

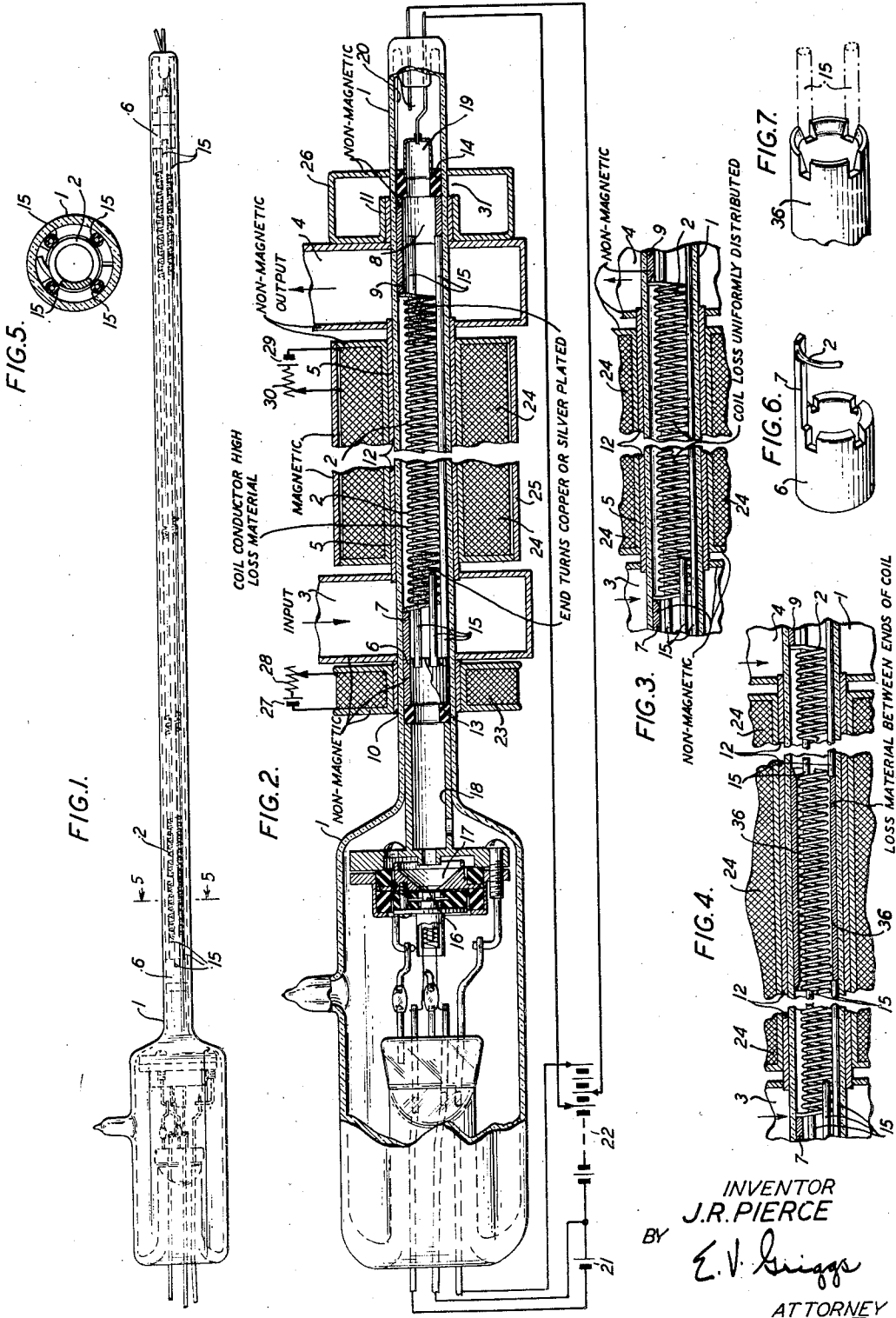
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J. R. PIERCE
HIGH-FREQUENCY AMPLIFIER

