CHAPTER I

INTRODUCTION

The word "Circulator" was originally coined by Fox (89) for the non-reciprocal microwave device that had four ports only, permitting the sequential transmission of r.f. Power, and is indicated by the circuit symbols in fig. I.1. In an ideal n-port circulator when all of its n-ports are matched, the r.f. Power when fed at port 1 may flow only from port 1 to port 2 or from port 2 to port 3 and so on according to the sequence 1 → 2 → 3 → ... n → 1, with no reverse-coupling between port 2 to port 1, or port 3 to port 2 and so on. And further, it introduces cross-coupling between ports not adjacent to each other, that is, between port 3 and port 1 or between port 4 and port 1 and so on. The following are various kinds of microwave ferrite circulators studied by a number of scientists in the field, are briefly described.

I.1. POLARIZATION CIRCULATORS

One type of polarization circulator, employing Faraday-rotation effect, reported (111, 117, 118, 190) has four output ports corresponding to the different polarizations at each end of the device. It is indicated schematically in fig. I.2, with four output ports at different polarizations. This device making use of the 45° Faraday-rotation of plane of polarization, has been called polarization-circulator. The power when fed into the first port of the device with polarization 'a' is turned into polarization 'b' at the second port. Again the power fed at the second port with polarization 'b'
Fig. 1.1. N-PORT CIRCULATOR

Fig. 1.2. POLARIZATION CIRCULATORS

a. Circulator
b. Circuit symbol
is turned into polarization 'c' and similarly the polarization 'c' is turned into 'd' polarization and 'd' polarization is turned into minus 'a' polarization.

Another polarization circulator has been built by combining one gyrator with two magic tees shown in fig. I.3. A signal introduced at port 1, splits into two side-arms of the hybrid junction. Each portion travels an electrical path of equivalent length to combine in phase, at the left hybrid and emerges at port 2. The signal introduced at port 2 splits equally between the two side-arms but the gyrator rotates one portion to 180°. The waves of opposite phase recombine at the right hybrid junction and the total signal emerges at port 3. Similarly energy is transmitted from port 3 to port 4 and port 4 to port 1, simultaneously introducing cross-coupling between E- and H-arms under matched conditions. Since this device has all of the fundamental properties of rotating plane of polarization, it is also suggested that it be called a polarization-Circulator.

The X-band polarization circulator developed (116) was capable of handling a peak power 500 kw and an average power of 500 watts in waveguide version. This circulator gives an insertion loss of 0.5 dB, the cross-coupling down by 20 dB, and approximately giving 25 percent bandwidth.

In addition, as one goes to frequencies below 1000 MHz the properties of phase shifters employed in circulator deteriorate rapidly increasing the loss above 2 dB, making it impossible to build a circulator below 500 MHz.
a. Circulator

b. Circuit symbol for Circulator

Fig. I.3. POLARIZATION CIRCULATOR
(\textit{Syrator} + Magic tees)

a. Four-Arm Turnstile

b. Three-Arm Turnstile

Fig. I.4. TURNSTILE CIRCULATORS
I.2 TURNSTILE CIRCULATORS

Allen (4) has reported 4-port circulator, based on the well known 4-arm turnstile junction and Fowler's (86) and Schang-peterson's (198) circulators based on the 3-arm turnstile junction. Also Owen-Barnes (176) reported a very compact turnstile circulator. In these types of circulators, a matched turnstile junction is used and the circular arm is terminated by the Faraday rotator in front of an adjustable short circuit plunger. Allen treated the device as an inter-connection of two distinct components and assuming that the Faraday rotator was a reflectionless one and demonstrated that the circulating action could be achieved by suitably adjusting the plane of polarization and the phase of the reflected wave in the circular arm. A typical device is shown in the fig. I.4. Under the matched conditions of the turnstile circulator, power fed into the port 1 will emerge at port 2 after suitable rotation and reflection from the turnstile circular arm, decoupling the adjacent port 4 and introducing cross-coupling with the rest of the ports. Similarly power from port 2 goes to port 3 and from port 3 to port 4 and so on. As an alternative arrangement for a circulator using a symmetrical ring structure, Vartanian (221) had proposed 3-port circulator using three gyrators. However a more useful type of symmetrical ring circulator is obtained by simply inter-connecting six 3-port turnstile circulators. If the bias fields for the six circulators, all have the same polarity, this structure functions as a 6-port circulator as shown in fig. I.5. A new form of seven port circulator was also
Fig. I.5. SIX-PORT RING CIRCULATOR
(Plan of the device)

