8 Ferrite devices

8.1 INTRODUCTION

In Chapter 1 we saw that certain media known as gyromagnetic media have the property that positive and negative circular polarized waves have different propagation constants. These propagation constants can be altered by changing the static magnetic field applied to the medium. In this chapter we examine the ways in which the gyromagnetic properties of ferrites are used to make non-reciprocal devices and devices whose properties can be varied electrically.

8.2 MICROWAVE PROPERTIES OF FERRITES

Electrons possess a magnetic dipole moment but, in most materials, the electrons are paired in such a way that their dipole moments are opposite and the net dipole moment is zero. The special properties of ferrites arise because they contain unpaired electrons which are, therefore, free to respond to external magnetic fields.

Quantum theory (Bleaney and Bleaney, 1976) shows that an electron has a magnetic moment $m = 9.27 \times 10^{-24}$ A m^2 and an angular momentum $P = 0.527 \times 10^{-34}$ J s; these vectors are parallel to each other but in opposite directions. The ratio of the magnetic moment to the angular momentum is called the gyromagnetic ratio. It can be written

$$\gamma = \frac{m}{P} = g\ 8.79 \times 10^{10}\,\mathrm{c\,kg^{-1}}. \tag{8.1}$$

The constant g is known as the Lande factor. It has a value of 2 for free electrons and between 1.9 and 2.1 for electrons in most ferrites.

When an electron is placed in a static magnetic field the torque exerted on it by the field interacts with the angular momentum as shown in Fig. 8.1. The torque is

$$\boldsymbol{T} = \boldsymbol{m} \wedge \boldsymbol{B}_0 = -\gamma \boldsymbol{P} \wedge \boldsymbol{B}_0 \tag{8.2}$$

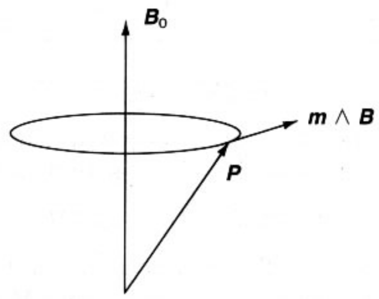

Fig. 8.1 Precession of the magnetic dipole moment of an electron around the direction of a static magnetic field.

and the equation of motion is

$$\frac{\mathrm{d}\boldsymbol{P}}{\mathrm{d}t} = -\gamma \boldsymbol{P} \wedge \boldsymbol{B}_0. \tag{8.3}$$

The rate of change of angular momentum is constant and directed at right angles to both $\boldsymbol{B}_0$ and $\boldsymbol{P}$. The tip of the vector $\boldsymbol{P}$ therefore traces a circle about the direction of the magnetic field with an angular velocity, known as the Larmor frequency,

$$\omega_0 = \gamma B_0 \tag{8.4}$$

which is independent of the angle between $\boldsymbol{P}$ and $\boldsymbol{B}_0$. The behaviour of the electrons is very like that seen when the axis of a spinning top moves in circles around the vertical. On a macroscopic scale the contributions of the individual dipoles can be summed to give a total dipole moment $\boldsymbol{M}$ per unit volume. The magnetic flux density within the material can then be written

$$\boldsymbol{B} = \mu_0(\boldsymbol{H}_0 + \boldsymbol{M}), \tag{8.5}$$

where $\boldsymbol{H}_0$ is the magnetizing field. Making use of (8.1) we can write, by analogy with (8.3)

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = -\gamma\mu_0 \boldsymbol{M} \wedge \boldsymbol{H}. \tag{8.6}$$

Now suppose that an small a.c. field is superimposed upon the static field so that

$$\boldsymbol{H} = \boldsymbol{H}_0 + \boldsymbol{H}_1 \mathrm{e}^{\mathrm{j}\omega t} \tag{8.7}$$

and

$$\boldsymbol{M} = \boldsymbol{M}_0 + \boldsymbol{M}_1 \mathrm{e}^{\mathrm{j}\omega t}. \tag{8.8}$$

Substituting these expressions into (8.6) we obtain

$$\frac{dM_0}{dt} + j\omega M_1 e^{j\omega t} = -\gamma\mu_0(M_0 \wedge H_0) - \gamma\mu_0(M_0 \wedge H_1)e^{j\omega t} - \gamma\mu_0(M_1 \wedge H_0)e^{j\omega t}, \tag{8.9}$$

where second-order terms have been neglected. Equating the terms with $e^{j\omega t}$ dependence on the two sides of the equation gives

$$j\omega M_1 = -\gamma\mu_0(M_0 \wedge H_1) - \gamma\mu_0(M_1 \wedge H_0). \tag{8.10}$$

If the static field is aligned with the z axis and the field strength is large enough to magnetize the material to saturation then M_0 must also be parallel to the z axis. Equation (8.10) can then be written in component form as

$$j\omega M_x + \omega_0 M_y = \omega_M H_y \tag{8.11}$$

$$-\omega_0 M_x + j\omega M_y = -\omega_M H_x \tag{8.12}$$

$$j\omega M_z = 0, \tag{8.13}$$

where $M_1 = (M_x, M_y, M_z)$, $H_1 = (H_x, H_y, H_z)$ and $\omega_M = \mu_0\gamma M_0$.

