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NON-RECIPROCAL WAVE TRANSMISSION

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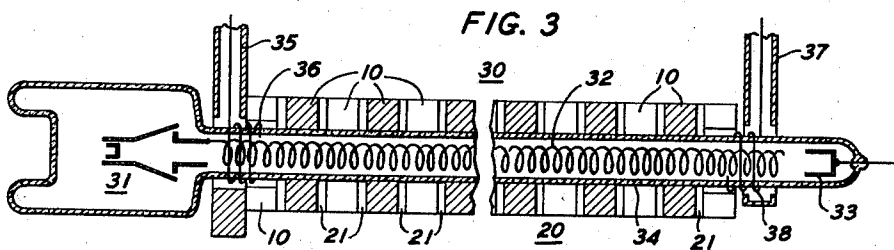
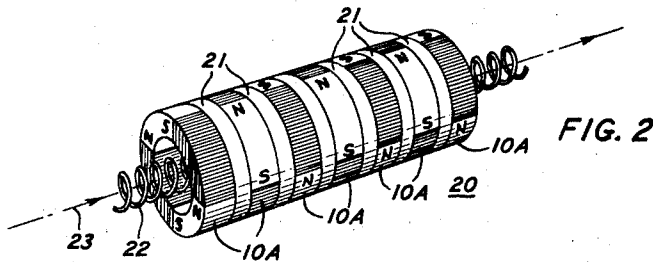
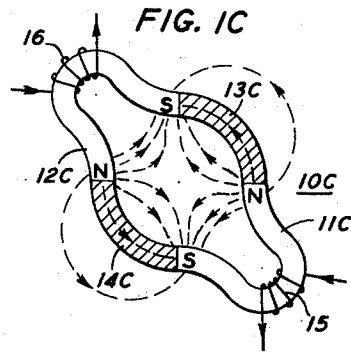
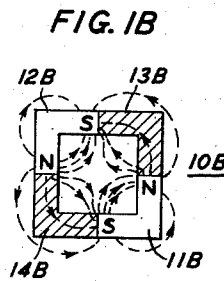
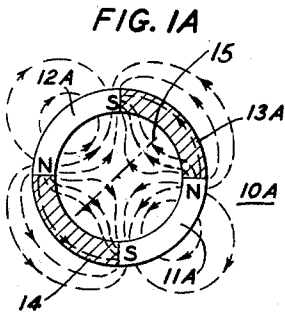
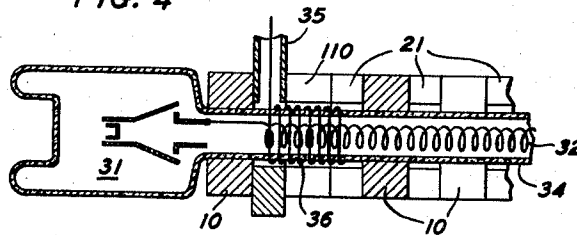


FIG. 4



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NON-RECIPROCAL WAVE TRANSMISSION

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16 Claims. (Cl. 315—3.5)

This invention relates to apparatus for focusing an electron stream and for providing selective attenuation to an electromagnetic wave in a device which utilizes the interaction between an electromagnetic wave and an electron stream and more, particularly in a device of the kind which is commonly designated a traveling wave tube.

In such a tube an electromagnetic wave propagates along an interaction circuit past which is projected an electron stream in field coupling relationship with the electromagnetic wave over a plurality of operating wavelengths. In practice, it is found that there are various problems associated with the operation of such devices.

First, because of the relatively long length of the electron path and because of the space charge forces acting in an electron stream when the electron density is high, as is generally desirable, it is important to provide focusing to keep the electron flow cylindrical during its travel past the interaction circuit.