2,602,148

Filed Oct. 22, 1946

2 SHEETS—SHEET 1



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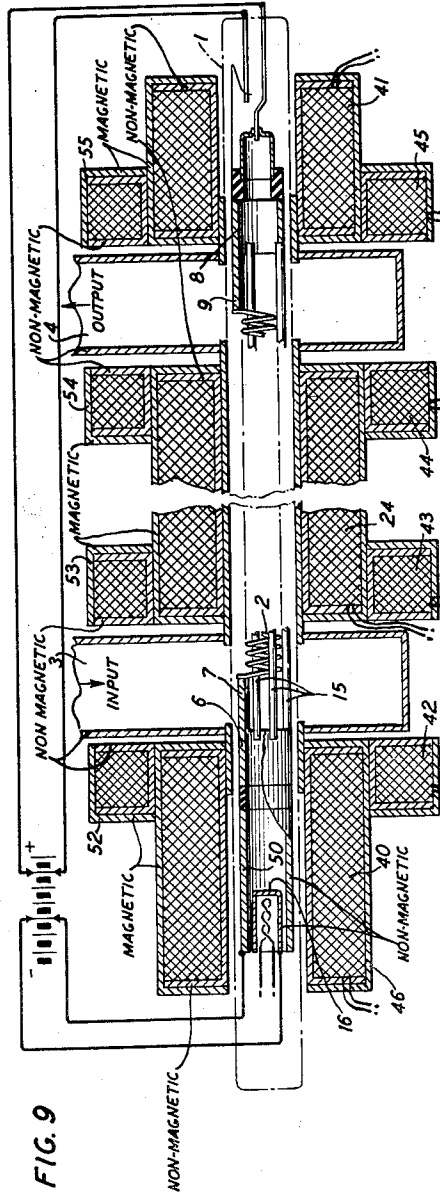
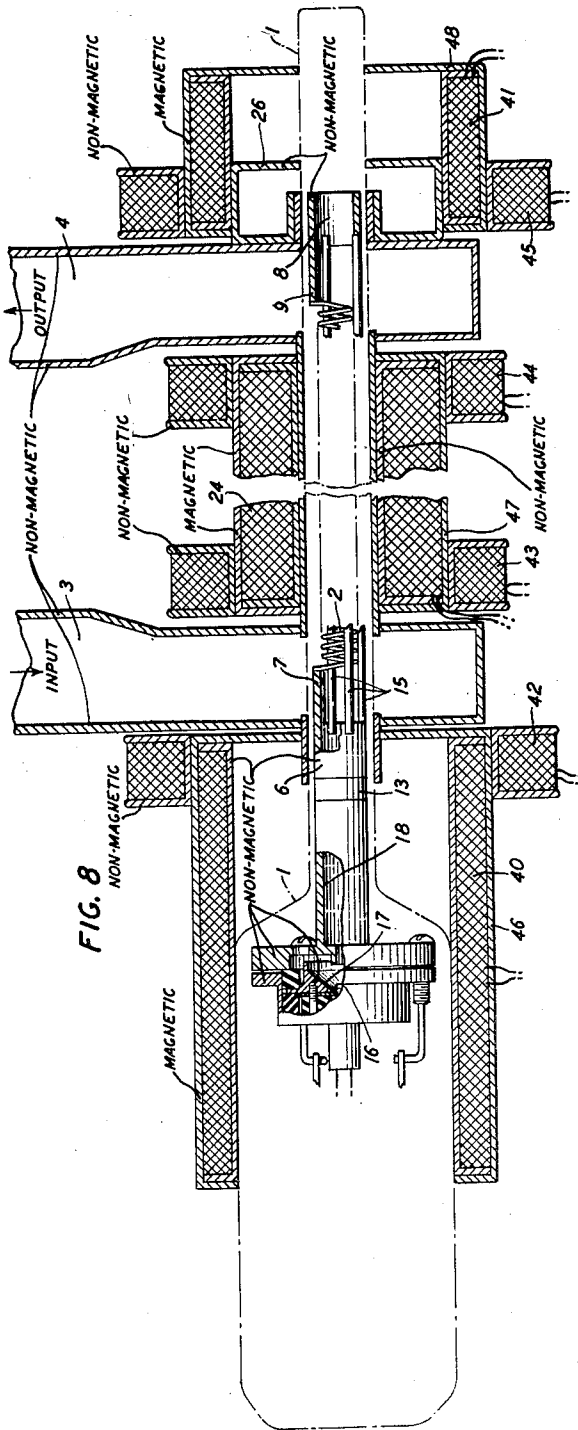
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2 SHEETS—SHEET 2



