

Jan. 26, 1960

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2,922,917

NONRECIPROCAL ELEMENTS IN MICROWAVE TUBES

Filed Dec. 21, 1953

3 Sheets-Sheet 1

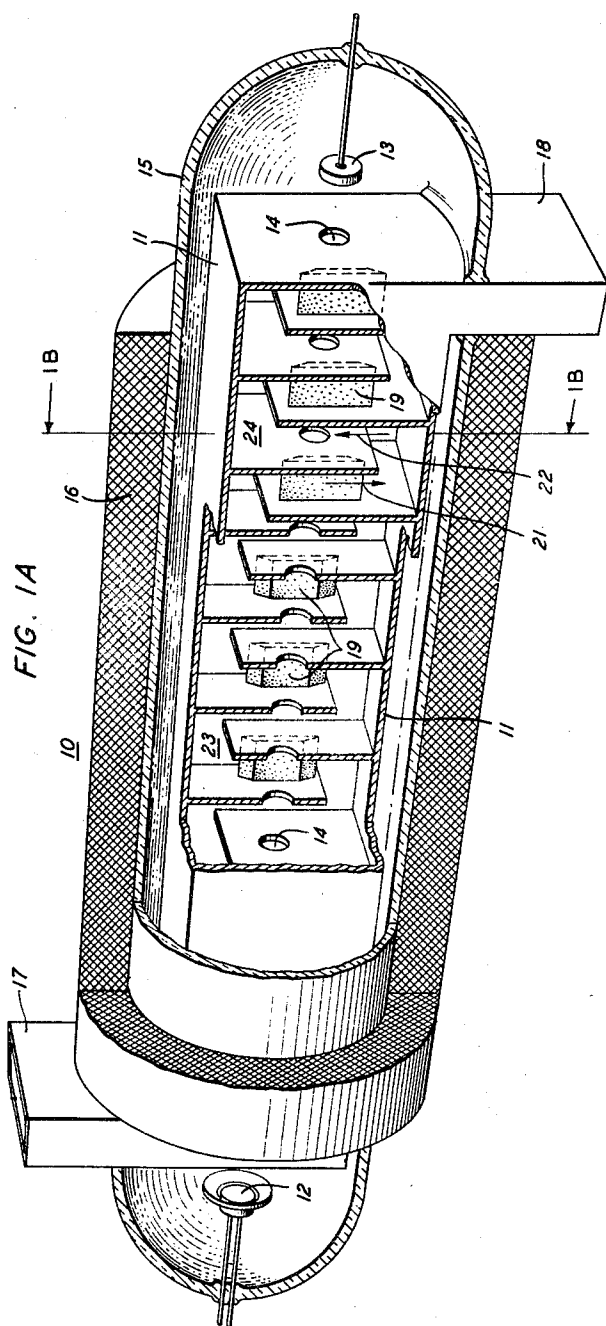
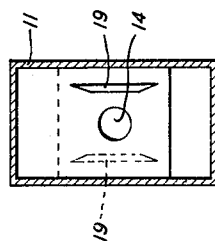


FIG. 1B



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3 Sheets-Sheet 2

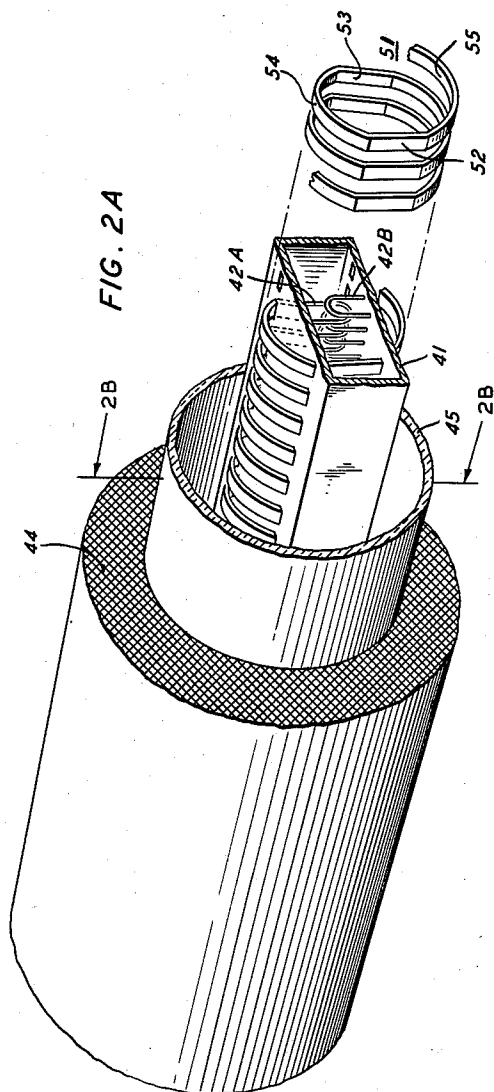
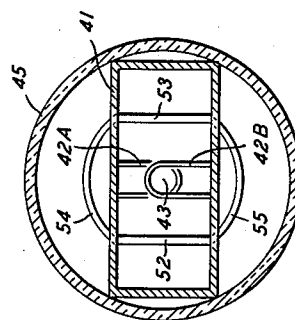