Additionally, it has been found that some consideration must be given to the problems of wave distortion and stability in these interaction devices. In particular, it is extremely difficult to secure accurate impedance matches between the interaction circuit and the microwave signal input and output connections thereto for the broad frequency range over which the tube amplifies. Any mismatch at the input or output coupling elements results in reflections of both noise and the microwave signal back and forth along the interaction circuit. Such reflections tend to cause signal distortion and in extreme cases may result in instability. As a consequence it is now the usual practice to insert attenuation or loss in the traveling wave path to absorb the reflected wave energy. Moreover, it is particularly desirable to insert loss which is nonreciprocal so that when associated with the interaction circuit, the circuit will provide unidirectional propagation whereby wave energy reflected from the output will be absorbed and the signal wave proper will be relatively unaffected. In a copending application, Serial No. 362,177, filed June 17, 1953, by R. Kompfner and H. Suhl, there is developed in more detail the advantages of such nonreciprocal loss.

An object of the present invention is to provide a simple structure which functions both to focus a stream of charged particles and to provide nonreciprocal transmission in a microwave path.

It has been known heretofore that there exist substances which make use of gyromagnetic phenomena to provide nonreciprocal 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." For a 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 Ferro-

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magnetic Faraday Effect at Microwave Frequency and Its Application—A Microwave Gyrator," by C. L. Hogan. In the present invention, ferrites are employed to achieve nonreciprocal attenuation in the wave circuit.

5 Additionally, there has recently been developed a technique for focusing a beam of charged particles which has been described as "strong focusing," which utilizes a succession of transverse magnetic field regions which cooperate with the longitudinal velocity of the charged particles. The principle of "strong focusing" as applied to the problem of focusing a stream of charged particles is described in an article entitled "The Strong Focusing Synchrotron—A New High Energy Accelerator," in the Physical Review, vol. 88, pages 1190-1196. In such 10 focusing systems a succession of quadrupolar magnetic field regions is positioned along the beam path, the quadrupolar field in successive regions being oriented so that the beam is focused alternately in two mutually perpendicular planes. The strength and periodicity of the magnet sections are adjusted so that the transverse excursions of the edge particles are small. In particular, it has been found advantageous to employ quadrupole magnets for establishing the successive magnetic field regions and to rotate successive magnets 90 degrees for 20 arranging the successive quadrupolar fields in quadrature. In the present invention quadrupolar magnetic focusing is used to focus the electron beam. The term quadrupole as used herein signifies the characteristic of having four poles. The term quadrupolar field is used to designate a field of the kind that is provided by a set of four pole pieces of identical strength symmetrically disposed about a center point, adjacent pole pieces being of opposite polarity.

An important feature of the present invention is a 35 novel structure which provides the dual function of focusing and selectively attenuating. To this end, in one specific embodiment, the structure comprises a linear array of axially disposed annular members surrounding a path of electron flow. Each annular member forms a closed magnetic loop and includes a pair of magnets 40 symmetrically disposed around its periphery, and portions of ferrite material interspaced between the magnets. By making the strength of the magnets sufficient to cause saturation of the ferrite portions, there results a quadrupolar magnetic field in the region surrounded by the annular member. Successive annular members 45 along the electron path are rotated substantially 90 degrees for maintaining the successive quadrupolar fields substantially in quadrature while maintaining circumferential magnetization in the same sense in each of the annular members.

In operation, the electron beam is projected longitudinally along the aperture through the linear array of axially disposed annular members and is effectively constrained in a beam configuration by the focusing action of the successive quadrupolar magnetic fields.

Moreover, such a structure, when positioned to surround a helical conductor of the kind which forms the most common form of interaction circuit for a traveling wave, will provide nonreciprocal loss to the wave propagated along the helical conductor. In particular, this arrangement is especially advantageous for use at very high frequencies for reasons which will be discussed more fully hereinafter.