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HIGH-FREQUENCY AMPLIFIER

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1

This invention relates to high frequency wave amplifiers, particularly such amplifiers incorporating a portion of wave transmission path several wavelengths long and along which a stream of electrons is projected such that the electron stream may interact with the electric field of a high frequency wave transmitted along the path and produce amplification of the wave.

A particular object of the invention is to provide means whereby efficient operation of such a device is facilitated by improved collimation of the electron stream and direction of it along the wave transmission path.

A collateral object is to provide improved means for supporting along its length an elongated helix forming part of the wave transmission path.

Another object is to provide in such a device means for producing a uniform axial magnetic field along the path of the electron stream from its origin at the cathode throughout the region of interaction with the high frequency field.

Difficulties have been experienced in the operation of very high frequency amplifiers with respect to securing satisfactory gain and adequate band width. Useful in overcoming such limitations is a type of amplifier which incorporates within it a portion of the transmission path of the high frequency wave to be amplified, the path portion being designed to slow the velocity of the wave through the device to be comparable to a practical electron velocity. An electron stream is projected along the path portion through the electric field accompanying the wave at a velocity near that of the wave so that high frequency energy is transferred from the electron stream to the wave along the path portion. With the favorable impedance relations which are possible in such an arrangement and the absence of sharply tuned circuits both high amplification and wide band width are possible.

One form of such an amplifier utilizes in the transmission path portion a conductor wound in the form of a relatively long helix and the electron stream is projected along the axis of the helix to interact with the high frequency electric field therein. Such an amplifier is described in my copending application Serial No. 640,597, filed January 11, 1946. Since the gain of the amplifier depends upon the interaction between the electron stream and the electric field traveling along with it, it is desirable that this interaction be as complete as possible. Attaining this involves problems of accurately aligning the helix and other tube elements and maintaining colli-

2

imation of the paths of the electrons in the stream so that as many as possible of the electrons will travel through the helix without striking the conductor and thus may interact with the high frequency field along the entire length of the helix.

Solutions of these problems according to this invention are had by utilizing novel means to support the helix along its length so that it is straight and in line with the projected stream of electrons and by using systems of solenoids producing axial magnetic fields to constrain the electrons to travel axially along the helix.

The invention, its objects and advantages, are explained more fully in the following description and the accompanying drawings, in which:

Fig. 1 is a general view of a vacuum tube according to the invention showing the proportions of one embodiment of such a tube and indicating the general arrangement of the helical coil, its supports and the electron gun for projecting an electron stream through the coil;

Fig. 2 shows incorporation of a tube generally like that of Fig. 1 into an amplifier;

Fig. 3 shows modification of the coil portion of Fig. 2 wherein the loss in the coil is distributed uniformly along its length;

Fig. 4 illustrates a modification of the coil portion of Fig. 2 in which loss is added to the central portion of the coil by the placing of loss material there;

Fig. 5 is a section through a portion of the tube of Fig. 2 to illustrate the construction;

Fig. 6 shows a detail of Fig. 2;

Fig. 7 shows a detail of Fig. 4;

Fig. 8 illustrates an arrangement of solenoids to produce a uniform magnetic field along the entire electron path in an amplifier such as is shown in Fig. 2;

Fig. 9 is a modification of Fig. 6 using a slender tube of uniform diameter to facilitate use of the system of solenoids to produce a uniform magnetic field.

