June 5, 1962 G. S. UEBELE ETAL 3,038,131

MICROWAVE SWITCHING DEVICE

Filed Nov. 25, 1958 4 Sheets-Sheet 1

Fig. 1.

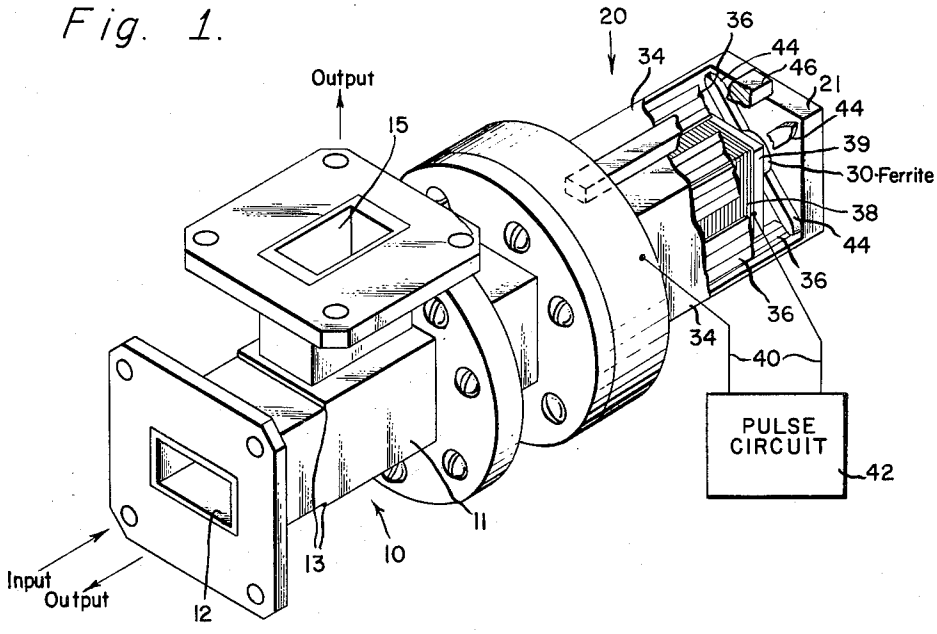


Fig. 2.

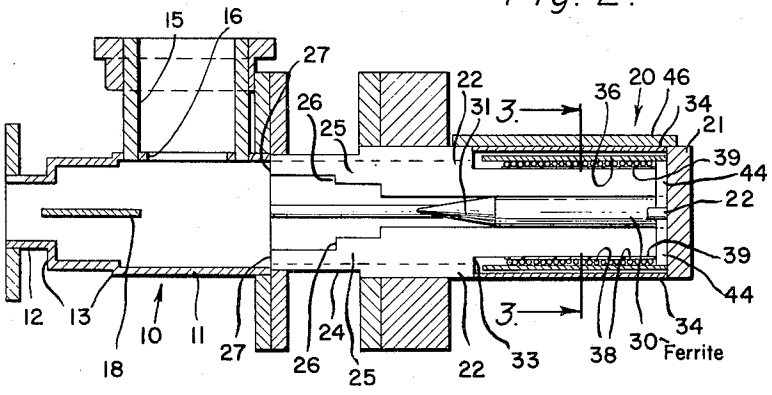
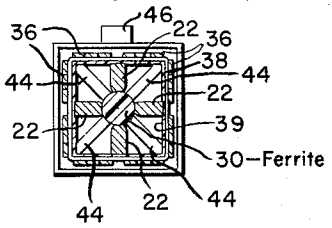


Fig. 3.



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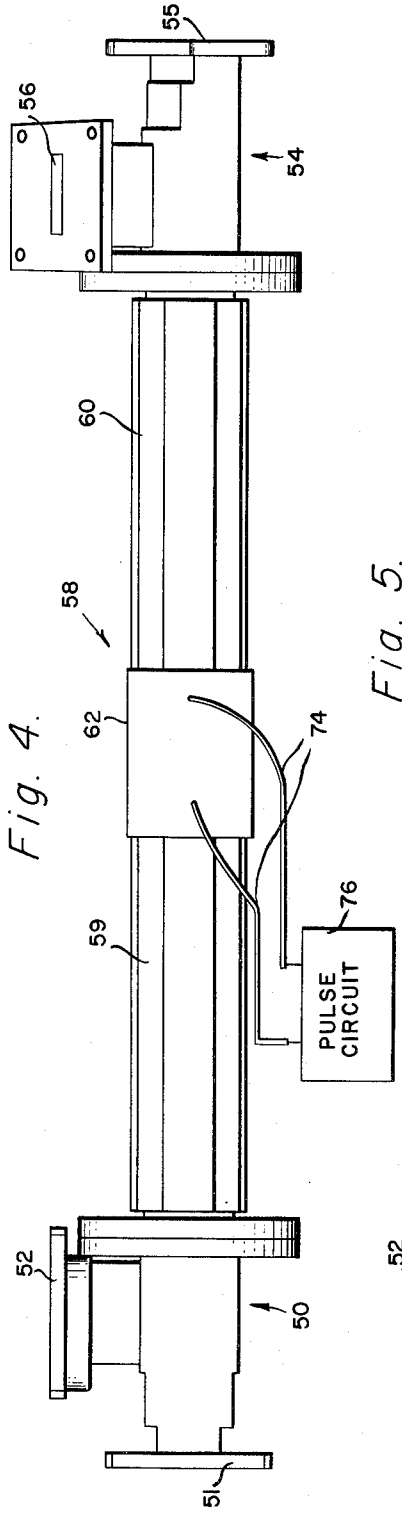


Fig. 4.

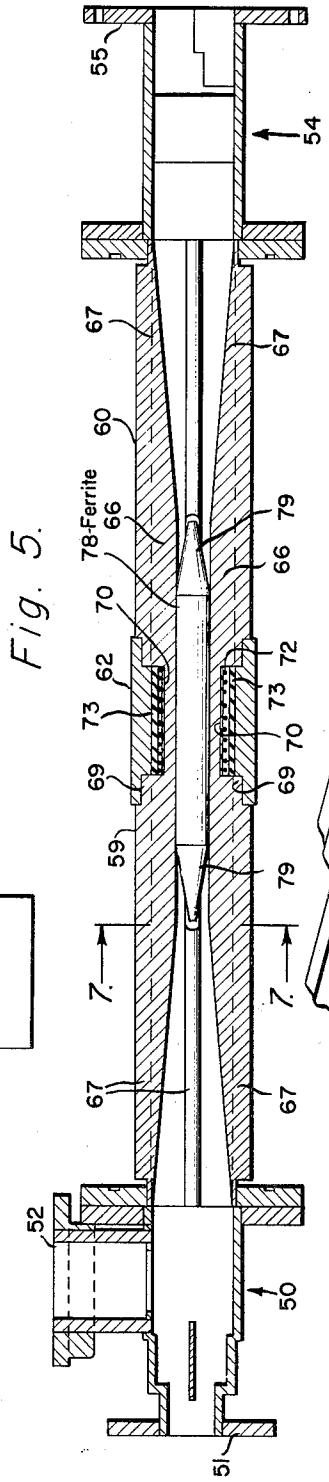


Fig. 5.