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

65 Figs. 1A through 1C show illustrative forms of quadrupole type magnets containing sections of ferrite for use in the practice of the invention;

70 Fig. 2 shows as an illustrative embodiment of the invention, a linear array of several members of the

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quadrupole type magnets surrounding a helical slow wave structure;

Fig. 3 is a diagrammatic illustration showing the novel focusing arrangement embodied in a traveling wave tube; and

Fig. 4 is a diagrammatic illustration showing an alternative arrangement for coupling into a traveling wave tube which is provided with the novel focusing arrangement.

Typically for focusing in accordance with the spirit of the invention there is desired a magnetic field configuration transverse to the path of electron flow, of the kind shown in Fig. 1A, where the desired field pattern is achieved by annular member 10A which includes a quadrupole arrangement of a pair of magnets 11A and 12A interspaced by a pair of ferrite sections 13A and 14A. By arranging the pair of magnets to be series aiding as shown a single complete magnetic loop will be described by the annular member wherein magnetic lines of force will pass circumferentially through this member. As the strength of the magnets is increased the ferrite sections become saturated and the lines of force tend to fringe around the sections of ferrite, approaching as a limit, the field which would exist in the absence of these ferrite sections. The electron beam in passing transversely through such a field configuration (moving longitudinally perpendicular to the plane of the paper) tends to be focused in the plane shown by line 15. To transform this planar focusing into linear focusing, a linear array of such members is provided and their field patterns are rotated 90 degrees periodically along the longitudinal path of flow so that the electron beam is focused alternately in two mutually perpendicular planes, the intersection of which describes a line. By adjusting the strength and periodicity of the successive regions of transverse electromagnetic fields the lateral excursion of the electrons from a linear beam can be made very small.

The periodic rotating of successive fields along the longitudinal path of flow may be more clearly seen by referring to Fig. 2. This figure shows a linear array of annular members of the type described above, successive members being advantageously spaced apart by nonmagnetic spacing rings 21. As discussed above, successive annular members are arranged substantially in quadrature in order to obtain successive regions of transverse magnetic fields along the axis of the array, each of which is rotated 90 degrees with respect to adjacent regions.

In operation, the path of flow is along such axis, and a slow wave is propagated by means of helical conductor 22 surrounding and in coupling relation with the electron beam.

In addition to the electron focusing action described, arrangement 20 also provides nonreciprocal attenuation to a wave traveling along the helix 22. As is described in the aforementioned copending application Serial No. 362,177, filed June 17, 1953, by R. Kompfner and H. Suhl, if the ferrite is biased by a magnetic field in a given plane, the attenuation it provides to a radio frequency wave whose magnetic vector is circularly polarized in a plane at right angles to that of the biasing magnetic field will vary with the direction of the rotation of the circular polarization. In particular, by having the lines of biasing magnetic field in the ferrite circumferential, and concentric with the helix axis, this condition of perpendicularity is satisfied in all the radial planes and the attenuation of a wave passing along the helix 22 will vary with the direction of propagation of the wave.

In order to obtain nonreciprocal attenuation properties it is important to operate with the ferrite near ferromagnetic resonance. Additionally, it is characteristic of most ferrite materials that the field strength required to achieve ferromagnetic resonance varies directly with the frequency of operation. Accordingly, for operation

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at very high frequencies the field strength required to achieve ferromagnetic resonance is sufficiently strong to cause the magnetic saturation of the ferrite sections. This produces the fringing effect which results in the transverse quadrupolar field desired for focusing. For this reason the invention is particularly adapted to high frequency operation wherein both the nonreciprocal attenuating properties of the ferrite and the transverse quadrupolar field associated with the various annular members, by virtue of the ferrite being saturated, are realized.

Alternative forms of quadrupole type magnetic members suitable for use in this same way are shown in Figs. 1B and 1C. Fig. 1B shows a focusing member 10B having a centrally located square aperture. This member comprises two permanent magnets 11B and 12B and two sections of ferrite 13B and 14B interposed between the magnets, for forming a quadrupolar field as described with reference to Fig. 1A. Alternatively, Fig. 1C shows focusing member 10C having two electromagnets 11C and 12C, and two sections of ferrite 13C and 14C interposed therebetween. By adjusting the current through windings 15 and 16 the strength of the electromagnets can be adjusted. Other forms will become apparent to one skilled in the art.