Fig. I.6. WAVE GUIDE CIRCULATORS

a. H-plane Circulator
b. E-plane Circulator
c. 4-port Circulator
d. Cross-guide Circulator
reported by Goller (95). An 8-port symmetrical ring circulator can be obtained by connecting the four 4-port circulators in a square array. These circulators used transverse biasing field strengths less than 100 oersteds, gave useful bandwidth of the order of 3 percent in X-band for isolation greater than 40 dB, with no deterioration of forward-loss or VSWR characteristics.

I.3. WAVEGUIDE CIRCULATORS

The waveguide junction circulators are of two types. These are of H-plane (24, 60, 80, 90, 150, 166, 178, 195, 222) and E-plane junctions (34, 63, 81, 98, 155, 229, 236, 237), with three identical waveguides intersecting at 120 degrees to form a symmetrical Y-shaped figure. At the junction region a ferrite post is located in the E-plane junction and a ferrite disc is fixed in the H-plane junction and the ferrites are transversely magnetized by the d.c. field as shown in fig. I.6. It is clear from the geometrical symmetry that if r.f. power is fed into one of the waveguides, it emerges at the adjacent waveguide in the direction of circulation and isolating the third waveguide. The circulation action can be accomplished by choosing the correct ferrite rod or disc-dimensions with proper saturation magnetization, and the biasing-field of proper magnitude, and such device is termed as the H-plane and E-plane waveguide circulator.

Another type of waveguide circulator, uses slabs (227) along each side of the three waveguides. This is done in such a way that almost all the microwave energy is trapped in one of the slabs in so called "Ferrite dielectric mode" and then guided continuously by the slab from another wave-
guide into an adjacent one. Lax and Button (151) have calculated the field distribution for symmetrical slabs of ferrite, transversely magnetized.

Four port waveguide circulator (55, 64, 155, 204) can be developed by cascading two three port Y-junction H-plane or E-plane circulators separated by about one half guide-wavelength and 5-port circulators can be obtained by cascading three identical 3-port circulators.

Cross-guide 4-port circulators (55, 64) are also built with four waveguides intersecting at 90 degrees, giving an insertion-loss of 0.25 dB, in X-band region as reported. These waveguide circulators are smaller in size and lighter in weight than the Faraday rotation or rectangular waveguide phase type circulators due to low external d.c. magnetic fields used. In the case of 4-port waveguide circulators, the insertion-loss between adjacent ports is also of 0.25 dB, and between diagonal ports, it is of 0.5 dB. The minimum isolation between ports 1 and 4 is 20 dB and between ports 1 and 3 it is 40 dB.

I.4. STRIP-LINE CIRCULATORS

Strip-line circulator (29, 83, 132, 142, 164, 212, 238) consists of a tri-plate metal junction sandwiched by two ferrite discs. The whole assembly in turn is placed in a non-magnetic aluminium circular resonant cavity, to which three ports are built. The top and the bottom flat plates of the cavity serve as ground planes to the strip transmission lines. The arms of tri-plate junction are connected to the centre
Fig. 1.7. STRIP-LINE CIRCULATOR

Fig. 1.8. MICROSTRIP CIRCULATOR

( Garnet substrate)
conductors of the coaxial N-type connectors fixed at the periphery of the circular cavity and the d.c. magnetic field is applied perpendicular to the plane of the ferrite discs. Under suitable selected geometry of the ferrite discs, strip-transmission lines and the enclosed cavity, when an external d.c. biasing field is applied, this device works as a microwave circulator for the sequential transmission of r.f power and it readily gives out narrow-bandwidth. Under matched conditions it leads to broad-band circulation (139, 188, 199, 206, 207) and the schematic diagram of typical device is shown in fig. I.7. The studies on the broad-band matching techniques relevant to strip-line circulator are carried out by present investigator and the details are presented in subsequent chapters.

