March 29, 1960 S. SENSIPER 2,930,927

TRAVELING-WAVE TUBE

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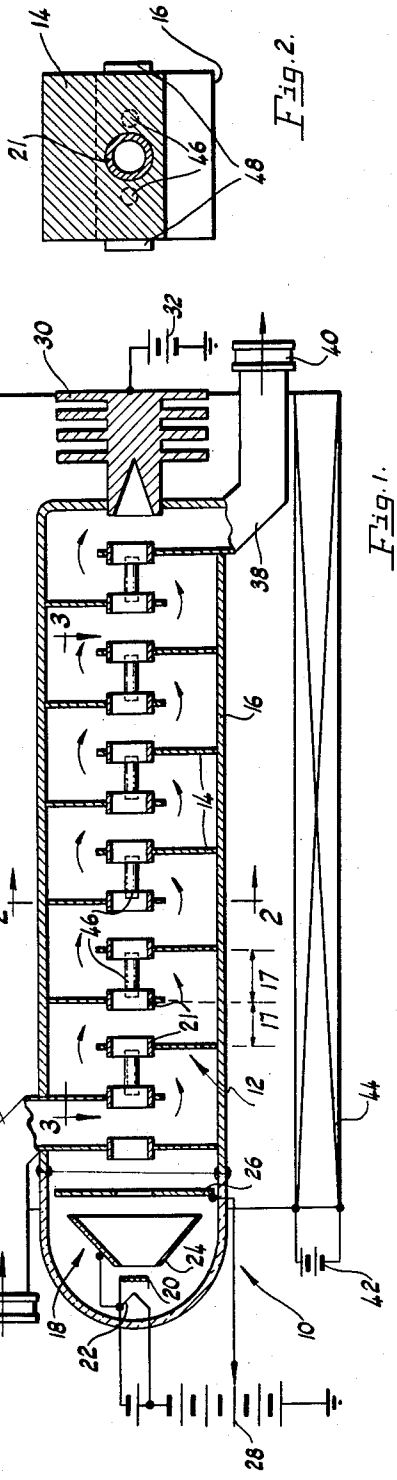


Fig. 1.

Fig. 2.

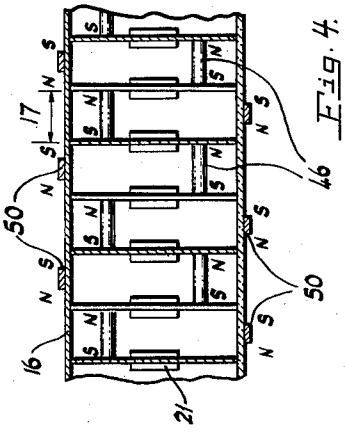


Fig. 4.

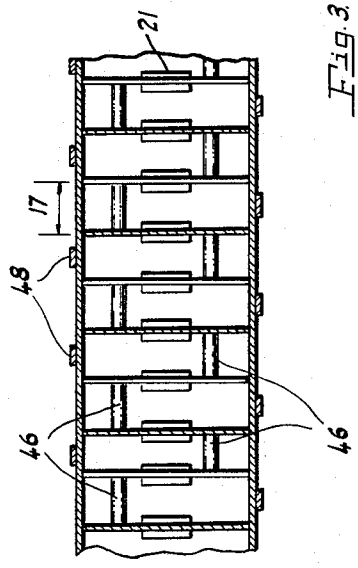


Fig. 3.

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TRAVELING-WAVE TUBE

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10 Claims. (Cl. 315—3.5)

This invention relates to microwave devices and particularly to traveling-wave tubes incorporating a slow-wave structure of the folded or loaded waveguide type and which have nonreciprocal attenuation characteristics.

