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2,911,554

NON-RECIPROCAL WAVE TRANSMISSION DEVICE

Filed June 17, 1953

2 Sheets-Sheet 1

FIG. 1

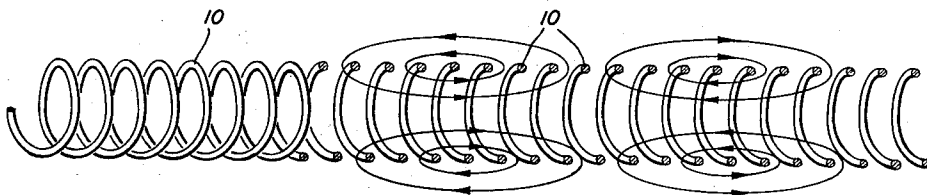


FIG. 2

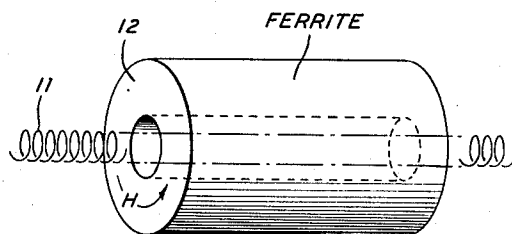
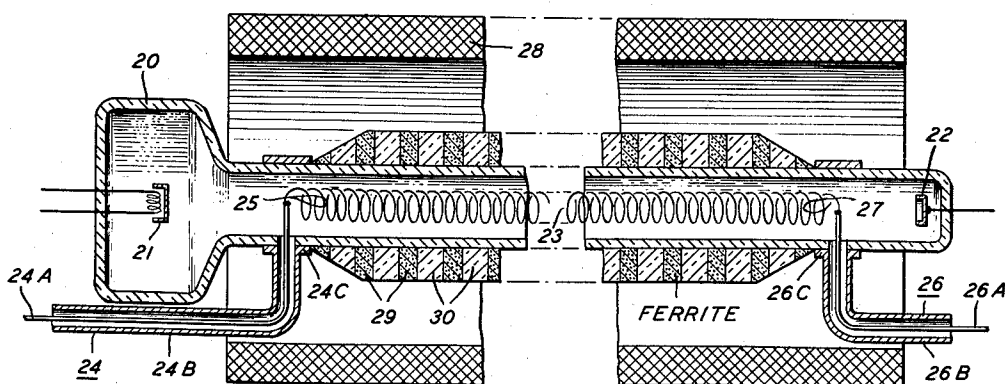