By way of example, the focusing arrangement 20 of Fig. 2 is shown embodied in a traveling wave tube 30 in Fig. 3. In this tube, electron gun 31 and target 33 are positioned within an evacuated envelope 34 and maintained at suitable operating voltages by lead-in conductors not shown, for establishing an electron beam along the length of the envelope between these electrodes. The electrodes are shown schematically for purposes of simplification. Helix 32 is positioned to surround the electron path for propagating an electromagnetic wave in coupling proximity to the electron flow and is maintained at a suitable potential for accelerating the electrons passing along the path. Transducers in the form of coupled helices, by way of example, are provided for intercoupling between the external coaxial lines 35 and 37 and helix 32. The general principles of coupled helix transducers of this kind are described in an application Serial No. 355,028, now United States Patent 2,811,673, issued October 29, 1957, of R. Kompfner. When operating as a forward wave amplifier coaxial line 35 serves as the input terminal and the wave energy propagating therealong is coupled to helix 32 via helix 36. The wave energy is amplified in passing along the helical slow wave circuit in the direction of electron flow by the now well-known process of energy interchange between the electrons in motion and the electromagnetic field. The amplified wave is then coupled from the helical slow wave circuit 32 to helix 38 and passes along coaxial line 37 to utilization means. Focusing arrangement 20 is interposed between the input and output coupling connections to focus the electron beam within the tube and to provide nonreciprocal attenuation to the wave passing along helix 32. As shown in Fig. 3 arrangement 20 is positioned to surround envelope 34. Alternatively, the focusing arrangement may be positioned within the envelope. In either case the arrangement is preferably in close proximity both to the slow wave circuit for maximizing the nonreciprocal attenuation properties of this circuit and to the path of flow for optimum focusing action.

Although the focusing arrangement 20 has been discussed with reference to its use in a forward wave amplifier, it is understood that this arrangement is applicable also to backward wave amplifiers and to backward wave oscillators. The tube shown in Fig. 3 may be adapted for use as a backward wave amplifier. For such operation, coupling element 38 now serves as the input coupler to slow wave circuit 32 and coupling element 36 serves as the output coupler therefrom. Reversal of the nonreciprocal attenuation effect is achieved by changing the direction

of the magnetic field passing through the ferrite sections for reversing the direction of its high attenuation characteristic. For backward wave operation, high attenuation is provided in the path of the wave traveling in the direction of electron flow and low attenuation in the path of the wave traveling in the opposite direction. The wave, in passing along the helix 32 in a direction opposite the direction of electron flow, is amplified and then coupled to coaxial line 35 via helix 36. All reflections from the output coupling element are suppressed by the high attenuation in the wave path in the direction opposite to the electron flow. It is also to be noted that when operating as a backward wave amplifier it is generally desirable to employ a ribbon helix whereas for forward wave amplification a wire helix is usually preferable.

Similarly, for use in a backward wave oscillator it is desirable to have the wave circuit very lossy in the direction from the electron source to the target. In such a case too, a ribbon helix wound to have a circumference of approximately a half wavelength at the operating frequency serves as an efficient interaction circuit.

