

JOSEPH HELSZAJN

**MICROWAVE POLARIZERS,
POWER DIVIDERS,
PHASE SHIFTERS, CIRCULATORS,
AND SWITCHES**


IEEE PRESS

WILEY

**Microwave Polarizers, Power Dividers,
Phase Shifters, Circulators, and Switches**

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Joseph Helszajn

Heriot Watt University, Edinburgh, UK

WILEY


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Contents

Preface *xiii*

Acknowledgments *xv*

List of Contributors *xvii*

- 1 Microwave Switching Using Junction Circulators** *1*
Joseph Helszajn
- 1.1 Microwave Switching Using Circulators *1*
 1.2 The Operation of the Switched Junction Circulator *1*
 1.3 The Turnstile Circulator *4*
 1.4 Externally and Internally Latched Junction Circulators *7*
 1.5 Standing Wave Solution of Resonators with Threefold Symmetry *7*
 1.6 Magnetic Circuit Using Major Hysteresis Loop *8*
 1.7 Display of Hysteresis Loop *9*
 1.8 Switching Coefficient of Magnetization *11*
 1.9 Magnetostatic Problem *13*
 1.10 Multiwire Magnetostatic Problem *14*
 1.11 Shape Factor of Cylindrical Resonator *15*
 Bibliography *16*
- 2 The Operation of Nonreciprocal Microwave Faraday Rotation Devices and Circulators** *19*
Joseph Helszajn
- 2.1 Introduction *19*
 2.2 Faraday Rotation *20*
 2.3 Magnetic Variables of Faraday Rotation Devices *25*
 2.4 The Gyration Network *27*
 2.5 Faraday Rotation Isolator *29*
 2.6 Four-port Faraday Rotation Circulator *30*
 2.7 Nonreciprocal Faraday Rotation-type Phase Shifter *31*
 2.8 Coupled Wave Theory of Faraday Rotation Section *32*
 2.9 The Partially Ferrite-filled Circular Waveguide *33*
 Bibliography *34*

- 3 Circular Polarization in Parallel Plate Waveguides 37**
Joseph Helszajn
- 3.1 Circular Polarization in Rectangular Waveguide 37
- 3.2 Circular Polarization in Dielectric Loaded Parallel Plate Waveguide with Open Sidewalls 40
- Bibliography 47

- 4 Reciprocal Quarter-wave Plates in Circular Waveguides 49**
Joseph Helszajn
- 4.1 Quarter-wave Plate 50
- 4.2 Coupled Mode Theory of Quarter-wave Plate 53
- 4.3 Effective Waveguide Model of Quarter-wave Plate 58
- 4.4 Phase Constants of Quarter-wave Plate Using the Cavity Method 59
- 4.5 Variable Rotor Power Divider 62
- Bibliography 63

- 5 Nonreciprocal Ferrite Quarter-wave Plates 65**
Joseph Helszajn
- 5.1 Introduction 65
- 5.2 Birefringence 65
- 5.3 Nonreciprocal Quarter-wave Plate Using the Birefringence Effect 67
- 5.4 Circulator Representation of Nonreciprocal Quarter-wave Plates 71
- 5.5 Coupled and Normal Modes in Magnetized Ferrite Medium 72
- 5.6 Variable Phase-shifters Employing Birefringent, Faraday Rotation, and Dielectric Half-wave Plates 73
- 5.7 Circulators and Switches Using Nonreciprocal Quarter-wave Plates 76
- 5.8 Nonreciprocal Circular Polarizer Using Elliptical Gyromagnetic Waveguide 77
- Bibliography 79

- 6 Ridge, Coaxial, and Stripline Phase-shifters 81**
Joseph Helszajn
- 6.1 Differential Phase-shift, Phase Deviation, and Figure of Merit of Ferrite Phase-shifter 82
- 6.2 Coaxial Differential Phase-shifter 82
- 6.3 Ridge Waveguide Differential Phase-shifter 88
- 6.4 The Stripline Edge Mode Phase-shifter 90
- 6.5 Latched Quasi-TEM Phase-shifters 91
- Bibliography 92