FIG. 2B



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3 Sheets-Sheet 3

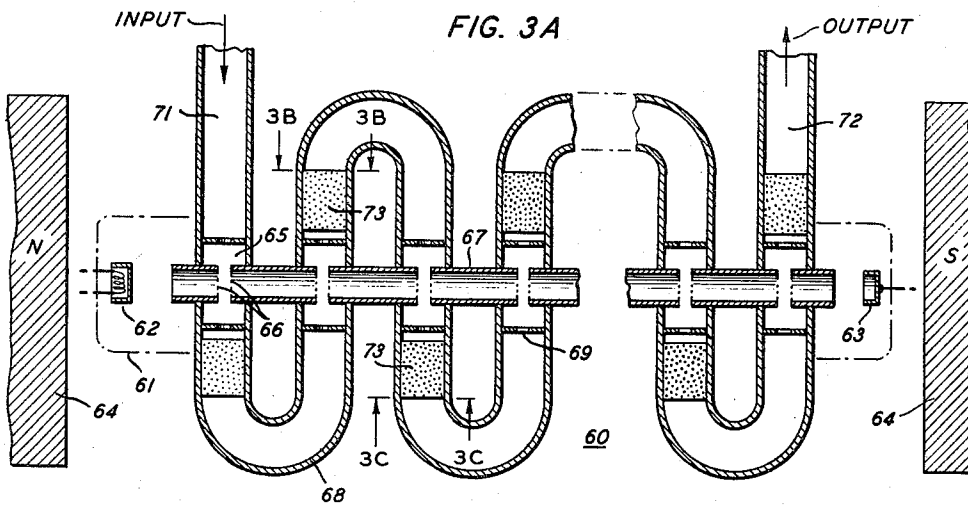


FIG. 3B

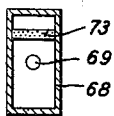


FIG. 3C

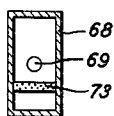


FIG. 4C

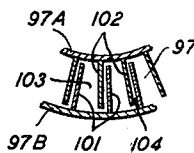


FIG. 4B

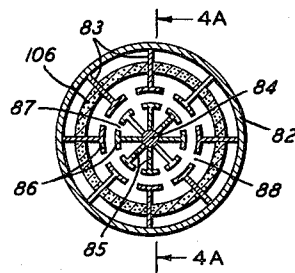
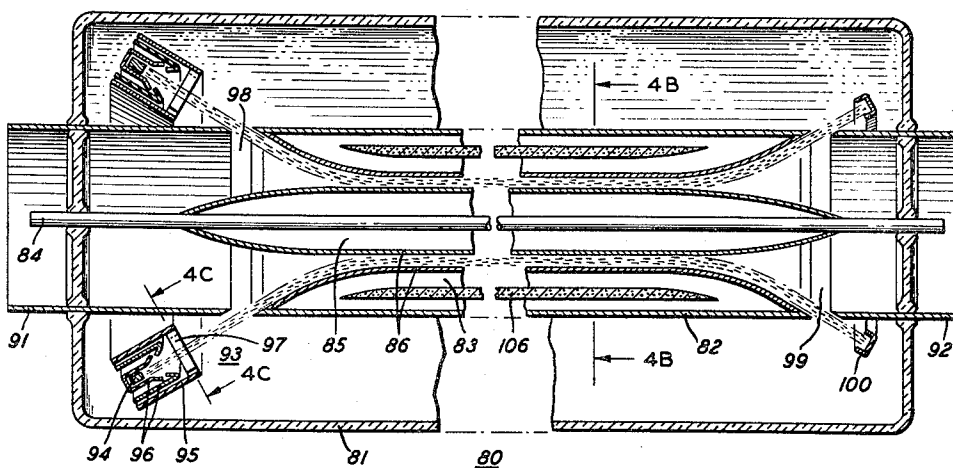


FIG. 4A



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NONRECIPROCAL ELEMENTS IN MICROWAVE TUBES

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Application December 21, 1953, Serial No. 399,252

25 Claims. (Cl. 315—3.5)

This invention relates to radio frequency apparatus which utilizes the interaction between an electromagnetic wave and an electron beam to secure gain to the wave. Typical of such apparatus are traveling wave tubes, both of the backward wave and forward wave types, and multicavity klystrons of the kind which utilize wave guide coupling between successive cavities.

In such apparatus, it is generally advantageous for efficiency and stability to limit the interaction to a wave having a particular direction of travel through its wave guiding circuit relative to the direction of electron flow therepast and, accordingly, to suppress any waves traveling through the wave guiding circuit in the direction opposite to that of interest.

The present invention relates to the use in such apparatus of ferrites and similar ferromagnetic isolator elements which produce in the wave guiding circuit nonreciprocal attenuation effects as a result of gyromagnetic resonance phenomena. In a copending application Serial No. 362,193, filed June 17, 1953, by S. E. Miller there are discussed in detail the principles applicable to the use of ferrites and similar ferromagnetic materials for producing nonreciprocal effects. In particular, it is taught that a wave guiding structure may be made nonreciprocal in its attenuation properties by the insertion therein of a septum of suitable material positioned in the region of circular polarization of the magnetic vector and biased magnetically close to the point of gyromagnetic resonance in a direction perpendicular to the plane of the circularly polarized magnetic vector. It will often be convenient hereinafter when discussing this effect to make specific reference only to ferrites but it is to be understood that other suitable materials exhibiting gyromagnetic resonance properties similarly are intended. In a copending joint application Serial No. 362,177, filed June 17, 1953, by R. Kompfner and H. Suhl, it is taught that the use of a circumferentially magnetized ferrite cylinder surrounding the helix circuit of a helix-type traveling wave tube results in a helix circuit which is nonreciprocal in its transmission characteristics. Such an arrangement makes possible a highly improved form of helix-type traveling wave tube. The present invention relates to the extension of these principles to radio frequency apparatus which utilize other forms of wave guiding circuits.

An object of the present invention is to facilitate the use of nonreciprocal wave guiding circuits in radio frequency apparatus which employ relatively long electron beams.

Another object of the invention is to achieve, without disturbing the electron beam, the desired magnetic bias needed in the ferrite elements which are inserted along the wave guiding path for achieving nonreciprocal transmission properties.

Another object is to employ the same magnetic field both for focusing the electron beam and for biasing the ferrite elements.

In one aspect the invention relates more particularly to apparatus in which the longitudinal magnetic field

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characteristically employed for focusing the electron beam in its path of flow is simultaneously used to provide the magnetic bias necessary in the ferrite elements which are introduced along the wave guiding circuit to provide the nonreciprocal properties. To this end, it is advantageous to include in the wave guiding circuit sections of rectangular wave guide whose longitudinal axis extends normal to the longitudinal magnetic field and whose side walls extend parallel to the magnetic field and in which there are inserted ferrite septa extending across between the broad side walls of the wave guide and intermediate between the wave guide axis and a narrow side wall. Alternatively, it is advantageous to include in the wave guiding circuit a section of rectangular wave guide whose axis extends in the direction of the longitudinal magnetic field. In this instance the ferrite element is inserted in helical form partially within and partially without the wave guide whereby the longitudinal magnetic flux in following the helical configuration of the element biases the element in a peripheral direction such that in the portions included within the wave guide the magnetic bias of the ferrite is suitable for imparting nonreciprocal attenuation properties to the wave guide.

In another aspect, the invention relates to a traveling wave tube for the amplification of circular electric waves which utilizes electrostatic focusing and in which the wave guiding circuit can be made to have the desired nonreciprocal transmission properties by the insertion of a ferrite element permanently magnetized in a peripheral direction in a manner not to interfere with the focusing.