Rearranging equations (8.11) and (8.12) gives

$$M_x = \chi H_x + j\varkappa H_y \tag{8.14}$$

$$M_y = -j\varkappa H_x + \chi H_y, \tag{8.15}$$

where

$$\chi = \frac{\omega_0\omega_M}{\omega_0^2 - \omega^2} \tag{8.16}$$

and

$$\varkappa = \frac{\omega\omega_M}{\omega_0^2 - \omega^2}. \tag{8.17}$$

Substituting (8.14) and (8.15) into (8.5) yields the matrix equation

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \mu_0 \begin{pmatrix} 1+\chi & j\varkappa & 0 \\ -j\varkappa & 1+\chi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} H_x \\ H_y \\ H_z \end{pmatrix}. \tag{8.18}$$

This equation shows that in a magnetized ferrite material the directions of the small-signal $\boldsymbol{B}$ and $\boldsymbol{H}$ vectors are not the same as each other. The matrix (8.18) is called the tensor permeability of the material.

The preceding theory has assumed that there are no losses. In fact ferrites are lossy at microwave frequencies. It has been found that the effects of loss can be represented by replacing ω_0 in (8.16) and (8.17) by $(\omega_0 + j\omega\alpha)$, where α is a constant.

Studies of the propagation of plane TEM waves through a magnetized ferrite show that circularly polarized waves propagating in the direction of the static magnetic field have interesting properties. Consider, therefore, a circularly polarized wave whose magnetic field vector is given by

$$H_\pm = H_c(\hat{x} \mp j\hat{y}) \tag{8.19}$$

(see Section 1.7). We will assume that the magnetic field vector is parallel to the x, y plane. When (8.19) is substituted into (8.18) the result is

$$B_x = \mu_0(1 + \chi \pm \varkappa)H_c$$
$$B_y = \pm j\mu_0(1 + \chi \pm \varkappa)H_c \tag{8.20}$$

so that

$$B_\pm = \mu_\pm H_\pm, \tag{8.21}$$

where

$$\mu_\pm = \mu_0(1 + \chi \pm \varkappa). \tag{8.22}$$

The importance of this result is that for circularly polarized waves the permeability is a scalar not a tensor. Moreover its value is different for positive and negative polarizations. From (8.16), (8.17) and (8.22) we obtain

$$\mu_\pm = \mu_0\left(1 + \frac{\omega_M}{\omega_0 \mp \omega}\right). \tag{8.23}$$

This equation reveals a very important property namely that there is a resonance in the permeability for positive polarized waves but not for negative polarization. When the effects of losses are included (8.23) becomes

$$\mu_\pm = \mu_0\left[1 + \frac{(\omega_M/\omega_0)}{1 \mp \dfrac{\omega}{\omega_0}(1 \mp j\alpha)}\right]. \tag{8.24}$$

This can be written in terms of real and imaginary parts as

$$\mu_\pm = \mu'_\pm + j\mu''_\pm. \tag{8.25}$$

Figure 8.2 shows how these quantities vary with normalized frequency for typical values of ω_0 and ω_M. The propagation constants of circularly polarized waves are given by

$$k_\pm = \omega\sqrt{(\varepsilon\mu_\pm)}. \tag{8.26}$$

From this equation and Fig. 8.2 it can be seen that at most frequencies the propagation constants of the two waves are markedly different. Moreover the negatively polarized wave is virtually lossless at all frequencies whilst the positively polarized wave suffers strong attenuation at frequencies close to resonance. These properties are exploited in a variety of microwave devices described in the remainder of this chapter.

The theory of ferrites given in this section is only strictly applicable to a homogeneous material. In practice, ferrites are normally made as sintered blocks of polycrystalline material. The number of magnetic domains con-

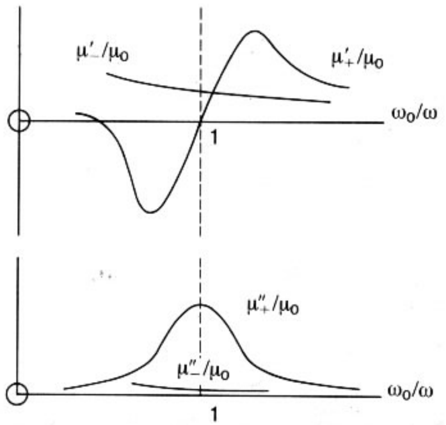

Fig. 8.2 Real and imaginary parts of the permeability of a magnetized ferrite for positive and negative circularly polarized waves.

tained in each crystal is determined by its size. The movement of domain walls within the crystals introduces losses and, for a material magnetized to saturation, this broadens the resonance somewhat but does not increase the propagation losses very much. When the material is not magnetized to saturation the effects of the different directions of magnetization of the domains must be taken into account by statistical methods. For further information on the properties of ferrites see Baden-Fuller (1987).