Fig. 2 illustrates a wave amplifier utilizing a tube such as that shown in Fig. 1. Fig. 2 is drawn to a larger scale than Fig. 1 in order to show more clearly details of construction. Since it is then not possible to show the full length and keep within the limitations of the space available the amplifier is shown broken in the center of the helical coil in conventional manner. The proportions of the tube illustrated are those of the complete smaller scale showing of Fig. 1. It will be noted that the tube envelope 1 and the helical coil 2 are quite long and slender. In one embodiment the helix was about 11 inches long

and the tube envelope about 18 inches long. Furthermore, the length is not limited to that indicated and may be less or much greater within practical limitations.

In Fig. 2 the high frequency wave energy to be amplified enters the device through the input wave guide 3 and leaves through the output wave guide 4. It travels through the amplifier between the two wave guides along the helical coil 2, the ends of which are coupled to the two wave guides by the strips 7 and 9 which are integral with and project from the short cylindrical terminating members 6 and 8 which fit snugly into the straight tubular portion of the evacuated envelope 1. To make clear the construction, the member 6 and associated strips 7 with connection to the end of the helix are shown enlarged in Fig. 6. The ends of the helical coil 2 are electrically connected to the ends of the strips 7 and 9. These strips being in the fields of the guides through which the envelope passes transfer high frequency energy from and to the input and output guides respectively and they are made a suitable length to give a good impedance match between the wave guide and the coil. The strips may be looked upon as antennas, strip 7 receiving energy from the field in the input guide 3 and strip 9 radiating energy into the field of the output guide 4. The cylindrical members 6 and 8 may be electrically $\frac{1}{4}$ wavelength long and with the annular electrically conducting shielding members 10 and 11 around the tube envelope form open-ended lines presenting a low impedance to the ends of the strips 7 and 9 opposite the coil 2. Effectively it may be said that the strips are terminated in the low impedance capacitances between members 6 and 10 and between 8 and 11. Usually a cylindrical conducting shielding member 12 surrounding the helix and connecting the shells of the wave guides is employed. This, however, is not essential.

The coil 2 provides a high frequency transmission path several wavelengths long, for instance 40 wavelengths in one embodiment of the invention which was operated at a frequency of about 4,000 megacycles. In the same embodiment the coil was of .027 inch diameter steel wire wound .167 inch inside diameter, 20 turns per inch and about 11 inches long. The wire of the coil need not be of steel but may be of any suitable conducting material and it is preferable sometimes to employ a non-magnetic material. Molybdenum has been used. The wire should not be so fine as to introduce excessive stray inductance nor should the spacing between turns be so small as to introduce excessive stray capacitance. It has been found quite satisfactory to make the spacing between turns and the diameter of the wire approximately equal.

The velocity of the high frequency wave along the axis of the coil is less than its velocity along the wire of the coil depending upon the radius of the coil and the pitch of the winding, the axial velocity being approximately the velocity along the wire divided by $2\pi rn$ where π is 3.1416, r is the radius of the coil in inches and n is the number of turns per inch. Thus the coil may be designed so that the velocity of the wave along the axis of the coil is reduced to be near the velocity of an electron stream projected therealong, and, in operation, preferably slightly less than that of the stream, such a velocity relation being necessary to obtain amplification of the wave. Final adjustment of the electron stream

velocity may be made by adjustment of the electron accelerating voltage.

The cylindrical coil terminating members 6 and 8 are positioned in the envelope 1 by the ceramic spacers 13 and 14. The coil is positioned longitudinally and coaxially in the envelope 1 by the round rods 15 which fit into circumferentially spaced notches in the members 6 and 8. The rods are thus spaced around the coil between it and the envelope as shown in Fig. 5. These rods may be of any suitable insulating material which will not introduce excessive loss or capacitance in the circuit. One material satisfactorily used is known as "Zircon," a ceramic material containing zirconium oxide. Care is taken to form the slender portion of the envelope 1 surrounding the coil so that its interior is uniform in diameter, accurately dimensioned and very straight axially. The coil 2 and the rods 15 are also accurately dimensioned so that when mounted in the envelope the coil is held snugly, accurately straight and centered in the envelope. This use of such rods to position the coil is a very important feature of the device as it contributes to efficient operation by facilitating projection of the electron stream along the length of the coil without great loss of electrons to the coil conductor.

