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H. SUHL ET AL

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NONRECIPROCAL WAVE GUIDE COMPONENT

Filed June 24, 1954

FIG. 1

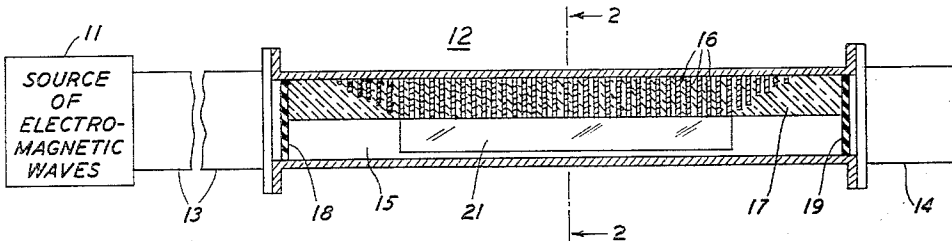


FIG. 2

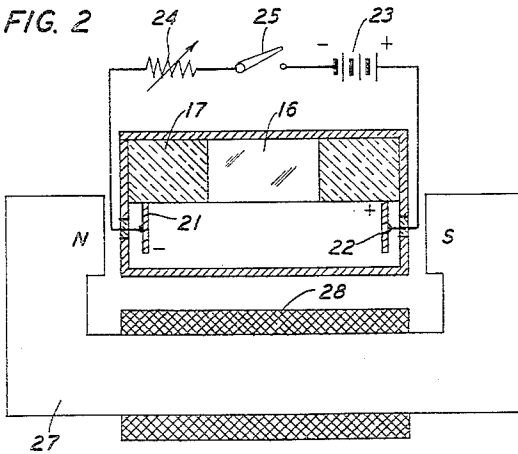


FIG. 3

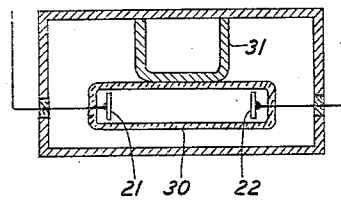


FIG. 4

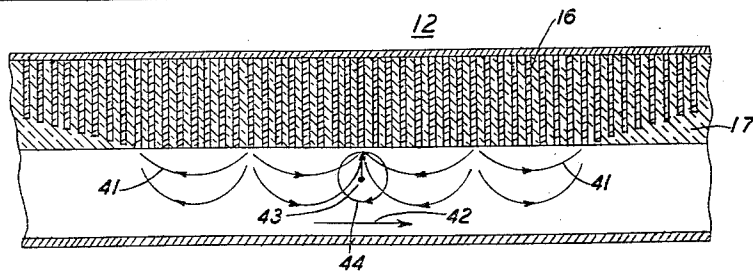
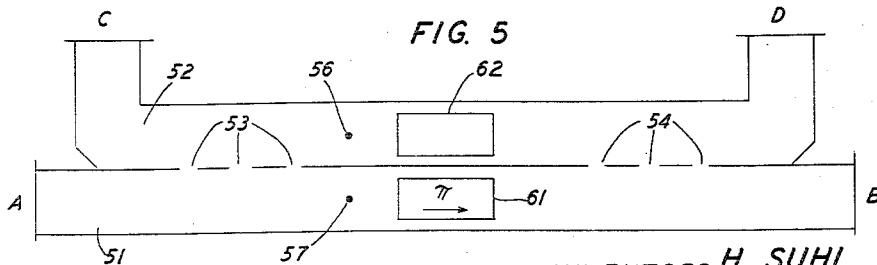


FIG. 5



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NONRECIPROCAL WAVE GUIDE COMPONENT

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5 Claims. (Cl. 333—31)

This invention relates to improvements in nonreciprocal electromagnetic wave guide components.