- 7 Finite Element Adjustment of the Rectangular Waveguide-latched Differential Phase-shifter 95**
Joseph Helszajn and Mark McKay
- 7.1 Introduction 95
- 7.2 FE Discretization of Rectangular Waveguide Phase-shifters 97
- 7.3 LS Modes Limit Waveguide Bandwidths 98
- 7.4 Cutoff Numbers and Split Phase Constants of a Twin Slab Ferrite Phase-shifter 99
- 7.5 The Waveguide Toroidal Phase-shifter 102
- 7.6 Industrial Practice 103
- 7.7 Magnetic Circuits Using Major and Minor Hysteresis Loops 103
- 7.8 Construction of Latching Circuits 106
- 7.9 Temperature Compensation Using Composite Circuits 107
 Bibliography 109
- 8 Edge Mode Phase-shifter 111**
Joseph Helszajn and Henry Downs
- 8.1 Edge Mode Effect 112
- 8.2 Edge Mode Characteristic Equation 115
- 8.3 Fields and Power in Edge Mode Devices 115
- 8.4 Circular Polarization and the Edge Mode Effect 118
- 8.5 Edge Mode Phase-shifter 120
- 8.6 Edge Mode Isolators, Phase-shifters, and Circulators 123
 Bibliography 124
- 9 The Two-port On/Off H -plane Waveguide Turnstile Gyromagnetic Switch 127**
Joseph Helszajn, Mark McKay, Alicia Casanueva, and Angel Mediavilla Sánchez
- 9.1 Introduction 127
- 9.2 Two-port H -plane Turnstile On/Off Switch 127
- 9.3 Even and Odd Eigenvectors of E -plane Waveguide Tee Junction 129
- 9.4 Eigenvalue Adjustment of Turnstile Plane Switch 130
- 9.5 Eigen-networks 132
- 9.6 Numerical Adjustments of Passbands 133
- 9.7 An Off/On H -plane Switch 134
 Bibliography 136
- 10 Off/On and On/Off Two-port E -plane Waveguide Switches Using Turnstile Resonators 137**
Joseph Helszajn, Mark McKay, and John Sharp
- 10.1 Introduction 137
- 10.2 The Shunt E -plane Tee Junction 138

- 10.3 Operation of Off/On and On/Off E -plane Switches 140
- 10.4 Even and Odd Eigenvector of H -plane Waveguide Tee Junction 141
- 10.5 Phenomenological Description of Two-port Off/On and On/Off Switches 142
- 10.6 Eigenvalue Diagrams of Small- and Large-gap E -plane Waveguide Tee Junction 144
- 10.7 Eigenvalue Diagrams of E -plane Waveguide Tee Junction 145
- 10.8 Eigen-networks of E -plane Tee Junction 146
- 10.9 Eigenvalue Algorithm 147
- 10.10 Pass and Stop Bands in Demagnetized E -plane Waveguide Tee Junction 148
Bibliography 150

- 11 Operation of Two-port On/Off and Off/On Planar Switches Using the Mutual Energy–Finite Element Method 153**
Joseph Helszajn and David J. Lynch
- 11.1 Introduction 153
- 11.2 Impedance and Admittance Matrices from Mutual Energy Consideration 154
- 11.3 Impedance and Admittance Matrices for Reciprocal Planar Circuits 157
- 11.4 Immittance Matrices of n -Port Planar Circuits Using Finite Elements 160
- 11.5 Frequency Response of Two-port Planar Circuits Using the Mutual Energy–Finite Element Method 161
- 11.6 Stripline Switch Using Puck/Plug Half-spaces 166
Bibliography 169

- 12 Standing Wave Solutions and Cutoff Numbers of Planar WYE and Equilateral Triangle Resonators 171**
Joseph Helszajn
- 12.1 Introduction 171
- 12.2 Cutoff Space of WYE Resonator 172
- 12.3 Standing Wave Circulation Solution of WYE Resonator 174
- 12.4 Resonant Frequencies of Quasi-wye Magnetized Resonators 175
- 12.5 The Gyromagnetic Cutoff Space 179
- 12.6 TM Field Patterns of Triangular Planar Resonator 180
- 12.7 $TM_{1,0,-1}$ Field Components of Triangular Planar Resonator 182
- 12.8 Circulation Solutions 182
Bibliography 184

- 13 The Turnstile Junction Circulator: First Circulation Condition** 185
Joseph Helszajn
- 13.1 Introduction 185
- 13.2 The Four-port Turnstile Junction Circulator 186
- 13.3 The Turnstile Junction Circulator 188
- 13.4 Scattering Matrix 190
- 13.5 Frequencies of Cavity Resonators 193
- 13.6 Effective Dielectric Constant of Open Dielectric Waveguide 193
- 13.7 The Open Dielectric Cavity Resonator 196
- 13.8 The In-phase Mode 198
- 13.9 First Circulation Condition 200
Bibliography 200
- 14 The Turnstile Junction Circulator: Second Circulation Condition** 203
Joseph Helszajn and Mark McKay
- 14.1 Introduction 203
- 14.2 Complex Gyrator of Turnstile Circulator 204
- 14.3 Susceptance Slope Parameter, Gyrator Conductance, and Quality Factor 207
- 14.4 Propagation in Gyromagnetic Waveguides 208
- 14.5 Eigen-network of Turnstile Circulator 209
- 14.6 The Quality Factor of the Turnstile Circulator 211
- 14.7 Susceptance Slope Parameter of Turnstile Junction 213
Bibliography 213
- 15 A Finite-Element Algorithm for the Adjustment of the First Circulation Condition of the H-plane Turnstile Waveguide Circulator** 217
Joseph Helszajn
- 15.1 Introduction 217
- 15.2 Bandpass Frequency of a Turnstile Junction 219
- 15.3 In-phase and Counterrotating Modes of Turnstile Junction 221
- 15.4 Reference Plane 222
- 15.5 FE Algorithm 222
- 15.6 FE Adjustment 224
- 15.7 The Reentrant Turnstile Junction in Standard WR75 Waveguide 230
- 15.8 Susceptance Slope Parameter of Degree-1 Junction 230
- 15.9 Split Frequencies of Gyromagnetic Resonators 233
References 236