The electron stream originates at the cathode 16 which is indirectly heated from source 21 and is positioned in the aperture of the electrostatic focusing electrode 17. This focusing electrode is so shaped and positioned with respect to the cathode surface as to direct the electrons into nearly parallel paths toward the anode or collector 19. To further form the electron flow into a narrow beam the magnetic focusing coil 23 provides a final adjustment before the electron stream enters the helix. This coil may be energized from any suitable direct current source, such as battery 27 and rheostat 28, to produce a desired steady axial magnetic field. A longer coil or solenoid 24 extending along the helix provides an axial magnetic field there to keep the electron beam from spreading as it passes through the helix. This coil also may be energized from any suitable direct current source, such as battery 29 and rheostat 30. The use of both of these coils is very desirable. A magnetic shield 25 surrounds the solenoid 24 and serves to protect the long electron path from the effects of stray magnetic fields.

The source 22 supplies potential to the accelerating electrode 18, to the helix 2 (through lead 20 which carries past the insulating member 14) and to the collecting electrode 19 where the electron stream terminates. The cavity resonator 26 coupled through the gap 31 in the resonator shell serves as a choke resonant at the mid-frequency of the band to be amplified to minimize the leakage of high frequency energy from the amplifier along the lead connected to the helix from source 22.

It is important in an amplifier of the type described to have a certain amount of attenuation to the high frequency wave inherent in the wave transmission circuit along which the electron stream amplifies the wave energy. That is, attenuation in the circuit when the tube is not energized and there is no electron stream. Such attenuation is effective no matter which direction through the device a wave travels and is therefore effective in preventing oscillations or tendency toward them from seriously limiting the amplification which may be obtained. It

promotes isolation of the input and output of the amplifier and avoids limitations imposed by disturbances due to reflections therebetween. This attenuation may be introduced in various ways and may be either uniformly or non-uniformly distributed along the circuit in the amplifier. This subject-matter is disclosed and claimed in my copending application Serial No. 640,597, filed January 11, 1946, referred to above. As shown in Fig. 2 the wire of the helix 2 may be of high loss material such as iron or Nichrome and in order to concentrate the attenuation to a degree in the central portion of the coil the end portions may be plated with low loss material such as copper or silver as indicated in the figure by the shading of the end turns of the coil. By varying the thickness of the plating and the number of turns plated the attenuation may be desirably distributed.

Should it be desirable to keep the attenuation uniformly distributed along the helix the coil may be uniformly plated or, as shown in Fig. 3, the coil may be unplated and of uniform resistance throughout. Only the helical coil portion of the device is shown in Fig. 3, the remainder being identical with such portions of Fig. 2. Designations of the elements of Fig. 3 are the same as in Fig. 2.

Fig. 4 shows an alternative method of concentrating attenuation in the central portion of the helix. Only the coil portion of the device is illustrated, the remainder being identical with Fig. 2. Designations are the same as in Fig. 2. In Fig. 4 a tube of loss material 36 is placed around the central portion of the helix in the space between the helix 2 and the envelope 1. This tube takes the place of the rods 15 in supporting that portion of the helix surrounded by it, the rods having lengths removed from them along the extent of the tube of loss material. Fig. 7 illustrates the tube of loss material 36 and how the rods 15 fit into it to show the construction more clearly than is possible in Fig. 4. The ends of the tube of loss material 36 have circumferentially spaced notches the same as members 6 and 8 in Fig. 2 into which the cut ends of the rods fit just as the other ends fit into the notches of members 6 and 8. In Fig. 4 each rod in effect, instead of extending continuously from a notch in member 6 to a notch in member 8 as in Fig. 2, extends from a notch in member 6 to a notch in the near end of member 36 and then continues from a notch in the far end of member 36 to a notch in member 8. The member 36 may be of any suitable material which will introduce the desired loss when placed in the high frequency field adjacent to the conductors of the helix. A mixture of ceramic and metallic materials has been used.