A nonreciprocal wave transmission device is one in which the attenuation or phase shift of waves propagating through the device is different for opposite directions of transmission. It has previously been proposed to obtain nonreciprocal effects in a rectangular wave guide, by locating an element of ferrite asymmetrically in the wave guide and applying a transverse magnetic field thereto ("A Nonreciprocal Microwave Component," M. L. Kales, H. N. Chait, and N. G. Sakiotis, Journal of Applied Physics, volume 24, No. 6, June 1953, pages 816 and 817). However, this type of nonreciprocal device is not altogether satisfactory under certain circumstances. For example, at lower microwave frequencies, below frequencies in the order of 1,000 megacycles, nonreciprocal units employing ferrites tend to become unduly long and bulky.

Accordingly, one object of the present invention is to reduce the size and cost of nonreciprocal rectangular wave guide components for lower microwave frequencies.

Another problem in the use of nonreciprocal ferrite structures lies in the difficulty of pulsing or modulating the transmitted microwaves. In microwave units in which the nonreciprocal element is solid ferrite, the nonreciprocal effect may only be varied by changing the intensity of the steady biasing magnetic field. Inasmuch as the magnet which provides the field is usually of substantial inductance or is a permanent magnet, it is not practical to make rapid changes in the nonreciprocal effect, for pulsing or other modulation purposes.

Therefore, an other object of the present invention is to increase the speed and ease of varying the nonreciprocal effect in wave guide components.

In accordance with the present invention, nonreciprocal effects are obtained through the application of a transverse magnetic field to a wave guide component containing a medium having mobile electrostatic charges. More specifically, and in accordance with an illustrative embodiment of the invention, an impedance structure extends into the wave guide component from one of its sides, and the medium in the wave guide is ionized gas. In addition, the nonreciprocal effect may be varied or eliminated by varying the extent of ionization of the gas in the electromagnetic wave guiding structure.

The invention may be more readily understood by reference to the following description taken in conjunction with the accompanying drawings forming a part thereof, in which:

Fig. 1 is a partial cross-sectional view of a wave guide system including a nonreciprocal wave guide component in accordance with the invention;

Fig. 2 is a cross-sectional view taken along line 2—2 of Fig. 1;

Fig. 3 is an alternative arrangement which may be

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employed in the nonreciprocal structure shown in Figs. 1 and 2;

Fig. 4 is an enlarged longitudinal section of the structure of Figs. 1 and 2 showing the electric field configuration; and

Fig. 5 illustrates a four-terminal nonreciprocal structure utilizing the principles of the invention.

Fig. 1 shows, by way of example and for purposes of illustration, a source of electromagnetic waves 11 coupled to one end of the nonreciprocal wave guide component 12 by means of the rectangular wave guide 13. An output wave guide 14 is shown coupled to the other end of wave guide section 12. Within the wave guide component 12 is an impedance structure 16 including a plurality of fins which extend inwardly from one of the broad walls of the wave guides as indicated more clearly in the cross-sectional view of Fig. 2. The lower open portion 15 of the wave guide section 12 is filled with a medium having free electrostatic charges. Specifically, ionized gas at low pressure is contained in this region 15 of the guide section 12 by the dielectric windows 18 and 19. The electrodes 21 and 22 which maintain the gas discharge are shown in Fig. 2. A suitable source of voltage 23, a variable resistance 24, and a switch 25 are employed to control the intensity of the gas discharge. The switch 25 may be mechanically operated and may be employed to pulse the ionized medium and thus start and stop the nonreciprocal action. Similarly, the variable resistance 24 may be employed to vary the nonreciprocity of the wave guide component by changing the extent of ionization of the gas discharge. To confine the gas discharge to the region 15 below the impedance structure 16, a suitable low loss dielectric material such as mica may be inserted between the fins 16, or the entire impedance structure 16 may be embedded in low loss plastic material 17. A magnet 27 which may be either a permanent magnet or an electromagnet having a coil 28, provides a steady magnetic field transverse to the wave guide section 12 and in the same direction as the gas discharge.

As illustrated in Fig. 1, the impedance, or slow wave transmission, structure 16 is tapered at each end to provide a gradual transition for the electromagnetic waves from the TE₀₁ mode in the rectangular wave guide 13 to the field configuration which will be present in the central portion of the wave guide section 12. The electric field components of this latter electromagnetic field configuration are illustrated in Fig. 4, which will be discussed in greater detail hereinafter.