Various embodiments of the invention are to be described. In a forward wave type traveling wave amplifier embodiment, the wave guiding circuit comprises a hollow rectangular wave guide which is folded back and forth on itself in serpentine fashion for forming a succession of transverse folds, successive folds being apertured for passage therethrough of an electron beam. The ferrite elements are inserted in successive folds in such a manner that the longitudinal magnetic field used to focus the electron beam simultaneously serves to bias the ferrite elements appropriately whereby the hollow rectangular wave guide provides high attenuation to waves traveling therethrough in the direction opposite to that of the electron flow while providing low attenuation to waves which are traveling in the direction of electron flow and with which the electron beam is interacting to provide gain thereto. In an amplifier of this kind the ferrite element serves both to suppress the tendency towards backward wave type oscillations which is a characteristic of an amplifier using a wave guiding structure of this kind and to reduce the effect of mismatches at the input and output coupling connections which also may give rise to oscillations or signal degradation. Alternatively, by reversing the direction of the longitudinal magnetic field relative to the direction of electron flow, the folded wave guide circuit can be made to have nonreciprocal attenuation properties which favor interaction between the electron beam and an oppositely directed or backward traveling wave for use in a backward wave oscillator or amplifier.

Several other embodiments are illustrated to show how the principles of the invention may be extended to multicavity klystrons and other forms of traveling wave tubes.

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

Fig. 1A shows in cut-away view a folded wave guide circuit type of traveling wave tube which utilizes ferrite septa to make the folded wave guide circuit nonreciprocal in accordance with the invention, and Fig. 1B is a transverse view of the tube taken along the line 1B of Fig. 1A;

Fig. 2A shows in cut-away view a portion of a traveling wave tube which employs a loaded rectangular wave guide as the wave guiding circuit and which employs a helical ferrite element to make the wave circuit nonreciprocal in accordance with the invention, and Fig. 2B is a transverse view of the tube taken along the line 2B of Fig. 2A;

Fig. 3A is a longitudinal sectional view of a multicavity klystron which utilizes for coupling between successive cavities sections of rectangular wave guide which are made nonreciprocal in accordance with the invention, and Figs. 3B and 3C are sections taken along the lines 3B and 3C, respectively, of Fig. 3A; and

Fig. 4A shows as another embodiment of the invention in longitudinal sectional view a traveling wave tube for the amplification of circular electric waves which utilizes a ferrite cylinder which is magnetized circumferentially. Fig. 4B is a transverse sectional view of the tube taken along the line 4B of Fig. 4A, and Fig. 4C in a section of a portion of the tube taken along the line 4C of Fig. 4A.

With particular reference now to the drawings, in the traveling wave tube 10 shown in Figs. 1A and 1B a rectangular hollow wave guide 11 a plurality of operating wavelengths long is folded back and forth on itself to form a serpentine wave guiding structure, the broad dimension of the wave guide being normal and the narrow dimension of the wave guide being parallel to the longitudinal axis of the tube. Successive folds of the wave guide are apertured for passage therethrough of an electron beam which flows in a direction parallel to the narrow dimension of the wave guide and the electric vector of the guide. To this end, an electron source 12 and a target electrode 13 at opposite ends of the wave guiding circuit and aligned with the apertures 14 define a path of flow of an electron beam through successive folds. An evacuated glass envelope 15 encloses the various tube elements. Flux producing means external to the envelope are employed to create a longitudinal magnetic field parallel to the path of flow for focusing the electron beam. In the embodiment illustrated a surrounding solenoid 16 serves as the flux producing means. The wave guide 11 is of a non-magnetic material, such as copper, so as not to disturb this magnetic field.

The tube 10 is designed for use as a forward-type traveling wave amplifier. To this end, a transverse electric input wave to be amplified is supplied to the upstream or electron source end 17 of the wave guiding structure and the output wave is abstracted at the downstream or collector end 18. The wave guiding structure usually will be provided with tapered transition regions at its ends for minimizing mismatches with external wave guiding connections. However, mismatches will still generally occur, and unless suitable measures are taken, components of radio frequency signal, together with noise components, tend to be reflected back and forth along the wave interaction circuit. Such components will be amplified in successive forward travels of the interaction circuit, resulting in signal degradation and even tube instability. Additionally, even apart from mismatches at the circuit ends, in a tube utilizing an intermittent interaction type of wave circuit as is formed by the folded wave guide, there will be set up by the noise components on the electron beam a backward traveling wave which will interact with the forwarding moving electron beam. Such a backward traveling wave will at the very least reduce the efficiency of the amplifier for amplifying forward traveling waves and may in some instances set up backward wave type oscillations. For these reasons, it has become usual traveling wave tube practice to insert loss in the wave circuit to absorb these unwanted waves traveling in a direction opposite to that of the wave to be amplified. For increased gain and efficiency, it is preferable to introduce along the wave circuit loss which affects only the undesired wave com-

ponents, i.e., to make the wave circuit nonreciprocal in its attenuation characteristics. In the aforementioned Miller application, various arrangements are described for making a hollow wave guide nonreciprocal in its attenuation properties. It is characteristic of such arrangements that a septum of ferrite or similar paramagnetic material which exhibits gyromagnetic resonance effects is positioned along the wave guide at a region where the polarization of the magnetic vector is substantially circular and the septum is biased magnetically to a point close to magnetic resonance in a direction at right angles to the plane of rotation of the circularly polarized magnetic vector. In particular, it is found that in a hollow rectangular wave guide the septum is most advantageously positioned in a region intermediate between one narrow side wall and the wave guide axis, extending longitudinally parallel to the wave guide axis and magnetized in a direction parallel to the side walls and the electric vector in the wave guide. In such an arrangement, it is found that the direction of low attenuation is related to the direction of the biasing magnetic field and on which side of the wave guide axis the septum is positioned.

It is in accordance with the invention to make the wave circuit nonreciprocal by the insertion therealong of septa 19 of ferrite and similar materials exhibiting gyromagnetic resonance phenomena and to utilize the longitudinal magnetic field used to focus the electron beam to provide the biasing magnetic flux necessary for making such septa exhibit the desired gyromagnetic resonance effects.

In examining the serpentine wave guiding structure with reference to the view shown in Fig. 1A, it will be noted that the direction of wave propagation reverses with successive folds, for example being from the top of the paper to the bottom in fold 21, and from the bottom to the top in fold 22. However, the direction of the applied longitudinal magnetic field is uniform in successive folds. Accordingly, to provide that waves traveling from the input to the output connections of the wave guide encounter low attenuation in successive folds while oppositely traveling waves encounter high attenuation, ferrite septa are positioned in successive folds extending between the broad side walls of the wave circuit alternately on opposite sides of the wave guide axis relative to the narrow side walls of the wave guide.