8.3 RESONANCE ISOLATORS

A very useful microwave device known as an isolator exploits the difference in the attenuation of positive and negative circularly polarized waves. The magnetic field components in a rectangular waveguide are given by

$$H_y = \frac{E_0}{Z_0}\frac{\lambda_0}{\lambda_g}\sin\left(\frac{\pi y}{a}\right)\cos(\omega t - k_g z) \quad (8.27)$$

$$H_z = \frac{E_0}{Z_0}\frac{\lambda_0}{\lambda_c}\cos\left(\frac{\pi y}{a}\right)\sin(\omega t - k_g z) \quad (8.28)$$

from (2.46) and (2.47). These fields are in phase quadrature so they constitute a circularly polarized field at a plane where their amplitudes are equal, that is

$$\frac{1}{\lambda_g}\sin\left(\frac{\pi y}{a}\right) = \pm\frac{1}{\lambda_c}\cos\left(\frac{\pi y}{a}\right) \quad (8.29)$$

or

$$\tan\left(\frac{\pi y}{a}\right) = \pm\frac{\lambda_g}{2a}. \quad (8.30)$$

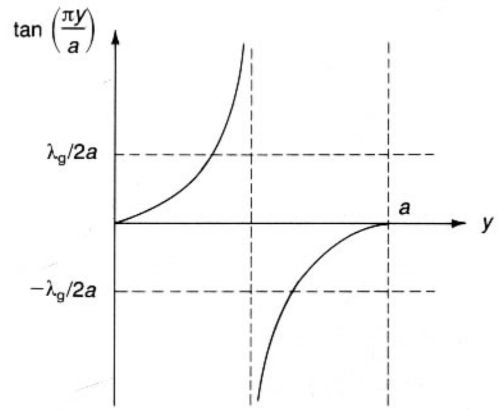

Fig. 8.3 Graphical solution of equation (8.30).

The solutions to this equation are indicated graphically in Fig. 8.3. There are two symmetrically placed planes parallel to the narrow wall of the waveguide for which (8.29) is satisfied. Now the direction of the circular polarization depends upon the direction of power flow in the waveguide. So, if a ferrite sheet is inserted in the waveguide at one of the planes indicated in Fig. 8.3 and subjected to a static magnetic field in the x direction, then waves travelling in one direction will be attenuated much more strongly than those travelling in the other direction. The magnitude of the static magnetic field must be chosen so that the ferrite is resonant at the signal frequency. Figure 8.4(a) shows the arrangement of a ferrite resonance isolator of this kind.

The isolator shown in Fig. 8.4(a) is unsatisfactory in a number of ways. The plane at which the ferrite must be placed depends on frequency as can be seen from Fig. 8.3 and the resonance band of the material is narrow. The device illustrated is, therefore, inherently narrow band. The presence of the ferrite perturbs the fields so that they are not exactly like those in an empty waveguide. Finally the thin sheet of ferrite is unable to dissipate much heat and the properties of the material are dependent on temperature. A better arrangement is that shown in Fig. 8.4(b) where the ferrite is in the form of strips in good thermal contact with the wall. The magnetic field is arranged so that it varies over the ferrite by the use of air gaps. In this way different parts of the ferrite are resonant at different frequencies and the device can be made broad band. Dielectric material is also sometimes used to ensure that the fields are truly circularly polarized. Isolators which work on this principle can be obtained which cover the entire frequency band of the waveguide with forward and reverse insertion losses of 1 dB and 30 dB respectively.

