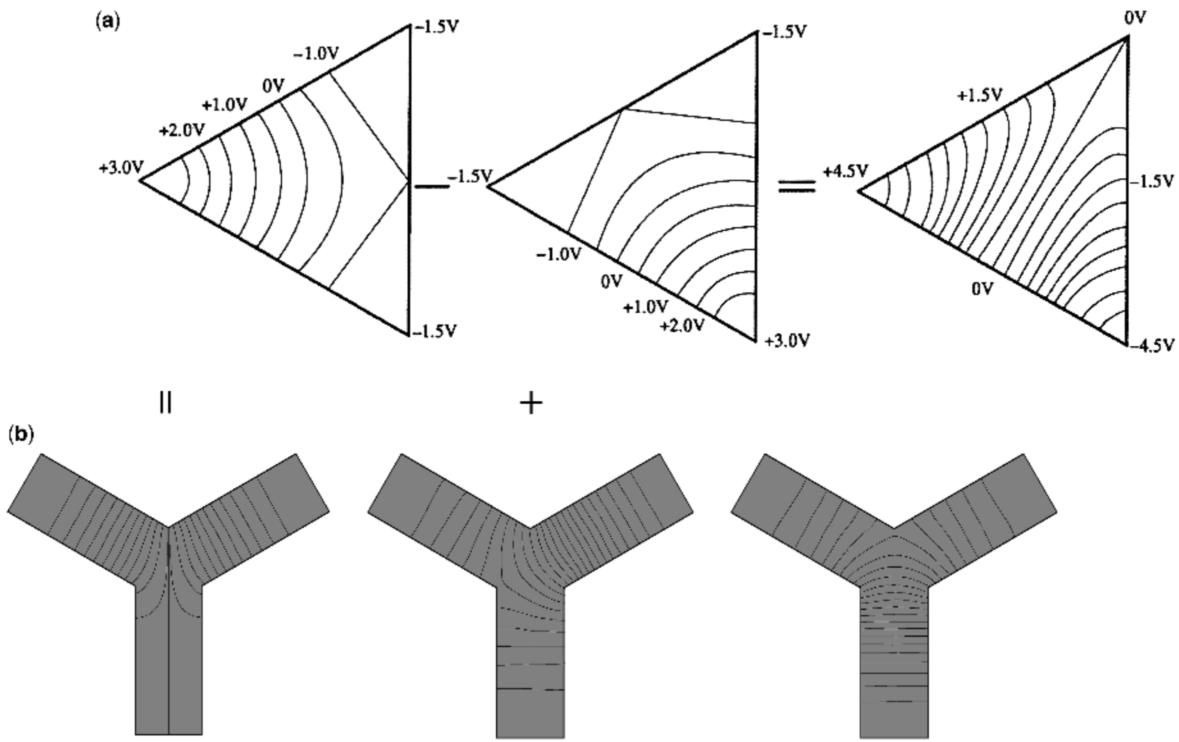


FIGURE 1.7 Standing wave solution of 3-port circulator using (a) triangular resonator and (b) wye resonator. (Reproduced with permission from J. Helszajn, D. S. James, and W. T. Nisbet, Circulators using planar triangular resonators, *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-27, February 1979.)

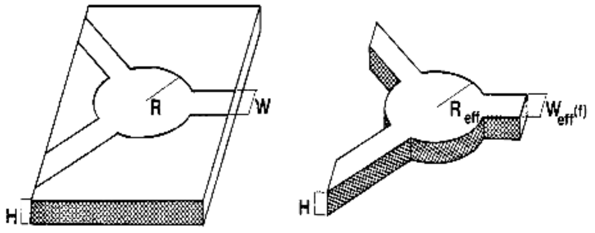


FIGURE 1.8 Equivalent waveguide model of planar disk.