As a result in the cutaway view shown in Fig. 1A, in the first portion 23 which is cut along the tube axis, septa can be seen in the one set of alternate folds while in the second portion 24 in which the near side wall is cut away septa can be seen in the other set of alternate folds. In the sectional view of Fig. 1B, the relative positions on opposite sides of the wave guide axis of the septa are more clearly visible. The various septa advantageously may extend along the major portion of each fold. Additionally, by displacing the septa sufficiently from the path of flow so as not to intercept the electron beam, a continuous septum may be used in each fold. It is of course unnecessary to insert a septum in each fold. However, the discrimination resulting is related to the length of the path along which selective attenuation is provided so that for high discriminations, it is advantageous to insert as long a cumulative length of ferrite as practical. To minimize the reflections at the discontinuities resulting from the insertion of the septa in the wave guide, each is advantageously made to have a tapered transition section at its ends.

In other respects, the tube described is operated as a conventional traveling wave tube. For amplification, the velocity of the beam is adjusted so that a group of electrons see substantially the same phase of the electric field of the traveling wave at each region where the electron beam passes through the wave circuit. The velocity of the electron beam is controlled by the accelerating potential between the electron source and the

wave circuit which potential is provided by lead-in connections from a suitable voltage source (not shown), while the axial velocity of the wave can be controlled by the length and spacing of the folds.

The tube described can be readily modified for operation in a backward wave mode. For operation as a backward wave amplifier the input and output connections 17 and 18 simply are reversed. Moreover, for discriminating against forward traveling waves the direction of the longitudinal magnetic field is reversed for reversing the direction of the biasing magnetic field acting on the septa. Additionally, adjustment will need to be made in the accelerating voltage for maintaining the synchronism necessary between the phase velocity of the wave and the electron beam velocity.

Moreover, if the tube is to be used as a backward wave oscillator, it will be necessary additionally to increase the beam current beyond the value necessary to initiate oscillations and it will be advantageous to terminate the collector end of the wave circuit in a dissipative reflectionless termination and abstract the oscillatory energy at the electron source end of the wave circuit. The general principles of a backward wave oscillator are described in an article entitled "Backward Wave Tubes," by R. Kompfner and N. T. Williams, published on pages 602-617 of the Proceedings of the I.R.E., November 1953. As is set forth there, in backward wave tube operation the electron beam is made to interact with a negative space harmonic of a wave traveling along the interaction circuit in the direction opposite that of electron flow.

It can be seen that the principles applicable to this tube can be extended to tubes which employ an interdigital wave circuit of the kind which is in essence a folded wave guide circuit. However, in some instances an interdigital wave circuit may be more realistically viewed as a wave guide which is merely loaded by a linear array of interleaved finger elements.

For example, Figs. 2A and 2B show a portion of a traveling wave tube which is essentially of the kind described more fully in my United States Patent 2,895,071, issued July 14, 1959, and which employs as the wave circuit a section of rectangular wave guide 41 which is loaded with an interdigital array of U-shaped conductive elements, forming the two sets 42A and 42B which extend from the two opposite broad walls of the wave guide, overlapping in a region 43 past which is projected an electron beam. Flux producing means, such as the solenoid 44 external to the evacuated glass envelope 45, provides a longitudinal magnetic field parallel to the wave guide axis for focusing the electron beam in its flow past the linear array of elements.

It is characteristic of this loaded wave guide that the normal electric mode of waves propagating therealong will be distorted by the finger elements and axial electric field components will exist between adjacent elements having strong spatial harmonic components. Electrons moving axially through the overlapping region 43 will move in a substantially unidirectional field provided they take about one-half the period of the propagating wave to move the distance between adjacent elements when the wave-length in the guide is long compared to this spacing. This is true whether the electrons and propagating waves are moving either in the same or in opposite directions. Accordingly, for stability and minimum signal degradation, it is desirable to make the wave interaction circuit nonreciprocal.

In general, as is pointed out in the aforementioned Miller application, to make a rectangular wave guide nonreciprocal it is advantageous to insert therein a ferrite septum for extending across between the two broad side walls in a region between one side wall and the axis of the wave guide and to bias this septum magnetically in a direction parallel to the side walls. Moreover, the nonreciprocal effect is enhanced by utilizing separate septa

on opposite sides of the wave guide axis provided that the two septa are oppositely biased.

The problem posed in the utilization of these principles in a tube of the kind shown in Figs. 2A and 2B is that the magnetic field used to focus the electron beam is in an axial direction, whereas a magnetic field normal to the axial direction is needed for biasing septa inserted therein to achieve nonreciprocal properties.

In the tube shown in Figs. 2A and 2B, this problem is met by the insertion along the wave interaction circuit of a coiled magnetic element 51. The coiled element 51 comprises ferrite portions 52, 53 within the wave guide and extending across between the broad side walls of the wave guide on opposite sides of the wave guide axis and portions 54 and 55 external to the wave guide for bridging portions 52 and 53 and forming therewith a continuous low reluctance magnetic path. A portion of the magnetic flux provided by the solenoid 44 is shunted to this low reluctance magnetic path. Accordingly, the ferrite portions 52 and 53 will be biased magnetically in a helical direction and so will have components of field both in the axial direction and in a transverse direction perpendicular thereto. By properly choosing the pitch angle of the helix, the components in the transverse direction can be made larger than the axial components. These transverse components will be oppositely directed in ferrite portions 52, 53 on opposite sides of the wave guide axis. Accordingly, these transverse components are both in a direction suitable for biasing magnetically the ferrite portions 52 and 53 for making the wave guide 41 nonreciprocal in its attenuation characteristics. Additionally, by positioning portions 54 and 55 which serve to make the magnetic path continuous external to the wave guide, these portions in which the magnetic bias is unsuited for nonreciprocal attenuation action are kept from affecting the wave propagation in the wave guide. Since it is evident that portions 54 and 55 external to the wave guide serve merely to complete the low reluctance path and do not affect the transmission properties of the wave guide, it is sufficient that these portions be of any suitable material having a low magnetic reluctance, such as soft iron. Accordingly, the helical element 51 can be composite in nature, the portions 52 and 53 being of ferrite and the portions 54 and 55 being of soft iron. Moreover, the helical element 51 need not be continuous since this would require it to be threaded through the wave guide walls. If the thickness of the wave guide's broad side walls is sufficiently small relative to the spacing between turns of the helix, it will be adequate merely to bring the various portions forming the helical element 51 flush with the broad side walls of the wave guide, the helical magnetic path then including the thicknesses of these side walls. It should also be evident that the helix need not be symmetrical in form, the pitch may vary along its length and the various portions may be curved or relatively straight and flat.