FIG. 3



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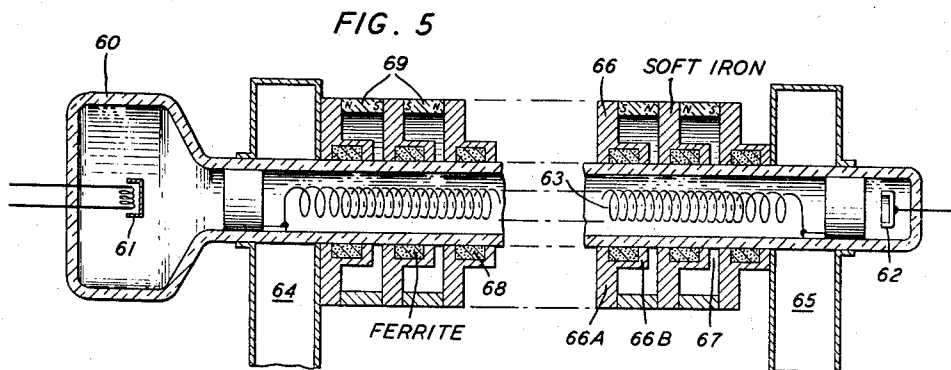
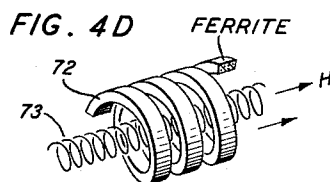
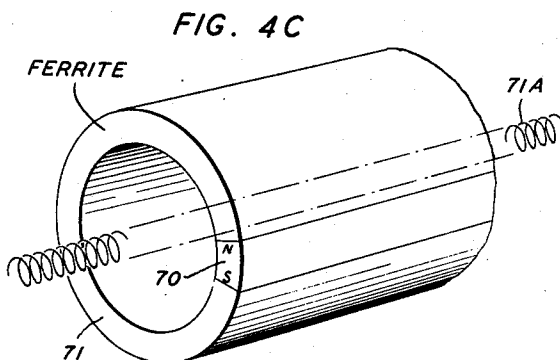
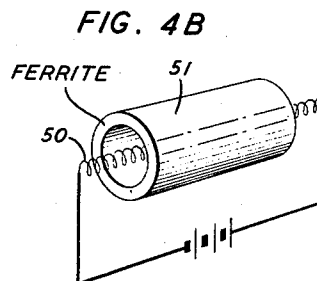
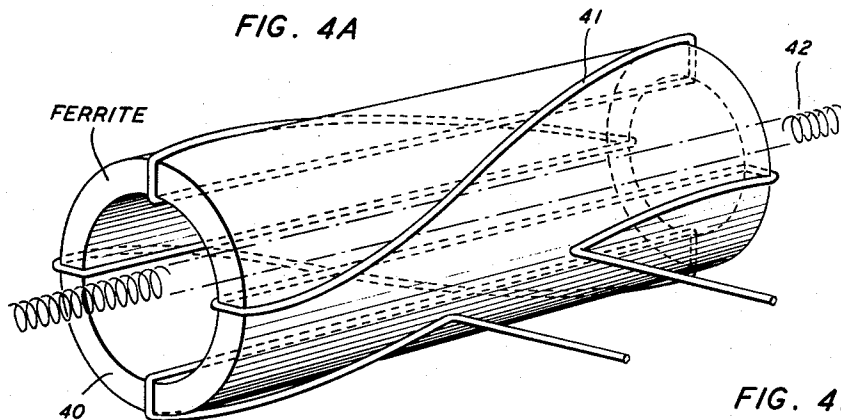
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1

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NON-RECIPROCAL WAVE TRANSMISSION DEVICE

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Application June 17, 1953, Serial No. 362,177

9 Claims. (Cl. 315—3.5)

This invention relates to electromagnetic wave transmission apparatus, and more particularly to devices which have non-reciprocal transmission characteristics i.e., whose transmission characteristics are different in the two directions of transmission possible through such devices.

An important object of the invention is a novel non-reciprocal radio frequency transmission device.

In a broad aspect, the invention provides a radio frequency transmission device which in one direction permits transmission therethrough with low and even negative attenuation while in the other direction it inserts high attenuation.

In another important aspect, this invention relates to radio frequency devices which utilize the interaction between a traveling electromagnetic wave and an electron stream over a distance a plurality of operating wavelengths long to secure amplification to the traveling wave. Such devices are now generally termed traveling wave tubes.

A more specific object of the present invention is to increase the gain and overall efficiency of such tubes.

Another object of the present invention is to improve the noise figure of such tubes.

It shall be convenient to describe the principles of the invention with specific reference to incorporation in such tubes. In the past, it has generally been necessary in traveling wave tubes to insert considerable high frequency attenuation or loss in the traveling wave path in order to maintain stability and avoid long-line impedance effects. The reason for this is that it is extremely difficult to secure accurate impedance matches between the traveling wave tube interaction circuit and the signal input and output coupling connections thereto over the broad frequency range in which the tube amplifies. Components of radio frequency signal, together with noise components, tend, therefore, to be reflected back and forth along the interaction circuit. Such components are amplified in successive forward traversals of the interaction circuit and may produce oscillations, resulting in tube instability. Moreover, when such components are reflected back to the input end of the interaction circuit out of phase with the incoming signal wave, the signal wave is degraded, resulting in what may be termed long-line impedance effects. The insertion of attenuation or loss in the traveling wave path absorbs these reflected components traveling in the direction opposite to that of the electron flow. However, such loss also absorbs proportionally energy from the signal wave traveling in the direction of electron flow. Some discrimination in the two directions is achieved, however, because the signal modulations on the electron stream move along only in the direction of electron flow. In general, if the loss in the traveling wave path in the absence of the electron stream exceeds the net forward gain at all frequencies, the tube is stable, with the following exception: if the wave interaction circuit supports spatial harmonic components, backward wave type oscillations may be set up when the

2

beam current is high. The insertion of loss along the traveling wave path in the conventional manner will generally affect the ability to provide gain and to oscillate in the backward wave mode to about the same degree.