Traveling-wave tubes generally employ a slow-wave structure to propogate an electromagnetic wave along the path of an electron stream. The longitudinal velocity of the wave should be such as to effect interaction between the electron stream and the wave, this electromagnetic wave being known as a traveling wave. "Slowing down" the traveling wave to approximately the velocity of the electron stream in order to secure this interaction is normally accomplished by a folded waveguide, a helix, a serpentine structure, or one of various other configurations. It is well known that an appropriate electron stream in association with such a structure may deliver energy or "push" in a manner to cause amplification or gain to microwave signals traveling along the slow-wave structure. The gain may be effective throughout an exceedingly broad range of frequencies. However, it is very difficult to provide an output circuit with an impedance that matches that of the slow-wave structure over the operable frequency range. This fact usually results in a portion of the energy of the electromagnetic waves appearing at the output circuit being reflected and propagated back towards the input, low signal level, end of the slow-wave structure. When this reflected portion of the output wave arrives at the input circuit, a portion may again be reflected and propagated, with consequent amplification, towards the output circuit. Such a re-reflection may result in self-oscillation and cause the tube to be inoperable or impractical for operation in the frequency ranges wherein such oscillation occurs.

A common method of precluding such oscillations is to place attenuation means along the length of the slow-wave structure so as to absorb the reflected energy and preclude its regenerative build-up. Such means are generally, however, inherently reciprocal in nature and decrease the forward or desired gain of the traveling-wave tube. This sacrifice of forward gain is a practical solution in low-powered tubes, or in other cases where efficiency of operation is not of prime importance.

However, where maximum gain and efficiency is desired, as in a high-powered tube, a nonreciprocal loss is imperative. In this connection, the phenomenon of ferromagnetic resonance in a biased ferromagnetic dielectric substance, known as a ferrite, has been utilized in traveling-wave tubes to provide a nonreciprocal loss. In order to utilize this phenomenon in a waveguide excited conventionally, as in the TE_{10} mode of propagation, a ferrite element may be disposed within the waveguide, near and parallel to the shorter height waveguide wall. The elongated element is usually placed in the region in which the radio frequency magnetic field appears circularly polarized. This region of circular polarization is off-center, to one side of the waveguide, for a direction of propagation in one direction in the waveguide, and off-center to the other side of the waveguide for the opposite direction of propagation. When a transverse, biasing magnetic field is applied along the elongated ferrite placed in this manner, ferromagnetic gyro-resonance may occur in the ferrite and the incumbent losses effectively attenuate radio frequency energy traveling in one direction, although substantially not affecting microwaves traveling in the opposite direction.

Various means have been devised for utilizing this phenomenon in a traveling-wave tube. In a copending application entitled "Traveling-Wave Tube," by Samuel Sensiper, Serial Number 473,856, filed December 8, 1954, now Patent No. 2,806,972, and assigned to the assignee of the present invention, there is disclosed one such arrangement. In one form of the invention there described are means for utilizing the axial magnetic field provided for focusing and confining the electron stream. A folded waveguide slow-wave configuration is folded back and forth across the electron stream. The arrangement is such that, in the region of the electron stream and the ferrite slabs there utilized, the direction of propagation of microwaves is perpendicular to the direction of the axial magnetic field. Hence, that field is utilized as well to bias the ferrite slabs for gyro-resonance attenuation. Properties and examples of ferrite materials which may be utilized for gyro-resonance are described in an article entitled "Ferrites In Microwave Applications," by J. H. Rowen, pages 1333–1369, Bell System Technical Journal, November 1953 (New York).

The above-described invention is of great practical benefit, particularly for circuits of simple form. It may be desired, however, to provide other circuits having even higher efficiency and greater forward to backward loss ratios. In such cases, it is recognized that ferrite slabs distort the magnetic fields involved, specifically, the static focusing field and the radio frequency magnetic components. This distortion may impose limitations on the efficiency of many high-powered traveling-wave tube amplifier designs.

It is therefore an object of this invention to provide an improved traveling-wave tube.

It is another object of the present invention to provide a high-power, high-efficiency traveling-wave tube having improved unidirectional or nonreciprocal attenuation characteristics.

Still another object of this invention is to provide an improved broadband amplifier having greater gain over a wider range of frequencies than has heretofore been possible.

It is another object of the invention to provide such apparatus utilizing ferrites biased by the axial electron stream focusing field.