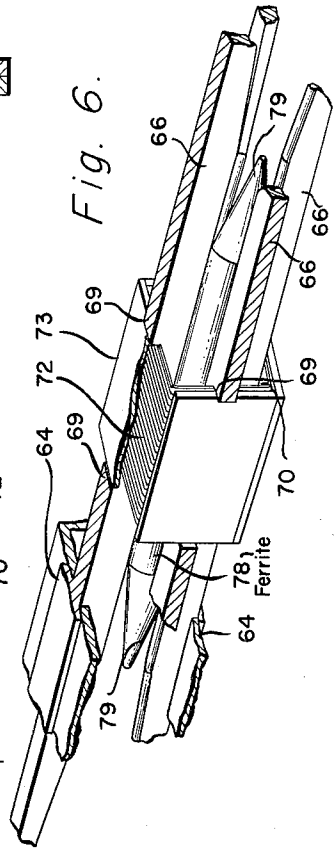


Fig. 6.

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Fig. 7.

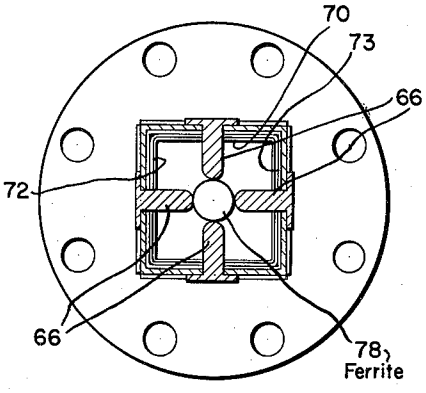


Fig. 8.

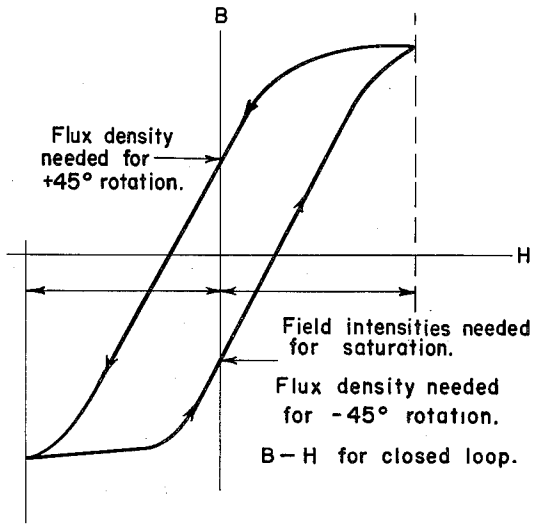


Fig. 10.

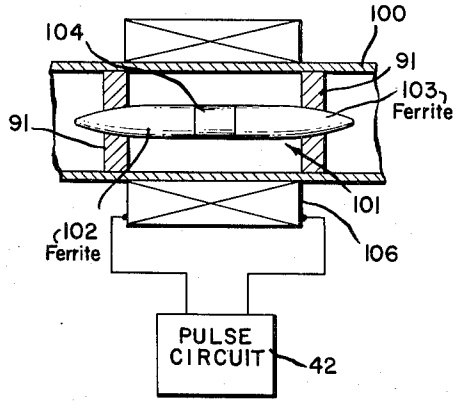
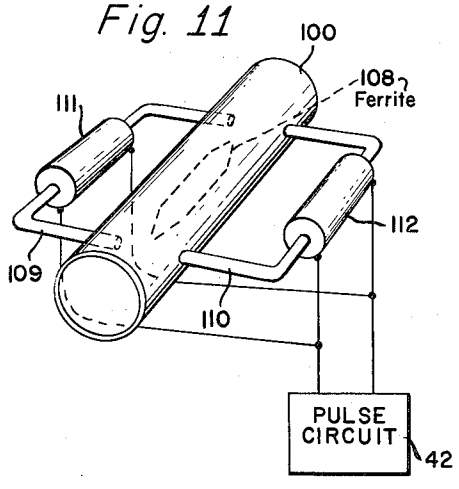


Fig. 11



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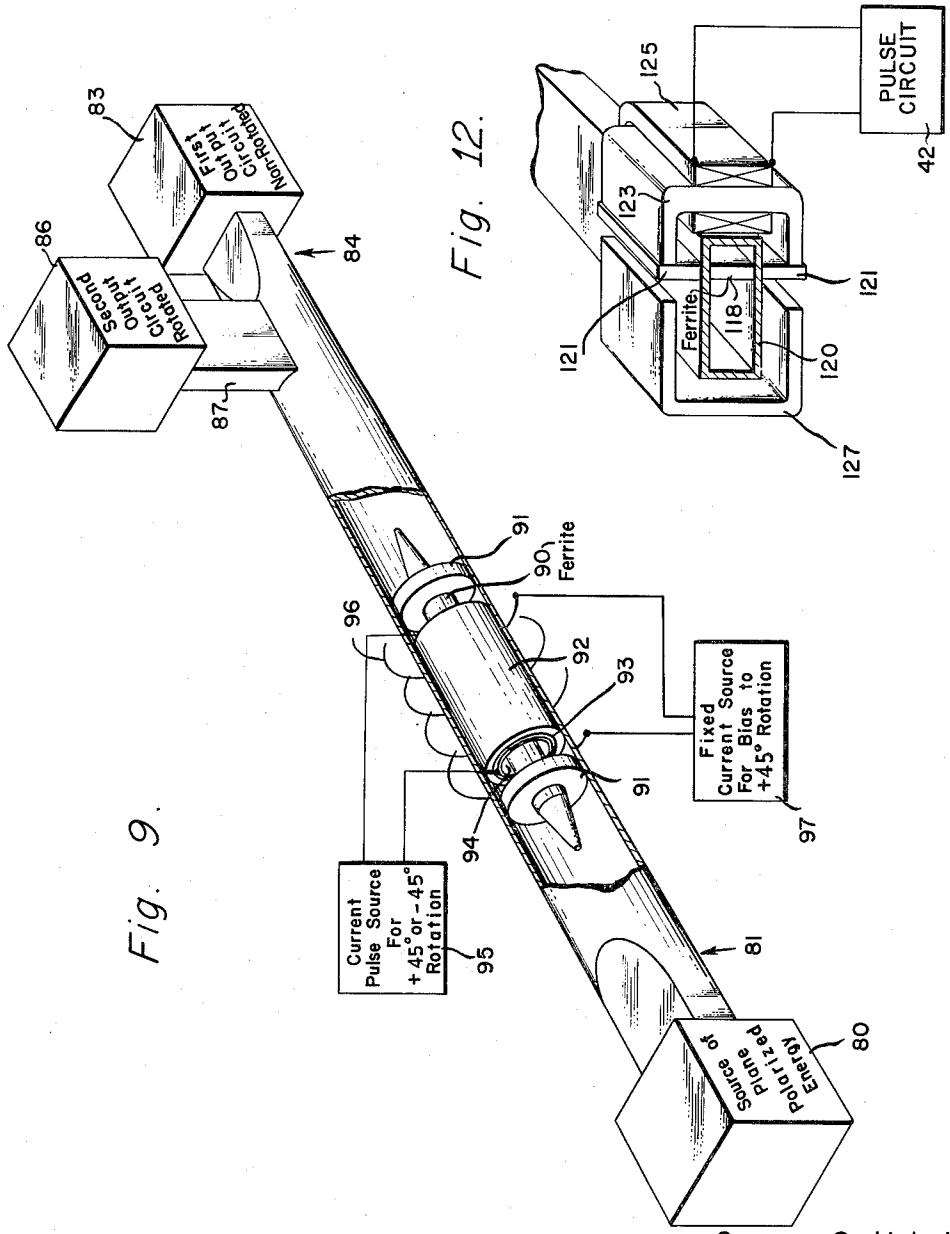


Fig. 9.

