
The Stripline Circulator

Theory and Practice

By

J. HELSZAJN



A JOHN WILEY & SONS, INC., PUBLICATION

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Preface

The stripline junction circulator is a unique nonreciprocal device, which is embodied in many pieces of microwave equipment. The text is devoted to the theory and practice of this class of circulator. It starts with a chapter on the architecture of stripline circulators, and chapters on the tensor permeability in a magnetic insulator, and on the spatial shape demagnetizing factors of magnetic insulators. It continues with chapters on the scattering, eigenvalues, and admittance descriptions of the circulator as well as on its degree-1 and degree-2 one-port circuits. These chapters embody various classic experimental procedures for the characterization of the classic circulator. It proceeds with a block of chapters dealing with properties of gyromagnetic planar cloverleaf, wye, irregular hexagonal, and triangular resonators and the use of magnetic walls. The lumped element single junction circulator is dealt with as a preamble to dealing with the distributed circulator in that it embodies all the theoretical considerations of the general problem. Synthesis of the classic junction using a disk resonator is dealt with separately, as is the important Green's function and the finite element method. Special attention is devoted throughout to bridging the gap between its circuit and electromagnetic descriptions. These chapters are followed by one that deals with circulators employing triangular and irregular hexagonal gyromagnetic resonators. A separate chapter provides a detailed investigation of the frequency responses of the classic circulator using very weakly, weakly, strongly, and very strongly magnetized disk resonators. Still another chapter is devoted to the theory of the negative permeability circulator. The text continues with two chapters on circulators using wye resonators and a chapter on the little understood four-port single junction. A block of three chapters deals with the synthesis problem and the frequency responses of reciprocal and nonreciprocal junctions. The last two chapters but one are devoted to the fabrication of UHF and microstrip circulators. The last chapter deals with some discrepancies between idealized or theoretical models and

practice. A number of important topics such as spinwave instabilities and nonlinear effects in magnetic insulators have been omitted from the text in order to keep what is already a large volume in check. These topics are in every case already in place in a number of classic textbooks. Inevitably, some works, which have appeared elsewhere, have been duplicated for the sake of understanding.

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

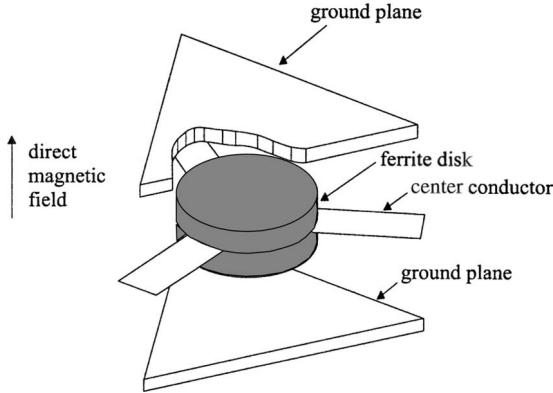


FIGURE 1.1 Schematic diagram of three-port stripline circulator.

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

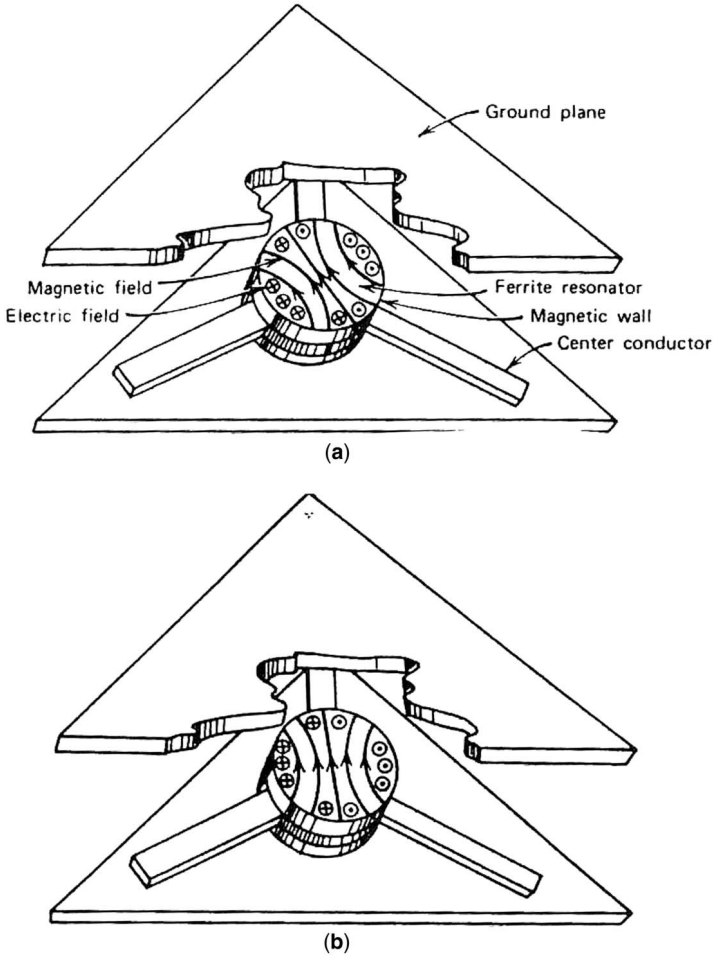


FIGURE 1.2 (a) Standing wave patterns in (a) demagnetized stripline junction and (b) magnetized stripline junction. (Reproduced with permission from C. E. Fay and R. L. Comstock, Operation of the ferrite junction circulator, *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-13, pp. 15–27, January 1965.)

combination of voltage settings at each port:

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

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.