- 16 The E-plane Waveguide Wye Junction: First Circulation Conditions** 239
Joseph Helszajn and Marco Caplin
- 16.1 Introduction 239
- 16.2 Scattering Matrix of Reciprocal *E*-plane Three-port *Y*-junction 240
- 16.3 Reflection Eigenvalue Diagrams of Three-port Junction Circulator 242
- 16.4 Eigen-networks 244
- 16.5 Pass Band and Stop Band Characteristic Planes 246
- 16.6 The Dicke Eigenvalue Solution 247
- 16.7 Stop Band Characteristic Plane 248
- 16.8 The *E*-plane Geometry 249
- 16.9 First Circulation Condition 251
- 16.10 Calculations of Eigenvalues 253
- Bibliography 254
- 17 Adjustment of Prism Turnstile Resonators Latched by Wire Loops** 257
Joseph Helszajn and William D'Orazio
- 17.1 Introduction 257
- 17.2 The Prism Resonator 258
- 17.3 Split Frequency of Cavity Resonator with Up or Down Magnetization 260
- 17.4 Quality Factor of Gyromagnetic Resonator with Up and Down Magnetization 261
- 17.5 Shape Factor of Tri-toroidal Resonator 262
- 17.6 Squareness Ratio 264
- 17.7 The Complex Gyrator Circuit of the Three-port Junction Circulator 265
- 17.8 The Alternate Line Transformer 266
- 17.9 Effective Complex Gyrator Circuit 267
- Bibliography 267
- 18 Numerical Adjustment of Waveguide Ferrite Switches Using Tri-toroidal Resonators** 269
Joseph Helszajn and Mark McKay
- 18.1 Introduction 269
- 18.2 The Tri-toroidal Resonator 270
- 18.3 The Wire Carrying Slot Geometry 272
- 18.4 The Magnetostatic Problem 273
- 18.5 Quality Factor of Junction Circulators with Up and Down Magnetization 274

18.6	Split Frequencies of Planar and Cavity Gyromagnetic Resonators	275
18.7	The Split Frequencies of Prism Resonator with Up and Down Magnetization	276
18.8	Exact Calculation of Split Frequencies in Tri-toroidal Cavity	277
18.9	Calculation and Experiment	278
18.10	Tri-toroidal Composite Prism Resonator	279
18.11	Tri-toroidal Wye Resonator with Up and Down Magnetization	280
	Bibliography	282
19	The Waveguide H-plane Tee Junction Circulator Using a Composite Gyromagnetic Resonator	285
	<i>Joseph Helszajn</i>	
19.1	Introduction	285
19.2	Eigenvalue Problem of the H -plane Reciprocal Tee Junction	286
19.3	Electrically Symmetric H -plane Junction at the Altman Planes	289
19.4	Characteristic Planes	290
19.5	The Septum-loaded H -plane Waveguide	292
19.6	The Waveguide Tee Junction Using a Dielectric Post Resonator: First Circulation Condition	294
19.7	The Waveguide Tee Junction Circulator Using a Gyromagnetic Post Resonator: Second Circulation Condition	296
19.8	Composite Dielectric Resonator	297
	Bibliography	299
20	0°, 90°, and 180° Passive Power Dividers	301
	<i>Joseph Helszajn and Mark McKay</i>	
20.1	Introduction	301
20.2	Wilkinson Power Divider	302
20.3	Even and Odd Mode Adjustment of the Wilkinson Power Divider	302
20.4	Scattering Matrix of 90° Directional Coupler	305
20.5	Even and Odd Mode Theory of Directional Couplers	309
20.6	Power Divider Using 90° Hybrids	311
20.7	Variable Power Dividers	313
20.8	180° Waveguide Hybrid Network	314
	Bibliography	318
	Index	321

Preface

Ferrite phase-shifter and control devices are widely used in conjunction with passive microwave circuits in beam shaping and steering of array antennas and in multichannel switching. The intention of this text is to provide the reader with some preliminary insight into the operation of some basic ferrite control devices and to note some system uses. In the beam steering application, variable phase-shifters are employed to tilt the beam of a simple one-dimensional array or more sophisticated two- and three-dimensional ones. Beam shaping is achieved by using variable power dividers and switches. At modest microwave wavelengths, this is often done with the aid of semiconductor devices, but at very high power levels and at millimeter wavelengths, ferrite devices are used almost exclusively. A drawback of the ferrite control device is its longer switching time; its microwave power rating is, however, usually superior. Although many ferrite devices are nonreciprocal, this is often not essential or indeed desirable in the control area. Mechanically actuated passive switches and variable phase shifters using rotatable half-wave plates are other possibilities. Multichannel switching may consist of making provisions for switching on a standby transmitter in case of a failure mode in some simple radar or satellite equipment or it may involve the control of a high-power signal using Butler matrices; it may also be utilized in the construction of multipoint power combiners. The three-port junction circulator is, of course, also ideally suited for switching a signal at one port to any of $n - 1$ others. Frequency reuse where spatially isolated beams operate in the same frequency band is another area where power dividers and variable phase shifters are required. Switching of the hand of polarization of a wave or rotating its polarization are other applications. Microwave ferrite phase-shifters and other devices essentially rely for their operation on the different birefringences exhibited by a magnetized magnetic insulator under the influence of different direct and alternating magnetic fields. Nonlinear effects or spinwave instabilities at large signal levels are a separate consideration.