Fig. 12.

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MICROWAVE SWITCHING DEVICE

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Filed Nov. 25, 1958, Ser. No. 776,386
4 Claims. (Cl. 333—7)

This invention relates to microwave transmission and control devices, and particularly to switching devices which utilize magnetized ferromagnetic elements.

Electronic devices which operate in the microwave region of the frequency spectrum and which utilize the gyromagnetic properties of certain ferromagnetic elements are being increasingly employed. As is now well known, magnetized ferromagnetic elements within a microwave transmission or propagation device can be employed to provide a number of effects which have wide utility in microwave systems. Thus, when a ferromagnetic element is positioned along the central axis of the hollow waveguide and subjected to an axial magnetic field, there may be provided a rotation of plane polarized energy within the waveguide which can be compared to the Faraday rotation earlier observed in the optical region of the spectrum. This class of devices is in fact usually referred to as employing Faraday rotation. When polarization sensitive elements are used with these Faraday rotators, the result may be a switching arrangement or an energy circulating arrangement or one of the various other forms of energy controlling devices utilized in microwave systems.

The arrangements heretofore provided for the establishment of the desired magnetic field within an active ferromagnetic element have suffered from certain disadvantages which have usually imposed operating or economic limitations on the systems in which the devices are used. With the Faraday rotation type devices, for example, it may be desired to switch energy at extremely high rates of speed but with closely controlled accuracy. When the magnetic field applied to the ferromagnetic element varies, however, there is subsequent variation in the angular rotation within the waveguide, so that the polarization sensitive outputs derive varying amounts of energy. In many instances even a slight deviation in the amount of energy derived will have an appreciable effect upon the reliability of the information which the system is processing. In many instances extreme measures have had to be taken to overcome these inaccuracies. Thus, complicated circuits have been evolved to hold the magnetizing currents constant. The use of these control arrangements does not always insure sufficient accuracy, and even when it does may be objectionable from the standpoints of size and economy.

An object of this invention is to provide a switching arrangement for microwave systems which operates with a minimum of current and which avoids the need for regulating circuits.

An arrangement constructed in accordance with this invention may utilize, as a principal feature, a ferromagnetic element disposed in a hollow waveguide. If centrally disposed, the ferromagnetic element may be arranged to provide Faraday rotation of energy transmitted along the waveguide. A magnetic return path structure may be disposed within the waveguide, at least partially encompassing the ferromagnetic element and providing a low reluctance medium for a substantial part of the axial magnetic field through the ferromagnetic element. At least one of the two magnetizable elements, the ferromagnetic element and the return path structure, may be constructed of a material having substantial magnetic retentivity. Specifically, the selected member may have a residual magnetic field, after being driven to saturation,

which is sufficient to provide a static magnetic field through the ferromagnetic element of enough magnitude to provide a desired degree of Faraday rotation of energy transmitted along the waveguide. In conjunction with this arrangement may be employed a driving coil affixed to the return path structure. The application of a driving pulse of selected magnitude and direction through the driving coil thus provides a sufficient magnetic field of proper direction through the active ferromagnetic element to provide a desired Faraday rotation without further circuitry being needed. A further feature resides in the use of a static magnetic bias to establish zero net magnetization of the active element when no Faraday rotation is to be used. The static bias permits the use of driving currents which establish saturation, rather than more precisely controlled currents to establish demagnetization.

In accordance with other features of this invention, the arrangement above described may be utilized to provide various forms of switching and circulating arrangements having particular advantages. The energy may be rotated from a given direction 45 degrees in either direction to be provided as output to either one of two polarization sensitive terminals. A fixed biasing field, equivalent to 45 degrees of rotation, may be superimposed on a ferromagnetic element and the residual magnetic field used to augment or cancel this rotation, so that rotation of from zero to 90 degrees is provided. In another arrangement, the retained field may be utilized together with a ferromagnetic element positioned within a short circuited, reflecting waveguide section, and the magnetic field established may be substantially completely defined by the active ferromagnetic element and the enclosing return path structure. In accordance with other features of this invention, the ferromagnetic element itself may be a composite structure consisting both of active ferromagnetic materials and other materials which may have appreciable magnetic retentivity and be arranged in a combination to provide sufficient rotation through the use of pulsing currents and residual magnetism. Various forms of transverse field devices for rectangular waveguide may be provided. Arrangements thus constructed in accordance with this invention may be utilized as switches and energy transfer devices including duplexing and circulating arrangements.

The novel features of this invention, as well as the invention itself, may be better understood from the following description, taken in conjunction with the accompanying drawings, in which like reference numerals refer to like parts, and in which:

FIG. 1 is a perspective view, partially broken away, of a microwave energy switch in accordance with the invention;

FIG. 2 is a side sectional view of the arrangement of FIG. 1;

FIG. 3 is an end sectional view of the arrangement of FIG. 1, taken along the lines 3—3 in FIG. 2 looking in the direction of the arrows therein;

FIG. 4 is a side elevation view of a second arrangement in accordance with the invention utilizing an internal coil and a ferromagnetic cylinder within a waveguide and encompassing a central ferrite member;

FIG. 5 is a side sectional view of the arrangement of FIG. 4, showing internal details of the arrangement;

FIG. 6 is a fragmentary view of the central portion of the arrangement of FIG. 5, showing the ferromagnetic cylinder and the central ferrite pencil;

FIG. 7 is an end view of the arrangement of FIGS. 4–6, taken along the line 7—7 in FIG. 5, and looking in the direction of the arrows;

FIG. 8 is a graph of the magnetization characteristics

of ferrite materials which may be employed in accordance with the invention;

FIG. 9 is a simplified perspective view, partially broken away, of another arrangement in accordance with the invention, utilizing the retentive properties of a return path element for magnetizing an active ferromagnetic element;

FIG. 10 is a simplified elevation view of another arrangement in accordance with the invention utilizing the retentive properties of a magnetic material to achieve Faraday rotation;

FIG. 11 is a side sectional simplified view of another arrangement for achieving Faraday rotation in accordance with the invention, and

FIG. 12 is a perspective view, simplified and partially broken away for purposes of illustration, exemplifying an arrangement in accordance with the invention for providing transverse field operation with a ferromagnetic element in a microwave waveguide.

An arrangement in accordance with the invention, referring now to FIGS. 1, 2 and 3, may utilize a ferrite element within a microwave waveguide, in conjunction with magnetic field elements within the waveguide, to establish a desired energy rotation of microwave energy upon the application of a pulsing current. The arrangement may include an orthogonal mode transducer **10** using a square waveguide body **11** having a central longitudinal axis. To the square waveguide body **11** may be coupled a first rectangular input waveguide **12** which is colinear with the square waveguide body **11** and which has its broad walls parallel to a selected pair of the walls of the square waveguide body **11** and the first rectangular waveguide **12** to provide, for energy supported in the dominant mode of the first rectangular waveguide **12**, a smooth transition to the equivalent mode in the square waveguide body **11**. A second rectangular waveguide **15** may be coupled to one of the walls of the square waveguide section **11** which is coplanar with the broad walls of the first rectangular waveguide **12**. The central axis of the second rectangular waveguide **15** is normal to the axis of the square waveguide body **11**, and the broad walls of the second rectangular waveguide **15** lie in planes parallel to the narrow walls of the first rectangular waveguide **12**.