From the illustrative embodiments already described, it can be seen how the principles of the invention may be applied to traveling wave tubes which utilize a section of rectangular wave guide as the wave guiding circuit. These same techniques may be applied to other forms of microwave amplifiers utilizing rectangular wave guide sections for which nonreciprocal properties are desirable.

In Fig. 3A there is shown schematically a multicavity klystron 60 which utilizes rectangular wave guides for coupling between successive resonant cavities. At opposite ends of an evacuated envelope 61, an electron source 62 and target electrode 63 define a longitudinal path of flow of an electron beam. Suitable flux producing means, for example the permanent magnet 64, is used to provide a longitudinal magnetic field for focusing the electron beam. Spaced apart along the path of flow are a succession of cavity resonators 65, each apertured for passage therethrough of the electron beam,

Across the pair of central apertures in each resonator is a pair of grids 66 which define therebetween a coupling gap in which the beam and the electric field in the cavity interact in the manner characteristic of klystron operation. Successive resonators are bridged along the path of flow by conductive cylinders 67 which serve as drift tubes. Successive resonators are also coupled by rectangular wave guide coupling sections 68 positioned to have their broad side walls perpendicular to the plane of the paper and their narrow side walls parallel to the plane of the paper. Each resonator is provided with irises 69 by way of which coupling is made to the wave guide sections. The wave to be amplified is applied to the input connection 71 and the amplified wave is abstracted at the output connection 72.

As in the case of the traveling wave tubes described above, it is advantageous to limit the interaction to the electron beam and a wave traveling from the input to the output connections of the tube. Here, this end is achieved by making the wave guide paths 68 which couple successive resonators nonreciprocal in their attenuation characteristics. To this end, a septum 73 of ferrite material is inserted in each rectangular wave guide section 68, for making the wave guide nonreciprocal. Each septum extends between opposite broad side walls of the wave guide intermediate between one side wall and the wave guide axis, so that the longitudinal magnetic field utilized for focusing the beam will also serve to supply the desired magnetic bias, as best seen in Figs. 3B and 3C. The relative position in each section with respect to the wave guide axis of each septum similarly is here related to the direction of travel of the wave which is to be favored.

The operation of such a multicavity resonator is similar to that of the usual multicavity resonator which employs coupling connections between successive cavities. The length of each wave guide coupling section and the velocity of the electron beam is adjusted so that a group of electrons sees the same phase of the electric field of the wave as it traverses the successive gaps in the cavity resonators where interaction between the beam and the signal wave occurs.

In the illustrative embodiments described hitherto, the principles of the invention have involved utilizing the longitudinal magnetic field used for focusing the electron beam simultaneously to bias ferrite elements inserted in the wave guiding path to make the wave guiding path nonreciprocal. In the last embodiment to be described specifically, an electrostatic field is employed to focus the electron beam in a manner which does not require a magnetic field, and accordingly the ferrite to be inserted for achieving nonreciprocal properties preferably should be biased in a manner which does not interfere with this electrostatic focusing of the beam.

In Figs. 4A, 4B and 4C there is shown a traveling wave tube 80 which employs electrostatic focusing to keep the electron flow cylindrical. This traveling wave tube is designed for the amplification of circular electric waves of the kind which are dominant in a circular wave guide and which are customarily designated as the TE_{01} circular waves. The various tube elements are enclosed in an evacuated envelope 81. The wave guiding circuit comprises a section 82 of circular wave guide which is loaded along a portion thereof to facilitate interaction with the electron flow. To this end, from the inner surface of the wave guide, there extends inwardly towards the wave guide's axis a series of projections or spokes 83 spaced circumferentially and extending longitudinally. Additionally from a conductive axial rod 84 extending longitudinally along the wave guide axis for serving as a hublike member there projects outwardly a series of projections or spokes 85 spaced circumferentially, extending longitudinally, and aligned radially with the projections 83 from the inner wall of the wave guide. Each of the projections supports at its end a longitudinal cylin-

drical segment 86, the various segments associated with each set of projections being spaced apart for forming inner and outer sets of gaps 87 and 88, respectively, spaced circumferentially. The circular electric wave propagating along the wave guide 82 establishes between the gaps both of the inner and outer sets of cylindrical segments fringing electric fields with circular components. In operation the electron flow is adjusted to interact with these fringing electric fields. To minimize reflections the inner and outer projections at the two ends of the loaded portion are tapered in length to form gradual transitions from the unloaded wave guide ends to the intermediate uniformly loaded wave guide section. Input waves are applied to one end of the loaded guide and abstracted at the other end by circular wave guide coupling connections 91 and 92, respectively.

The traveling wave will have its phase velocity reduced somewhat in propagating through the loaded wave guide because of the presence of the projections but generally this phase velocity will still be faster than any velocity which can be conveniently realized for the electron beam. Accordingly, traveling wave tube operation of the usual kind cannot be achieved. Moreover, in this case the electric field of the traveling wave will be in a circular direction and so not conducive to interaction with electrons flowing longitudinally with no circular component.

Fortunately, both these problems may be solved by imparting a circular or twisting component to the electrons in their path of flow. Moreover, this can be accomplished conveniently consistent with electrostatic focusing if the electrons are given a rotational component and then projected through an annular passage formed between two cylindrical electrodes between which exists a radial electrostatic field for providing a radially inward force on the electrons. In such a focusing scheme, the various parameters are adjusted so that equilibrium is maintained between the radially outward space charge forces in the beam, the centrifugal force on the electrons resulting from the rotational component, and the radially inward forces resulting from the electrostatic field set up between the two cylindrical electrodes defining the annular passage of the electron stream. The principles of focusing arrangements of this kind are set forth in my United States Patent No. 2,812,467, issued November 5, 1957.

To this end, tube 80 incorporates an electron gun 93 which includes an annular cathode 94 which surrounds the circular wave guide and with which are associated the usual beam forming and accelerating electrodes 96. The electron gun preferably is partially enclosed within a metallic magnetic shield 95 to minimize the disturbing effect of any stray magnetic fields. The shield is provided with an annular opening 97 by means of which the beam exits from the shield. The cathode and its associated electrodes are adjusted to provide conical flow which converges and passes into the circular wave guide through the annular slit 98 in the wave guide wall. This slit is sufficiently narrow that the wave guiding properties of the wave guide are not appreciably disturbed. The electron beam is thereafter focused for cylindrical flow in the annular passage between the inner and outer sets of cylindrical segments, and for conical flow beyond the loaded portion of the wave guide for exit from the guide through the annular slit 99 for collection by the annular target electrode 100.