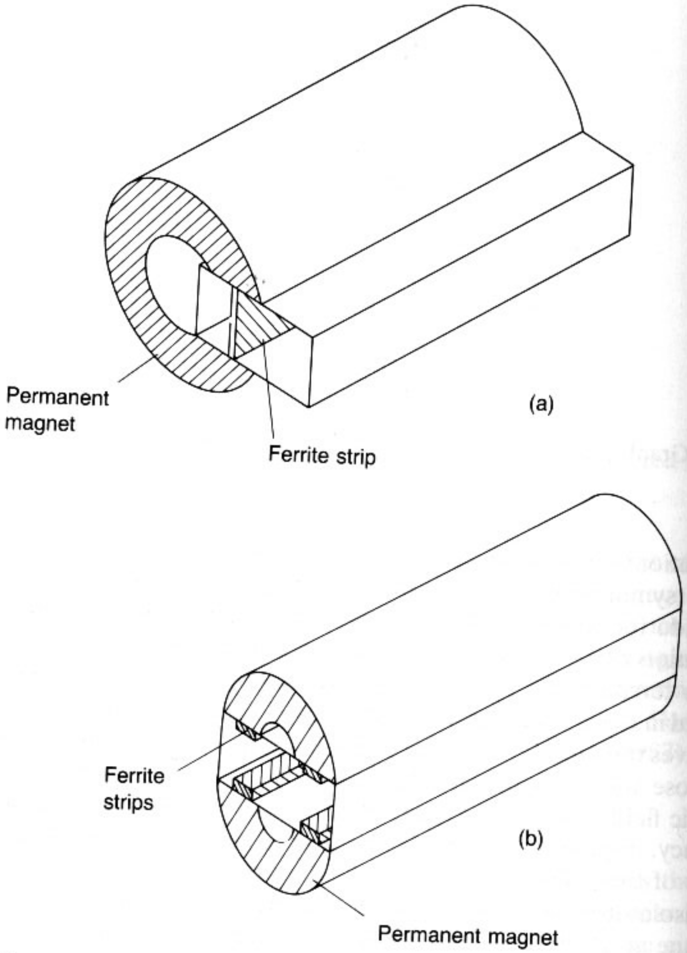

Fig. 8.4 Two types of ferrite resonance isolator.

8.4 PHASE SHIFTERS AND CIRCULATORS

Away from resonance the dependence of the permeability of a ferrite material with magnetic field can be used to make a variable phase shifter. In waveguide the arrangement is similar to that shown in Fig. 8.4(b) with the permanent magnet replaced by an electro-magnet. The phase shift is different for waves travelling in opposite directions because of the difference between the effective permeability for positively and negatively polarized waves. When such a device is designed to produce a difference of 180° between the phase shifts for forward and backward waves it is known as a gyrator.

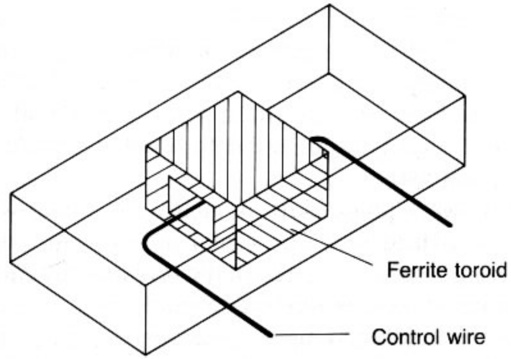

Fig. 8.5 Arrangement of a ferrite latching phase shifter.

If a fixed, switchable, phase change is required a latching phase shifter may be used. This device is shown in Fig. 8.5. A ferrite toroid is placed within a rectangular waveguide with its vertical sections arranged in the region of circularly polarized field. A control wire passes through the toroid enabling it to be magnetized in either direction by a pulse of current. The phase shift produced is adjusted by changing the length of the ferrite toroid.

A circulator is a device with three or more ports which has the property that a signal injected at one port emerges from the next one. This is shown diagrammatically in Fig. 8.6(a). One important application of this device is

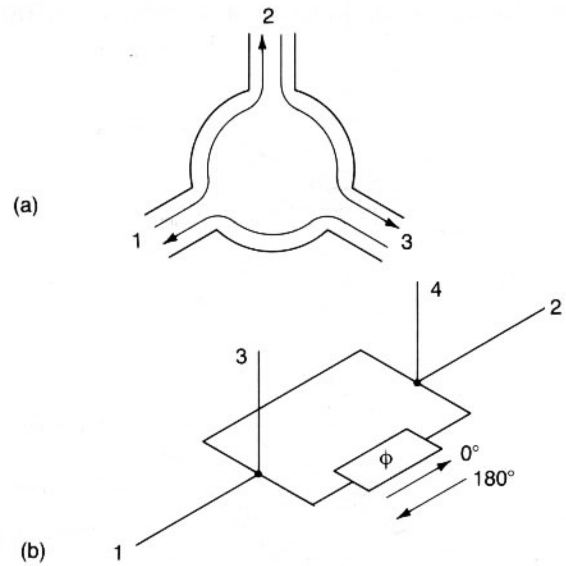

Fig. 8.6 (a) Schematic diagram of a circulator, (b) arrangement of a phase-shift circulator.

in separating the transmitted and received signals in a microwave communication system. In that case port 1 would be connected to the transmitter, port 2 to the antenna and port 3 to the receiver. Ideally the circulator would ensure that none of the transmitter power would find its way back to the receiver. A number of types of circulator exist which use the properties of ferrites in different ways.

Figure 8.6(b) shows a phase-shift circulator. A signal which enters at port 1 is split by a hybrid tee. The signal in one arm passes through a gyrator which has a phase shift of zero in the forward direction. The signals in the two arms meet at a second hybrid tee and, because they are in phase with each other, the combined signal emerges at port 2. If the signal is injected at port 2 the gyrator causes the signals in the two arms to be in antiphase so that the recombined signal emerges at port 3. Signals injected at ports 3 and 4 produce signals in antiphase in the two arms which recombine to give outputs at ports 4 and 1 respectively. The device therefore behaves as a four port circulator.