Briefly, these and other objects are achieved in the present invention by a combination of relatively slender ferrite rods and a folded waveguide or loaded waveguide type of slow-wave structure. The ferrite rods are disposed longitudinally that is, axially, along the slow-wave structure and in the region in which the radio frequency field of the undesired reflected portion of the traveling-wave is circularly polarized. The ferrite rods are placed on opposite sides of adjacent cells defined by the slow-wave structure and interconnected by drift tubes such that microwave energy in alternate cells is traversing the electron stream in opposite directions. The present invention provides an arrangement which greatly reduces the distorting effects of the relatively low μ ferrite rods on the magnetic fields which are employed. Compensating magnets or ferromagnetic elements are disposed in a region external to the interaction cells. These very high μ field distorting members far from the beam are so arranged in the combination as to compensate for the use of the ferrite, lower μ, field distorting members close to the interaction space and to the beam. The combination thus

provides fields shaped to a uniform value. The high μ soft iron or permanent magnet members can be disposed external to the structure, on the internal surface thereof, or imbedded in the wall of the structure.

The novel features of this invention, as well as further objects and advantages of the invention as regards its structure and method of operation, will be more clearly understood when considered in the light of the following description, taken in conjunction with the accompanying drawings, in which like reference numerals refer to like parts, and in which:

Fig. 1 is a schematic view, shown partly in section, of a traveling-wave tube embodying the present invention;

Fig. 2 is a cross-sectional view of the traveling-wave tube of Fig. 1 taken along the section lines 2—2;

Fig. 3 is a longitudinal section of the tube of Fig. 1 taken along section lines 3—3; and

Fig. 4 is a longitudinal sectional view, similar to that of Fig. 3, of an alternative embodiment of the present invention.

Referring now with more particularity to the drawings, in Fig. 1 there is shown a traveling-wave tube **10** in which a folded waveguide type of slow-wave structure **12** is utilized for effectively slowing down microwave energy traversing along the longitudinal axis of the tube **10** from left to right (as seen in the figure) through the tube **10**. It will be understood by those skilled in the art that the tube shown has been simplified for clarity and is not drawn to scale. The slow-wave structure **12** comprises a series of transverse vanes **14** which alternately project from opposite sides of an enveloping waveguide wall **16**. The vanes **14**, as well as the waveguide walls **16**, are composed of a conductor which is nonmagnetic, such as copper or brass. The vanes **14** are mounted conductively on the waveguide walls **16** at spaced intervals, which spacing thereby provides interconnected interaction cells **17**. An interaction cell **17** as utilized here is a volume limited by the planes of two adjacent vanes **14** and the four waveguide walls **16**. Through substantially the center of each cell **17** passes an electron beam **19**. The velocity of the electrons is approximately that of the electromagnetic energy which is made to propagate the length of the slow-wave structure **12**. The electromagnetic energy is axially effectively slowed down by the tortuous or serpentine path formed by the alternating configuration of the vanes **14**. The vanes **14** are relieved, as shown, in the area where the electron beam would otherwise intersect with the vanes. Associated with each vane **14** there is a nonmagnetic drift tube **21** secured within the opening for the beam **19**. The drift tubes **21** are thus disposed in axial alignment along the length of the slow-wave structure **12** and form the path for the electron beam **19** through and in energy exchange relationship with microwave energy in each of the interaction cells **17**. The drift tubes **21** preclude interaction between the election beam and the traveling waves in the cells **17**, except in the region of each cell near its center where the traveling wave is in proper phase relation with the bunching or density modulation signal on the electron beam **19**.

Near the lefthand extremity of the traveling-wave tube **10** is an electron gun **18** which may be comprised of the usual cathode **20**, heated by a filament **22** to emit the stream of electrons which is shaped and focused by a focusing electrode **24** into an electron beam **19**. An anode **26** accelerates the beam to a high velocity. A voltage source **28** is tapped at appropriate potentials to provide operating voltages to these electrodes **20**, **24**, **26**. Near the righthand extremity of the tube **10** is a collector electrode **30** which intercepts the stream of electrons and dissipates their kinetic energy.