In order to obtain effective focusing throughout the entire length of the interaction circuit it is necessary that the electrons be focused into a beam from the onset of their emission from the electron gun and maintained in this beam until they have substantially reached the collector. Ordinarily, the electron gun focusing electrode system will provide the necessary focusing of the beam from the electron emissive cathode through the gun structure to the extremity of the gun assembly. The focusing efficiency will be enhanced by designing the coupling elements and particularly the input coupling element to have a minimum dimension in the longitudinal direction, thereby minimizing the axial length between the gun assembly and the region in which the focusing arrangement 20 becomes effective. An alternative scheme, shown in Fig. 4, is to increase the spacing between successive focusing members and to couple through the focusing assembly 20 to the interaction circuit. In this way, the focusing arrangement may include one or more magnetic members between the cathode of the electron gun and the coupling connection adjacent the electron source. In this embodiment the coaxial line 35 is of nonmagnetic material and serves as one of the spacing elements. This technique allows coupling connections to be made at any desired points along the length of the interaction circuit. As shown in Fig. 4, the inner dimensions of the magnetic element 110 are advantageously made large enough to permit insertion of the helix 36 used for coupling, whereas the inner dimensions of other magnetic elements are preferably smaller so that these elements will closely surround the envelope 34. The dimensions of the spacing elements transverse to the axis of focusing assembly 20 are not material and, in the embodiment of Fig. 4, are substantially the same as those of element 110. In this manner the linear array of magnetic members may be made to extend continuously along the entire length of the envelope thereby effecting the desired electron beam focusing.

Although the various embodiments of the invention have been described with respect to their nonreciprocal attenuation properties it is understood that the focusing arrangement may also be operated to provide nonreciprocal phase shift characteristics to a wave circuit. Broadband nonreciprocal phase characteristics will be best obtained by operating below the ferromagnetic resonance of the ferrite material as is described in a copending application Serial No. 362,193, filed June 17, 1953, by S. E. Miller. In such regions the phase shift provided by the ferrite is substantially constant with frequency and varies with the direction of propagation of a wave passing through. A wave propagated along the helix in one direction will receive substantially different phase shift than a wave propagated along the helix in the opposite

direction, and each of these phase shifts is independent of changes in frequency of the wave over a very broad band. This effect may be used, in special cases, to minimize any tendency of the tube to oscillate in a backward wave mode.

It is further understood that the specific embodiments described are merely illustrative of the general principles of the invention. Various other arrangements may be devised by one skilled in the art without departing from the spirit and scope of the invention. In particular, various modifications of the shapes of the focusing members may be desirable for special applications. Further, the quadrupole magnetic member may be replaced by a magnetic member forming a hexapolar or octopolar transverse magnetic field including three or four magnets arranged as described above and interspaced by sections of ferrite. In such an arrangement successive members will be rotated

$$\frac{2\pi}{n}$$

radians where n is the number of magnetic poles of the magnetic member. Alternatively, it may be desirable to replace the ferrite sections by sections of other suitable material exhibiting gyromagnetic resonance. Moreover, it may be desirable to arrange focusing members in a linear array where the different members of the array are characterized by different frequencies of ferromagnetic resonance (as by use of different ferrite materials for different members) whereby the nonreciprocal attenuation properties are realized over a wider band of frequencies than is possible with an array of members of identical frequency characteristics.

What is claimed is:

1. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means defining a path of electron flow, a slow wave transmission circuit disposed along said path of flow, and means disposed around said path of flow for both focusing said stream and providing nonreciprocal attenuation to the signal traveling along the slow wave circuit, said means including a plurality of hollow members disposed in a linear array, each member including two regions of gyromagnetic material and magnets interspaced between said regions for establishing a quadrupolar field in the space enclosed by the member, and successive members shifted substantially 90 degrees relative to each other for maintaining successive quadrupolar fields in quadrature.

2. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means defining a path of electron flow, a slow wave transmission circuit comprising a helical conductor disposed along said path of flow, and a cylindrical shell surrounding said electron stream in close proximity thereto and in coupling proximity to said slow wave transmission circuit for both focusing the electron stream and providing nonreciprocal attenuation to the signal traveling along the slow wave circuit, said cylindrical shell comprising a plurality of annular members each of said annular members including two arcuately shaped sections of ferrite each subtending an angle of substantially 90 degrees relative to each other and magnetic means for saturating said ferrite comprising two arcuately shaped permanent magnets each subtending an angle of substantially 90 degrees and interposed between the two sections of ferrite in series aiding polarity forming a closed annular magnetic loop for maintaining a quadrupolar magnetic field within the region enclosed by the annular loop, and successive annular members rotated 90 degrees in a circumferential direction for maintaining successive quadrupolar fields in quadrature.