1.7 DROP-IN AND PACKAGING TECHNIQUES

An ongoing activity in the area of microstrip devices is that of integration of the microstrip circulator or isolator in the subsystem. Some possibilities include an all-ferrite substrate, a suitable magnetic ferrite region inserted into a nonmagnetic ferrite plate, a ferrite puck inserted into a hole in a dielectric substrate, and a ferromagnetic film deposited on a dielectric sheet. The choice of technique used in any given application will be at least partly determined by cost and size considerations as well as performance. A number of drop-in techniques have also evolved over the years. One problem with this sort of fabrication is the transition between the microstrip circuit and the transmission line. Figure 1.9 shows one possibility that permits a planar resonator to be mounted onto an existing alumina substrate. Figure 1.10 illustrates a ferrite or garnet resonator embedded in an alumina substrate.

1.8 SWITCHED RESONATORS

The direction of circulation of a circulator is determined by that of the direct magnetic field. It may therefore be employed to switch an input signal at one port to either one of the other two. This may be done by replacing the permanent magnet by an

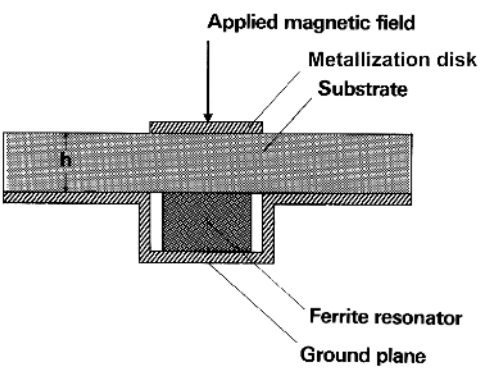
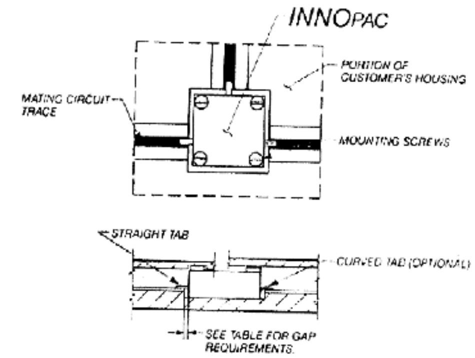
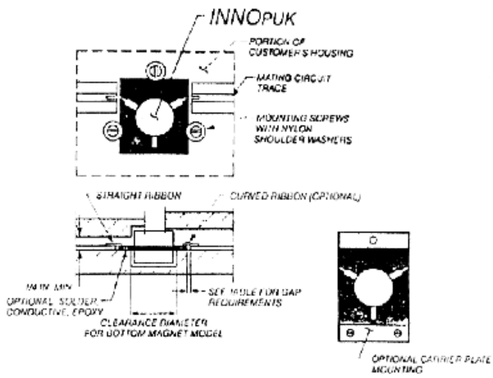


FIGURE 1.9 Mounting arrangement of planar resonator on back of microstripline.



Microstrip circulator on alumina substrate. (Courtesy INNOWAVE Inc., CA, USA)



: Microstrip circulator on garnet substrate (Courtesy INNOWAVE INC., CA, USA)

FIGURE 1.10 Microstrip circulator on alumina substrate.

electromagnet or by latching the microwave ferrite resonator directly by embedding a current-carrying wire loop within the resonator. One practical arrangement is illustrated in Fig. 1.11. This sort of switch is particularly useful in the construction of Butler type matrices in phased array systems. The switching power necessary to actuate this sort of circuit is determined by the stored energy in the magnetic circuit and the switching time. Switching times between 10 ns and 1 ms are achievable depending on whether the gyromagnetic circuit is internally or externally magnetized.