The square waveguide body **11** supports orthogonally disposed energy modes (modes which are normal and independent with respect to each other). The orthogonal mode transducer **10** operates to divert each of these individual modes to a selected one of the first and second rectangular waveguides **12** and **15** respectively. To this end, the broad wall of the transducer **10** to which the second rectangular waveguide **15** is coupled includes a coupling slot **16**, and the transition section defined by the step sections **13** includes a centrally disposed conductive septum **18**. The septum **18** lies in a plane which is substantially normal to the vectorial components of the dominant mode supported within the first rectangular waveguide **12**. Energy in a first direction of linear polarization, normal to the broad walls of the first rectangular waveguide **12**, is transferred through the square waveguide body **11** without passing out the coupling slot **16** to the second rectangular waveguide **15**. Energy transmitted in the opposite direction, and with a like polarization, similarly does not excite the coupling slot **16** and is not affected by the conductive septum **18**, so that it is returned out the first rectangular waveguide **12**. Energy supported in the second rectangular waveguide **15** excites the coupling slot **16** but sees an effective short circuit at the conductive septum **18** and is accordingly transferred through the square waveguide body **11**. This energy is, however, orthogonal with respect to that previously discussed. Energy having the second direction of polarization transferred into the square waveguide body **11** is directed out the second rectangular waveguide **15** alone.

Consequently, the operation of the orthogonal mode transducer **10** is to couple energy of different polarizations from the separate waveguide arms **12** and **15** to the common body **11**. Energy provided to the square waveguide body **11** is effectively switched either to the first rectangular waveguide **12** or to the second rectangular waveguide **15**, dependent upon the direction of polarization of the energy. In the present example, it is assumed that energy provided to the first rectangular waveguide **12** is to be the input to the associated microwave device. Outputs may be taken either from the first rectangular waveguide **12** or the second rectangular waveguide **15**, depending upon which associated microwave device (not shown) of the related microwave system is to be employed. Conventional flanges may be employed at the various extremities of the orthogonal mode transducer **10** for coupling to the associated waveguide or other microwave elements.

With the orthogonal mode transducer **10** may also be employed a reflective microwave device which includes means for selectively rotating the direction of polarization of the microwave energy. This arrangement may include a square waveguide section **20** which terminates at its end opposite to the orthogonal mode transducer **10** in a conductive reflecting plate **21**. The square waveguide **20** is capable of supporting microwave energy in various positions of rotation and is colinear with and has internal dimensions like the square waveguide body **11** of the orthogonal mode transducer **10**. Additionally, this square waveguide **20** may be a rigid waveguide, having four ridges **22** (best seen in FIGS. 2 and 3) extending from the walls of the waveguide **20** toward the central axis of the waveguide. The square waveguide section **20** may be coupled to the body portion **11** of the orthogonal mode transducer **10** by a square waveguide coupling section **24** having matching internal dimensions and impedance matching transition ridges **25** (best seen in FIG. 2). The impedance matching transition ridges **25** consist of successive steps **26** and **27** between the full ridges **22** in the square waveguide **20** and the unridged body **11** of the orthogonal mode transducer **10**. Each of the transition ridges **25** registers with a different one of the ridges **22** of the square waveguide **20** and lies in the same plane as the associated ridge **22**. The transition section **24** may be coupled by flanges to both the orthogonal mode transducer **10** and the square waveguide section **20**. It will be understood, however, that this arrangement is provided for simplicity and ease of manufacture, and that if desired the square waveguide section **20** may be coupled directly to the orthogonal mode transducer **10** or that other forms of transition sections might be utilized. The sections shown, however, may be readily assembled and when constructed in the manner indicated consist of separate parts which may be individually fabricated quite simply.

With the square waveguide **20** thus constructed, there is a central aperture defined by the innermost surfaces of the ridges **22**. Within this aperture, and along the central axis of the square waveguide **20** may be placed an elongated rod or pencil of ferromagnetic material **30**. The ferromagnetic pencil may have an impedance matching taper **31** at its end closest to the orthogonal mode transducer **10** and may abut the conductive reflecting plate **21** at the other end. The term ferromagnetic is here employed to designate the class of materials, including ferrite and garnet type materials, which have the effects on microwave energy previously mentioned, when combined with appropriate magnetic fields. The arrangement of the ferromagnetic pencil **30**, which is in this instance assumed to be ferrite, is here intended to provide Faraday rotation of energy within the square waveguide **20**.

The varying magnetic field to be applied through the ferrite pencil **30** to achieve Faraday rotation is, as indicated above, an axial magnetic field, and one which extends in this instance along the central axis of the square waveguide **20**. The means for establishing this magnetic field is one of the important features of the present exemplification of the invention. The internal ridges **22** of the square waveguide **20** have cutout por-

tions 33 adjacent the walls of the waveguide 20. These cutout portions 33 are defined by a reduction in the outer dimension of the ridges 22, the cutouts extending from the reflecting plate 21 for a distance along the length of the ferrite pencil 30. The walls of the square waveguide 20 may at this point be comprised of relatively thin wall sections 34 coextensive with the cutout portions 33. Thus between the thin wall sections 34 and the cutout portion 33 of the ridges 22 there may be considered to be a volume conforming to the walls of the waveguide 20 and extending therearound.

Within this volume defined by the cutout portions 33 and the thin wall sections 34 may be positioned an arrangement for providing both the establishment and maintenance of the desired magnetic field. A number of strips 36 of material having selected magnetic properties may extend parallel to the waveguide 20 axis and adjacent to the thin wall sections 34. The strips 36 may abut the reflecting plate 21 and be coextensive with a principal portion of the length of the ferrite cylinder 30. As best seen in FIGS. 1 and 3, these strips 36 may be grouped adjacent the corners of the waveguide 20. Within the structure thus formed and having a like square section, when viewed along the axis of the waveguide 20, may be a conductive coil 38 wound to define a helix having its axis coextensive with the axis of the waveguide 20. The helical coil 38 may in turn be wound upon and supported by a rectangular form 39 concentric with the waveguide 20 and contacting the cutout portions 33 in the ridges 22. The support form 39 thus supports the helical coil 38 which in turn supports the magnetizable strips 36. This arrangement may be referred to as a return path structure for the magnetic field through the ferrite pencil 30. The support form 39 is preferably of a material which is substantially transparent to microwave energy. Leads 40 from the helical coil may be coupled to an external source of a driving current, which in this instance is given the general designation of a pulse circuit 42. The pulse circuit 42 may be any conventional driving circuit for applying a momentary current of desired magnitude to the helical coil 38.

Positioned adjacent the reflecting plate 21 and extending diagonally from the ferrite pencil 30 to each corner of the return path structure may be a different magnetizable cross piece 44. The magnetizable cross pieces 44 may have one end registering with the ferrite pencil 30 and the other end shaped to register with the associated magnetizable strips 36, and may be fixed, as by an adhesive, to the reflecting plate 21.

