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MICROWAVE FERRITE SWITCH

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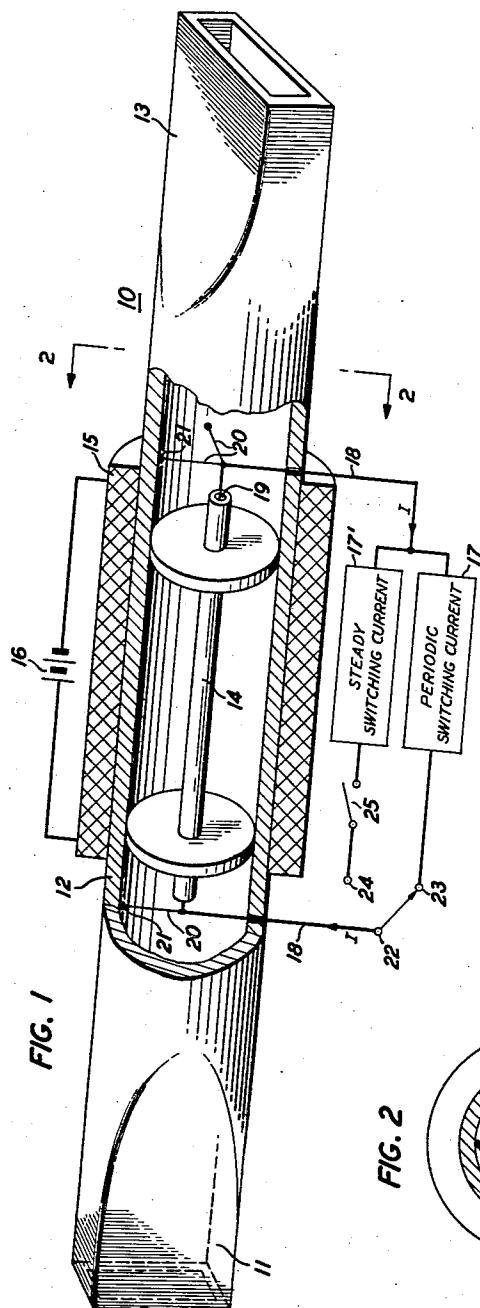


FIG. 1

FIG. 2

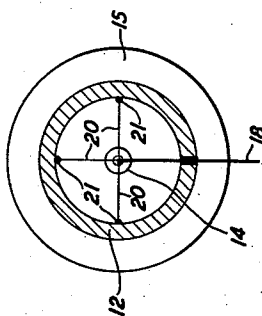


FIG. 3

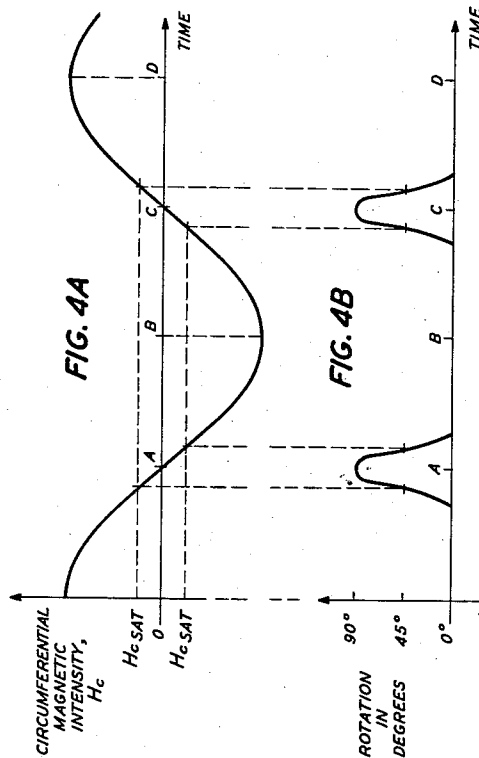
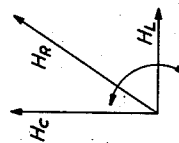


FIG. 4A

FIG. 4B

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MICROWAVE FERRITE SWITCH

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9 Claims. (Cl. 333-98)

This invention relates to electromagnetic wave transmission and, more particularly, to rapid acting microwave switches of the magnetically controllable Faraday effect type.