Other impedance structures which provide a high frequency electric field configuration similar to that shown in Fig. 4 may be employed in place of the finned structure 16. One such alternative structure is illustrated in Fig. 3. The impedance structure of Fig. 3 includes a plurality of hairpin-like elements 31 which are longitudinally distributed along the wave path in a manner similar to the fins shown at 16 in Fig. 1. In addition the gas discharge is shown confined to the region below the slow wave transmission structure 31 by means of the glass envelope 30. This arrangement for confining the ionized gas is also applicable to the structure of Figs. 1 and 2. Although the glass envelope 30 in Fig. 3 or the dielectric material 17 shown in Figs. 1 and 2 are useful in confining the discharge to the region of the wave path below the impedance structure 31 or 16, respectively, this may also be accomplished by suitable adjustment of gas pressure and the potential between electrodes 21 and 22, in the absence of the envelope 30 and the dielectric material 17 and with the gas filling the wave guide structure between windows 18 and 19.

Before proceeding with the explanation of the mode of operation of the present structures, reference is made to an article entitled "Magneto-Optics of an Electron Gas with Guided Microwaves" by L. Goldstein, M. Lampert, and J. Heney, which appeared at pages 956 and 957 of the June 15, 1951, issue of vol. 82 of the Physical Review. In the experiments described in this article the Faraday effect was observed in a circular wave guide filled with ionized gas, and having a longitudinal field applied thereto.

The nonreciprocal structures disclosed in Figs. 1-4, for example, are similar to that described in the above-identified article in the type of medium used and in the use of a biasing magnetic field, but the resemblance stops at this point. Specifically, nonreciprocal effects are achieved in accordance with the present invention through the use of a transverse magnetic field and by the restriction of the magnetically polarized medium to a portion of the cross section of the wave transmission circuit.

The nonreciprocal transmission properties of the structures of Figs. 1 through 3 are based on the fact that oppositely circularly polarized radio frequency electric field components see different effective values of permeability when properly oriented with respect to the polarized medium. In particular, the ionized gas, or other medium having free electric charges, must be magnetically polarized in a direction perpendicular to the plane of the circularly polarized radio frequency electric field components.

The physical explanation for the different impedance which is observed for the radio frequency electric waves of opposite circular polarizations, involves the rotation of the electrostatically charged particles under the influence of the biasing magnetic field. Specifically, in a gas discharge arrangement as illustrated in Fig. 2 the free electrons will have a circular component of motion resulting from random movements of the electrons in directions perpendicular to the magnetic field established by the magnet 27, in addition to the linear component of motion resulting from the electric field between electrodes 21 and 22. These principles of motion of charged particles in a magnetic field, including the fact that period and the angular velocity of the electrons are independent of the speed of the electron or the radius of the circular path, are set forth in many electronic texts, and will not be analyzed in further detail here. In the gas discharge, therefore, there are many electrons having circular components of motion perpendicular to the magnetic field, and all of the electrons are revolving in the same direction and at the same angular velocity.

When a high frequency electric field having circular components which are also perpendicular to the magnetic field is applied to the medium described above, substantial coupling between the rotating electrons and the circularly polarized electric field may occur. More particularly, if the electric field is rotating in the same direction as the electrons and has about the same frequency, the electrons can absorb large amounts of energy from the electric field, the energy being absorbed into the electrons as increased radii of the circular components of the electron path. If the electric field is rotating in a sense opposite to that of the electrons, however, little or no coupling will obtain.

The nonreciprocity of the structure shown in Figs. 1 through 3 will now be shown in conjunction with the diagram of Fig. 4 in which the instantaneous electric field pattern 41 of an electromagnetic wave is shown. Assuming for the moment that the electromagnetic wave is propagating from left to right as indicated by the arrow 42, the direction of rotation of components of the electric field will be considered at some point 43 within the ionized gas medium. With the field configuration as illustrated by pattern 41 in Fig. 4, the electric vector

at a point 43 is directed upwardly. As the pattern 41 moves off from left to right, however, the electric vector will rotate in a clockwise direction as indicated by the arrow 44 encircling point 43. Assuming that the magnetic field is oriented so that this is also the direction of rotation of the electrons in the ionized gas medium, there will be strong coupling between the electromagnetic wave and the medium for waves propagating from left to right. In the case of waves propagating from right to left, however, it may be readily observed that the electric field associated with point 43 has counterclockwise circular components, and therefore will not couple with the charge particles in the magnetically polarized medium.