Accordingly, although loss insertion is generally beneficial in suppressing oscillations due to internal reflections, it reduces the available overall gain, makes for reduced overall efficiency especially in high-power tubes, and additionally causes deterioration in noise figure particularly of low-noise tubes. Moreover, if the loss is applied heavily over only a short distance along the helix, some reflection of power is liable to occur at the loss and this causes a deterioration in the frequency response of the tube.

Accordingly, specific objects of the present invention are to maintain stability and reduce long-line effects in traveling wave tubes with a minimum effect on gain, efficiency and noise figure.

It has been known hitherto that there exist substances which make use of gyromagnetic phenomena to provide non-reciprocal phase velocities and attenuation constants. Typical of such phenomena are the Hall effect, the cyclotron resonance in a plasma, Faraday rotation, and ferromagnetic resonance. It has been known that the last two effects are of special importance in a class of ferromagnetic substances known as "ferrites" which are relatively homogeneous crystalline compounds comprising the reaction product of iron oxide and at least one other metallic oxide and which in a particular state of magnetization will have a non-reciprocal effect on circularly polarized waves propagating therethrough.

For a more detailed description of the relevant theory, reference is made to an article in the Bell System Technical Journal, January 1952, pages 1-31, entitled "The Ferromagnetic Faraday Effect at Microwave Frequencies and Its Application—A Microwave Gyrator," by C. L. Hogan.

A feature of the present invention is the use of the ferromagnetic resonance and Faraday effect in ferromagnetic substances such as ferrites, to provide substantially unidirectional loss in a wave guiding path. In the more usual case, in traveling wave tubes in which amplification is achieved by interaction between an electron stream and a wave traveling in the direction of the electron stream (generally designated as the forward direction) the loss is made predominant in the backward direction. In the case in which amplification is achieved by interaction between an electron stream and an oppositely directed (or backward) traveling wave, as is characteristic of backward wave amplifiers and oscillators, the loss is made predominant in the forward direction. In accordance with one aspect of the invention, an element of ferrite is disposed adjacent the wave interaction circuit in a region where the radio frequency waves traveling therealong have large circularly polarized magnetic components and the state of magnetization of the ferrite is adjusted to have magnetic lines of intensity extend perpendicular to the planes of rotation of the circularly polarized magnetic components of the radio frequency waves. In this way, waves traveling along the interaction circuit in a chosen direction are appreciably attenuated while similar electromagnetic waves traveling along the interaction circuit in the opposite direction are little affected.

In specific illustrative embodiments of the invention, to be described in detail hereinafter, a helical conductor serves as the wave interaction circuit and a hollow cylinder of ferrite biased to a state of circumferential magnetization surrounds the helix for providing the desired directly selective loss. In such an arrangement, it has been discovered that the radio frequency magnetic field outside the helix is elliptically polarized with the planes of polarization substantially coinciding with planes

3

through the axis of the helix. Accordingly, in planes passing through the helix axis a wave traveling along the helix in one direction has a circularly polarized component of one sign (it will be convenient to describe as of positive sign a circular polarization which rotates clockwise when looking along a north-to-south pole biasing magnetic vector, and of negative sign a circular polarization which rotates counterclockwise) and a wave traveling in the opposite direction has a circularly polarized component of opposite sign. Since in a ferrite the permeability for a radio frequency wave whose magnetic intensity is at right angles to the biasing lines of D.C. magnetic intensity of the ferrite will be affected oppositely by the sign of the circular polarization, the wave propagating along the helix will be attenuated in traveling past the ferrite cylinder in amounts which depend on its direction of travel. In specific illustrative embodiments of the invention described, a longitudinal magnetic field is employed to aid in focusing the electron beam, and so advantageously a series of longitudinally spaced ferrite cylinders surrounds the helix, each biased to a circumferential state of magnetization.

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawings in which:

Fig. 1 shows the magnetic lines of intensity associated with a radio frequency wave propagating along a helix;

Fig. 2 shows a ferrite cylinder surrounding a helix which is biased in a circumferential direction in accordance with one aspect of the invention for introducing non-reciprocal attenuation to waves propagating along the helix;

Figs. 3 and 5 each show longitudinal cross sections of traveling wave tubes utilizing ferrite elements in accordance with the invention; and

Figs. 4A through 4D illustrate various possible arrangements for achieving a circumferential magnetic field in a cylindrical ferrite element for use in the practice of the invention.