A source of potential **32** is connected between the collector electrode **30** and ground, making the collector electrode **30** positive with respect to the slow-wave structure **12**. Thus, secondarily emitted electrons from the slow-wave structure **12** will not find their way back into the interaction region of the tube **10** to give rise to noise or other interference. Connected to the lefthand extremity, or input end, of the tube **10** is an input waveguide section **34** connected by a flange to external circuitry (not shown). The coupling flange may include a microwave window **36** to thus allow a pressure differential between the exterior and the evacuated interior of the tube **10**; similarly, an output waveguide section **38** is connected to the output end of tube **10** where again the coupling flange may include a microwave window **40**. Disposed about substantially the length of tube **10** and energized by a source of potential **32** is a focusing solenoid **44** for constraining or confining the electron beam to its axial path along the tube **10**.

Disposed in each interaction cell **17** formed by the vanes **14** along slow-wave structure **12** is an elongated ferrite rod **46**. The rods **46**, as may be seen more clearly from Fig. 3, are disposed on opposite sides of the cells in alternating fashion along the length of the tube **10**. The rods **46** are substantially parallel to the axis of the tube **10** and are laterally displaced therefrom. The ferrite rods lie in a plane substantially equidistanut from the side of tube **10**, represented in Fig. 2 as the top surface of the tube **10**. The rods are approximately of the same axial length as each cell **17**, and are supported thereacross by being secured, at each end of each rod, to a pair of adjacent vanes **14**. The properties of the ferrite material of these rods **46** are described in the above-mentioned article by Rowen in the Bell System Technical Journal. The ferrite rods **46** may, for example, be composed of ferrite material known commercially as Ferramic A, Ferramic G, Ferramic R–1, ferroxcube 104 or ferroxcube 106.

The sectional views of Fig. 2 and Fig. 3 illustrate the compensating means of the invention in the form of magnetic material, such as soft iron slabs **48**, associated with each interaction cell **17** to balance out or correct the distortion of the magnetic field caused by the insertion of the ferromagnetic dielectric material of the ferrite rods close to the electron stream as discussed below. The slabs **48** are shown placed on the exterior of waveguide **16** near each cell **17**, directly opposite from the respective ferrite rod **46** in the respective cell. The shape and size of slabs **48** is best determined empirically by placing just enough iron on the waveguide wall to minimize the interception of electrons in the beam **19** by the drift tubes **21**.

Referring to Fig. 4, an alternative embodiment is shown in which, although the ferrite rods **46** are specified similarly to those of Fig. 1–Fig. 3, the magnetic field compensation means are small permanent magnets **50** placed outside the waveguide **16** and associated with each interaction cell **17**. Again, the exact size and shape of the magnets is best determined by empirically minimizing electron beam interception by the slow-wave circuit elements of the tube **10**.

In the operation of the present invention, microwave energy is impressed upon input waveguide section **34** of tube **10**, and is caused to propagate the length of the slow-wave structure **12** in an undulating fashion, as is indicated by arrows in Fig. 1. The microwave energy thus impressed upon and propagated by the slow-wave structure **12** is emitted from the tube **10** to the output waveguide section **38**. The electron gun **18** projects a stream of electrons along the axis of the tube **10**, through the drift tubes **42**, to the collector electrode **30** which collects the stream electrons and dissipates their energy. An appropriate coolant (not shown) may be forced past the fins of the collector electrode **30** to aid in cooling it.

An axial magnetic field produced by the solenoid **44** is used in a conventional manner to focus the stream of electrons along the indicated axial path through the drift tubes **42**. In accordance with the present invention, however, the same axial magnetic field is also used to bias