8.5 JUNCTION CIRCULATORS

A particularly compact form of circulator can be made by putting a piece of magnetized ferrite in the centre of a waveguide or microstrip junction. Figure 8.7 shows the arrangements of these two types. The junctions are symmetrical so, in the absence of the ferrite the input signal would excite equally the other two ports.

Consider first the waveguide junction shown in Fig. 8.7(a). An input

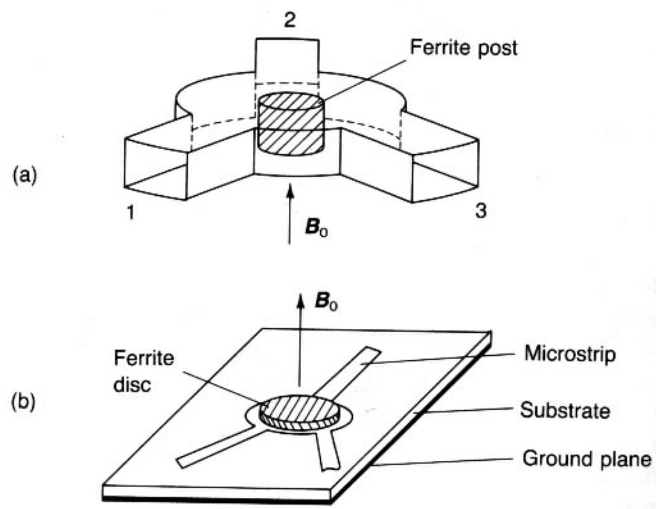

Fig. 8.7 Ferrite junction circulators: (a) waveguide, and (b) microstrip.

signal at port 1 can be thought of as coupling into the annular space around the ferrite rod. The symmetry of the system requires that a pair of waves of equal amplitude should be excited travelling round the circumference of the cavity in opposite directions. If the ferrite rod were replaced by a metal one then the phases of the signals excited at ports 2 and 3 would be the same. The presence of the ferrite alters the balance between the electrical lengths of the clockwise and counterclockwise paths. The dimensions of the cavity and of the ferrite and the strength of the magnetic field can be chosen so that the two waves are in antiphase at port 3. All the input power is then coupled out at port 2. Because of the symmetry of the device the same relationships hold for signals injected at ports 2 and 3 with cyclical permutation of the ports.

The microstrip junction circulator shown in Fig. 8.7(b) works in the same way as the waveguide one. An alternative view of the process is to consider the junction as a resonator. The size of the junction is chosen so that the TM_{011} resonance coincides with the centre frequency of operation. All possible orientations of this mode can be represented as sums of the two modes with null planes at right angles shown in Figs. 8.8(a) and (b). An input signal at port 1 only excites the first of these two modes. Now any

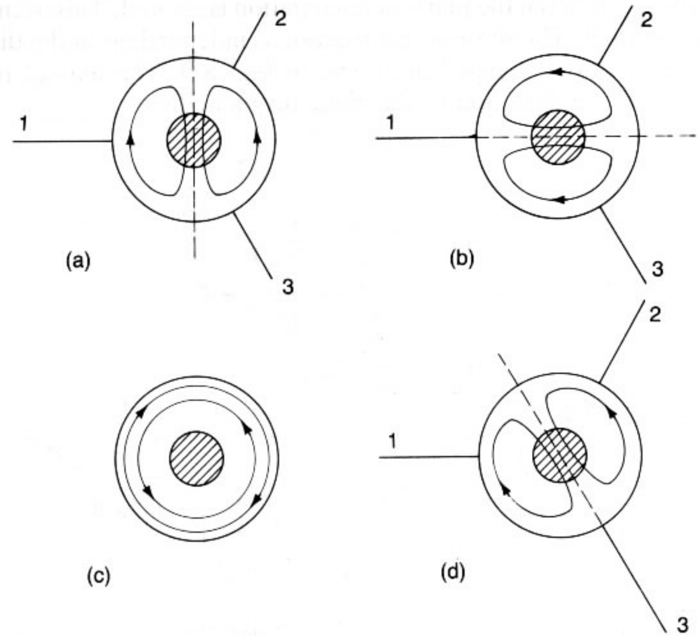

Fig. 8.8 Operation of a ferrite junction circulator: the normal modes (a) and (b) of the TM_{011} resonance of the junction can be thought of as the superposition of circulating waves (c). The propagation of these waves is affected differently by the ferrite for the two directions so that the null plane is rotated as shown in (d).

resonance can be thought of as the superposition of pairs of equal and opposite waves. In this case the waves are circumferential waves as shown in Fig. 8.8(c). The presence of the ferrite alters the propagation constants of these two waves so that their resonant frequencies differ from one another. If the operating frequency is chosen to lie between these two resonant frequencies the effect is that the two waves are excited with different phases. When they are superimposed the result is that the null plane is found to be rotated from its original position (Fig. 8.8(a)) somewhat as shown in Fig. 8.8(d). The dimensions of the ferrite and the strength of the field are chosen so that the null plane is aligned with port 3.