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List of Contributors

Mr. Marco Caplin

RF Designer
Apollo Microwaves Ltd
Dorval, Quebec
Canada

Professor Alicia Casanueva

Communication Engineering
Department
University of Cantabria
Santander
Spain

Mr. William D’Orazio

RF Designer
Apollo Microwaves Ltd
Dorval, Quebec
Canada

Mr. Henry Downs

Chief Science Officer – EVP
Engineering
Mega Industries, LLC
Gorham, ME
USA

Dr. David J. Lynch

Director
Filtronic Wireless Ltd
Salisbury, MD
USA

Dr. Mark McKay

Principal Engineer
Honeywell
Edinburgh
UK

Professor Angel Mediavilla Sánchez

Communication Engineering
Department
University of Cantabria
Santander
Spain

Professor John Sharp

Professor Emeritus
Napier University
Edinburgh
UK

1

Microwave Switching Using Junction Circulators

Joseph Helszajn

Heriot Watt University, Edinburgh, UK

1.1 Microwave Switching Using Circulators

Since the direction of circulation of a circulator is determined by that of the direct magnetic field, it may be employed to switch an input signal at one port to either one or the other two. Switching is achieved by replacing the permanent magnet by an electromagnet or by latching the microwave ferrite resonator directly by embedding a current carrying wire loop within the resonator.

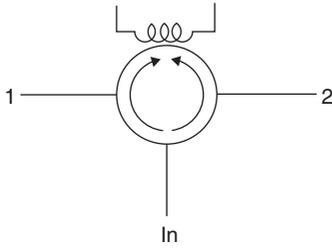
The schematic diagram of a switched junction is shown in Figure 1.1a. It is particularly useful in the construction of Butler-type matrices in phase array systems. A single-pole three throw version is depicted in Figure 1.1b.

Two common arrangements in which ferrite circulators may be employed to obtain microwave switching are separately illustrated in Figure 1.1c and 1.1d. The first uses a circulator in conjunction with a pin diode switch to vary the short-circuit plane terminating port 2. A transmission analog phase shifter is therefore obtained between ports 1 and 3 with this mode of operation. The second version is also a transmission configuration but now a switchable circulator is used to control the path between ports 1 and 3 of the circulator. The switching speed of the pin device is normally the faster one.

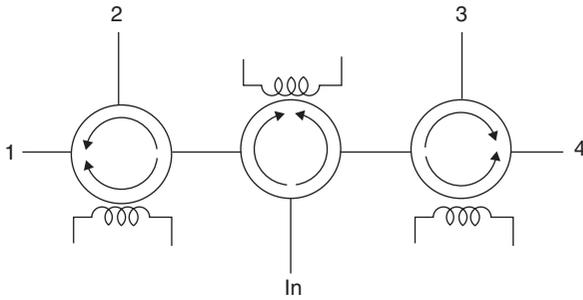
1.2 The Operation of the Switched Junction Circulator

The adjustment of a fixed field circulator or a switched circulator is a two-step procedure. The first fixes its midband frequency and the second its gyrotropy. A phenomenological description of these two operations is illustrated in

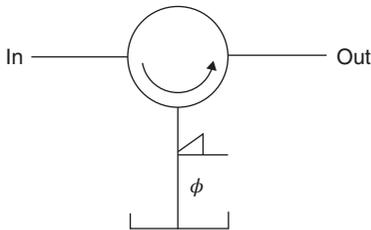
(a)



(b)



(c)



(d)

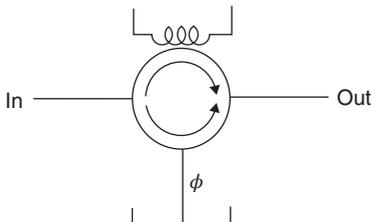


Figure 1.1 Microwave phase shifter using (a) schematic of circulator switch, (b) SP4T Butler switch using circulators, (c) pin diode switch and fixed circulator, and (d) switched circulator.