1.9 COMPOSITE RESONATORS

The conventional stripline junction relies for one of its two circulation conditions on an open dielectric resonance in a demagnetized ferrite or garnet geometry. The

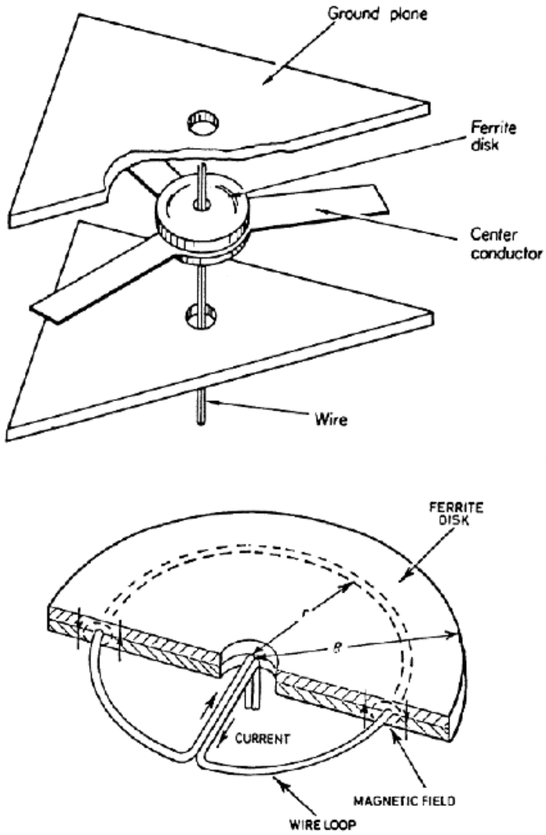


FIGURE 1.11 Details of wire loop in switched resonator.

maximum average power that such a circulator can handle is determined by the temperature drop across the thin dimension of the structure and its surface area. The thermal conductivity of the ferrite material is relatively low. For instance, the thermal conductivity of WESGO AL-995 ceramic is 29.31 $\mathrm{W/m \cdot {}^\circ C}$ (70×10^{-3} $\mathrm{cal \cdot m/s \cdot {}^\circ C}$) and that of beryllia oxide is 219.81 $\mathrm{W/m \cdot {}^\circ C}$ (525×10^{-3} $\mathrm{cal \cdot cm/s \cdot {}^\circ C}$). For ferrites it is 2.09 $\mathrm{W/m \cdot {}^\circ C}$ (5×10^{-3} $\mathrm{cal \cdot cm/s \cdot {}^\circ C}$). One way to overcome this difficulty is to employ composite resonators in the design. Such resonators have mainly been utilized in the construction of devices capable of handling hundreds of watts of mean power. Figure 1.12 depicts one planar and one radial configuration. A further advantage of this class of resonator is that the temperature stability is improved because many dielectric materials are temperature stable.

The second circulation relates the gyrator conductance, the susceptance slope parameter, and the split frequencies of the junction to the specification of the device—a large separation between the split frequencies being essential for the realization of high-quality circulators. Substituting a dielectric for part of the ferrite material

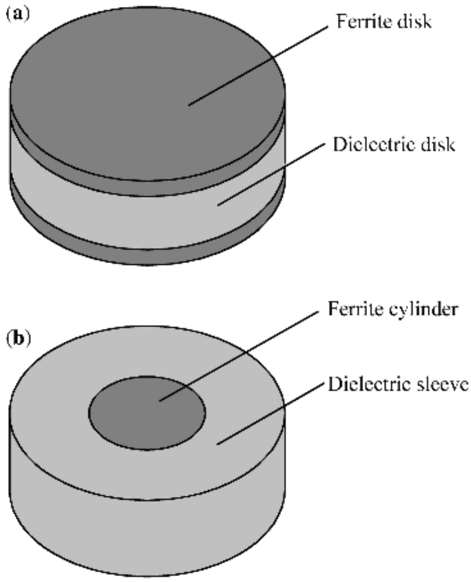


FIGURE 1.12 (a) Axial composite resonator and (b) radial composite resonator.

reduces the difference between the split frequencies of the junction; a compromise is therefore necessary between the microwave specification and the power rating of the device.