If one of the ports of a three-port junction circulator is terminated by a matched load the result is an isolator. Devices described as isolators are sometimes junction circulators with one port matched internally. High-power isolators, needed to protect the power amplifiers of transmitters from reflected signals, are made by terminating one of the ports of a circulator by a high-power matched load.

8.6 FARADAY ROTATION DEVICES

In Chapter 1 we saw that when a plane-polarized wave passes through a gyromagnetic material the plane of polarization is rotated. This is known as Faraday rotation. The sense of the rotation is independent of the direction of propagation of the signal as shown in Fig. 8.9. The axis of rotation coincides with the direction of the static magnetic field.

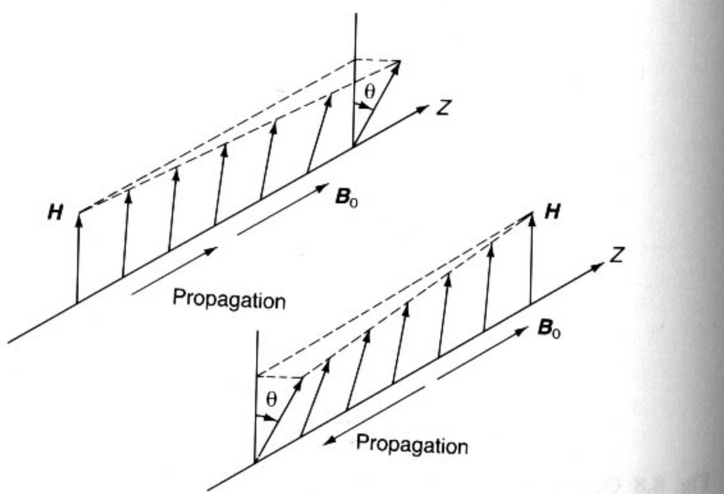

Fig. 8.9 Faraday rotation of the plane of polarization of a wave in a gyromagnetic material. The sense of rotation is the same for both directions of propagation.

Because Faraday rotation is a non-reciprocal phenomenon it can be used to make gyrators and isolators. Figure 8.10 shows the arrangement of a Faraday rotation gyrator. The dimensions of the device and the strength of the static field are chosen so that the plane of polarization of the wave is rotated through 90°. The figure shows how the plane of polarization is rotated for both forward and backward waves. It is evident that the difference between the phase shifts for the two waves is 180°. If it is inconvenient to have the input and output waveguides rotated with respect to each other a waveguide twist can be added to bring them back into line. Although the theory given in this book only covers the propagation of plane waves in infinite gyromagnetic madia it can be shown that Faraday rotation devices can work satisfactorily when the ferrite is in the form of a rod on the axis of the waveguide. A Faraday rotation gyrator can be used in place of a resonance gyrator to make a phase shift isolator.

An alternative type of isolator which makes use of Faraday rotation is shown in Fig. 8.11. The input and output wave guides are rotated by 45° with respect to one another and the central section introduces 45° of

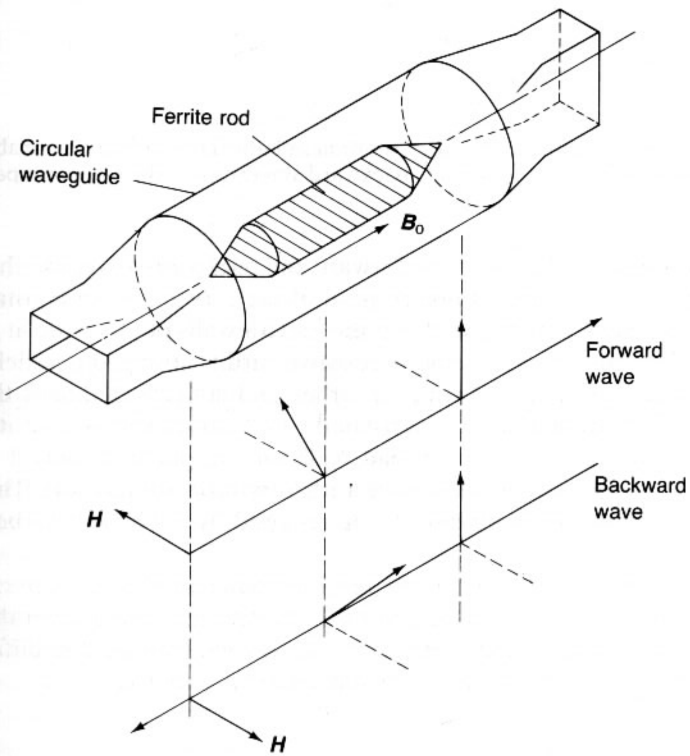

Fig. 8.10 (a) Arrangement of a Faraday rotation gyrator. The plane of polarization of a wave is rotated as it passes through the device is shown in (b).