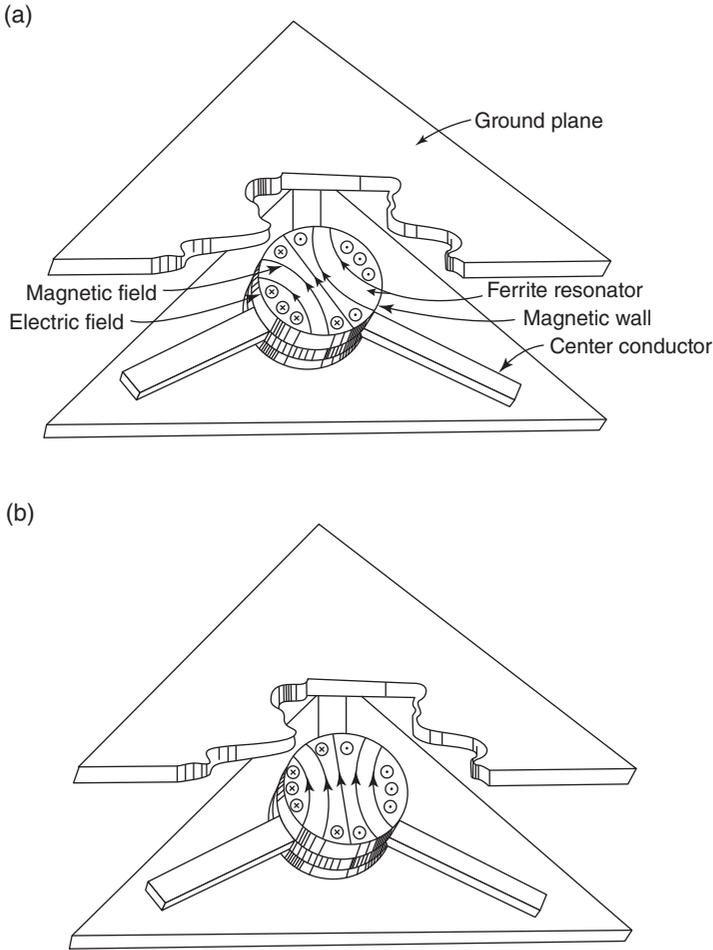


Figure 1.2 Standing wave patterns in (a) demagnetized stripline junction and (b) magnetized stripline junction.

Figure 1.2a and b in the case of a stripline geometry. The direction of circulation is here fixed by the sense of the direct magnetic field intensity along the axis of the resonator. This may be done by either internally latching the hysteresis loop of the magnetic insulator between its two remanent states or by having recourse to an external magnetic circuit. The electric field pattern may be rotated either clockwise or anticlockwise by splitting the degeneracy of the counterrotating field patterns of the resonator. A latched stripline geometry is indicated in Figure 1.3.

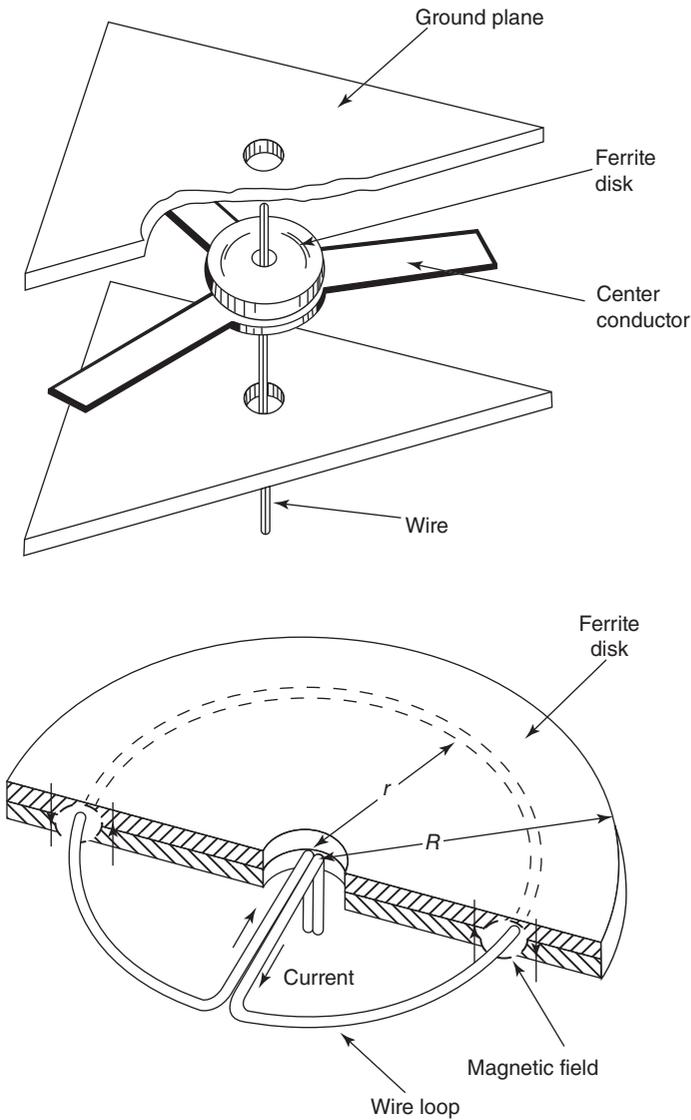


Figure 1.3 Current and magnetic field in ferrite disc.