The magnetizable structure thus formed defines a substantial portion of a magnetic flux path. The magnetic flux extends axially and centrally along the waveguide 20 within the ferrite pencil 30, and may be visualized as extending out through the cross pieces 44 and extending through the strips 36. The direction of the flux is of course dependent upon the direction of magnetization. Between the ends of strips 36 and the tapered end 31 of the ferrite pencil 30 there may be seen to be a magnetic gap which will be discussed later. A static biasing field extending longitudinally through the ferrite pencil may be established by a permanent or electromagnet. Here a permanent magnet 46 is provided for purposes of illustration, the permanent magnet 46 being a bar magnet affixed to a wall 34 of the waveguide 20. The strength and direction of the magnetic field created by the permanent magnet 46 is determined in accordance with considerations given below. This static biasing field is completed axially through the ferrite pencil 30 in part through the presence of the magnetic gap. Thus shunt felds can be minimized or avoided.

The magnetic retentivity of the material in the ferrite strips 36 and in the cross pieces 44 is here arranged to have important operating significance. Specifically, the residual magnetism of the ferrite strips 36 is such that in the arrangement with the ferrite pencil 30 and with the biasing field a sufficient static magnetic field can be provided to achieve desired amounts of rotation of microwave energy. In this sense, the ferrite pencil 30 may be considered to be the active element, and the return path cylinder a static element which makes possible the Faraday rotation achieved by the active element. It is clear that the intensity of the magnetic field provided by the return path cylinder is dependent both upon the retentivity of the magnetizable strips 36 and the cross pieces 44 and upon the volume and configuration of the material contained in the return path cylinder, as well as the magnetic gap. While FIGS. 1, 2 and 3 are not drawn to scale, the approximate representations shown have been found to provide proper flux paths for the operation described below.

The material which may be employed for the ferrite strips 36, or for both the ferrite strips 36 and the cross pieces 44, may be one of a number of different types of material which are relatively "hard" magnetically and which can retain an appreciable portion of their magnetism when the magnetic applied field is removed. These materials are not so magnetically hard, however, as to require significantly higher magnetic fields in order to have a change in their condition of magnetization. A number of different ferromagnetic compositions is available for this purpose, including a number of the ferrite materials and a number of ferrous materials. In the present example it is assumed that the magnetizable elements 36 and 44 will be driven to saturation in one direction. The amount of magnetization retained after saturation and in the absence of an applied external field, except for the static field, is therefore determinative of the strength of field applied to the active element. This is pointed out in order to further recognize the fact that the volume and configuration of the magnetizable elements may have to be altered if a different material, having different retentivity, is employed.

In the operation of the arrangement of FIGS. 1, 2 and 3, it is desired to switch input energy provided from the first rectangular waveguide 12 back to the first rectangular waveguide 12, or selectively, to provide such energy to the second rectangular waveguide 15. Thus the first rectangular waveguide 12 serves both as an input and one output for microwave energy, and the second rectangular waveguide 15 serves as the other output. Such arrangements have wide utility in microwave systems in switching different signals to different elements or in diverting high power signals to a different channel than low power signals. The switching action in the present instance is to be accomplished under control of the pulse circuit 42 and the biasing magnet 46. When energy is to be returned back to the first rectangular waveguide 12 output, the ferrite pencil 30 is to have zero net magnetization. For this condition of operation it is assumed that a reset condition has previously been established. When the energy is to be switched to the second rectangular waveguide 15 as output, therefore, a pulse is provided to effect the switching action. Output thereafter is provided from the second rectangular waveguide 15, until a reset signal is provided from the pulse circuit 42 to return the active ferrite element to zero net magnetization.

In operation, linearly polarized input energy having a direction of polarization supported by the dominant mode within the first rectangular waveguide 12 is provided through that waveguide through the orthogonal mode transducer 10. Such energy does not, as described above, couple into the second rectangular waveguide 15 but passes into the transition section 24 and then into the square waveguide section 20. In the absence of a magnetic field in the return path cylinder and the ferrite pencil 30, such energy is simply reflected from the reflecting plate 21 back through the square waveguide section 20, the transition section 24 and the orthogonal mode transducer 10 to the first rectangular waveguide 12.

When a magnetizing pulse of sufficient amplitude is provided from the pulse circuit 42, however, the ferrite strips 36 and the cross pieces 44 are momentarily driven to saturation in the selected direction. Thereafter the pulse is terminated and the residual magnetic field retained. The net magnetic field consists both of the residual magnetic field within the strips 36 and cross pieces 44 and the static biasing field created by the permanent magnet 46 and extending through the magnetic gap and the ferrite pencil 30.

The driving pulse need only be a fraction of a microsecond to establish the saturation magnetization and the desired retained magnetic field. This magnetic field is substantially completely within the square waveguide 20 and extends through the ferrite strips 36, the cross pieces 44, the ferrite pencil 30 and between the tapered end 31 of the ferrite pencil 30 and to the adjacent ends of the ferrite strips 36. Because the ferrite strips 36 are grouped at the separate corners of the square waveguide 20, the flux path for the retained field is similarly concentrated. The presence of the cross pieces 44 further contributes to the low reluctance path for the retained magnetic field, and it is found that the magnetic circuit thus provided is extremely efficient. The direction of the magnetic field existing within the active element, the ferrite pencil 30, is selected in the direction which is desired. In the present instance, either one of the directions of rotation may be utilized. The intensity of the net magnetic field established in the static condition is selected to be such that a 45 degree rotation of microwave energy is provided by the ferrite pencil 30. The net magnetic field is determined by the static field established as a result of the operation of the pulse circuit 42 and the static biasing field generated by the permanent magnet 46. In the selected direction of magnetization for energy rotation, the biasing field tends to increase the net magnetic field, because the biasing field is utilized to cancel the retained field in the opposite direction of magnetization. A further description of this relationship is given below. The net field, however, can be established at a desired level and adjustments can be made by variation of the length of the ferrite pencil 30 or other means.

Upon establishment of the desired magnetic field in the return path cylinder by passage of the driving pulse through the coil 38, therefore, microwave energy from the input is rotated within the square waveguide section 20. This rotation is 45 degrees and may in the present instance be assumed to be clockwise, as viewed from the input end of the device. This 45 degree rotation is only that provided by transmission past the ferrite pencil 30 in one direction, however. In effect, the energy reflected from the reflecting plate 21 has been rotated 45 degrees. Because of the nonreciprocal nature of ferromagnetic materials, however, the microwave energy is rotated a further 45 degrees as it is transmitted along the waveguide back toward the input end. This feature enables the utilization of a lesser magnetic field when rotation is to be provided.

The energy provided back from the square waveguide 20 and the transition section 24, therefore, is orthogonal with respect to the input energy. Such energy sees an effective short circuit at the conductive septum 18 within the orthogonal mode transducer 10 and furthermore excites the radiation aperture 16 coupled to the second waveguide arm 15. Accordingly, such energy is switched out the second waveguide arm 15. If thereafter it is desired to switch back to the first condition of operation, in which inputs are reflected back, the pulse circuit 42 need only establish saturation of the retentive element in the opposite direction. A momentary pulse of sufficient amplitude through the coil 38 to drive the ferrite strips 36 and cross pieces 44 to saturation will thereafter provide a retained static magnetic field of opposite polarity. The net magnetic field, however, which is the sum at the ferrite pencil 30 of the retained field and the static biasing field, is arranged to be zero, so that no rotation is provided and signals are returned to the input 12.