The rotational twist is imparted to the electrons as they exit from the magnetic shield. To this end, vanes extend into the annular opening 97 in the magnetic shield from the inner and outer walls defining the annular opening, the two sets of vanes 101, 102 from the two walls being interleaved in the annular opening. The two sets are interleaved as is shown in Fig. 4C in such a fashion that there are formed between adjacent vanes two sets of gaps 103, 104, one set of alternate gaps 103 being relatively wide to permit passage therethrough of the incident

portion of the electron beam, the other set of alternate gaps 104 being relatively narrow to inhibit passage there-through of the incident portion of the beam. The two sets of vanes are maintained at different D.-C. potentials whereby there is set up in the gaps electrostatic fields transverse to the direction of flow. For this purpose suitable lead-in connections (not shown), maintain the two opposite walls 97A and 97B forming the opening 97 at different D.-C. voltages. The electrostatic fields in each of the gaps between adjacent vanes will reverse with successive gaps, being in the same direction of rotation in each of the wide gaps. Accordingly, those electrons passing through the wide gaps will all be given a spin in the same direction, and there will exit from the magnetic shield a beam which is rotating in a particular direction with a predetermined velocity.

After passing through the annular slit 98 in the wave guide wall, the conical electron beam is gradually transformed into a cylindrical beam. Various electrode systems are known to workers in the art for achieving these ends. In particular, it will be desirable to utilize the geometry of the transition region of the loading projection members 83, 85 in the circular wave guide to this end. Once the flow is made cylindrical it is maintained that way for passage through the gap between the inner and outer sets of cylindrical segments 86 by a balance between the centrifugal force resulting from the beam's rotation, the radially outward space charge force and a radially inward force resulting from an electrostatic field set up between the inner and outer sets of cylindrical segments 86. To this end, suitable lead-in connections (not shown) maintain the outer set of segments at a negative potential with respect to the inner set.

The operation is analogous to that of a conventional traveling wave tube. The rotating annular electron beam in passing through the fringing electric fields set up across the gaps 87 and 88 and having components in the circular direction interacts therewith and its velocity and density modulated in a peripheral direction. By properly adjusting the longitudinal and rotational velocity components of the beam, the spacing of the gaps 87, 88 between adjacent segments 86 of each set and the axial velocity of wave propagation through the guide, a group of electrons can be made to see substantially the same phase of the circular electric field each time it passes through a region of high fringing electric field. It is to be noted that each electron passes in turn through regions of high electric field corresponding to regions opposite gaps 87, 88 between adjacent segments 86 of each set and regions of low electric field corresponding to regions opposite the conductive segments 86. In this respect, the operation resembles spatial harmonic operation of the kind described in copending application Serial No. 99,757, filed June 17, 1949, by S. Millman and which issued as United States Patent 2,683,238 on July 6, 1954, where the electric field of the traveling wave is periodically shielded from the electron beam in regions where the beam and the electric field are not in suitable phase relative to one another for interaction.

In a traveling wave tube of this kind, as in conventional traveling wave tubes, it is desirable to make the wave circuit substantially unidirectional in its transmission properties. In the instant case where the direction of propagation of the wave to be amplified is in the longitudinal direction of electron flow, the wave guide 82 should offer low attenuation to such a wave and high attenuation to an oppositely traveling wave. Conversely, if as is possible the tube is operated to amplify a wave propagating through the wave guide in the direction opposite to the longitudinal direction of electron flow, the attenuating properties should be opposite. As is pointed out in the aforementioned Miller application, a circular electric wave guide can conveniently be made nonreciprocal in its attenuating characteristics by the insertion therein of a coaxial cylindrical element of ferrite

which is biased in a circumferential or peripheral direction. In the tube 80, the effect of a ferrite cylinder is achieved by a series of cylindrical ferrite segments 106 positioned in the regions between successive outer projections 83. If the thickness of these projections 83 is small, the succession of cylindrical segments 106 acts as a closed cylinder, little of the magnetic flux leaking in the gaps corresponding to the projections' thicknesses. The various cylindrical ferrite segments can each be permanently magnetized in the same peripheral direction so that the unitary assemblage is effectively magnetized in the appropriate circumferential direction.

What is claimed is:

1. In combination, an electron source and a target electrode defining therebetween a path of flow of an electron beam, flux producing means for forming a magnetic field parallel to the path of flow for focusing the electron beam, means including hollow wave guide sections for guiding an electromagnetic wave along the path of flow for interaction with the electron beam, and a plurality of gyromagnetic means positioned along the path of flow, said gyromagnetic means being offset relative to each other on opposite sides of the path of flow in said hollow wave guide sections in the magnetic field and biased thereby for making said wave guide sections nonreciprocal in their attenuation characteristics.

2. In combination, an electron source and a target electrode defining therebetween a longitudinal path of flow of an electron beam, flux producing means for forming a longitudinal magnetic field parallel to the path of flow for focusing the electron beam, wave circuit means providing a wave path in coupling relation with the electron flow including a rectangular wave guide folded back and forth on itself a plurality of times in serpentine fashion, successive folds being apertured for passage of the electron beam therethrough, and a plurality of gyromagnetic means positioned along the path of flow, said gyromagnetic means being positioned alternately on opposite sides of the path of flow in adjacent wave guide folds in the longitudinal magnetic field and biased thereby for making said wave circuit means nonreciprocal in its attenuation characteristics.

3. In combination, an electron source and a target electrode defining therebetween a longitudinal path of flow of an electron beam, flux producing means for forming a longitudinal magnetic field parallel to the path of flow, a wave interaction circuit positioned along the path of flow and including a rectangular wave guide which is loaded for setting up spatial harmonic components of waves propagating through said wave guide interaction with the electron flow, and a plurality of gyromagnetic means positioned along the path of flow, said gyromagnetic means being offset relative to each other on opposite sides of the path of flow in said wave guide and biased by the longitudinal magnetic field for making the wave guide nonreciprocal in its attenuation characteristic.

4. In combination, an electron source and a target electrode defining therebetween a longitudinal path of flow of an electron beam, flux producing means for forming a longitudinal magnetic field parallel to the path of flow, a wave guide circuit positioned along the path of flow comprising a rectangular wave guide which is loaded for exciting spatial harmonic components of waves traveling therealong suitable for interaction with the electron flow, and means for making the wave guide nonreciprocal in its attenuation properties, said means comprising portions within and without said wave guide for forming a low reluctance path to the longitudinal magnetic field, the portions of said magnetic means within the wave guide being offset relative to each other on opposite sides of and along the path of flow and biased by the longitudinal magnetic field.