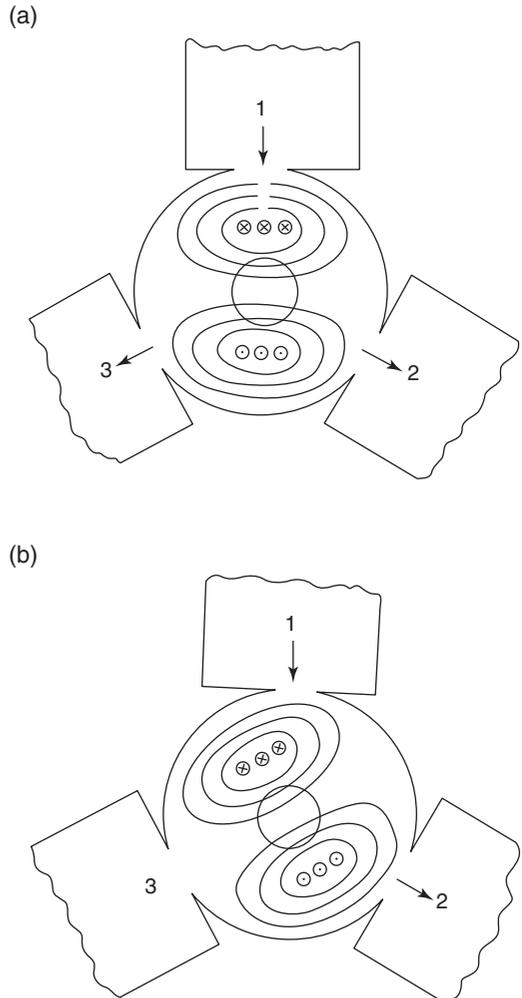
1.3 The Turnstile Circulator

The waveguide junction switch is usually but not exclusively based on a Faraday rotation effect along a quarter-wave long cavity resonator open-circuited at one flat face and short-circuited at the other. Its first circulation condition is a 90°

cavity with no rotating of the electric field pattern, which is again a figure of eight pattern. Its second circulation condition is obtained by replacing the dielectric resonator by a gyromagnetic insulator. The effect is to rotate the polarization of the electric field by a 15° angle in the positive direction of propagation and a further 15° in the opposite direction. The total rotation places an electric null at a typical output port.

Figure 1.4a and b are sketches of the electric and magnetic HE_{11} standing wave patterns about midway along the cavity. The electric field is zero at the electric wall of the cavity, whereas the magnetic field is zero at its magnetic flat wall.

Figure 1.4 (a) Ferrite unmagnetized; first circulation condition. (b) Ferrite magnetized; second circulation condition.



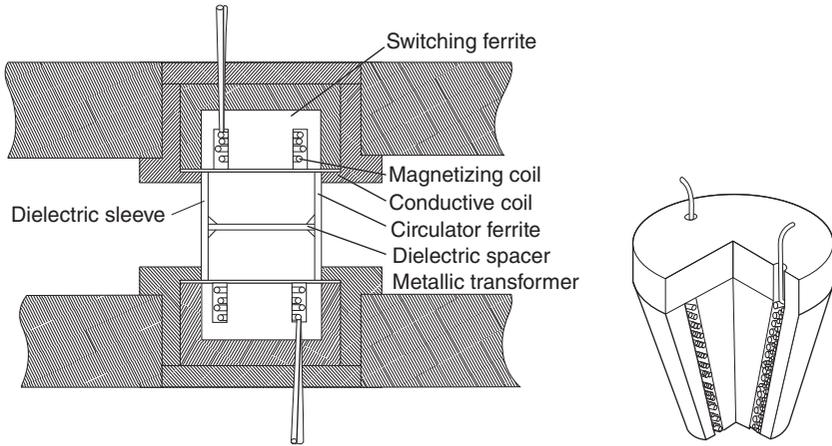
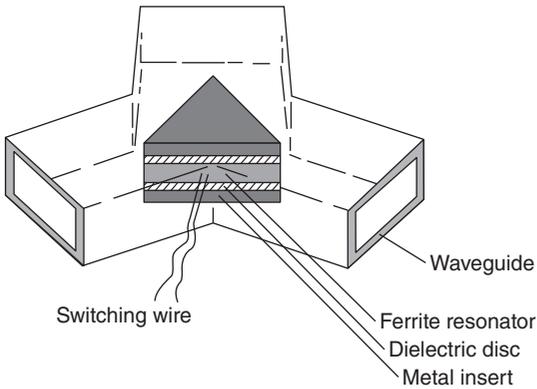


Figure 1.5 Schematic diagram of externally latched circulator using a post-resonator waveguide junction.

(a)



(b)

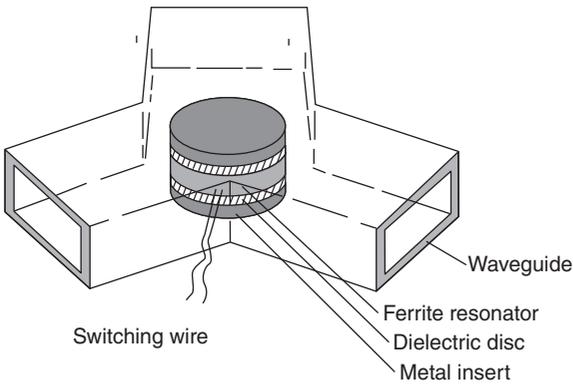


Figure 1.6 Schematic diagram of waveguide junction circulator using a partial height: (a) triangular and (b) circular resonator with a wire loop.