1.10 POWER RATING OF GYROMAGNETIC RESONATOR

Important aspects of microwave components are its peak and average power ratings. The peak power rating is usually fixed by arcing and by nonlinear effects in magnetic insulators due to spinwave instabilities. The average power rating is restricted by the temperature rise of the device, which may to some extent be mitigated by cooling it by forced air or water. The power dissipated in the device has its origin in dielectric losses and linear and nonlinear magnetic ones and dissipation in the striplines. The choice of resonator in any particular situation is dictated by one or both of these difficulties. The family of planar resonators is in general suitable for the construction of devices with modest mean power ratings. Composite resonators are used where a compromise between mean and peak power is necessary. Insertion losses on the order of 0.06 dB are not unusual in practice. The power rating of a typical circulator is dependent on the choice of resonator, the connector size, the frequency, the bandwidth, the available ferrite material, the cooling arrangement, the temperature range, pressurization, and the outline drawing to mention but some considerations that enter into any design. It is therefore difficult to compile precise recommendations in any particular situation.

1.11 QUARTER-WAVE COUPLED CIRCULATOR

Any gyromagnetic resonator with threefold symmetry suitably placed at a junction of three striplines may be adjusted to produce an ideal three-port circulator at a single frequency. Practical circulators, however, have to operate over finite frequency intervals with a specified ripple level or return loss and isolation. One way to realize a classical frequency response is to absorb each port of the gyromagnetic resonator into a two-port filter or matching network. A knowledge of the one-port complex gyrator circuit of the gyromagnetic junction at a typical port is sufficient for this purpose. One typical topology is indicated in Fig. 1.13. It consists of a quarter-wave unit element (UE) in shunt with the gyrator conductance of the junction. Figure 1.14

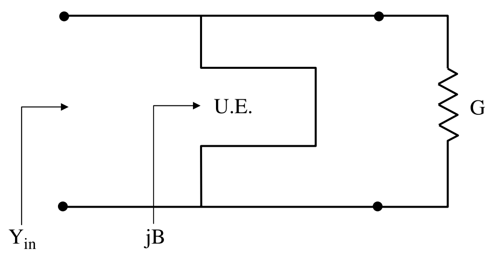


FIGURE 1.13 Complex gyrator circuit of three-port circulator.

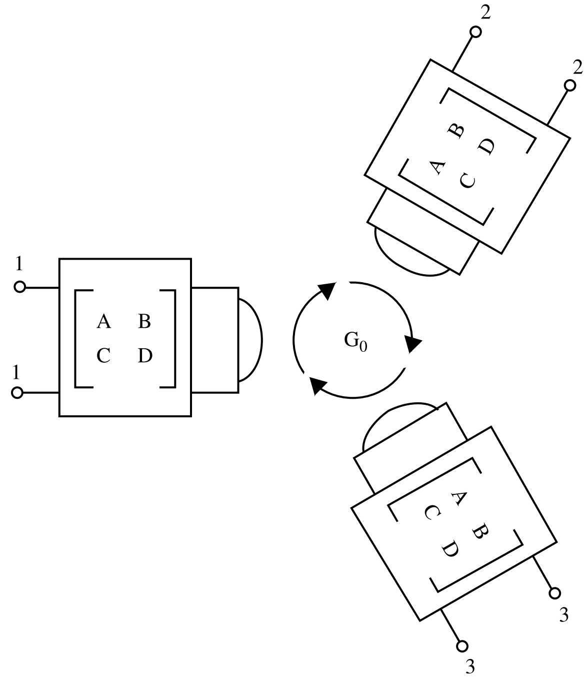


FIGURE 1.14 Topology of three-port circulators using two-port filter circuits.