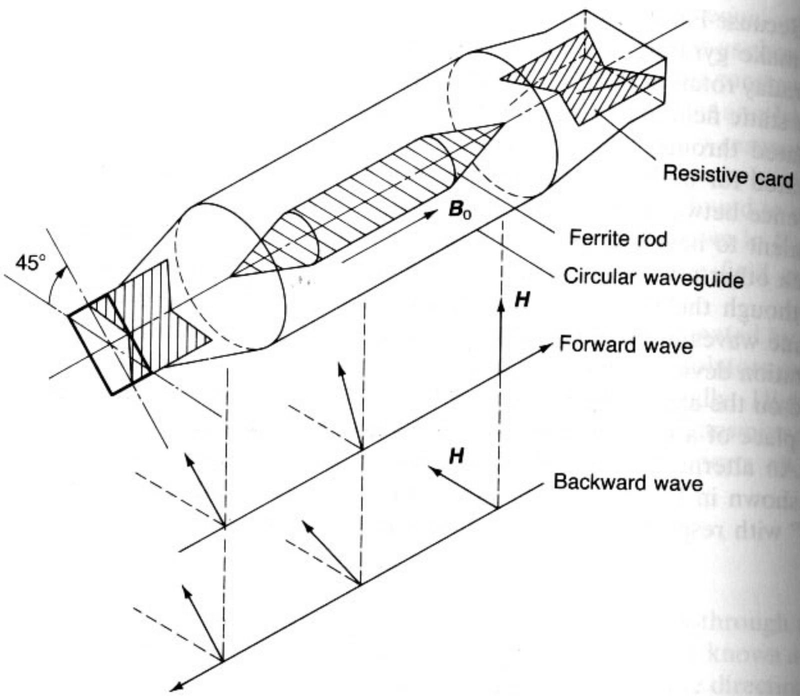

Fig. 8.11 Arrangement of a Faraday rotation isolator. Forward waves are absorbed by the resistive card at the output; backward waves travel through unimpeded.

Faraday rotation. The effects on forward and backward waves are shown in the diagram. The plane of polarization of the forward wave is rotated so that the magnetic field is parallel to the narrow walls of the guide at port 2. This mode is cut off and a vane of resistive card is arranged parallel to the electric field so that the power is absorbed and not reflected back through the device. A backward wave is rotated counterclockwise so that its magnetic field is parallel to the broad walls of the guide at port 1 and it therefore passes through the device with very little attenuation. The relative orientations of the guides can be restored by a 45° twist as before if necessary.

Faraday rotation devices are inherently narrow band because the rotation depends upon the electrical length of the ferrite. For this reason they are normally only used at millimetre wave frequencies where it is difficult to construct devices which rely on gyromagnetic resonance.

8.7 EDGE-MODE DEVICES

An interesting phenomenon occurs when a microstrip circuit is built on a ferrite substrate. It is found that the fields are concentrated under one edge

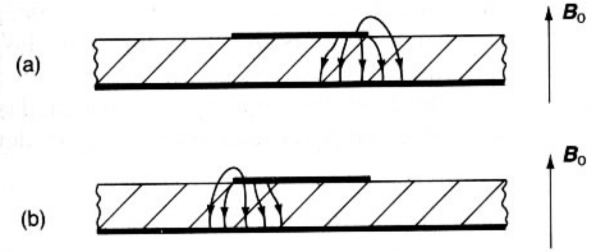

Fig. 8.12 Edge modes in a microstrip line on a ferrite substrate: (a) waves travelling into the paper, and (b) waves travelling out of the paper.

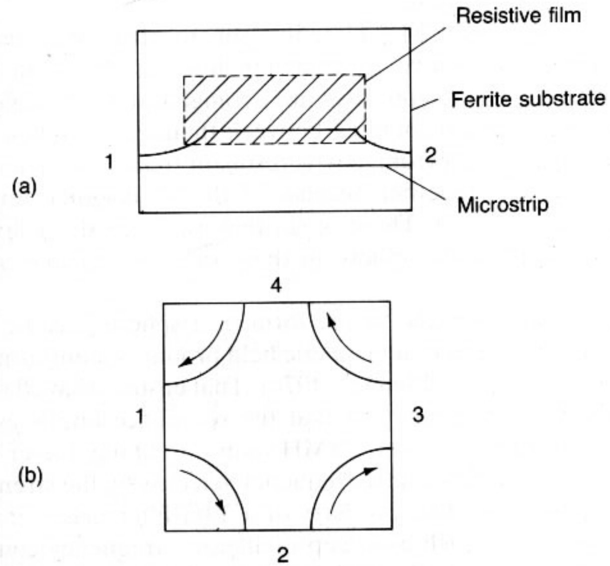

Fig. 8.13 Edge-mode devices: (a) edge-mode isolator, and (b) edge-mode circulator.

of the stripline depending upon the direction of propagation of the waves, as shown in Fig. 8.12. This effect can be used to make both isolators and circulators.