1.4 Externally and Internally Latched Junction Circulators

Circulators may be either actuated by an electromagnet or they may be operated by internally or externally latching the ferrite resonator. Figure 1.5 illustrates one externally latched arrangement. Figure 1.6a and b depict internally latched waveguide devices using half-wave or quarter-wave long resonators.

Figure 1.7 indicates the two possible wire configurations met in the construction of a waveguide switch using a prism resonator.

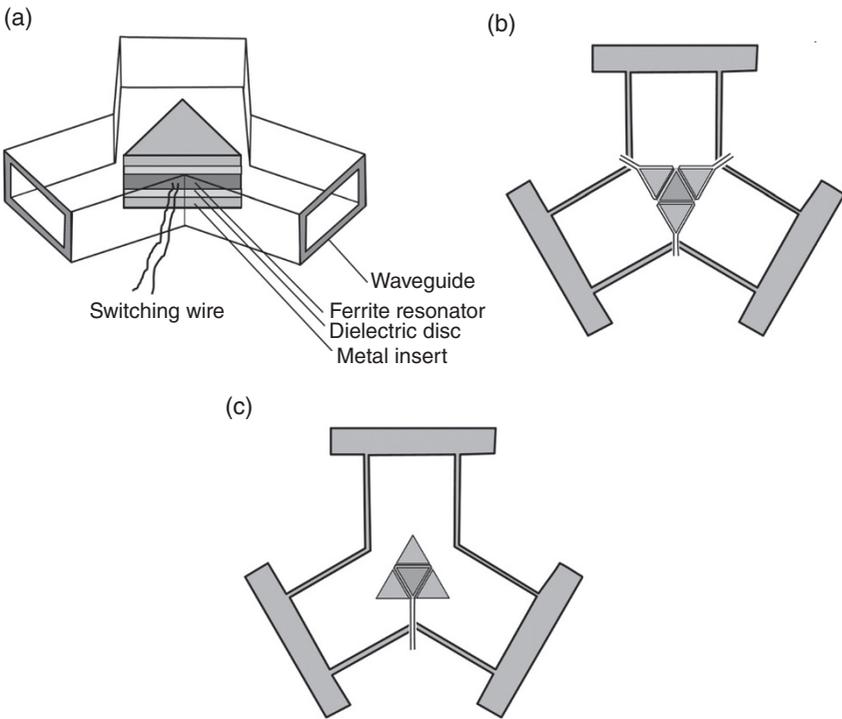


Figure 1.7 Schematic diagrams of waveguide circulators showing different switching wire configurations.

1.5 Standing Wave Solution of Resonators with Threefold Symmetry

Two resonators met in the design of switched circulators with threefold symmetry are the equilateral triangle structure and the quasi WYE geometry.

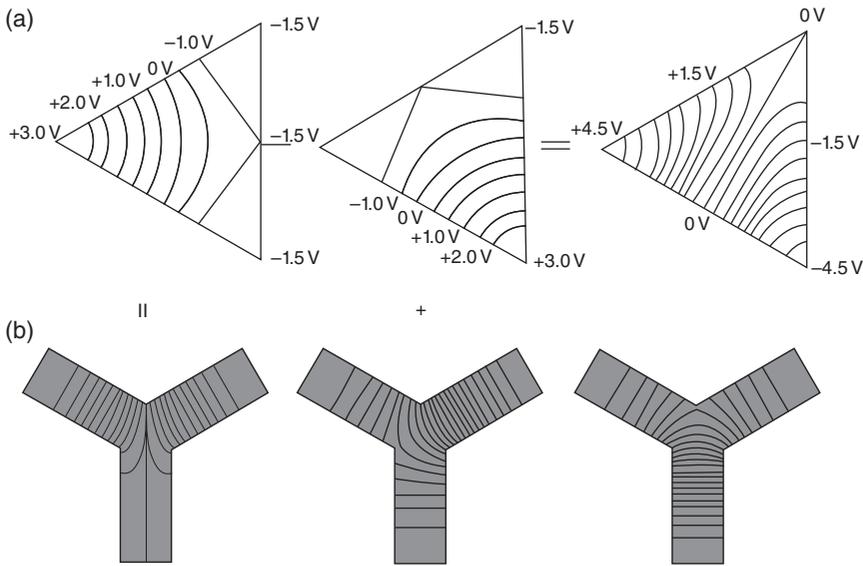


Figure 1.8 Standing wave solution of three-port circulators using (a) triangular resonator and (b) WYE resonator.

The standing wave solution of the second circulation solutions is here not obvious but each may be constructed by taking suitable linear combinations of those of the first circulation condition. Figure 1.8a and b illustrate the equipotential lines of the standing wave patterns in each situation.