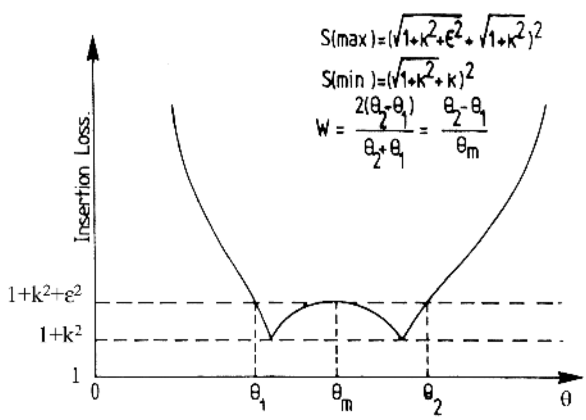


FIGURE 1.15 Frequency response of quarter-wave coupled junction circulation.

depicts the overall schematic arrangement. While a host of network solutions are possible in practice, the most common arrangement consists of one or more quarter-wave long impedance transformers. A typical frequency response of a circulator using a single quarter-wave long transformer at each port of the gyromagnetic resonator is indicated in Fig. 1.15. This sort of topology is a classic network problem in the literature and much of modern circulator practice rests on an understanding of this topic. The actual gain bandwidth of any circulator is fixed in practice by the quality factor of the gyromagnetic resonator and the topology of the filter circuit. It fixes the relationship between the isolation or return loss in decibels of the circulator and its bandwidth. A return loss or isolation of 23 dB (say) and a bandwidth of typically 25% is realizable in practice in conjunction with a single quarter-wave long impedance transformer. A similar return or loss or isolation specification is readily realizable over a bandwidth of between 40% and 66% using two such transformers.

1.12 FOUR-PORT SINGLE JUNCTION CIRCULATOR

While the three-port single junction circulator is the most common arrangement met in practice, four-port ones may also be realized without too much difficulty. Such junctions, in common with three-port devices, have some of the properties of a transmission line cavity resonator between ports 1 and 2, and a definite standing wave pattern exists within the junction with nulls at ports 3 and 4 also. An important difference between the two, however, is that the four-port device cannot be adjusted with external tuning elements only. This remark may be understood by recognizing that a four-port device can be matched without being a circulator. Scrutiny of its eigenvalue problem indicates that its adjustment requires three independent variables. These may be established in a systematic way by perturbing the scattering matrix

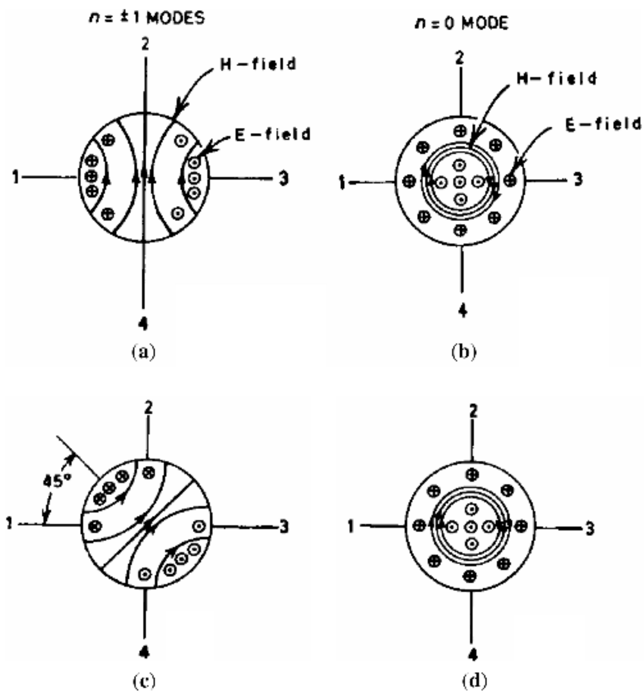


FIGURE 1.16 Standing wave solution of four-port single junction circulator: (a) $n = \pm 1$ for unmagnetized ferrite post, (b) $n = 0$ field patterns for unmagnetized ferrite post, (c) $n = \pm 1$ field patterns for magnetized ferrite post, and (d) $n = 0$ field patterns for magnetized ferrite post. (Reproduced with permission from C. E. Fay and R. L. Comstock, Operation of the ferrite junction circulator, *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-13, pp. 15–27, January 1965.)

eigenvalues one at a time on the unit circle until these coincide with those of an ideal circulator.