The advantages of this arrangement will now be apparent. In this connection, it should be noted that the use of the ridges 22 within the square waveguide 20 appreciably decrease the frequency sensitivity of the arrangement. Further, the use of the steps 26 and 27 in the transition ridges 25 appreciably decrease insertion losses and reflective effects which might otherwise be present. It is of particular significance, moreover, that the switching can be accomplished with very brief switching pulses in the manner indicated. With this arrangement, there is no need for a regulated current supply, as is required by the devices heretofore available. As a consequence the complexity of the associated equipment may be markedly decreased.

The regulating problems associated with providing a precise driving current for a period of time and under widely varying environmental conditions are substantially completely obviated. The driving pulses utilized need not be closely controlled and can be provided very simply by the discharge of signal storage devices. All that is required is a very brief driving pulse, which can be of the order of a microsecond or less, and which is of magnitude sufficient to establish saturation. The pulse can also be greater than the magnitude needed for saturation, and thus need not be precisely controlled. The use of the static biasing field is in this respect significant. The static biasing field can be generated very simply, as with the permanent magnet shown, but nevertheless can be very accurate. In this respect, the magentic gap which is utilized provides an important feature. With a closed magnetic path it might be difficult to establish the desired static biasing field, and to have the proper operative relationships when the field is shifted from one state to another. It will be recognized that this same arrangement could be used with different angles of rotation, and that if a reflective short circuit element is not to be utilized there can still be controlled switching of energy between different terminals. In combination with these features, use of an internal return path cylinder and a configuration which is very easily fabricated permits the provision of an extremely fast acting microwave switch of general application.

Another arrangement in accordance with this invention may achieve effective use of the retentivity of magnetizable material in combination with a pulsing source in a microwave device in a different manner. The arrangement illustrated in FIGS. 4–7, to which reference is now made, may be arranged as a circulator. It employs a first orthogonal mode transducer 50, a second orthogonal mode transducer 54, and an intermediate waveguide body 58. The first orthogonal mode transducer 50 may consist of a square to rectangular transition, as described in greater detail in the arrangement of FIG. 1, and may include a first rectangular terminal 51 and a second rectangular terminal 52 which is orthogonal with respect to the first. The second orthogonal mode transducer 54 may also be a transducer between a square waveguide and individual rectangular waveguides. In this instance, however, the rectangular waveguides may be disposed diagonally with respect to the square waveguide. Thus the second orthogonal mode transducer may include a third rectangular terminal 55 which is rotated 45 degrees clockwise (as viewed from the first rectangular terminal 51) and a fourth rectangular terminal 56 which is also rotated 45 degrees clockwise (as viewed from the second rectangular terminal 52). This arrangement is often employed in circulator devices when coupled, as is shown here, by an intermediate waveguide body 58 which includes means by which nonreciprocal rotation of energy may be achieved.

The waveguide body 58 is essentially a ridged square waveguide section. The square waveguide may consist of a pair of square waveguide bodies 59 and 60, each of

the walls of which has a longitudinal slot and each of which is coupled to a different one of the orthogonal mode transducers 50 or 54 respectively. The square waveguide structure may be completed by a central coupling structure consisting of a hollow square box member 62. The elements of the orthogonal mode transducers 50 and 54, the waveguide bodies 59 and 60 and the box member 62 are thus colinear. The ridges 66 provided within this square waveguide may be formed by T-shaped segments (best seen in FIG. 6) with the top of the T's resting on the outer surfaces of the waveguide portions 59 and 60 and the legs of the T's being the ridge segments 66. As shown, each of the ridge segments 66 may be coextensive with the waveguide body 58 and each may taper to the associated inner surface of the walls of the waveguide body 58 in each longitudinal direction. Transition sections 67 at each end of the ridges 66 provide a smooth transition for the passage of microwave energy within the waveguide body 58. The ridge sections 66 also include cutout portions 69 in their surfaces which are adjacent the walls of the waveguide body 58. These cutout portions 69 are centrally disposed with respect to the ridge sections 66 and to the waveguide body 58. Thus the cutout portions 69 define a central aperture concentric with the axis of the waveguide body 58 and extending around the waveguide body adjacent the box member 62.

Within this inner surface aperture is positioned a magnetizing and return path structure comprising a support form 70 which is preferably of a material substantially transparent to microwave energy and which is in contact with the cutout portions 69 in the ridges 66. A magnetizing coil 72 consisting of a conductive wire may be wound upon the support form 70, to have, like the support form 70, a hollow square cross section when viewed along the axis of the waveguide body 58. The winding of the magnetizing coil 72 is however helical with respect to the waveguide axis. Of like cross section, but encompassing the magnetizing coil 72 within the cutout portions 69 may be a return path structure 73 comprised of magnetizable material. Leads 74 may extend from the magnetizing coil 72 to a pulse circuit 76 which can provide momentary pulses of substantially selected amplitude and polarity, as is described in greater detail below.

A ferrite pencil 78 having tapered ends 79 may be positioned within the central aperture defined by the innermost portions of the ridged sections 66. The ferrite pencil is, as described in the arrangement first discussed, active in the Faraday rotation sense. Additionally, however, it is desired to use a ferrite material which provides magnetic retentivity as well as active microwave properties. This arrangement is made useful through its employment with a magnetizing structure and the return path internal to the waveguide.

The operation of the device which is illustrated in FIGS. 4–7 may be viewed as a Faraday rotation action, or in conjunction with the associated orthogonal mode transducers 50, 54, as a circulator action. Assuming that a 45 degree rotation is provided within the waveguide body 58, in a clockwise direction as viewed from the first rectangular terminal 51, the circulator action is as follows. Energy from the first terminal 51 is transferred out the third terminal 55. Energy from the third terminal 55 is, however, returned to the second rectangular terminal 52. Conversely, energy from the second terminal 52 is coupled out the fourth terminal 56, while energy from the fourth terminal 56 is returned to the first terminal 51. If the direction of magnetization of the ferromagnetic element is reversed and the Faraday rotation is given an opposite sense energy from the first terminal 51 is applied to the fourth terminal 56, and so on. This action remains the same and the Faraday rotation operation may be considered independently.

In the present arrangement the volume and disposition of the ferrite pencil 78 with respect to the return path structure 73 is again such as to establish and maintain an accurate static magnetic field indefinitely, once a driving pulse has been applied. The pulse circuit 76 provides a driving pulse of sufficient polarity and amplitude to drive the ferrite pencil 78 to saturation magnetization in a desired direction. The retentivity of the ferrite pencil maintains a given field strength following the termination of the magnetizing pulse. This effective field is kept at sufficient flux density to maintain the Faraday rotation action through the employment of the return path structure 73. A number of ferromagnetic materials are available which have sufficient retentivity as well as active properties. The relationship which should be established is determined by the length of the ferrite pencil 78, its volume, the extent of its magnetic retentivity, and the proximity and volume of the associated return path structure 73. Clearly, the return path structure 73 may itself have appreciable magnetic retentivity. In the present example, however, while the drawings are not to scale it has been found that the approximate configuration shown provides sufficient effective magnetization to maintain the desired 45 degree Faraday rotation of microwave energy.