5. In combination, an electron source and a target electrode defining therebetween a longitudinal path of flow of an electron beam, flux producing means for forming

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a longitudinal magnetic field parallel to the path of flow, means for propagating a wave for interaction with the electron flow including a plurality of cavity resonators coupled together by rectangular wave guide sections, and a plurality of gyromagnetic means positioned along the path of flow, said gyromagnetic means being positioned alternately on opposite sides of the path of flow in adjacent cavity resonators in said wave guide sections biased by the longitudinal magnetic field for making said wave guide sections nonreciprocal in their attenuation characteristics.

6. In combination, a rectangular wave guide having broad and narrow side walls folded back and forth on itself a plurality of times in a direction parallel to the narrow side walls, means for forming an electron beam for passage through successive folds of said wave guide, flux producing means for forming an axial magnetic field for focusing the electron beam, and a plurality of gyromagnetic elements positioned along the path of flow and biased by the magnetic field, said gyromagnetic elements extending across between the broad side walls of said wave guide in a region intermediate between a narrow side wall and the wave guide axis alternately on opposite sides of the path of flow in adjacent folds for making the wave guide nonreciprocal.

7. In combination, a rectangular wave guide having narrow and broad side walls, a plurality of conductive elements extending from the broad side walls of the wave guide in an interdigital array for setting up spatial harmonic components of waves propagating through said wave guide for interaction with the electron flow, means for forming an axial magnetic field for focusing the electron beam for flow past the interdigital array of elements, and magnetic means forming a low reluctance path around the path of electron flow in the region of the magnetic field including portions within and without said wave guide, the portions within said wave guide being gyromagnetic and offset relative to each other on opposite sides of and along the path of flow and biased by the magnetic field for making the wave guide nonreciprocal in its attenuation properties.

8. In combination, means forming a path of flow for an electron beam, a plurality of resonant cavities spaced apart along the path of flow for traversal by the electron beam, wave guide means for coupling successive cavities, and a plurality of gyromagnetic elements positioned along the path of flow, said gyromagnetic elements being offset relative to each other on opposite sides of the path of flow in said wave guide means for making the coupling substantially unidirectional.

9. In combination, a circular wave guide for propagating circular electric waves, conductive means in said wave guide for forming in a circular direction spaced regions of circular electric fields, means for forming an electron beam for flow through said wave guide, and means for imparting a rotational component to the electron beam whereby a group of electrons sees substantially the same phase of the circular electric field in its successive traversals of regions of circular electric fields.

10. In combination, a circular wave guide for propagating circular electric waves, a plurality of circumferentially spaced longitudinal conductive elements extending from the wall of said wave guide inwardly for defining therebetween in a circumferential direction a series of gaps in which the circular electric field is high, means for forming an electron beam for flow through said wave guide, and means for imparting a rotational component to the electron beam in its flow through the wave guide whereby a group of electrons sees substantially the same phase of the circular electric field in its successive traversals of regions of high electric field.

11. In combination, a circular wave guide for propagating circular electric waves, a first plurality of circumferentially spaced longitudinal conductive elements extend-

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ing from the wall of said wave guide, a second plurality of circumferentially spaced longitudinal elements extending radially from the wave guide axis, said first and second pluralities of elements cooperating to form in a circumferential direction alternate regions of high and low electric field, and means for projecting an annular cylindrical electron beam through said wave guide having axial and circumferential velocity components whereby a group of electrons sees substantially the same phase of the electric field in successive traversals of regions of high electric fields.

12. In combination, a circular wave guide for propagating circular electric waves, a plurality of circumferentially spaced longitudinal conductive elements extending in said wave guide forming regions of high circular electric fields spaced between regions of low circular electric waves, gyromagnetic means in said wave guide providing nonreciprocal properties to said wave guide, and means for projecting an annular cylindrical electron beam through said wave guide having axial and circumferential velocity components such that a group of electrons sees substantially the same electric field in successive traversals of regions of high electric fields.

13. An electronic device which in operation is to be positioned in an applied magnetic field comprising means forming an electron beam to be focused by the applied magnetic field, means including a hollow wave guide for propagating an electromagnetic wave in coupling relation with the electron beam for interaction therewith, and a plurality of gyromagnetic means positioned along the path of flow in the hollow wave guide, said gyromagnetic means being offset relative to each other on opposite sides of the path of flow and biased by the applied magnetic field for making the wave propagating means nonreciprocal in its attenuation characteristics.

14. The combination of claim 13 characterized in that the wave propagating means is made to have a low attenuation for waves propagating therethrough in the direction of electron flow and high attenuation for waves propagating therethrough in the direction opposite to that of the electron flow.

15. The combination of claim 13 characterized in that the wave propagating means is made to have a high attenuation for waves propagating therethrough in the direction of electron flow and a low attenuation for waves propagating therethrough in the direction opposite to that of the electron flow.

16. A high frequency oscillator comprising means forming an electron beam, means for providing a magnetic field for use in focusing the electron beam, a wave circuit for providing a waveguiding path for a traveling wave, the electron beam interacting with the negative space harmonic of the traveling wave whereby an oscillatory wave is set up which grows in amplitude with travel along the wave circuit in the direction opposite to that of the electron flow, gyromagnetic means positioned alternately on opposite sides of the path of flow along a substantial portion of the wave circuit in the path of the magnetic field to be biased thereby for providing a high attenuation to a wave traveling through the circuit in the direction of an electron flow and a low attenuation to a wave traveling in the wave circuit in a direction opposite to that of electron flow, and output means at the upstream end of the wave circuit for abstracting an oscillatory wave energy therefrom.

17. A traveling-wave tube comprising a waveguide structure having a periodic relationship with respect to a predetermined path whereby electromagnetic waves capable of being propagated by said waveguide structure form concomitant waves along said path having velocities substantially less than the velocity of light, at least one ferrite member disposed within said waveguide structure, said ferrite member being composed of longitudinal segments parallel to said predetermined path and transverse

to the direction of propagation of said electromagnetic waves through said waveguide structure, means for producing an electron stream, and means for producing a predetermined longitudinal magnetic field through said waveguide structure and parallel to said predetermined path to constrain said electron stream therealong and to develop a magnetomotive force across said longitudinal segments to attenuate at least a portion of the circularly polarized components of said electromagnetic waves..