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

An ideal circulator is now defined as

$$\frac{\rho_0 + \rho_- + \rho_+}{3} = 0 \quad (1.3a)$$

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

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

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

$$\rho_+ = \exp[-j2(\phi_1 + \phi_+ + \pi/2)] \quad (1.4a)$$

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

$$\rho_0 = \exp[-j(2\phi_0)] \quad (1.4c)$$

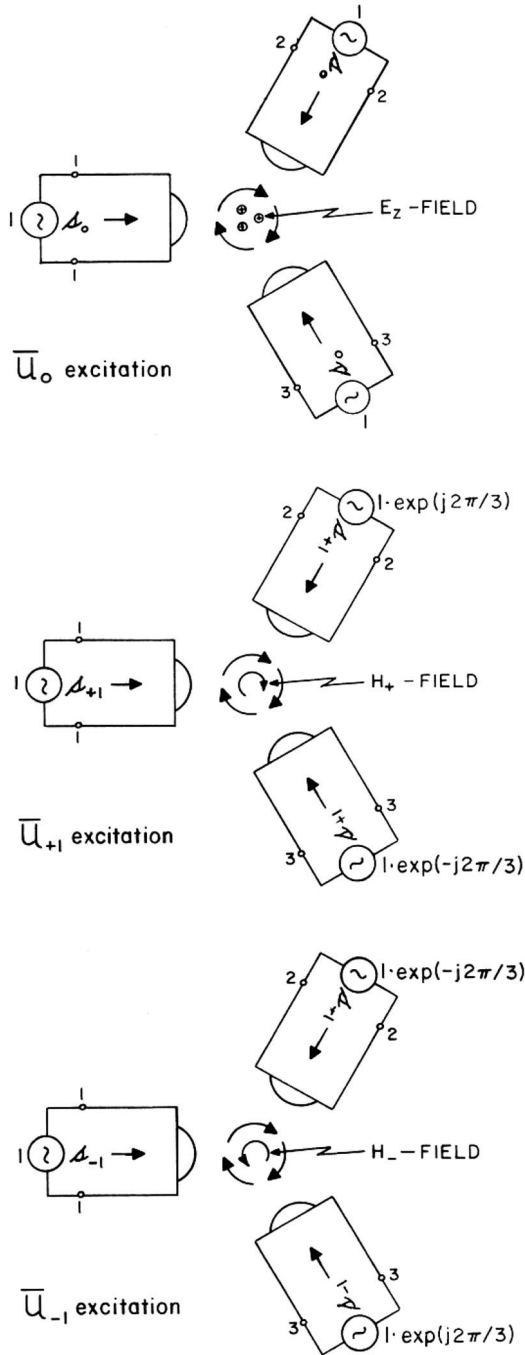


FIGURE 1.3 Voltage settings on three-port circulator.

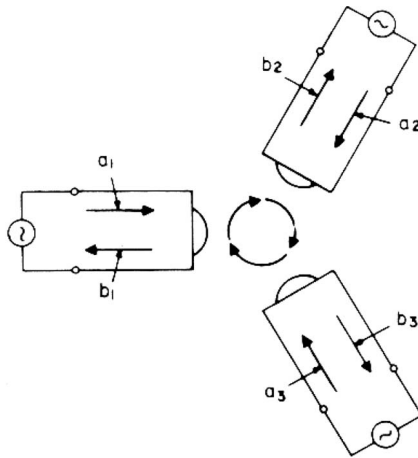
provided that

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

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

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:

$$S_{11} = \frac{b_1}{a_1} \Big|_{a_2 = a_3 = 0} \quad (1.6a)$$

$$S_{21} = \frac{b_2}{a_1} \Big|_{a_2 = a_3 = 0} \quad (1.6b)$$

$$S_{31} = \frac{b_3}{a_1} \Big|_{a_2 = a_3 = 0} \quad (1.6c)$$

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.

$$S_{11} = \frac{\rho_0 + \rho_+ + \rho_-}{3} \quad (1.7a)$$

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

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

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

$$S_{11} = 0 \quad (1.8a)$$

$$S_{21} = -1 \quad (1.8b)$$

$$S_{31} = 0 \quad (1.8c)$$

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

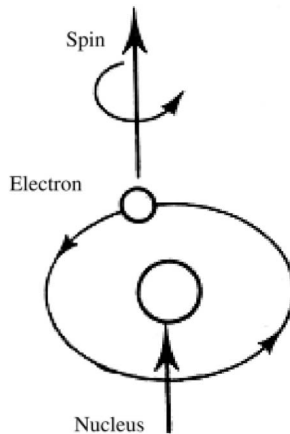


FIGURE 1.5 Atomic orbit.

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

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