In a practical embodiment of this invention, an active ferrite pencil 78 of .250 inch diameter and 3 inches length was employed in a 0.8 inch by 0.8 inch waveguide having ridges .270 inch high. Fifty-eight turns of No. 27 wire were employed in the magnetizing coil 72. A ferrite material was used for the return path structure 73.

A number of other considerations also contribute to the advantageous operation of this arrangement. The tapered ferrite pencil and the associated return path structure 73 and the magnetizing coil 72 are so disposed as to introduce little insertion loss and reflective effects within the waveguide body 58. The use of the ridges 66 not only provides a broader band operation, where a frequency range is to be utilized, but also provides a ready means for positioning the ferrite pencil 78 and for holding the magnetizing coil 72 and the return path structure 73.

Again, however, an important feature of this arrangement resides in the fact that while the associated circuitry is greatly simplified the device can provide substantially constant operation. The pulses applied need not be precisely controlled, because they need only exceed the saturation magnetization level. Further, they can be of extremely short duration, and thus very precisely mark the initiation of the time at which switching is to take place. Furthermore, the switching action provided is positive in both directions, being dependent only upon the selection of the direction of rotation which is desired. It has been found that the degree of rotation which results is extremely accurate and maintained substantially indefinitely without change. Thus, as above, the need for a current control is eliminated.

The operation of these devices in response to a pulse source of current may be better understood with reference to FIG. 8. The graph of flux density vs. field intensity there shown is the hysteresis loop for a ferromagnetic material having the desired retentive properties. The loop is of the general form encountered with ferromagnetic materials, and provides the desirable properties for an arrangement of this nature. FIGURE 8 is the curve which exists for a closed magnetic loop. With an air gap in the device the hysteresis loop would be of a slightly different form, and would usually be less upright. The crossing lines of the hysteresis loop relative to the flux density, for the ferromagnetic device containing an air gap, would be at a lower density. With the use of a static biasing magnet, however, the net flux density in the polarity which is used for rotation will add the biasing flux to the retained flux to achieve the amount of flux needed for a selected degree of rotation. With the retained field being of opposite polarity, this static biasing flux could effectively cancel the retained flux. The variable introduced by the length of the ferrite can be adjusted to in-

sure the proper amount of rotation. The field intensity required to establish saturation magnetization is not excessive as would be the case in an extremely "hard" magnetic material. Nevertheless, an appreciable flux density exists when the magnetic field is removed, so that the retentivity can be used to provide active Faraday rotation properties in a ferrite itself or in some other member of a flux path structure.

A different arrangement having desirable properties for other applications is illustrated in simplified form in FIG. 9. This arrangement utilizes a constant biasing field through the active ferromagnetic element, together with a controllable field established through the retentive material which either augments or cancels the biasing field. In this arrangement, energy from a source of plane polarized energy **80** may be provided through a switch section **81** to a rotation section waveguide **82** which is here shown as circular. Outputs from the circular waveguide **82** are provided to either one of two polarization direction sensitive microwave circuits. A first of these output circuits **83** is coupled through a circular to rectangular transition **84** in such fashion as to pass microwave energy having the same direction of polarization as the input energy. A second output circuit **86** is coupled through a rectangular waveguide **87** so as to extract from the circular waveguide **82** energy which has been rotated 90 degrees from the original input direction of polarization.

Within the circular waveguide **82** is employed a Faraday rotation device in accordance with the features of the present invention. An elongated ferrite pencil **90** supported by disks **91** which are substantially transparent to microwave energy, is positioned axially along the circular waveguide **82**. A magnetic return path cylinder **92** is positioned between the disks **91** and concentric with the ferromagnetic pencil **90**. The return path cylinder **92** is of magnetizable material and completes the flux path with the ferromagnetic pencil **90** within the waveguide **82**. In the present example, the ferromagnetic pencil **90** has the desired magnetic retentivity, although either or both members of the flux path structure could have such properties. On the inner surface of the return path cylinder **92** may be a magnetizing coil **93** disposed on a support form **94** in a fashion similar to the arrangement described in conjunction with FIGS. 4–7. The arrangement of the return path cylinder **92**, the coil **93** and the inner support **94** will accordingly not be described in greater detail. Leads from the coil **93** extend to an external pulse source **95**. An external bias coil **96** may also be wound about the waveguide **82**, to define a helical coil structure with respect to the axis waveguide **82**. The terminals of the external bias coil **96** may be coupled to a fixed current source **97**. The external bias coil **96** is comparable to the permanent bias magnet of the arrangement of FIG. 1. It will be understood that different magnetic field generating devices could be employed to provide the desired static biasing field, as long as the field is of sufficient density and in a proper direction through the ferrite element.

In the present example, it is desired either to pass non-rotated energy through the circular waveguide **82** to the first output circuit **83**, or to rotate the energy 90 degrees for transmission to the second output circuit **86**. The fixed current source **97** coupled to the external coil **96** therefore provides a regulated amount of current to establish a tendency to a 45 degree rotation of energy within the waveguide **82** through the action of the ferromagnetic pencil **90** under the resulting static biasing magnetic field. In conjunction with this biasing effect, however, the current pulse source **95** provides the desired cancelling or augmenting magnetic field. Here again, the volume and disposition of the various magnetic elements may be so selected as to provide a 45 degree rotation, through the retained magnetic field alone, when the magnetically retentive member (in this case the pencil **90**) has been driven to saturation in the desired direction. In consequence, when the applied current pulse establishes a direction of magnetization which opposes that of the fixed current source **97**, there is no net magnetization of the ferromagnetic pencil **90** and microwave energy from the source **80** is transmitted through the circular waveguide **82** to the first output circuit **83**.

On the other hand, when the current pulse source establishes a field which augments the static biasing field of the fixed current source **97**, a total rotation of 90 degrees is provided, and the energy is transmitted out the second output circuit **86**. In the present example, the +45 degree rotation is taken as that which is clockwise looking from the input end toward the output end, although the rotation can be in either direction by arrangement of the field direction and the ferromagnetic element position. Among the advantages of this arrangement are the fact that a full 90 degree rotation may be provided without extensive current drain or an excessive length of ferromagnetic pencil. The fixed current source **97** is not required to be a switched source, so that it may be regulated precisely without requiring complicated additional circuitry. With this arrangement, the net magnetic field for switching is very quickly established but at the same time very precise. Here again, the action of the coil **96** in conjunction with the magnetic gap between the return path cylinder **92** and the ferromagnetic pencil **90** is of importance. The biasing field through the ferromagnetic pencil **90** is readily established but does not interfere with the establishment of the switching field through the use of pulses.

It will be apparent that a number of different arrangements may be used to provide the self-retained magnetic flux in conjunction with the driving pulse circuit. In FIG. 10 is illustrated an arrangement in which energy within a circular waveguide **100** is rotated by a composite element **101**. The composite element may consist as shown of ferrite end portions **102** and **103** which are joined to a magnetizable center portion **104** which is or is not active in the Faraday rotation sense, but which combines with the tapered end portions **102** and **103** to establish the desired magnetic field. The pencil **101** may be held in place by dielectric support members **91** and may be encompassed, outside the waveguide **100** by a driving coil **106**, the terminals of the coil **106** being coupled to the pulsing circuit **42**. In this arrangement, the magnetizable center portion **104** of the Faraday rotation pencil **101** is selected to have the desired magnetic retentivity to provide a given amount of Faraday rotation of microwave energy. Accordingly, this arrangement, like those previously described, need only be pulsed to establish the static magnetic field which will provide the desired rotation. The advantages of this arrangement include its compactness and ease of manufacture.