I.5. MICRO-STRIP CIRCULATORS

A ferrimagnetic micro-strip junction circulators fabricated by Hershenov (112, 113, 114, 115) and other workers (167, 168, 184, 185, 198), exhibited their performance characteristics in X-band region extremely well. These were significantly smaller and lighter than the present day X-band waveguide circulators. These devices can ideally be incorporated into sophisticated microwave integrated circuits and also be directly connected to other components with their micro-strip transmission line connections. The device consists of a substrate of 0.023 inch thick, with a hole in the centre into which is epoxied a garnet disc, 0.23 inch in diameter and 0.023 inch thick. The microstrip-lines and the copper coating on the garnet are produced by copper eva-
poration, following chrome flash (112). The underside of the garnet and substrate which rest on a brass ground plane is completely coated with copper. Microstrip transmission lines are connected to OSM-connectors using transition. The D.C. biasing fields are applied transversely either by using electromagnets or oriented permanent magnets of 0.3 inch dia., 0.15 inch in height, embedded in the ground plane. Even without optimizing microstrip dimensions and contact transitions to the OSM-connectors, it was reported that these devices gave 9.7 percent bandwidth, and even more (234) for greater than 20 dB isolation and insertion-loss of less than 0.4 dB. A typical device is shown in fig. I.8.

1.6. LUMPED ELEMENT CIRCULATORS

The lumped element circulators are developed by Dunn and Roberts (71) in Melabs-USA and by Konishi (134, 135) in Japan and the other scientists (17, 32, 45, 67, 129, 130, 131, 159, 185, 228). These circulators, at frequencies 1000 MHz and below up to 35 MHz are inconveniently large because of the increase of the ferrite disc diameters with the increase of the wavelength and so, are very expensive. A different approach to design these circulators, utilizes the lumped element techniques which are natural and convenient for the above frequency range, and as a result the size of the circulator, and ferrite volume, do not increase with the wavelength.

The lumped, non-reciprocal element in the circulator consist of ferrite disc with three coils wound on it, so that the magnetic fields of the coils are oriented at 120 degrees with respect to each other. A d.c. magnetic field sufficient
1.9. LUMPED ELEMENT CIRCULATORS

a. Series tuned circulator

b. Shunt tuned circulator

c. Triple tuned Circulator
in strength to bias the ferrite, above resonance (i.e., ferromagnetic resonance frequency greater than the operating frequency of the circulator) is applied normal to the plane of the disc. This symmetrical but non-reciprocal element can be used to form a circulator by connecting capacitors either in series or shunt with the load and source impedance as shown in fig. I.9. Konishi reported that the size of the circulators in VHF and UHF bands is approximately 0.78 to 1.18 inch in diameter and the ferrites used is about 0.39 to 0.59 inch in diameter and 0.39 to 0.78 inch thick. The centre-frequency of the circulator can be adjusted by changing only the values of capacitances added at each terminal without changing the applied d.c field and also the internal mechanism around the ferrite. Typical circulators have 50 percent bandwidth for 20 dB isolation, 2.0 dB insertion-loss at 600 MHz centre-frequency. Another type of circulator is one with insertion loss of 0.25 dB, 6.5 percent bandwidth at 700 MHz. One more circulator was experimented at centre-frequency of 12 MHz with 2.0 dB, insertion-loss and one percent bandwidth.

In single tuned circulators, wide-bandwidth (165, 85) can be obtained only at the expense of increased insertion-loss by biasing close to resonance. Double tuned or multituned circulators gave broader bandwidths than the single tuned circulator.