It is well known that rotation of the plane of polarization of linearly polarized electromagnetic wave energy occurs when said energy is transmitted through a properly dimensioned wave guide section containing a longitudinally magnetized element of Faraday effect material. Generally, the biasing magnetic field is provided by a solenoid type structure which is placed around the wave guiding path itself. For many switching applications such an arrangement provides a satisfactorily rapid variation of the magnetic intensity within the Faraday element in response to changes in the magnetic flux produced by the externally located solenoid. However, when a rapid switching rate is contemplated, e.g., a rate above one megacycle per second in a guide with a wall thickness of five mils, the impedance presented to the high frequency switching field components by the wave guide wall itself substantially prevents the switching components from reaching the ferrite material. This shielding effect occurs because the wave guide wall acts as a short circuited turn at the switching frequencies, thereby preventing rapid variation of the magnetic flux within the guide. One suggested solution to this problem in the past has been to utilize a wave guide having a wall thickness less than the depth of energy penetration for the switching field components. Such a guiding structure is both difficult in manufacture and fragile in maintenance. In addition, the upper switching frequency limit is again determined by the wall thickness since in order to confine the microwave energy the guide wall must have a thickness greater than the depth of penetration of the microwave energy. An additional solution to the switching problem lies in placing the biasing solenoid within the guide. However, such an arrangement tends to distort the microwave energy and, in addition, the switching rate is limited by the high inductance associated with a coil surrounding a magnetic material of the Faraday effect type.

It is, therefore, an object of this invention to switch microwave energy in a Faraday effect device at a rate limited only by the intrinsic characteristics of the Faraday effect material itself.

It is a more specific object to switch microwave energy in a Faraday effect device in response to switching field components extending in a plane which is angularly related to the components of a magnetic biasing field extending in a direction normally producing rotation.

In a principal embodiment of the invention a round wave guide section containing an element of axially magnetized Faraday-effect material is placed between first and second terminal wave guide sections of polarization selective rectangular guide which are oriented such that only energy of a polarization normal to that propagated in the first section is propagated in the second. The parameters of the rotation producing element are adjusted to produce the proper amount of rotation to permit substantially complete transmission through the switch. In accordance with the present invention, magnetic switching field components which are directed normal both to the direction of the axial magnetic field which produces the Faraday rotation and to the direction of the magnetic field components associated with electromagnetic wave energy

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propagating within the guide section containing the Faraday-effect element are applied directly to the element. The switching field components have at least two magnitude values, the first of which is zero value and the second of which is a value exceeding that value required magnetically to saturate the material comprising the element. The switching field may, of course, vary smoothly between these values and the non-zero limit may be either positive or negative. The rapidity with which a microwave switch in accordance with the present invention is capable of acting derives from the speed with which orientation and reorientation of the direction of the spins associated with portions of the atoms within the material may be accomplished by first and second simultaneously present magnetic biasing components one of which is of constant intensity and one of which varies in intensity.

The above and other objects of the present invention, its features, its nature, and its various advantages will appear more fully upon consideration of the accompanying drawing and the detailed description thereof which follows hereinbelow.

In the drawing:

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

FIG. 2 is a transverse cross sectional view of the switch of FIG. 1;

FIG. 3 is a vector diagram of the primary magnetic biasing forces which produce switching action; and

FIGS. 4A and 4B are graphical representations of the magnetic control and energy output characteristics associated with the microwave switch of FIG. 1.

Referring more particularly to the drawing, FIG. 1 is a partially broken away perspective view of a microwave switch 10 in accordance with the present invention. Shown is a terminal guide section 11 of rectangular transverse cross section which supports a linearly polarized electromagnetic wave energy and which tapers into a guide 12 of circular transverse cross section. Joined to guide 12 is a terminal guide section 13 also of rectangular transverse cross section which is oriented to accept only linearly polarized wave energy polarized at an angle, illustrated in FIG. 1, for example, as 90 degrees, with respect to the polarization of wave energy in guide 11. The dimensions of terminal guide sections 11 and 13 are preferably chosen so that these guides accept only dominant mode TE_{10} wave energy in which the electric vector, which determines the plane of polarization of the wave energy, is parallel to the short dimension of the rectangular guide. By means of smooth transitions between the guides of rectangular and circular transverse cross section, the TE_{10} mode in guides 11, 13 becomes the TE_{11} mode in guide 12. The dimensions of guide 12 are also preferably chosen so that only the dominant TE_{11} wave mode will propagate therein.