the nonreciprocal attenuating ferrite elements **46**. The ferrite rods **46** are placed in the region of circular polarization of the radio frequency magnetic fields of reflected microwave energy being undesirably propagated in the backward direction (from right to left as viewed in the drawing). To prescribe analytically exactly where the ferrite rods should be placed is exceedingly difficult because of the aberrations from a plane front wave as the microwave energy radiates around the 180° turns of the slow-wave structure **12**. The placements shown are approximate, however, and may be varied empirically for a specific design and operation to provide optimum results. The use of ferrite rods **46** instead of slabs of ferrite improves the nonreciprocal effect by an order of magnitude due to the concentration of ferrite material in the region of circular polarization. However, the use of the ferrite rods **46** causes a distortion of the axial focusing magnetic field. This distortion is balanced or compensated for by the ferromagnetic material slabs **48**, which appear in Figs. 2 and 3, or by the permanent magnets **50**, shown in Fig. 4. These compensating members likewise distort the magnetic field, but in a manner to substantially cancel out the distortion due to the ferrite rod combination of high μ field distorting members far from the beam and is equivalent to the use of low μ field distorting members close to the beam. The result is a shunting of the field to a uniform value. The soft iron members **48** may be placed external to the structure on the wall or imbedded in the wall of the tube **10**.

The alternate arrangement shown in Fig. 4 utilizes permanent magnets **50** to oppose the induced leakage field of the ferrite rods **46** and thus return the field to its original mean value rather than to shunt it. As shown by the north-south markings on the magnets **50** and ferrite rods **46** in Fig. 4, the leakage field from the permanent compensating magnets **50** opposes the induced leakage field of the ferrite rods **46** so as to restore the axial field in the region of the beam to its original value.

In a specific, practical example of the present invention, by using soft iron slabs immediately exterior to the waveguide wall **16** in the relative positions shown by the figures, loss ratios of the order of 10 to 1 in decibels have been readily achieved. In the particular tube referred to, the axial length of the interaction cells, that is, the distance between adjacent vanes **14**, is .157 inch. The ferrite rods have the same length and are .032 inch in diameter. The outer diameter of the drift tubes is .187 inch and .092 inch in length. The soft iron slabs are .03 inch thick and .078 inch square and are symmetrically disposed on wall **16**, as shown in Fig. 2.

There has thus been disclosed a traveling-wave tube utilizing longitudinal ferrite rods which are biased by the longitudinal focusing magnetic field. A very high attenuations ratio is achieved and defocusing problems caused by distortion effects on the beam by the ferrite rods are solved by high μ field compensation means disposed in a manner to cancel out the field distortion effects of the ferrite rods.

What is claimed is:

1. A traveling-wave tube comprising means for projecting an electron stream along a predetermined path; magnetic means providing a longitudinal magnetic field for focusing said electron stream; a folded waveguide type slow-wave structure comprising adjacent interconnected interaction cells disposed along said predetermined path; and nonreciprocal ferromagnetic gyroresonance attenuation means including an elongated ferrite rod disposed in one of said cells substantially parallel to said predetermined path and field compensation means disposed in the proximity of said cell in a manner to compensate for magnetic field distortion caused by said ferrite rod.

2. A traveling-wave tube comprising: means for projecting an electron stream along a predetermined path; a folded waveguide type slow-wave structure for providing electromagnetic energy exchange between microwaves traveling therealong and said electron stream; said slow-wave structure being of the form to provide adjacent interconnected interaction cells along said predetermined path for effectively causing said microwave energy to propagate in undulating fashion back and forth across said predetermined path; nonreciprocal attenuation means comprising an elongated ferrite rod disposed in one of said cells substantially parallel to said predetermined path, said ferrite rod being laterally disposed from said path and having a diameter sufficiently small as to lie substantially only in the region of circular polarization of the radio frequency magnetic fields of said microwave energy propagating in a direction opposite to that of said electron stream whereby ferromagnetic gyro-resonance losses in said ferrite substantially eliminate said backwardly propagating microwave energy while not appreciably affecting microwave energy traversing said slow-wave structure in the direction of projection of said electron stream.

3. A traveling-wave tube comprising means for projecting an electron stream along a predetermined path; slow-wave structure waveguide means disposed about said electron stream in microwave energy exchange relation therewith and including transverse loading vanes extending inwardly from a pair of oposite walls of said waveguide in an alternating arrangement whereby microwave energy traversing said waveguide slow-wave structure is caused to undulate back and forth across said electron stream; nonreciprocal attenuating means including elongated ferrite rods disposed parallel to said predetermined path between adjacent pairs of said transverse vanes and particularly disposed in the region of circular polarization of the radio frequency magnetic fields associated with microwave energy traversing said slow-wave structure in a direction opposite to that of said electron stream; magnetic focusing means for providing a biasing magnetic field in said ferrite rods whereby said microwave energy traversing said tube oppositely to said electron stream is unidirectionally attenuated by virtue of ferromagnetic gyro-resonance losses in said ferrite rods.