18. A traveling-wave tube comprising a conductive member providing a longitudinal rectangular enclosure for propagating electromagnetic waves, said longitudinal rectangular enclosure having periodically spaced apertures and being folded back and forth in a manner to cause said apertures to define a predetermined path, a plurality of ferrite members disposed within said enclosure, said ferrite members being constituted of longitudinal segments parallel to said predetermined path and transverse to the direction of propagation of said electromagnetic waves through said longitudinal rectangular enclosure, means for producing an electron stream, and means for producing a predetermined longitudinal magnetic field through said conductive member and parallel to said predetermined path to constrain said electron stream therealong and to develop a magnetomotive force across said longitudinal segments to attenuate at least a portion of the circularly polarized components of said electromagnetic waves.

19. A traveling-wave tube comprising a conductive member providing a longitudinal rectangular enclosure for propagating electromagnetic waves, said longitudinal rectangular enclosure having periodically spaced apertures through the broad sides thereof, and being folded back and forth in a manner to cause said apertures to define a predetermined path, a plurality of ferrite slabs disposed on alternate sides of said path within said longitudinal enclosure, said ferrite slabs being constituted of longitudinal segments disposed parallel to said path and transverse to the direction of propagation of said electromagnetic waves through said longitudinal rectangular enclosure, means for producing an electron stream, and means for producing a predetermined longitudinal magnetic field through said conductive member and parallel to said predetermined path to constrain said electron stream therealong and to develop a magnetomotive force across said longitudinal segments to unidirectionally attenuate said electromagnetic waves.

20. The traveling-wave tube as defined in claim 19 wherein said ferrite slabs are spaced from 10% to 40% of the width of said rectangular enclosure from the nearest respective side thereof.

21. In combination, in a travelling-wave tube, a slow-wave structure having a longitudinal axis, and a ferromagnetic attenuating structure disposed helically about said slow-wave structure, said attenuating structure comprising a plurality of elongated ceramic ferrite bodies disposed in planes perpendicular to said axis, and a plurality of elongated ferromagnetic bodies, disposed parallel to said axis, said ceramic ferrite bodies being disposed alternately between said ferromagnetic bodies, said ferromagnetic bodies having a permeability substantially greater than that of said ceramic ferrite bodies.

22. In a traveling-wave tube, a slow-wave structure, and a ferromagnetic attenuating structure disposed about said slow-wave structure, said attenuating structure comprising a first set of elongated ceramic ferrite bodies disposed on one side of said slow-wave structure, a second set of elongated ceramic ferrite bodies disposed alternately between said first set of elongated ceramic ferrite bodies on the opposite side of said slow-wave structure, all of said ferrite bodies being disposed in planes transverse to the longitudinal axis of said slow-wave structure, a first set of elongated ferromagnetic bodies, each being connected from one of said first set of ferrite bodies to the next succeeding one of said second set of ferrite

bodies, and a second set of elongated ferromagnetic bodies, each being connected from the ends of one of said second set of ferrite bodies opposite the ends of said second set of ferrite bodies connected to said first set of elongated ferromagnetic bodies to the next succeeding one of said first set of said ferrite bodies, said elongated ferromagnetic bodies having a permeability substantially higher than that of said ceramic ferrite bodies.

23. In combination, in a traveling-wave tube, a slow-wave structure, and a ferromagnetic attenuating structure disposed about said slow-wave structure, said attenuating structure comprising a first set of elongated ceramic ferrite bodies disposed in a first axial plane on one side of said slow-wave structure, a second set of elongated ceramic ferrite bodies disposed in a plane parallel to said first plane adjacent said slow-wave structure on the side of said slow-wave structure opposite said first plane, each one of said second set of elongated ceramic ferrite bodies being disposed alternately between two adjacent ones of said first set of elongated ceramic ferrite bodies, all of said ferrite bodies being disposed in planes transverse to the longitudinal axis of said slow-wave structure, a first set of elongated ferromagnetic bodies, each being connected from one of said first set of elongated ceramic ferrite bodies to the next succeeding one of said second set of elongated ceramic ferrite bodies, and a second set of elongated ferromagnetic bodies, each being connected from the ends of one of said second set of said elongated ceramic ferrite bodies opposite the ends of said second set of elongated ceramic ferrite bodies connected to said first set of elongated ferromagnetic bodies to the next succeeding one of said first set of elongated ceramic ferrite bodies, all of said elongated ferromagnetic bodies having a permeability substantially higher than that of said ceramic ferrite bodies.

24. In a traveling-wave tube, a slow-wave structure, and a ferromagnetic attenuating structure disposed about said slow-wave structure, said attenuating structure comprising a first set of elongated ceramic ferrite bodies disposed on one side of said slow-wave structure, a second set of elongated ceramic ferrite bodies disposed alternately between said first set of elongated ceramic ferrite bodies on the opposite side of said slow-wave structure, all of said ferrite bodies being disposed in planes transverse to the longitudinal axis of said slow-wave structure, a first set of elongated ferromagnetic bodies, each being connected from one of said first set of ferrite bodies to the next succeeding one of said second set of ferrite bodies, a second set of elongated ferromagnetic bodies, each being connected from the ends of one of said second set of ferrite bodies opposite the ends of said second set of ferrite bodies connected to said first set of elongated ferromagnetic bodies to the next succeeding one of said first set of said ferrite bodies, said elongated ferromagnetic bodies having a permeability substantially higher than that of said ceramic ferrite bodies, and means for maintaining an axial magnetic field through said ferromagnetic attenuating structure.

25. In a traveling-wave tube, a slow-wave structure, and a ferromagnetic attenuating structure disposed about said slow-wave structure, said attenuating structure comprising a first set of elongated ceramic ferrite bodies disposed in a first axial plane on one side of said slow-wave structure, a second set of elongated ceramic ferrite bodies disposed in a plane parallel to said first plane adjacent said slow-wave structure on the side of said slow-wave structure opposite said first plane, each one of said second set of elongated ceramic ferrite bodies being disposed alternately between two adjacent ones of said first set of elongated ceramic ferrite bodies, all of said ferrite bodies being disposed in planes transverse to the longitudinal axis of said slow-wave structure, a first set of elongated ferromagnetic bodies, each being connected

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from one of said first set of elongated ceramic ferrite bodies to the next succeeding one of said second set of elongated ceramic ferrite bodies, a second set of elongated ferromagnetic bodies, each being connected from the ends of one of said second set of said elongated ceramic ferrite bodies opposite the ends of said second set of elongated ceramic ferrite bodies connected to said first set of elongated ferromagnetic bodies to the next succeeding one of said first set of said elongated ceramic ferrite bodies, all of said elongated ferromagnetic bodies having a permeability substantially higher than that of said ceramic ferrite bodies, and means for maintaining an axial magnetic field through said ferromagnetic attenuating structure.

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