Figs. 8 and 9 illustrate amplifiers similar to that of Fig. 2 but with additional solenoid coils to assist in projecting the electron stream through the helical coil with minimum loss of electrons to the conductor of the coil. To simplify these figures details of the vacuum tubes and their power sources which are shown in Fig. 2 and described in connection therewith are omitted.

Fig. 8 illustrates an amplifier and the tube identical with that shown in Fig. 2 except for the addition of the solenoid coils 4, 41, 42, 43, 44 and 45, and the magnetic shields 46, 47 and 48, the construction of the electron gun elements of non-magnetic material, the elimination of coil 23 and the shield 25 which is replaced by shield 47 and

the narrowing of the wave guides to shorten the axial length not encircled by a magnet coil. The purpose of the system of coils shown is to provide a uniform axial magnetic field the entire length of the electron path. The coils therefore extend so as to include the cathode and are arranged so that the uniformity of the field may be maintained where the tube passes through the input and output wave guides where it is necessary to interrupt the continuity of the coils along the axis. In order to maintain this uniformity of field the coils 40, 24 and 41, which encircle the tube envelope 1 as closely as possible, are equipped with magnetic shields 46, 47 and 48 which are carried over the ends of the coils to near the tube envelope and coils 42, 43, 44 and 45 encircle these shields close to and at both sides of both wave guides. The shields act as magnetic pole-pieces for the coils 42, 43, 44 and 45, and makes it possible to produce in the tube envelope where it passes through the wave guides axial fields which are uniform with respect to (and in effect continuations of) the field throughout the other portions of the tube envelope along the length of the electron path. This result is accomplished by adjustment of the relative excitations of the several coils, which excitations may be had from any suitable direct current sources such as illustrated in Fig. 2 where battery 27 and rheostat 28 are shown. In this manner curved magnetic lines of force along the electron path are avoided and the resulting improved direction of the electrons along the entire length of the helix enhances the utilization of the electron stream and the performance of the amplifier.

Fig. 9 illustrates an amplifier the same as that shown in Fig. 8 except that the vacuum tube envelope is uniformly slender throughout its length rather than enlarged in diameter at one end to accommodate the electron gun, an appropriately smaller electron gun is used, the resonant cavity choke 25 in Fig. 8 is omitted, and coils 42, 43, 44 and 45 are equipped with magnetic shields 52, 53, 54 and 55. The elements of the Fig. 9 embodiment function generally the same as the corresponding parts of Fig. 8, the uniformly slender tube and omission of the resonant cavity choke, however, permitting a more compact assembly. The electron gun is necessarily smaller than that of Fig. 8 and is shown simply as a cathode 16 and focusing electrode 50. As in Fig. 8 the gun elements should be of non-magnetic material. Any suitable gun design may be employed. The shields 52, 53, 54 and 55 are shown as an alternative to the Fig. 8 arrangement where such shields are not used. These shields serve to confine the magnetic fields of the coils with which they are associated but are not essential to operation of the amplifier.

The various illustrative embodiments have been described in the interest of a complete disclosure of the invention. Modifications may occur to those skilled in the art and it is not intended that the invention be considered limited to the exact embodiments shown.

What is claimed is:

1. A wave amplifying device comprising a transmission line including a conductor in the form of an elongated helix, means for producing a beam of electrons traveling with suitable velocity lengthwise of the helix and in space occupied by the electric field of said helix when said transmission line is energized, a plurality greater than two of rods of insulating material ex-

tending lengthwise of the helix, and means for supporting said rods substantially continuously along their lengths to be accurately straight and parallel to each other and spaced around the circumference of the helix external thereto and in contact therewith whereby the helix is held axially straight and accurately parallel with the direction of projection of said beam of electrons.

2. A high frequency wave amplifier comprising a transmission line which includes a conductor in the form of a helix, means for producing a beam of electrons traveling with suitable velocity lengthwise of the helix and in space occupied by the electric field of said helix when said transmission line is energized, a rigid envelope comprising a straight cylindrical portion surrounding said helix coaxially and spaced radially therefrom and a plurality of rods of insulating material extending axially and distributed around the helix in the annular space between the helix and the envelope, the said rods closely fitting the said space in radial directions and being held in positions around the circumference of the helix whereby the helix is held coaxial with and straight within the said straight cylindrical portion of envelope.