With reference now to the drawings, Fig. 1 is a longitudinal section taken along the axis of a helically wound conductor 10 along which is propagating a radio frequency wave. It has been discovered that the lines of magnetic intensity associated with the propagating wave are loops which lie almost entirely in radial planes taken along the helix axis. Here in the interest of simplicity, the loops of magnetic intensity are shown as lying entirely in the radial plane which is also the plane of the paper. At points surrounding the helix, the magnetic intensity has components which are elliptically polarized. It is found that although the ellipticity becomes more circular with increasing distance from the helix, the magnetic intensity falls off with increasing distance from the helix. In the practice of the invention, it is advantageous to locate the ferrite material both in a region of high magnetic intensity and in a region of circular polarization. However, it is usually found that for traveling wave tube operation it is preferable to have the ferrite cylinder surround the helix as closely as possible. The direction of the rotation of the circularly polarized magnetic intensity depends on the direction of wave propagation, being reversed for the different directions of wave propagation. For example, as shown, in the region surrounding the helix the rotation is counter-clockwise for a wave traveling from left to right and clockwise for a wave traveling from right to left, while in the region enclosed by the helix the converse is true. This means merely that at a given point the magnetic vector describes essentially a circle lying in a radial plane, the direction of rotation of which vector depends on the direction of travel of the wave. In accordance with the invention this difference in direction of rotation of the circularly polarized components of waves traveling in opposite directions along a helical interaction circuit is utilized to provide a difference in attenuation in the two directions.

4

In Fig. 2, a helical conductor 11 is shown surrounded by a hollow cylinder of ferrite 12 whose state of magnetization is circumferential, as is shown, with magnetic lines of intensity lying in transverse planes, perpendicular to the radial planes through the helix axis where the radio frequency magnetic lines have large circularly polarized components. As is well known, if the magnetic intensity of the ferrite is biased in a given plane, the attenuation for a radio frequency wave whose magnetic intensity is circularly polarized in a plane at right angles to that of the biasing magnetic intensity will vary with the direction of the rotation of the circular polarization. In particular, if the ferrite is biased to a point near ferromagnetic resonance, the non-reciprocal nature of the attenuation is enhanced. It is in accordance with a specific embodiment of the invention applicable to helical wave guiding circuits to magnetize the ferrite to have magnetic lines of intensity in planes perpendicular to the helix axis. By having the lines of magnetic intensity in the ferrite circumferential and concentric with the helix axis, this condition on perpendicularity is satisfied in all the radial planes. In tests which have been conducted utilizing a ferrite cylinder having the composition $\text{Ni}_2\text{Zn}_7\text{Fe}_2\text{O}_4$, considerable non-reciprocal attenuation effects have been achieved with a circumferential applied magnetic field of ten to twenty oersteds.

It should be appreciated that in one aspect the invention provides an isolator which makes of a helical conductor a substantially non-reciprocal transmission element. Such a non-reciprocal helix transmission element has applications outside the field of traveling wave tubes. For example, it can be inserted serially in any appropriate transmission path to provide non-reciprocal transmission characteristics to the path. For example, the helix can be inserted in a coaxial transmission line, the helix being formed as a continuation of the inner conductor of the line to provide non-reciprocal attenuation characteristics to the line. As shall be seen hereinafter, this is essentially what is done in the traveling wave tube shown in Fig. 3. There, additionally, an electron stream is simultaneously projected past the helix to provide a negative attenuation in a preferred direction. Alternatively, the helix can be inserted serially between two wave guides as is characteristic of the traveling wave tube shown in Fig. 5.

By way of example for purposes of illustration, the helix type traveling wave tube shown schematically in Fig. 3 is provided with loss which is non-reciprocal in accordance with the principles set forth above. The various tube elements are housed in a glass envelope 20. At one end of the envelope, there is positioned the source of the electron beam, which has been shown simply here as an electron-emissive cathode 21. At the opposite end of the envelope there is positioned a target electrode 22 for collecting the spent electrons. Disposed along the path of electron flow is the helical conductor 23 which serves as the wave interaction circuit for propagating a slow electromagnetic wave in field coupling relation with the electron flow.