1.6 Magnetic Circuit Using Major Hysteresis Loop

The direct magnetic field in a junction circulator can be established using either an external electromagnet or it can be switched by current pulses through a magnetizing wire between the two remanent states of the major or indeed of a minor hysteresis loop of a closed magnetic circuit. The former arrangement requires a holding current to hold the device in a given state.

In the latter one, however, no such current is necessary; the device remains latched in a given state until another switching operation is required. The advantages and disadvantages of each type of circuit are understood.

Operation on the major hysteresis loop may be understood by scrutinizing the hysteresis loop in Figure 1.9, providing it is recognized that the size and shape of this loop may vary with the speed of the switching process. In this situation, the magnetization of the toroid is driven between two remanent states ($\pm 4\pi M_r$)

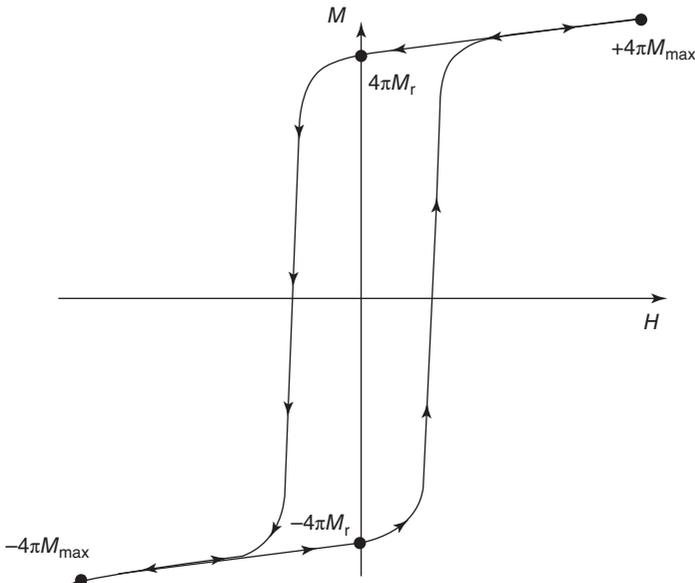


Figure 1.9 Typical hysteresis loop of a latching phase shifter operating with a major hysteresis loop switching.

equidistant from the origin by the application of a current pulse sufficiently large to produce a field perhaps three or five times that of the coercive force.

After this point is reached, the current pulse is removed and the magnetization will move to the remanent value ($\pm 4\pi M_r$) and remain there until another switching operation is desired. This sort of electronic driver circuit is relatively simple since it is only required that the toroids be driven back and forth between the major remanent states of the hysteresis loop.

1.7 Display of Hysteresis Loop

The magnetic properties and parameters of a magnetic core or toroid under different operating conditions, such as temperature, say, are best discussed in terms of the details of its hysteresis loop.

Some experimental quantities that are of particular interest include the saturation magnetization (M_0), the remanent magnetization (M_r), and the coercive force (H_c). The experimental display of such loops is therefore of some interest. One circuit that may be used for this purpose is outlined in Figure 1.10. This

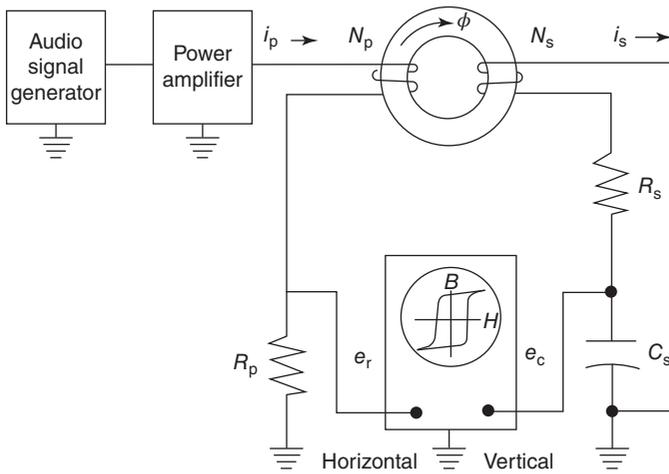


Figure 1.10 Schematic diagram of hysteresis display.

arrangement develops voltage V_p and V_i that are proportional to B and H , respectively.

The magnetic field (H) in the core is monitored by measuring the voltage (V_p) across a resistor in series with the primary winding, see Figure 1.10.

$$H = \frac{N_p}{I_p} \left(\frac{V_p}{R_p} \right), \text{A m}^{-1} \quad (1.1)$$

where I_p is the effective of the primary winding, N_p is the number of turns of the primary winding (10–30), and R_p is the resistor in series with the primary coil (10 Ω). The magnetization (B) is likewise evaluated by forming the voltage (V_i) across the capacitance of the RC integrator in the secondary circuit.

$$B \approx \frac{-V_i R_i C_i}{N_s A} \quad (1.2)$$

where R_i is the series resistance of the integrator (100 k Ω), C_i is the capacitance of the integrator (0.10 μF), N_s is the number of turns of the secondary winding (10–30), and A is the cross-sectional area of the core.

The data shown in Figure 1.11 on the effects of small air gaps on the squareness of the hysteresis loop have been obtained using the arrangement outlined here.