3. A wave amplifying device comprising a transmission line which includes a conductor in the form of an elongated helix, means for producing a beam of electrons traveling with suitable velocity lengthwise of the helix and in space occupied by the electric field of said helix when said transmission line is energized and a plurality greater than two of rods of insulating material extending lengthwise of the helix supported at a plurality of points along their lengths to be accurately straight and parallel to each other and spaced around the outer circumference of the helix and in contact therewith whereby the helix is held axially straight and accurately parallel with the direction of projection of said beam of electrons, the said helical conductor having substantial resistance and having turns at both ends plated with material of lower resistance than the material of said conductor whereby the high frequency attenuation of the helix is more concentrated in the central portion than at the ends.

4. A wave amplifying device having input and output terminals, therebetween an extended path capable of propagating a traveling electric wave, means for projecting an extended electron stream parallel to and inductively related to said path, steady magnetic field means located along said electron stream ahead of said path for focusing said stream as it approaches the region of said inductive relation, means between said region and said focusing means for impressing a wave to be amplified upon said path, said focusing means being positioned adjacent to said wave impressing means, and means in said path in the region of said inductive relation to attenuate substantially waves traveling counter to the said electron stream.

5. A wave amplifying device comprising a transmission path capable of guiding high frequency electrical waves, means to impress high frequency waves to be amplified upon an input end of said transmission path to permit travel of the waves along said path, electrode means for producing an electron stream having suitable velocity along said path in space occupied by a traveling electric field produced by said traveling waves when said high frequency waves are impressed and in the direction of travel of that field, said stream entering said field space as a

substantially unmodulated stream, a magnetic electron focusing lens comprising means located along said stream ahead of said wave impressing means and adjacent thereto to produce a steady magnetic field in a region traversed by the electron stream prior to its entrance into said electric field space, the said transmission path being characterized in that the propagation velocity of the said electric field therealong is substantially the same as the velocity of the electron stream passing through said field space whereby energy is transferred from the electron stream to the said waves along a length of said path traversed by the electron stream and means for incorporating into said transmission path in said electric field space high frequency loss whereby there is introduced substantial attenuation to waves in the path while permitting a net amplification of waves traveling in the direction of the said electron stream.

6. A wave amplifying device having input and output terminals, therebetween an extended path capable of propagating a traveling electric wave, means located at the input end of said path for impressing thereon high frequency waves to be amplified, means for projecting an extended electron beam parallel to and inductively related to said path, means for introducing high frequency loss into said path in the region of said inductive relation to attenuate substantially waves traveling counter to the said electron beam, means for producing a steady magnetic field parallel to and in the path of the electron beam before it reaches the region of said inductive relation and means for producing a steady magnetic field parallel to and along the path of the electron beam in the region of said inductive relation, said first-mentioned magnetic field means being located ahead of and adjacent to said wave impressing means.

7. An electronic device comprising means for projecting an electron stream along a path, a pair of coils encircling the said path each capable of being energized to produce steady axial magnetic fields along the said path, the two coils being spaced apart along the path, external magnetic shields enclosing each of the said coils but having apertures for passage of the electron stream along said path, another pair of coils each encircling one of the coils of first-mentioned pair of coils and the enclosing said magnetic shield whereby the said magnetic shields serve as polepieces for the second-mentioned pair of coils and the two pairs of coils may cooperate to produce a substantially uniform magnetic field extending along the path through the axes of the two first-mentioned coils and in the axial space between them.

8. A device according to claim 7 comprising an evacuated envelope enclosing the said electron path and having lateral dimensions substantially uniform along its length.

9. A device according to claim 7 comprising a path and having lateral dimensions which differ substantially along its length.