If the width of the microstrip is increased the edge modes tend to follow the edges. It is therefore possible to separate them. Figure 8.13(a) shows an edge-mode isolator. Waves travelling from port 1 to port 2 pass unattenuated whilst waves in the opposite direction pass into the region covered by the resistive film and are absorbed. This device can work over a very wide band (more than two octaves) because it does not depend upon resonance or phase shift for its operation. The insertion loss for backward waves can exceed 30 dB.

Figure 8.13(b) shows an edge-mode circulator. A signal injected at port

1 appears at port 2 and so on. Like the edge-mode isolator this device can work over a very broad band. There is also no reason why the number of ports should not be increased.

Edge mode devices suffer from the disadvantage that the loss is rather high in the forward direction compared with other kinds of device.

8.8 YIG FILTERS

In Chapter 7 we saw that resonators form the basis of microwave filters. The gyromagnetic resonance of ferrite materials can be used in the same way. Yttrium iron garnet (YIG) has a very narrow resonance so it is the usual choice for this purpose.

The basic element in a YIG filter is a sphere of the material which is coupled magnetically to two transmission lines as shown in Fig. 8.14. Because the two transmission lines are arranged at right angles to each other there is virtually no coupling between them except when the signal frequency is equal to the gyromagnetic resonant frequency. The resonance couples the two lines together because of the off-diagonal terms in the permeability tensor (8.18). These mean that a field in the x direction induces magnetisation of the sphere in the y direction as well as in the x direction.

The YIG element is made in the form of a sphere because it can be shown that a uniform external magnetic field produces a uniform magnetic field within it (Bleaney and Bleaney, 1976). That ensures that all the dipoles precess at the same frequency so that the resonance line is as sharp as possible. Bandwidths of around 20 MHz can be obtained over the range 500 MHz to 40 GHz with a centre frequency selected by the strength of the external magnetic field. This property of a YIG filter makes it especially useful for applications such as sweep oscillators, frequency counters and spectrum analysers because it can be tuned rapidly by electrical means.

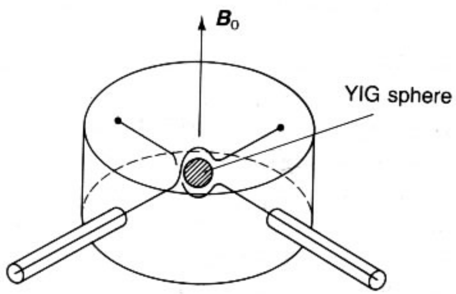

Fig. 8.14 Arrangement of a YIG filter.

8.9 CONCLUSION

In this chapter we have examined the microwave properties of ferrites and the ways in which they are exploited in a variety of devices.

Ferrites contain unpaired electrons whose magnetic dipole moments cause them to precess around the direction of an external magnetic field. The result of this precession is that the permeability of a magnetized ferrite is not a scalar as far as a.c. fields are concerned. There is coupling between the two field directions normal to the static magnetizing field which results in the Faraday rotation of plane-polarized waves. For circularly polarized waves the permeability is a scalar so these waves propagate through the ferrite in a stable manner. However it is found that the permeability is not the same for the two directions of circular polarization. In particular, for one of them, there is a resonance which produces strong losses.

The non-reciprocal properties of ferrites are put to use in isolators, circulators and filters. Isolators which allow a signal to pass unattenuated in only one direction make use of either the absorption peak or the non-reciprocal phase shift properties of a ferrite in a waveguide. Circulators in which a set of input and output ports are connected together in a cyclical manner can be made using non-reciprocal phase shifters. An alternative design which is particularly compact makes use of a ferrite loaded junction between waveguides or transmission lines.

Microstrip manufactured on a ferrite substrate shows the interesting property that the electric field of a wave is concentrated under one or the other edge of the stripline depending upon the direction of propagation. The effect is used to make a class of isolators and circulators employing edge modes.

Finally, the sharp resonance of yttrium iron garnet ferrite (YIG) is used to make electrically tunable filters with very narrow pass bands. These filters find application in a wide range of microwave instruments.

Further information on ferrites can be found in Baden-Fuller (1987).

EXERCISES

8.1 A ferrite material has a saturation magnetization of 0.36 T and a maximum relative permeability of 2000. Investigate the variation with frequency in the range 1 to 20 GHz of the real and imaginary parts of the permeability if the magnetizing field is 0.3 T. Assume that the damping constant $\alpha = 0.05$ and that $g = 2.0$.

8.2 Calculate the propagation and damping constants of the material in Question 8.1 over the same frequency range for positive and negative circularly polarized waves.

8.3 Investigate the solutions to equation (8.30) for frequencies in the range 8.0 to 12.0 GHz in WG16 waveguide.