Interposed between guide section 11 and guide section 13 in the path of wave energy propagating therebetween in guide 12 is suitable means of the type which produces a space rotation of the plane of polarization of this wave energy in response to a longitudinally directed magnetic biasing field component. One such means is a Faraday effect element having such properties that, in the presence of a magnetic biasing field directed parallel to the direction of wave propagation therethrough, an incident linearly polarized wave impressed upon a first side of the element emerges at the second side polarized at a different angle from the original wave and an incident polarized wave impressed upon the second side emerges at the first side with an additional rotation of the same angle. As illustrated by way of example in FIG. 1 of the drawing, this means comprises Faraday effect element 14 which extends longitudinally in guide 12. Element 14 may be

appropriately supported within guide 12 by extending it through centrally located apertures in dielectric spacers which may be of polyfoam to minimize impedance discontinuities and reflections. As a specific embodiment, element 14 may comprise magnetic material of the type commonly designated gyromagnetic material. The term gyromagnetic material is employed here in its accepted sense as designating the class of materials having portions of the atoms thereof that are capable of exhibiting a significant precessional motion at frequencies within the microwave frequency range, this precessional motion having an angular momentum, a gyroscopic moment, and a magnetic moment. Included in this class of materials are ionized gaseous media, paramagnetic materials, and ferromagnetic materials including the spinel ferrites and the garnet-like yttrium-iron compounds. One particular class of gyromagnetic materials suitable for use as nonreciprocal element 14 in the present invention comprise an iron oxide combined with a quantity of bivalent metal such as nickel, magnesium, zinc, manganese or other similar material. As a specific example element 14 may comprise nickel-zinc ferrite prepared in the manner described in United States Patent 2,748,353 which issued to C. L. Hogan on May 29, 1956. This material has been found to operate successfully as a Faraday-effect rotator for plane polarized electromagnetic wave energy to an extent of 90 degrees or more when placed in the presence of a longitudinally directed magnetic biasing component having a strength readily producible in practice. In addition, electromagnetic waves in the centimeter and millimeter wavelength range are transmitted through such material with negligible attenuation.

Suitable means for providing the longitudinally directed magnetic biasing field component necessary for production of Faraday rotation surrounds element 14. This means may be, for example, a solenoid 15 which surrounds guide 12 and which is energized by source 16. Alternatively, the requisite bias may be provided by a permanent magnet. The angle of rotation of plane polarized wave energy in element 14 is approximately directly proportional both to the longitudinal extent traversed by the waves and to the intensity of magnetization to which the element is subjected. It is thereby possible to choose the physical length of the element and the intensity of the biasing field to produce a resultant 90-degree rotation.

In accordance with the present invention, suitable means for producing second magnetic biasing field components which lie in planes angularly related to the direction of the rotation producing field are provided either by steady switching current source 17' or by periodic switching current source 17. Connected to sources 17 and 17' is a conductor 18 through which switching current flows. Whether a steady switching current or a periodic switching current is desired depends upon the particular application of the Faraday switch contemplated. Thus, if a repetitive pulse type output is desired, contacts 22 and 23 are connected. If, on the other hand, a gate type intermittent output is desired, contacts 22 and 24 are connected. By then opening and closing switch 25 either manually or automatically, output pulses of the desired length may be generated. Regardless of the particular one of sources 17, 17' chosen for the source of biasing current, the current from the chosen source flows through conductor 18 within element 14 in a direction parallel to the direction of energy propagation through guide 12; i.e., in axial alignment with guide 12. When current flows in a conductor, it is known that a resulting magnetic field is set up in the immediate vicinity of the current carrying conductor and that this magnetic field lies circumferentially about the conductor. Thus, the magnetic field produced by current flowing in conductor 18 permeates element 14 and acts as a second magnetic biasing field which is angularly related to the longitudinally directed biasing field already described above. In accordance with the

present invention, the circumferential magnetic biasing field is at least variable in intensity between zero and a single value greater than saturation. The relative amplitudes of the longitudinal and circumferential biasing fields will be more completely set out in a later portion of this specification.

Since conductor 18 extends transversely within guide 12 between the walls thereof and element 14, there is a tendency for waves passing thereby to be distorted by its asymmetrical relationship with respect to the energy propagation path. Accordingly, conductive wires 20 extend between the point at which conductor 18 changes in direction from transverse to longitudinal and points 21 located on the inside surface of guide 12 which are spaced 90 degrees apart from each other and which lie on a transverse plane through guide 12 containing the transverse portions of conductor 18. Each of the wires 20 is secured to guide 12 by an insulating connector at points 21. No conductive contact is thus maintained between any of wires 20 and guide 12. FIG. 2 of the drawing is a transverse cross sectional view of the structure of FIG. 1 taken at section line 2—2'. The grid of conductive wires presented by the transverse portion of conductor 18 and wires 20 is seen to be symmetrical with respect to guide 12 and to gyromagnetic element 14. Thus, distortion of the wave passing through guide 12 is minimized.