The four-port junction may be realized by having recourse to a linear combination of radial $TM_{\pm 1,1,0}$ and $TM_{0,1,0}$ modes. The field patterns in the demagnetized junction are depicted in Fig. 1.16a,b. The $TM_{0,1,0}$ mode is tuned to the frequency of the $TM_{\pm 1,1,0}$ modes with the help of a thin nonresonant capacitive post at the center of the junction instead of a resonant one. Figure 1.16c,d indicates the field patterns of the magnetized junction.

1.13 EDGE MODE CIRCULATOR

A junction that does not rely on a resonant effect in a gyromagnetic resonator is the edge mode arrangement. This effect is manifested by a suitably magnetized wide strip in a microstrip or stripline gyromagnetic line. The substrate is strongly magnetized perpendicular to the direction of propagation. The structure supports a TE-type solution in the transverse plane of the form

$$E_y = A\exp(-\alpha x)\exp(-j\beta z) \tag{1.9a}$$

$$H_x = \zeta_0 E_y \tag{1.9b}$$

$$H_z = 0 \tag{1.9c}$$

This solution indicates that the fields decay exponentially across the strip with no attenuation along the direction of propagation. The line also has the property that its field pattern is displaced to one side of the strip for one typical direction of propagation. It is displaced to the other side for the opposite direction of propagation. Once such a mode is established on one edge of the strip at one port, it may be wrapped at a second port by suitably bending the strip. Figure 1.17 illustrates one three-port structure. In principle, any number of ports may be connected in this way.

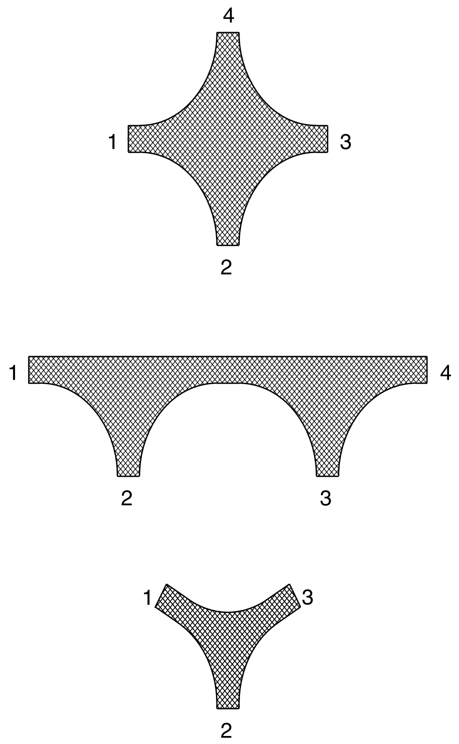


FIGURE 1.17 Topologies of edge mode circulators.

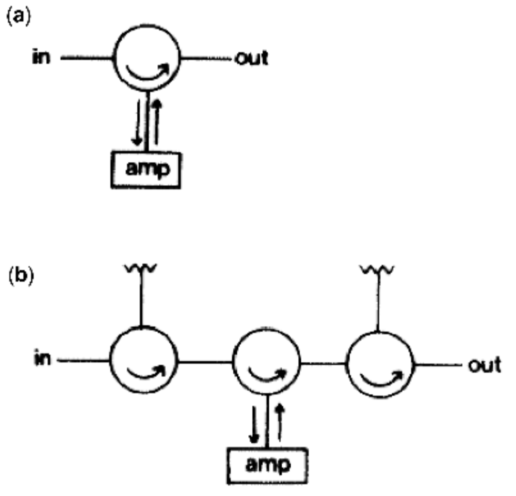


FIGURE 1.18 Single port amplifier using (a) three-port circulator and (b) five-port circulator.