Mathematical analysis corroborates the foregoing physical picture of the phenomenon, and provides a more complete relationship between the important parameters. The propagation constants (normalized to free space) for the structure of Figs. 1 through 4 is as follows:

$$\frac{\beta}{\omega\sqrt{\mu_0\epsilon_0}} = \frac{\eta}{\epsilon_0} Z(\omega) \pm \sqrt{\frac{\epsilon}{\epsilon_0} + \frac{\epsilon^2}{\epsilon_0^2} Z^2(\omega)}$$

Where the combined plus and minus sign ($\pm$) indicates that the normalized propagation constants for the two directions are different and may be determined for one direction by employing the plus (+) sign and for the other direction by using the minus (-) sign.

In the foregoing equation:

β is the propagation constant,
 ω is the angular frequency of the electromagnetic wave,
 μ_0 is the permeability in a vacuum,
 ϵ_0 is the dielectric constant in a vacuum,
 $Z(\omega)$ is the impedance of the impedance structure (such as 16) at the angular frequency ω , normalized to free space;

and where ϵ and η are the diagonal and the off-diagonal components, respectively, of the dielectric tensor, normal to the steady magnetic field, and are given by the relationships:

$$\epsilon = \epsilon_0 \left(1 + \frac{q^2}{\sigma^2 - 1} \right)$$

$$\eta = \epsilon_0 \frac{q^2 \sigma}{\sigma^2 - 1}$$

where σ is the ratio of the cyclotron resonance frequency at a given steady magnetic field, to the applied frequency; and where q is the ratio of the plasma frequency to the applied frequency.

Fig. 5 illustrates the application of the present invention to a nonreciprocal microwave switch structure of the general type disclosed in M. T. Weiss application Serial No. 374,511, filed August 17, 1953, now United States Patent 2,849,685, issued August 26, 1958. In the schematic diagram of Fig. 5, terminals A, B, C, and D represent either input or output terminals of the switching arrangement. Terminals A and B are interconnected by a conductively bounded rectangular wave guide 51. Similarly, the terminals C and D are interconnected by the wave guide 52 which is of rectangular cross-section and has one of its broader sides in common with rectangular wave guide 51. The common wall between wave guides 51 and 52 is provided with two sets of directional coupling apertures 53 and 54. These apertures may be formed as shown in Fig. 9.5-15(c) on page 351 of the text entitled "Principles and Applications of Wave Guide Transmission" by George C. Southworth, D. Van Nostrand and Co., New York, 1950.

Each of the sets of apertures 53 and 54 are adjusted to transmit one-half of the energy propagating in one of the wave guides into the other wave guide. Thus, the properties of the terminal coupling aperture 53 causes a division of energy applied at terminal A so that one-half of the applied energy appears at point 56 and the other

half continues in wave guide 51 to point 57. No energy applied to terminal A is coupled back to terminal C or is reflected back to terminal A. The symbol 61 which appears in wave guide 51 between the two sets of wave coupling apertures 51 and 54 represents a nonreciprocal structure, such as is disclosed in Figs. 1 through 3 of the present drawings, and which has a differential phase shift of 180 degrees. In other words, electromagnetic wave energy which is propagated through the structure 61 in one direction, is shifted in phase by 180 degrees as compared with energy passing through structure 61 in the opposite direction. The element 62, in the position in wave guide 52 corresponding to that of element 61 in wave guide 51, is a counterpoise which is similar in construction to the unit 61 with the exception that it has no nonreciprocal properties. The element 62 could for example, be the structure shown in Fig. 2 without the electromagnet or the external circuitry required for maintaining the gas discharge.