A different arrangement which may utilize an internal ferromagnetic element configuration of a largely conventional nature is shown in FIG. 11. In FIG. 11, it may be seen that there is a simplified representation of a ferromagnetic pencil **108** supported centrally within a circular waveguide **100** for providing Faraday rotation of microwave energy. The desired axial magnetic field may in this instance be provided by a pair of magnetizable U-shaped couplers **109**, **110**, each affixed to the waveguide **100** at points adjacent the opposite ends of the ferromagnetic pencil **108**. The magnetizable couplers **109**, **110** in this example are the elements having magnetic retentivity. A magnetizing coil **111** and **112** encompasses the different magnetizable couplers **109** and **110**, each of the magnetizing coils **111** and **112** being coupled to a pulse circuit **42**. Upon application of a pulsing current to the coils **111** and **112** a static magnetic field is established through the retentivity of the magnetizable couplers **109** and **110** such that an axial magnetic field exists through the ferromagnetic pencil **108**. Accordingly, Faraday rotation is again achieved which is accurate and reliable. The arrangements of

both FIGS. 10 and 11 can be utilized in the different configurations previously described, with or without static biasing fields, and for various circulating or switching purposes.

The principles of the present invention may also be utilized in other microwave devices which utilize the gyromagnetic nature of magnetized ferromagnetic materials. In all such devices there may be considered to be a gyromagnetic displacement of energy whether the energy is rotated, phase shifted or absorbed. A number of devices are available which employ ferrites within rectangular waveguides for phase shift and other purposes. Some such devices utilize a centrally disposed ferrite subjected to an axial magnetic field, while others employ ferrite elements positioned asymmetrically with respect to the broad walls of the waveguide. The principles of the invention may be utilized with either of these arrangements.

An example of such an arrangement is shown in FIG. 12, and consists of the type of transverse field phase shifter with rectangular waveguide which employs a ferrite in the form of a slab **118** extending normal to and between the broad walls of a rectangular waveguide **120**. This arrangement is merely illustrative of the class of devices, some of which use individual strips of ferrite against each of the broad walls. With this arrangement may be employed a pair of external pole pieces **121** which lie in the plane of the ferrite slab **118** but extend outwardly from the waveguide **120**. A substantial portion of the flux path for the ferrite slab **118** and transverse to the broad walls of the waveguide **120** may be provided by a pair of external magnets. A C-shaped electromagnet **123** on one side of the waveguide **120** may have its opposite extremities operatively coupled to the different pole pieces **121**. A magnetizing coil **125** about the principal leg of the C-shaped magnet **121** may provide, when energized, the desired transverse magnetic field through the ferrite slab **118**. Either the flux path completing member **123** or the ferrite slab **118** may be of the desired retentive magnetic properties, as outlined above. Pulse signals may be applied to the driving coil **125** from a pulse circuit **42**.

In conjunction with this arrangement may be utilized a permanent biasing magnet **127** of roughly horseshoe configuration. The permanent magnet **127** may have each of its open ends in operative relation to a different one of the pole pieces **121**, to provide a biasing magnetic field of desired density and direction through the ferrite slab **118**. The retained field, after saturation, and the biasing field are selected to add to a desired amount for one direction of saturation and to cancel each other in the opposite direction. In this arrangement also the static biasing through the ferrite slab **118** is made more useful by the use of a gap in the static biasing magnetic circuit, by spacing of the ends of the permanent magnet **127** from the pole pieces **121**.

The arrangement of FIG. 12 operates to provide what may be considered to be an incremental phase shift of microwave energy along the waveguide **120**. The manner in which the transverse field phase shifter operates is well known and need not be further described. With a biasing field selected with relation to the retained field, however, the application of a pulse from the pulse circuit **42** sufficient to provide saturation will indefinitely thereafter cause a predetermined amount of phase shift along the waveguide **120**. When no phase shift is desired the pulse circuit **42** need only provide an opposite pulse, so that the retained and biasing fields cancel. The utility of such an arrangement is readily apparent. Not only can such devices be utilized for controlled switching in circulator arrangements, but a number of incremental phase shifts may be combined to provide a total amount of phase shift of a closely controlled amount.

Thus there has been described an improved microwave Faraday rotation device which utilizes the retentivity of magnetic materials together with momentary current pulses to provide phase shifting and rotation of microwave energy utilizing ferromagnetic materials. Devices constructed in accordance with this principle operate precisely without high current requirements or without a need for accurate current regulation.

What is claimed is:

1. A microwave switching device comprising hollow waveguide means for propagating electromagnetic energy; magnetizable means including a ferromagnetic element disposed within said waveguide, and further including a magnetizable return path element at least partially encompassing said ferromagnetic element but providing a gap in the magnetic flux return path of said ferromagnetic element, at least a portion of said magnetizable means having sufficient magnetic retentivity to magnetize said ferromagnetic element to a selected degree; coil means disposed adjacent and magnetically coupled to said magnetizable means; and current pulsing means coupled to and supplying said coil means with a driving current having a magnitude to provide momentary saturation magnetization in that portion of said magnetizable means having magnetic retentivity.

2. A microwave switching device comprising hollow waveguide means for propagating electromagnetic energy; magnetizable means including a ferromagnetic element disposed within said waveguide, and further including a magnetizable return path element at least partially encompassing said ferromagnetic element but providing a gap in the magnetic flux return path of said ferromagnetic element, at least a portion of said magnetizable means having sufficient magnetic retentivity to magnetize said ferromagnetic element to a selected degree; static magnetic means magnetically coupled to said magnetizable means and supplying a magnetic biasing field of a selected density and direction to said magnetizable means; coil means disposed adjacent and magnetically coupled to said magnetizable means; and current pulsing means coupled to and supplying said coil means with a driving current having a magnitude to provide momentary saturation magnetization in that portion of said magnetizable means having magnetic retentivity.

3. A microwave switching device comprising hollow waveguide means having a closed conducting end portion for reflecting electromagnetic energy, said hollow waveguide being capable of supporting plane polarized microwave electromagnetic energy in various positions of rotation of polarization; waveguide means including a pair of polarization sensitive terminals for transmitting separately energy in positions of rotation which are orthogonal with respect to each other and rectangular with a given plane of polarization in said hollow waveguide; magnetizable means including a ferromagnetic element disposed centrally within said hollow waveguide and in contact with said closed conducting end portion, and further including a magnetizable return path element at least partially encompassing said ferromagnetic element but providing a gap in the magnetic flux return path of said ferromagnetic element, at least a portion of said magnetizable means having sufficient magnetic retentivity to magnetize said ferromagnetic element to a selected degree; coil means disposed adjacent and magnetically coupled to said magnetizable means; and current pulsing means coupled to and supplying said coil means with a driving current having a magnitude to provide momentary saturation magnetization in that portion of said magnetizable means having magnetic retentivity.

4. A device according to claim 3, wherein said device further includes static magnetic means magnetically coupled to said magnetizable means and supplying a magnetic biasing field of a density and direction to cancel substantially all said magnetic retentivity only in one direction of magnetization.

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