3. In combination a plurality of closed magnetic circuits each of said circuits comprising a plurality of magnets arranged to be series aiding and sections of gyromagnetic material interposed between said magnets and

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forming portions of each of said closed magnetic circuits, said plurality of circuits being axially aligned and successive magnetic circuits rotated

$$\frac{2\pi}{n}$$

radians relative to each other, where n is the number of magnetic poles in each of said circuits.

4. In combination a plurality of closed magnetic circuits each of said circuits comprising a plurality of permanent magnets arranged to be series aiding and sections of ferromagnetic material interposed between said permanent magnets and forming portions of each of said closed magnetic circuits, said plurality of circuits being axially aligned and successive magnetic circuits rotated substantially

$$\frac{2\pi}{n}$$

radians relative to each other, where n is the number of magnetic poles in each magnetic circuit, and means for providing a microwave transmission circuit coupled with and parallel to said magnetic circuits.

5. Electron beam focusing apparatus comprising a plurality of longitudinally disposed annular members forming a cylindrical shell, each annular member forming a closed magnetic circuit including a pair of magnets and regions of gyromagnetic material interspaced between said magnets in said circuit, for forming a quadrupolar field in the hollow of said section, and successive annular members rotated substantially 90 degrees relative to each other to provide successive quadrupolar fields substantially in quadrature.

6. Apparatus for focusing an electron beam and providing nonreciprocal attenuation to a wave path comprising a plurality of closed magnetic circuits each of said circuits including two permanent magnets arranged to be series aiding and two sections of gyromagnetic material interposed between said permanent magnets in said circuit, said closed magnetic circuits being axially aligned for passage of an electron beam axially therethrough and successive magnetic circuits being arranged in quadrature for forming within the said closed circuits a succession of quadrupolar magnetic fields substantially in quadrature.

7. Electron beam focusing apparatus comprising a plurality of hollow members coaxially disposed along a longitudinal axis each member including two quadrants of gyromagnetic material and magnets interposed between said quadrants for forming a quadrupolar field in the hollow of said members, and successive members rotated substantially 90 degrees relative to each other to provide successive quadrupolar fields substantially in quadrature.

8. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing an electron stream, a slow wave transmission circuit disposed along said electron stream, and means both for focusing said electron stream and providing nonreciprocal transmission in said slow wave circuit, said last-mentioned means comprising a plurality of members disposed in a longitudinal array, each member having at least four magnetic poles in a plane transverse to the path of an electron flow and including gyromagnetic material in coupling relation with said slow wave transmission circuit.

9. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing said electron stream, a slow wave transmission circuit comprising a helical conductor disposed along said electron stream, and means for both focusing said electron stream and providing nonreciprocal attenuation in said slow wave circuit, said last-mentioned means comprising a plurality of members disposed in a longitudinal succession for forming a succession of longitudinally ar-

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5 ranged regions of transverse magnetic fields each member having at least four poles in a plane transverse to the path of electron flow and including gyromagnetic material in coupling relation with the slow wave transmission circuit, and successive members rotated an angle equal to

$$\frac{2\pi}{n}$$

10 radians relative to each other where n is the number of poles in each of said members.

10. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing said electron stream, a slow wave transmission circuit disposed along said electron stream, and means for both focusing said electron stream and providing nonreciprocal attenuation in said slow wave circuit, said last-mentioned means comprising a plurality of members disposed in a longitudinal array for forming a longitudinal array of regions of transverse magnetic fields, each member having four poles in a plane transverse to the path of electron flow and including gyromagnetic material in coupling relation with the slow wave transmission circuit, said members apertured for passage of the electron stream and successive members rotated substantially 90 degrees relative to each other for arranging successive magnetic fields in quadrature.

11. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing said electron stream, a slow wave transmission circuit disposed along said electron stream, and means for both focusing said electron stream and providing nonreciprocal attenuation in said slow wave circuit, said last-mentioned means comprising a plurality of members disposed in a longitudinal array, each member having a centrally located aperture and a plurality of magnets circumferentially spaced around said aperture by regions of gyromagnetic material in a plane transverse to the path of electron flow, and successive members rotated circumferentially relative to each other a distance equal to the spacing between adjacent magnets.

12. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing an electron stream, a slow wave transmission circuit for propagating wave energy in coupling relation with said electron stream, and means for both focusing said electron stream and selectively attenuating wave energy passing along the slow wave circuit, said last-mentioned means comprising a plurality of apertured members disposed in a longitudinal array each member being a composite of regions of gyromagnetic material and of a plurality of magnets arranged for producing a biasing magnetic field in the gyromagnetic material which is substantially perpendicular to the circularly polarized component of the wave energy passing along said slow wave circuit and successive members rotated

$$\frac{2\pi}{n}$$

60 radians relative to each other where n is the number of poles in said member.

13. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing an electron stream, a slow wave transmission circuit for propagating wave energy in coupling relation with said electron stream, and means for both focusing said electron stream and selectively attenuating wave energy passing along the slow wave circuit, said last-mentioned means comprising a plurality of apertured members disposed in a longitudinal array each member including gyromagnetic material and having a pair of magnets arranged for producing a biasing magnetic field in the gyromagnetic material which is substantially perpendicular to the circularly polarized component of the wave energy passing along said slow wave circuit, and

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successive members rotated substantially 90 degrees relative to each other.

14. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing an electron stream, a slow wave transmission circuit for propagating wave energy in coupling relation with said electron stream, and means for both focusing said electron stream and selectively attenuating wave energy passing along the slow wave circuit, said last-mentioned means comprising a plurality of apertured members longitudinally disposed around the path of said electron stream, each member including gyromagnetic material and two magnets of sufficient strength for saturating the gyromagnetic material at the frequency of operation for producing a quadrupolar magnetic field in the region of the electron beam and arranged for producing a biasing magnetic field through the gyromagnetic material which is substantially perpendicular to the circularly polarized component of the wave energy passing along said slow wave circuit and successive members rotated substantially 90 degrees relative to each other for arranging successive magnetic fields in quadrature.

15. In a device which utilizes the interaction between an electromagnetic wave and an electron stream, means for providing an electron stream, a helix slow wave transmission circuit for propagating wave energy in coupling relation with said electron stream, and means for both focusing said electron stream and selectively attenuating the wave energy passing along the helix, said last-mentioned means comprising a succession of magnetic members apertured for passage of the electron beam, each member including gyromagnetic material and a plurality of magnets arranged for producing a focusing magnetic field within the region of the electron beam and for magnetically biasing the gyromagnetic material

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in a direction circumferential about the helix and successive members rotated a distance

$$\frac{2\pi}{n}$$

radians relative to each other where n is the number of poles in each of said members.

16. In combination, means forming an electron stream; a slow wave transmission circuit along the path of said stream for propagating therealong in coupling relation to said stream an electromagnetic wave whose magnetic field has a circularly polarized component; and means for both focusing said stream and selectively attenuating said electromagnetic wave including sections of gyromagnetic material disposed peripherally about the electron stream, and a plurality of magnets for saturating the gyromagnetic sections with a magnetic field, whereby a portion of said magnetic field fringes out of said sections to form a focusing field in the region of the electron stream, each magnet having its magnetic axis transverse to the path of flow, and being interposed between two of the plurality of gyromagnetic sections.

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