One such triple-tuned circulator reported by the above author (165) operated 400 MHz to 700 MHz range, using polycrystalline garnet material with \( 4\pi M_s = 1000 \) gauss.
Fig. 7.10. THIN FILM BROAD BAND WIPED - ELEMENT CIRCULATOR
The impedance plot for the above frequency range was very close, giving minimum-isolation of 17 dB and maximum insertion-loss of 1.0 dB.

There are thin-film element circulators developed by a number of scientists (125, 126, 127, 128) leading to miniaturization towards very compact devices, at and below L-band region, using the thin-film techniques. These new type of circulators are very broadband (122, 149) low-loss, easily tunable and compact. These circulators are suited for batch processing and inexpensive mass production. Thin-film techniques permit inter-weaving by the appropriate design of the masks and completely symmetrical structures could be obtained. A typical device is shown in fig. 1.10. Such thin-film circulators have 20 dB, minimum isolation, bandwidth of 410 MHz at centre frequency of 1.19 GHz, and insertion-loss less than 0.3 dB. To this end, Knerr (127, 128) focuses on the possibilities for a new generation of very fast switching circulators by using the semiconductor devices to accomplish the variation of capacitance in thin-film circulators.

I.7. SWITCHING CIRCULATORS

As with all types of circulators, if the sense of magnetic field is reversed, the direction of circulation reverses leading to design of modulators and switches possible (18, 20, 41, 79, 84, 94, 131, 152, 174, 181, 200, 201, 202, 208) as indicated in fig. I.11. Both solid and the dashed arrows represent the direction of circulation in the
Fig. 11. SWITCHING CIRCULATORS
(After Alvin Clavin)

a. Circulator

b. Switchable Circulator

c. Reciprocal single pole double throw switch

d. Reactive, single pole single throw switch
two states of the applied magnetic field. In one position the direction of circulation is \( \rightarrow b \rightarrow c \) and in the switched position, represented by the dashed arrow, the direction of circulation is \( a \rightarrow c \rightarrow b \). It is clear that the circuit of fig. I.11, represents a single pole, double-throw switch; that is, an input at terminal 'a' can be switched to terminal 'b' or terminal 'c' by changing the direction of applied magnetic field. The above device is also non-reciprocal and fast switching-times are difficult to achieve due to the demagnetizing fields and eddy currents present, which need more switching time to oppose the applied field.

It seems that 100 micro-seconds is the practical limit using reasonable switching power. By different combinations of switching methods, the field switches like SPST, SPDT and balanced switch can be obtained.

A latched circulator in micro-strip version does not require an external d.c. magnetic field. Operation of the circulator is at the remnant magnetization of the ferromagnetic material. A loop of wire positioned in the material is pulsed so that the enclosed magnetic material is magnetically saturated. The saturation magnetization falls to the remnant magnetization value (of the hysteresis loop for the material), when the pulse is turned off if a closed magnetic flux path is provided, i.e., energy is not required for the formation of the magnetic poles at surfaces with magnetic field discontinuities. If the pulse of the opposite sign is applied, the remnant magnetization of the material is oppo-
sitely directed. The two remnant states of the material permit switching the direction of circulation in the circulator thereby providing a method by which the device can be used as a switch.

It is aimed in this chapter, to introduce briefly, all types of circulators studied by the various scientists in the field and it can be recognized from the study of the above circulators that narrow-band and medium-band circulators can easily be obtained by carefully choosing the correct geometry, the magnetic parameters of the non-reciprocal elements (Ferrites and Garnets), suitable transmission lines, and with the methods of external biasing fields. (186, 188).

All the circulators reported above have operating bandwidths, ranging from narrow-band (143, 164, 183, 238) to the medium-band (188, 239) even approaching towards the broad-band (203) especially in the strip-line version when the device working at higher microwave frequencies. To achieve the later bands, special matching techniques have to be introduced in the devices about which the scientists have their own reservations. A few have been studied and attempted successfully by the present investigator and these are dealt with in later chapters.