Various arrangements are known for applying input and abstracting output waves from a helix. In the illustrative arrangement, input waves are supplied by the coaxial line 24 which is coupled to the input end of the helix. To this end, the conductor which forms the helix is extended through the tube envelope and makes electrical contact with the inner conductor 24A of the coaxial line. For impedance matching purposes, it is advantageous to increase gradually the pitch of the helix over an end region 25 and to decrease gradually the diameter of the coupling end of the inner conductor of the coaxial to the size of the diameter of the conductor forming the helix. The outer conductor 24B of the coaxial line advantageously is flared out at its end to form a collar which surrounds a portion of the tube envelope. Alternatively, the outer conductor 24B could be made

5

integral with a metallic shield surrounding the tube envelope. At the output end of the helix, the amplified waves are supplied to a coaxial line 26. The coupling connection here is similar to that at the input end, the inner conductor 26A of the coaxial line being connected to the conductor which forms the helix by way of a tapered impedance matching section 27 of helix and the outer conductor 26B of the coaxial line being formed into a collar which surrounds a portion of the helix envelope, and which alternatively could be made integral with a metallic shield surrounding the tube envelope.

Additionally it is customary to include a longitudinal magnetic field along the path of flow for keeping the flow cylindrical. For this purpose, in the tube depicted a solenoid 28 surrounds the tube envelope. The foregoing describes briefly the basic elements of a conventional helix-type traveling wave tube. As is set forth above, a feature of the present invention is an arrangement for introducing loss into the wave guiding path of the tube which affects waves traveling from the output end of the helix to the input end considerably more than waves traveling from the input to the output ends of the helix. It is generally desirable to have a difference of at least forty decibels between the two directions of transmission.

To this end, a succession of hollow ferrite cylinders or rings 29 are disposed around the tube envelope, each in a state of circumferential magnetization as described above. It is desirable to utilize a spaced succession of cylinders, as shown, instead of a single extended cylinder where there is employed a longitudinal magnetic field for beam focusing as is done here. In this way, the succession of non-magnetic gaps 30 between ferrite cylinders serves to keep the reluctance of the path through the succession of cylinders high to the longitudinal magnetic field. This is advantageous for minimizing the disturbance both on the axial magnetic field in the region of electron flow and on the circumferential magnetic field in the ferrite cylinders. It may be advantageous to fill the gaps 30 with a suitable non-magnetic material so that the succession of ferrite cylinders can be integrated into a single unit. It is also advantageous for minimizing reflection effects to taper the outer diameters of the end ferrite cylinders as shown.

Various arrangements are possible for magnetizing the ferrite cylinders in a circumferential direction as desired. The simplest physical arrangement is achieved if the cylinders are permanently magnetized. If the amount of intrinsic permanent magnetization of the ferrite material is insufficient, it may be desirable to mix the desired ferrite material with a magnetic material of high retentivity and the mixture given the biasing permanent magnetic intensity necessary for operation close to ferromagnetic resonance where the non-reciprocal attenuation property is appreciable. Alternatively, the cylinder can be formed of laminated layers of ferrite and a permanent magnet material. Along these same lines it may be desirable to use large compressive forces to permanently magnetize the ferrite to the desired value.

Alternatively, it is possible to provide the biasing magnetic field by means of a biasing electromagnetic coil. In Fig. 4A there is shown a ferrite cylinder 40 about which is wound a biasing coil 41 which, when energized, provides a circumferential magnetic field around the ferrite cylinder surrounding the helix.

Another arrangement for providing the desired biasing magnetic field is shown in Fig. 4B. Here a D.-C. energizing current is supplied to a conductor 50 passing axially through the ferrite cylinder 51. The conductor may be the helix itself, as shown, or simply a straight conductor.

Another arrangement is shown in Fig. 4C. Here the permanent magnet 70 is combined with a sector of ferrite 71 to form a closed loop surrounding the helix 71A.

Still another expedient which can be used advantageously to make the use of circumferentially magnetized ferrite elements compatible with the use of an axial mag-

6

netic field for focusing is illustrated in Fig. 4D. The ferrite element is formed as a helix 72 coaxial with the helical interaction circuit 73. Then, the focusing axial magnetic field in following the helical path of the ferrite becomes transformed into a helical magnetic field which has a circumferential component at right angles to the planes of rotation of the circularly polarized components of the radio frequency fields associated with the helical interaction circuit. In such an arrangement it will be characteristic that the sense of the winding of the ferrite helix determines the direction of induced magnetic flux and accordingly provides another parameter that can be used advantageously in fixing the direction of high loss.