As disclosed in the above-identified application of M. T. Weiss, four-terminal wave guide structures such as that shown in Fig. 5 have the property that energy applied at terminal A appears at terminal B; energy applied at terminal B emerges at terminal C; and energy applied at terminal C appears at terminal D; and finally, energy applied at terminal D appears at terminal A. This type of electrical circuit element is known as a circulator. The mode of operation set forth above, can readily be confirmed by tracing a signal of unity power through the apparatus while observing the limitations that (1) each of the sets of coupling apertures transmits one-half of the energy, (2) that the energy which passes through the coupling slots is shifted 90 degrees in phase, and (3) that energy passing from left to right through element 61 in the direction of the arrow, is shifted 180 degrees in phase while energy passing through from right to left is unchanged in phase.

When nonreciprocal units employing ionized gas are employed in circulators of the type shown in Fig. 5, microwave energy may be readily switched from one output terminal to another. This may be done by varying the ionization of the gas in the nonreciprocal unit. For example, referring to Fig. 2, the ionization may be pulsed by opening and closing the switch 25, or may be varied by adjusting the resistance 24. Thus, when it is desired to switch microwave energy applied to terminal A of Fig. 5, from terminal B to terminal D, the ionization in the nonreciprocal phase-shifting unit 61 is extinguished. The four-terminal unit becomes reciprocal under these circumstances and energy incident at terminal D will be applied to terminal A.

The slow wave transmission circuit made up of the fins 16 of Fig. 1 is useful in making the nonreciprocal structure more compact. However, the principles of the invention are also applicable to normal rectangular wave guides having transverse magnetic waves therein. For specific example, a rectangular wave guide in which an electromagnetic wave of the TM_{11} mode, is propagated will be considered briefly. In this case the ionizing electric and the steady biasing magnetic fields are again oriented parallel to each other and transverse to the longitudinal axis of the wave guide. In addition, the polarized ionized gas is confined to one-half of the cross-section of the rectangular wave guiding passageway. This structural arrangement provides the necessary difference in direction of rotation of the circularly polarized components of the high frequency electric field for microwaves propagating in opposite direction required for nonreciprocity.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, a wave guide, means for establishing a traveling electromagnetic wave having oppositely circularly polarized components of the electric field configuration in different respective cross-sectional regions of said wave guide, induction means for applying a transverse magnetic field to said wave guide; and a medium polarized by said induction means, and having free electrostatic charges included therein, located within one and only one of said regions.

2. In combination, a wave guide, means for establishing a traveling electromagnetic wave having oppositely circularly polarized components of the electric field configuration in different respective regions of said wave guide, induction means for applying a transverse magnetic field to said wave guide, ionizable gas located within one and only one of said regions, and means for ionizing said gas.

3. A nonreciprocal electromagnetic wave guide device comprising an elongated hollow conductively bounded wave guide, a slow wave transmission structure extending into a portion of said wave guide from one side wall thereof for generating a circularly polarized component of the electric field configuration in the remaining portion of said wave guide said slow wave structure comprising a plurality of longitudinally spaced conducting elements, means for providing ionized gas in said remaining portion of said wave guide adjacent the edges of said conducting elements, means for varying the ionization of said gas, and means for applying a transverse magnetic field to said gas.

4. In combination, a wave guide, means for applying traveling electromagnetic waves of a predetermined frequency to said wave guide in one direction, said electromagnetic waves having oppositely circularly polarized components of the electric field configuration in different transverse regions of said wave guide, means for applying the same type of electromagnetic waves to said wave guide in the opposite direction, means for providing ionizable gas in only one of said regions of said wave guide, means for ionizing said gas, and induction means for applying a transverse magnetic field to said ionized gas of sufficient strength to produce a cyclotron resonance frequency for the free electrons in said gas of the same order of magnitude as said predetermined frequency.

5. In combination, a rectangular wave guide, a slow wave transmission structure extending into said wave guide, means for applying traveling electromagnetic waves to said wave guide, said electromagnetic waves having oppositely circularly polarized components of the electric field configuration in different transverse regions of said wave guide, means for providing ionized gas in only one of said regions of said wave guide, and induction means for applying a magnetic field to said ionized gas in a direction transverse with respect to said wave guide and perpendicular to the plane of the circularly polarized components of the electric field.

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