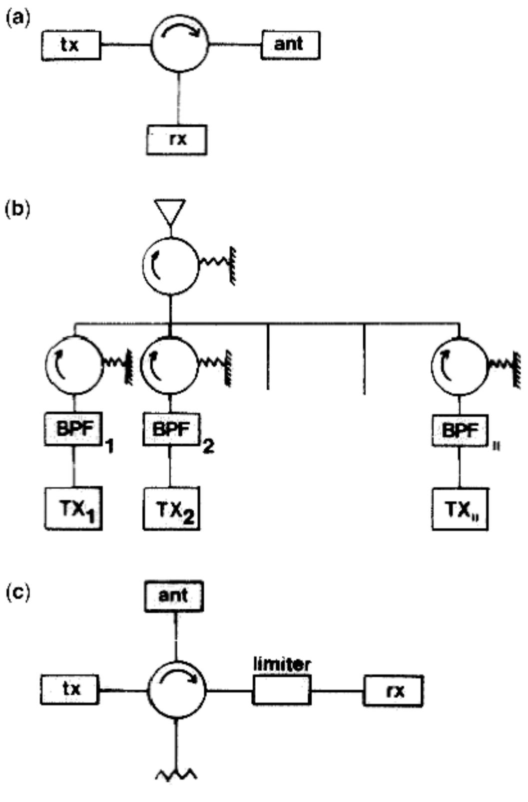


FIGURE 1.19 (a) Duplexing using single three-port circulator, (b) duplexing between closely spaced transmitters, and (c) high-power duplexer using four-port circulators.

1.14 SINGLE-PORT AMPLIFIERS USING JUNCTION CIRCULATORS

A simplified schematic of a reflection tunnel diode amplifier (TDA) that utilizes a circulator to separate the input signal from the amplified one is shown in Fig. 1.18a. When the gain of the amplifier is comparable to the isolation of the junction, it is often used in conjunction with five-port circulators. One such arrangement is depicted in Fig. 1.18b. The input and output junctions in this arrangement are connected as isolators in order to minimize gain variations due to source and load impedance variations. Here the magnetic field for the input circulator is sometimes supplied by an electromagnet. Reversal of the magnetic field in this circuit allows the TDA to be protected from radiofrequency leakage during the transmitting period by reversing the direction of circulation during this interval.

1.15 DUPLEXING USING JUNCTION CIRCULATORS

The ferrite circulator may also be used in duplexing systems for simultaneous transmission and reception of microwave energy with a single antenna. Here ferrite circulators replace conventional types of duplexing and are suited to both high- and low-power systems. Circulators are also employed in communication systems to eliminate mutual interference between closely separated transmitters. Figure 1.19b gives an example of a single antenna being shared by a number of

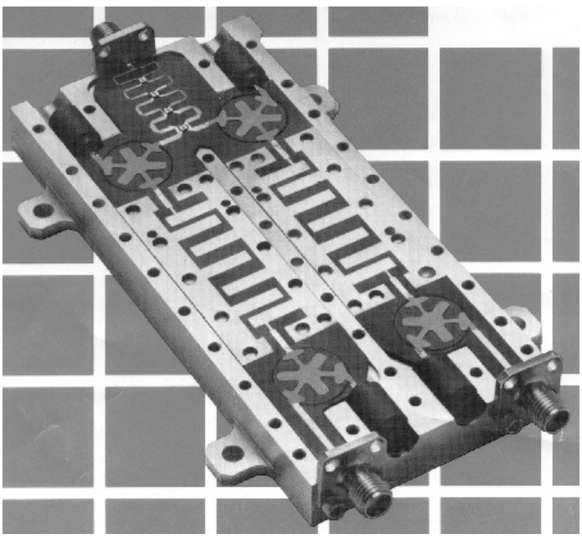


FIGURE 1.20 Microwave duplexer employing power splitters, isolators, and filters. (Courtesy of Dynatech Microwave Technology.)

transmitters with the help of circulators and bandpass filters (BPFs). Figure 1.19c illustrates a four-port high-port duplexer that utilizes a reflection limiter to protect the receiver during the transmission interval. Figure 1.20 illustrates a commercial duplexer using a power divider, ferrite isolators, and filters.