10. A wave amplifying device comprising a transmission line including a conductor in the form of an elongated helix, means for projecting a stream of electrons traveling with suitable velocity lengthwise of the helix and in space occupied by the field of said helix when said transmission line is energized, a plurality greater than two of rods of insulating material extending lengthwise of the helix, and means for supporting said rods substantially continuously along their lengths to be accurately straight and parallel to

each other and spaced around the circumference of the helix external thereto and in contact therewith whereby the helix is held axially straight and accurately parallel with the direction of projection of said stream of electrons, the said helix being characterized in that its attenuation to the wave to be amplified is substantially uniformly distributed along its length.

11. A wave amplifying device comprising a transmission line including a conductor in the form of an elongated helix, means for projecting a stream of electrons traveling with suitable velocity lengthwise of the helix and in space occupied by the field of said helix when said transmission line is energized, an annular member of material capable of absorbing energy from a high frequency field in which it is situated encircling the helix along a region between the two ends of the helix, a plurality of rods of insulating material extending lengthwise of the helix supported and spaced around the outer circumference of the helix and generally in contact therewith along each portion of the helix between the said annular member and the ends of the helix whereby the helix is held axially straight and accurately parallel with the direction of projection of the said stream of electrons.

12. In combination a pair of solenoid coils for producing axial magnetic fields, the coils being axially aligned but spaced from each other along the common axis and encircling space disposed along the common axis, the said coils having magnetic material upon their outer cylindrical surfaces and the end surfaces but not projecting into the said axial space encircled by the coils, a second pair of solenoid coils for producing axial magnetic fields encircling the said first pair of coils and their coverings of magnetic material, each of the second pair of coils encircling one of the first pair of coils and its covering, whereby the magnetic material coverings serve as pole-pieces for the second-mentioned pair of coils and may produce a field in the axial space between the two first-mentioned coils which is uniform with and continuous with the axial fields produced within these coils.

13. A wave amplifying device comprising a transmission line including a conductor in the form of an elongated helix, means for producing a beam of electrons traveling with suitable velocity lengthwise of the helix and in space occupied by the electric field of said helix when said transmission line is energized, a plurality, greater than two, of rods of insulating material extending lengthwise of the helix and means for supporting said rods along their lengths in spaced relationship around the circumference of the helix and in contact therewith whereby the helix is held axially straight and accurately parallel with the direction of projection of said beam of electrons.

14. An electron discharge device comprising an evacuated envelope having two ends, means at one end of said envelope for producing a stream of electrons, electric wave propagating means comprising a conductor in the form of an elongated helix extending lengthwise of and within said envelope, means for directing said electron stream lengthwise of and within said helix, electrode means at the other end of said envelope for collecting said electron stream and means comprising a plurality of members of electrically non-conductive material extending longitudinally along said helix and disposed between said helix and said envelope and end supports for maintaining all aforesaid means in spaced relationship between the said two ends.

15. An electron discharge device comprising an evacuated envelope, electric wave conducting means comprising a conductor in the form of an elongated helix within said envelope, means within said envelope for producing a beam of electrons traveling lengthwise of and in the field of said helix, coupling means at each end of said helix and connecting thereto for coupling said helix to external transmission circuits, each said coupling means including a section of hollow cylinder, electrode means for receiving said electron beam at the completion of travel through said helix, and means for maintaining all of said means in spaced relation within said envelope comprising a plurality of rods of electrically non-conductive material extending longitudinally along said helix and disposed between said helix and said envelope, fitting closely therebetween to maintain said helix accurately parallel with said envelope, the ends of said rods bearing against said hollow cylinders.

16. A wave amplifying device comprising a wave transmission circuit having an input end and an output end and comprising a conductor in the form of an elongated helix in an evacuated enclosure, means for producing a beam of electrons traveling lengthwise of and in the field of said helix, means to connect a source of input waves to be amplified to said input end and means to connect a load circuit for the amplified waves to said output end, at least one of said connecting means comprising a hollow wave guide and a length of conductor which is located in the field of the wave guide and connected to one of the ends of said helix, said wave guide intersecting the path of said electron beam so the beam traverses the space of the wave guide along a transverse dimension, the wave guide being tapered along its length so that said transverse dimension is substantially less where traversed by the electron beam than at points remote therefrom.

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