It is obvious from these various arrangements that there are a variety of ways for achieving the desired circumferential magnetization state for the ferrite elements surrounding the helix.

Moreover, it should also be evident from principles of operation set forth that the ferrite elements can be inserted within the region bounded by the helical conductor for acting on the magnetic field therein for achieving the desired non-reciprocal attenuation characteristics.

Additionally, there has been devised recently a technique for focusing an electron stream which utilizes a periodically varying longitudinal magnetic field. The general principles of such a focusing scheme are set forth in application Serial No. 362,310, filed June 17, 1953, by J. R. Pierce, now Patent No. 2,849,642. In Fig. 5, there is shown schematically a traveling wave tube incorporating such focusing principles which has been adapted to the principles of the present invention. The traveling wave tube in conventional fashion comprises an evacuated glass envelope 60, housing at opposite ends a source of electrons 61 and a target 62 therefor, and a helical conductor 63 disposed along the path of electron flow for forming the wave interaction circuit. Input waves to be amplified are applied from an input wave guide connection 64 coupled to one end of the helical conductor 63 and output waves are abstracted from the opposite end into an output wave guide connection 65. The periodically varying magnetic field for focusing the beam is achieved by a suitable permanent magnetic structure of which a typical form is here illustrated. A succession of annular elements 66 of a magnetic material, having a permeability higher than that of the ferrites to be used for achieving the non-reciprocal attenuation characteristics, such as soft iron, is disposed around the tube envelope, spaced apart therealong for forming a succession of gaps 67 adjacent the path of flow. Each annular element 66 has a flange-like portion 66A extending laterally away from the path of flow and a ring-like portion 66B extending longitudinally in the direction of flow. The inner surface of the ring-like portion 66B is provided with an annular gap wherein is positioned an annular ferrite element 68 of the kind described above, i.e., biased to a circumferential state of magnetization for providing non-reciprocal attenuation characteristics to electromagnetic waves traveling along the helical conductor. The successive magnetic elements 66 serve as pole pieces, adjacent elements being oppositely poled. To this end, cylindrical annular permanent magnets 69 magnetized in an axial direction are bridged between the ends, remote from the path of flow, of the flange-like portions 66A of adjacent magnetic elements 66. The orientation of the poles of successive permanent magnets 69 is reversed as shown in order to polarize adjacent magnetic elements 66 oppositely. By an arrangement of this kind, a succession of regions of longitudinal magnetic field, adjacent the gap regions 67, is set up along the path of flow, the direction of this field reversing with successive regions. The electron stream can be focused by such a periodically varying magnetic field as is described in detail in the aforementioned Pierce application. However, in the regions between the gaps 67 where there are positioned the ferrite elements, the longitudinal magnetic flux is almost entirely

confined to the interior of the ring-like portion 66B of each annular element 66 since the reluctance of this path is considerably lower than the reluctance of the path through the ferrite element. In this way, there will be little effect on the circumferential magnetic field with which each ferrite element 68 is biased. Alternatively, there may be inserted in each region of longitudinal magnetic field a helical section of ferrite of the kind shown in Fig. 4D. To compensate for the reversal in direction of the magnetic field in successive field regions the sense of the winding of successive helical sections can be reversed correspondingly.

It is known also that ferrites under proper states of magnetization exhibit non-reciprocal propagation characteristics in a manner analogous to the non-reciprocal attenuation properties described above. It is consistent with the general principles of the invention to utilize such non-reciprocal propagation characteristics by the inclusion of resistive material in the wave guiding path to achieve overall non-reciprocal attenuation properties.

It is also to be understood that although the invention has been described with specific reference to embodiment in a traveling wave tube which employs a helix as the wave interaction circuit, the principles are similarly applicable to traveling wave tubes incorporating other forms of wave interaction circuits. In applying the principles of the invention to such other forms of wave interaction circuits, there should first be analyzed the radio frequency lines of magnetic intensity associated with such circuits for the discovery of a region of circular polarization. Then, a ferrite element is there positioned in a state of magnetization to have its biasing lines of magnetic intensity at right angles to the circularly polarized components of the radio frequency field.