In the operation of the microwave switch of FIG. 1, dominant mode TE_{10} energy polarized in a direction parallel to the short sides of rectangular guide section 11 enters the switch 10 at terminal section 11 but it should be noted that the choice of terminal section 11 as the input is by way of example only and that terminal section 13 could equally well have been chosen. The TE_{10} energy is gradually transformed by traversal of the tapered guide portion between guide sections 11 and 12 into the TE_{11} wave mode in guide 12. Still polarized in the same direction as the energy which entered guide 11, the TE_{11} energy propagates past the grid comprising wires 20 and conductor 18 and is incident upon element 14. Element 14 is permeated by a longitudinal magnetic field generated by solenoid 15 and source 16. As stated above, an inherent characteristic of gyromagnetic material is that it be capable of significant precessional motion at frequencies of interest. This precessional quality arises from the fact that the unpaired spinning atomic portions within the material itself have angular momenta associated therewith and, under the influence of an external magnetic field, these spinning atomic portions may be aligned with the field direction. When the gyromagnetic material selected for use is of the class known as ferrites, the spinning atomic portions capable of precession are, in fact, electrons. Once these spinning electrons are aligned and their angular momenta have reached a condition of equilibrium, any deflection of the electron axes from alignment with the biasing field will result in a precession of the axes not unlike that exhibited by a spinning gyroscope which is deflected from its equilibrium position. In wave guide applications the electrons are readily deflected by the radio frequency magnetic field associated with propagating electromagnetic waves. In order that the deflection and the resulting precession be significant, the radio frequency magnetic intensity is preferably applied at right angles to the direction of the biasing magnetic field. Returning now to the propagating wave energy in guide 12, according to a simplified explanation of Faraday-effect rotation, a primary plane polarized wave incident upon the gyromagnetic element 14 produces two secondary waves in the material. These waves are circularly polarized in opposite rotational senses. It should be noted that for the rotating waves of either sense, the magnetic vector, which is always normal to the electric vector of a propagating electromagnetic wave, is also normal to the longitudinal biasing field. Thus, the conditions for the production of significant precessional motion exist. The effect of the precession upon the oppositely rotating waves is not, however, the same. As a result of the dif-

ferent effect produced by the precession, the oppositely rotating waves propagate with unequal phase velocities and, upon emergence from the gyromagnetically active region within guide 12, these secondary waves recombine to form a resultant primary wave which is, in general, polarized at a finite angle with respect to the polarization of the primary wave which was incident upon element 14. In effect, then, the polarization plane of the incident wave will be rotated by a traversal of element 14 under the biasing conditions and field relationship set out above. If the length of element 14 and the intensity of the biasing field are properly chosen, and in the absence of other magnetic influences to be discussed below, the amount of rotation can be set at 90 degrees. Under these conditions, the rotated TE_{11} wave after emergence from element 14 and propagation past the grid comprising wires 20 and conductor 18 is transformed by its traversal of the tapered guide portion between guide sections 12 and 13 into dominant mode TE_{10} wave energy. The energy in the TE_{10} mode is polarized in a direction parallel to the short sides of rectangular guide section 13 and is propagated therein without reflection. If the rotation is slightly different from 90 degrees, some energy will be reflected and some transmitted by guide section 13. If the polarization plane of the wave is not significantly rotated during its traversal of guide section 12, no significant transmission of energy through guide section 13 will occur. It may thus be seen that switch action may be obtained by providing two rotation states—zero degrees and 90 degrees—and by providing means for controlling which state the structure is in.

This controlling means, in accordance with the present invention, is a second magnetic biasing field angularly related to the longitudinal biasing field described above and having solely transverse components. Such a biasing field is represented by the circumferential field produced by current flowing through conductor 18 within element 14. By raising the amount of current flowing in conductor 18 the intensity of the circumferential magnetic field in element 11 is also raised. If this field is increased above the intensity of the longitudinal field, the equilibrium of the angular momenta of the aligned electron spins will be disturbed, and the spinning electrons will realign themselves in a direction parallel to the now predominant circumferential field. The RF magnetic vector components associated with the propagating TE_{11} mode wave energy are no longer everywhere normal to the direction of the predominating biasing field (i.e., to the direction of the aligned electron axes) and, therefore, the precessional action which resulted in Faraday effect rotation will not occur. When the element 14 is under the influence of the circumferential field, therefore, wave energy passes through guide 12 substantially unaffected by element 14 and, since there has been no polarization rotation, the energy is not of the proper polarization to be transmitted in guide section 13.