4. A traveling-wave tube comprising means for projecting an electron stream along a predetermined path; loaded waveguide type cells disposed along said predetermined path, the walls between adjacent ones of said cells being relieved about said predetermined path thus permitting the flow of said electron stream, adjacent ones of said cells being electromagnetically interconnected in a manner whereby microwave energy traversing the traveling-wave tube along said predetermined path is caused effectively to undulate back and forth across said electron stream as it propagates from cell to cell; nonreciprocal attenuation means including elongated ferrite rods supported in said cells between said walls parallel to said predetermined path and having a diameter and being disposed in a lateral position such that said ferrite rod lies substantially entirely in the region of circular polarization of the radio frequency magnetic fields of microwave energy traversing said traveling-wave tube in a direction opposite to that of said electron stream; magnet means for providing a longitudinal focusing field for said electron stream whereby said focusing field biases said ferrite rods in a manner such that said microwave energy traversing in a direction opposite to that of said electron stream is substantially absorbed in ferromagnetic gyro-resonance losses in said ferrite while not appreciably affecting microwave energy traveling in the opposite direction; and magnetic field compensating means disposed longitudinally even with said ferrite rods for substantially eliminating perturbations upon said magnetic fields by the presence of said ferrite rods.

5. The invention according to claim 4 in which said compensating means comprises ferromagnetic slabs disposed at a wall of said waveguide diametrically opposite from said ferrite rods.

6. The invention according to claim 4 in which said compensating means includes small permanent magnets

disposed longitudinally even with said ferrite rods at the wall of said waveguide diametrically opposite about said predetermined path from respective ones of said ferrite rods.

7. A traveling-wave tube comprising: means for projecting an electron stream along a predetermined path; an elongated waveguide disposed coaxially about and along said path; two sets of transverse loading vanes disposed perpendicularly to and spaced substantially evenly along the length of said waveguide and extending interdigitally from opposite sides thereof toward and beyond said path in a manner thereby to form adjacent interconnected interaction cells, each of said vanes being relieved in the region of its intersection with said stream; an elongated ferrite rod disposed in each of said cells laterally displaced from and substantially parallel to said path, said rods and said path lying substantially equidistant from said opposite sides of said waveguide, adjacent ones of said rods lying on opposite sides of said path and said rods having a length substantially equal to the axial length of its respective cell; and magnet means for providing a longitudinal magnetic field for focusing said electron stream and biasing said ferrite rods.

8. A traveling-wave tube comprising: means for projecting an electron stream along a predetermined path; an elongated waveguide disposed coaxially about and along said path; two sets of transverse loading vanes disposed perpendicularly to and spaced substantially evenly along the length of said waveguide and extending interdigitally from opposite sides thereof toward and beyond said path in a manner thereby to form adjacent interconnected interaction cells, each of said vanes being relieved in the region of its intersection with said stream; an elongated ferrite rod disposed in each of said cells laterally displaced from and substantially parallel to said path, said rods and said path lying substantially equidistant from said opposite sides of said waveguide, adjacent ones of said rods lying on opposite sides of said path and said rods having a length substantially equal to the axial length of its respective cell; magnet means for providing a longitudinal magnetic field for focusing said electron stream and biasing said ferrite rods; and magnetic field compensating means associated with each of said ferrite rods for substantially eliminating perturbations upon said magnetic field caused by the presence of said ferrite rods.

9. The invention according to claim 8 in which said compensating means comprises a ferromagnetic slab disposed in each of said interaction cells at the side of said waveguide diametrically opposite from said ferrite rod associated with that cell.

10. The invention according to claim 9 in which said compensating means includes a small permanent magnet disposed in each interaction cell longitudinally even with the ferrite rod associated with that cell at the side of said waveguide diametrically opposite from said ferrite rod.

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