What is claimed is:

1. In a device which utilizes the interaction between a traveling electromagnetic wave and an electron stream, a wave interaction circuit comprising a helix for propagating electromagnetic waves, means for forming an electron stream for flow past said helix and a cylindrical ferrite element surrounding and coaxial with the helix, and means providing in the ferrite element a steady magnetic field in a circumferential direction surrounding the electron stream.

2. In combination, first and second wave guiding means, means including a helical conductor for forming a slow wave path between said first and second means, and means for making said slow wave path nonreciprocal in its propagation characteristics comprising a gyromagnetic element surrounding the helical conductor, and means for providing a steady magnetic field through the gyromagnetic element in a circumferential direction surrounding the helical conductor.

3. In a device which utilizes the interaction between a traveling electromagnetic wave and an electron stream, means forming a slow wave path, means for forming an electron stream for flow past said slow wave path, an input connection for introducing an electromagnetic wave to be amplified into said wave path, an output connection for abstracting the amplified electromagnetic wave from said path, and a ferrite element extending along said path in a region of circular polarization of the magnetic field of electromagnetic waves traveling along said wave path, and means for establishing in the ferrite element a steady magnetic field perpendicular to the circularly polarized magnetic field components of said electromagnetic waves whereby the slow wave path exhibits non-reciprocal attenuation.

4. In a device which utilizes the interaction between a traveling electromagnetic wave and an electron stream, means forming a slow wave path, means forming an electron stream for flow past said slow wave path, an input connection for introducing an electromagnetic wave to be amplified in the same slow wave path, an output connec-

tion for abstracting the amplified electromagnetic wave from the wave path, and a gyromagnetic element extending along the wave path and positioned in a region where there are strong components of circularly polarized magnetic field, and means forming a steady magnetic field in the gyromagnetic element perpendicular to the planes of rotation of the strong components of the circularly polarized magnetic field of the traveling electromagnetic wave whereby the slow wave path exhibits non-reciprocal attenuation.

5. In a device which utilizes the interaction between a traveling backward wave and an electron stream, means forming an electron stream, means forming an extended slow wave path along the path of flow of the electron stream for propagating backward traveling electromagnetic waves in coupling relation with the electron stream, a gyromagnetic element positioned along said slow wave path in a region characterized by circularly polarized magnetic field components of waves propagating along the slow wave path, and means forming a steady magnetic field at right angles to the planes of rotation of the circularly polarized magnetic field components of the waves traveling along said slow wave path whereby the slow wave path exhibits non-reciprocal attenuation characteristics.

6. In combination, means forming an electron stream, a helical conductor disposed along the path of flow of said stream for propagating waves in coupling relation therewith, a plurality of magnetic elements spaced apart along the path of flow and surrounding the helix for forming along the path of flow a spatially alternating longitudinal magnetic field, a plurality of ferrite cylinders spaced apart along the path of flow surrounding the helix and adjacent said magnetic elements, and means for biasing said magnetic elements in a circumferential direction surrounding the electron beam to a state of circumferential magnetization.

7. In a traveling wave tube, means including a helical conductor for forming a slow wave circuit for propagating a traveling wave, means for forming an electron stream for flow past said helical conductor for interacting with said slow wave, means establishing a steady longitudinal magnetic field for focusing the beam in its path of travel past the helical conductor, and means comprising a helical element of gyromagnetic material positioned coaxial and coextensive with said helical conductor in the region of longitudinal magnetic field for making said slow wave circuit non-reciprocal in its propagation characteristics.

8. In a traveling wave tube, means including a helical conductor for forming a slow wave circuit for propagating an electromagnetic wave, means for forming an electron stream for flow past said circuit, a helical ferrite element coaxially surrounding the helical conductor, and means establishing a steady longitudinal magnetic field for focusing the stream in its path of travel past the helical conductor and for magnetizing in a circumferential direction said helical ferrite element to a steady value such that the slow wave circuit is non-reciprocal.

9. In combination, means forming an electron stream, a conductive helix positioned along the path of flow of said stream for providing a slow wave path for propagating a traveling wave in coupling relation with the electron stream, a helical ferrite element positioned coextensive and coaxial with said helix, and means for establishing a steady magnetic field along said helical ferrite element, whereby the conductive helix exhibits non-reciprocal attenuation characteristics.

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