It should, of course, be obvious that any angular relationship other than 90 degrees may be utilized between guide sections 11, 13. Under conditions other than the 90-degree relationship illustrated in FIG. 1, it would be necessary to adjust the length of element 14 and the strength of the biasing field produced by source 16 accordingly. If the angular relationship chosen is 45 degrees, a third rectangular wave guide terminal extending transversely from guide 12 at a location between guide 12 and the particular one of guides 11, 13 chosen as the input terminal, and adapted to support wave energy linearly polarized in a direction normal to that supported in the input terminal, could be used as both the third port of a three port circulator and as the port at which energy which enters the input terminal would appear when the switch is in a reflective state.

A more graphic understanding of the operation of microwave switch 10 may be gained from reference to FIGS. 3, 4A, and 4B.

FIG. 4A shows by way of example, the cosinusoidally varying intensity of a circumferential biasing field, designated H_C which may be used when practicing the present invention in a pulse generator application. At points A and C in time, H_C is of zero amplitude and at points O, B, and D, H_C is of its maximum amplitude. Between these extremes H_C varies smoothly. Before examining the effect of the application of H_C to gyromagnetic element 14, let us assume that a longitudinal magnetic biasing field H_L is first applied to this element in the microwave switch of FIG. 1 and that the intensity of this longitudinal field as well as the physical length of element 14 are adjusted to provide a 90-degree rotation of the plane of polarization of plane polarized waves passing through guide section 12. One consideration in selecting the intensity of the longitudinal field is the intensity necessary magnetically to saturate the material of which element 14 is composed. By way of definition, a gyromagnetic material is magnetically saturated when all the atomic portion spins of the class upon which interest is focused are aligned with and parallel to the biasing field. A field intensity in excess of the magnetic saturation intensity provides a precessional motion useful for the production of Faraday rotation no greater than a field intensity equal to the magnetic saturation intensity. It may, however, be desirable to select H_L to be slightly less than that necessary to saturate element 14 in order to retain a means of fine adjustment of the amount of rotation produced thereby. Under the influence of H_L , the electron spins in ferrite element 14 are nearly all aligned in the direction indicated by vector H_L in FIG. 3. From the physical explanation set out hereinabove, it is clear that under this condition Faraday rotation will occur when plane polarized wave energy passes through guide section 12, thereby producing an output at guide section 13.

With the longitudinal field still being applied, let us now assume that the circumferential field H_C is applied and begin our observation at point A in time. The intensity of H_C at point A is seen from FIG. 4A to be zero. Thus, no realignment of the spinning electrons occurs and Faraday rotation of magnitude 90 degrees produced by the longitudinal field alone is unaffected. FIG. 4B illustrates, using the same time axis as FIG. 4A, the net amount of Faraday rotation produced by element 14. At point A, this amount is 90 degrees. As the magnitude of H_C increases from zero, however, electron spins originally aligned with H_L begin to reorient their axes. The direction of their alignment is parallel to the vector resultant of vector H_L and vector H_C . The complete vector diagram is shown in FIG. 3. The varying intensity of H_C continues to increase until the magnetic saturation value in the circumferential direction is reached. Under this condition, the magnitude of H_C and H_L are approximately equal, and their resultant, H_R , will be at an angle of 45 degrees with respect to both biasing directions. The amount of Faraday rotation would, therefore, be reduced to approximately half its original value of 90 degrees. As the intensity of H_C increases beyond the saturation value it predominates over H_L and substantially all of the electron spins fall into alignment with H_C . As set out hereinabove substantially no Faraday rotation will be experienced by the wave energy when the electron spins are aligned circumferentially. This condition of alignment continues over a major portion of the period of the variation of H_C . It is not until its magnitude falls back toward zero in the vicinity of point C in time on FIG. 4A that H_L again regains control over the spinning electrons and Faraday rotation of magnitude 90 degrees as shown in FIG. 4B is experienced. Thus, in FIG. 3 vector H_C may be thought of as varying in length and sense as a function of time while vector H_L remains constant and vector H_R oscillates between a vertically upward and a vertically downward position. By properly select-

ing the current wave form which produces the magnetic intensity H_C , output pulses of any desired length and time separation may be produced. The response of the switch to changing current can be rapid since the circumferential magnetic field is generated within the ferrite by the current flow itself. No metallic walls or large air gaps are present to delay or even prevent the switching action. The switching speed of the entire device therefore has as its upper limit only the inherent limitation within the ferrite material itself on the speed with which its spinning electrons may be oriented and reoriented.

If, instead of a pulse generator action, a gating action is desired, the steady switching current shown as source 17' in FIG. 1 would be used. The switch 10 would not transmit as long as switch 25 is closed, and would transmit upon opening switch 25. Thus, by using a gating pulse to open switch 25, an output would be received at terminal 13 whenever the gating pulse is present.

In all cases it is understood that the above-described arrangement is merely illustrative of the many specific embodiments which can represent applications of the principles of this invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A microwave switch comprising an input wave guide section having a rectangular transverse cross section proportioned to support linearly polarized electromagnetic wave energy within a given frequency range in only one direction of polarization, an intermediate wave guide transmission section proportioned to support said energy in a multiplicity of polarizations within said frequency range, and an output wave guide section of rectangular transverse cross section proportioned to support said energy only in a direction of polarization related by a finite angle to said one direction of polarization, magnetically controllable means within said intermediate section, for rotating the direction of polarization of wave energy propagating therein, said means being subjected to a constant amplitude magnetic field of intensity and direction to rotate said direction of polarization through an angle equal to said finite angle, and means for varying said angle of rotation comprising a switching magnetic field directed angularly with respect to said constant amplitude field with intensities both greater than and less than the intensity of said constant amplitude field.

2. A microwave switch in accordance with claim 1 in which said finite angle is 90 degrees.

3. A microwave switch in accordance with claim 1 in which said magnetically controllable means comprises gyromagnetic material.

4. In combination, a section of hollow conductively bounded wave guide adapted to support traveling plane polarized electromagnetic wave energy within a given frequency range, an element of magnetically polarizable material exhibiting the gyromagnetic effect at frequencies within said given range extending longitudinally within said guide, first means for generating a longitudinal magnetic intensity of constant magnitude within said element, and second means for simultaneously generating a magnetic intensity in said element different in direction from said longitudinal direction and having a magnitude which varies between zero and values greater than said constant magnitude.

5. A wave guide section for high frequency electromagnetic wave energy, means for producing magnetically controllable Faraday rotation in response to a first magnetic biasing field, said means comprising an element of gyromagnetic material coaxially disposed within said

wave guide section, and conductive means extending within said gyromagnetic material for simultaneously applying an additional magnetic biasing field of variable intensity with magnitudes both greater than and less than the magnitude of said first magnetic biasing field.

6. A wave guide section according to claim 5 in which said additional biasing field extends circumferentially within said element.

7. A microwave switch comprising first, second and third wave guide sections coaxially disposed in longitudinal succession, said first wave guide section proportioned to support linearly polarized traveling electromagnetic wave energy within a given frequency range in only one direction of polarization, said third wave guide section proportioned to support said energy only in a direction of polarization related by a finite angle to said first polarization, said second wave guide section proportioned to support said energy in a plurality of polarizations, an element of gyromagnetic material extending coaxially within said second wave guide section, first means for impressing a magnetic field of constant magnitude upon said element in a longitudinal direction, second means for simultaneously impressing a magnetic field of variable magnitude upon said element in a circumferential direction, said circumferential field having magnitudes both greater than and less than the magnitude of said longitudinal field, said second means comprising a conductive member extending longitudinally within said gyromagnetic element and being subjected to a controllable electric current.

8. The combination according to claim 7 wherein said first and third wave guide sections are of rectangular transverse cross sectional geometry and said finite angle is 90 degrees.

9. In combination, a section of conductively bounded wave guide proportioned to support traveling plane polarized electromagnetic wave energy in a plurality of polarizations, an element of gyromagnetic material extending coaxially within said wave guide section, first means for impressing a longitudinal magnetic field of constant magnitude upon said element, second means for simultaneously impressing a circumferential magnetic field of variable magnitude upon said element comprising a conductive member longitudinally disposed within said element, said circumferential field having magnitudes both greater than and less than the magnitude of said longitudinal magnetic field, and controllable means for introducing an electric current in said conductive member.

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