Sept. 29, 1953 R. S. BAILEY 2,654,004

TRAVELING WAVE AMPLIFIER DEVICE

Filed Aug. 14, 1947 2 Sheets-Sheet 1

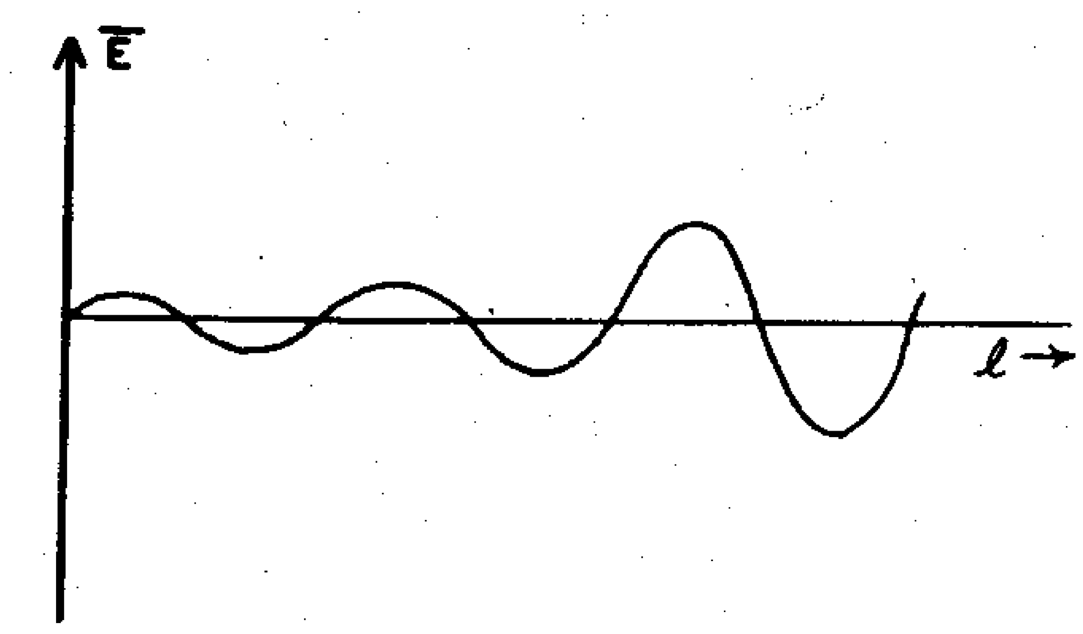

FIG. 2

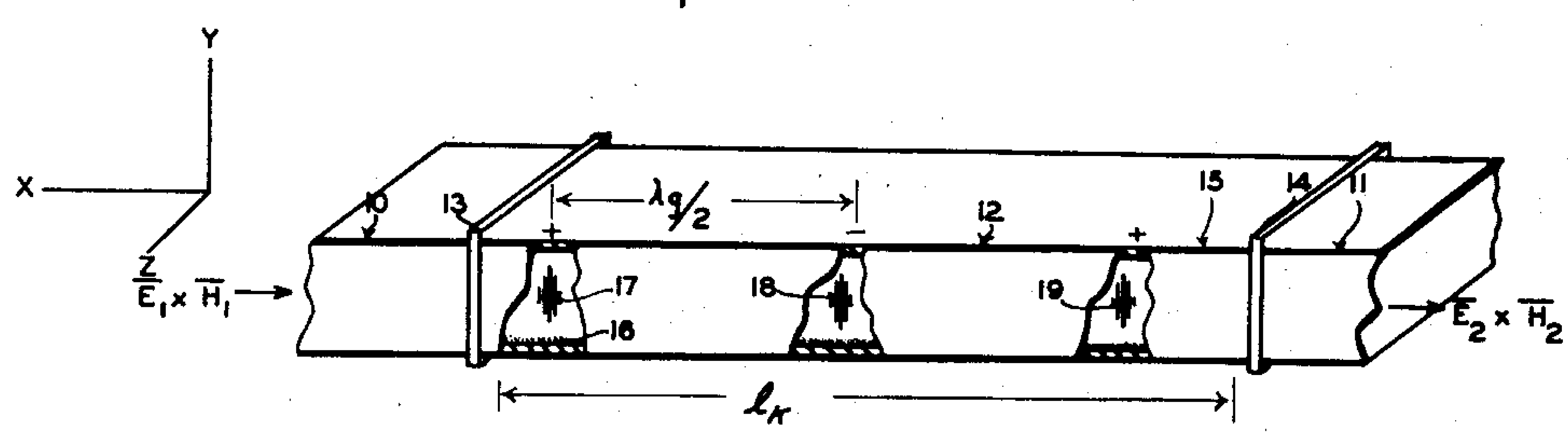

FIG. 1

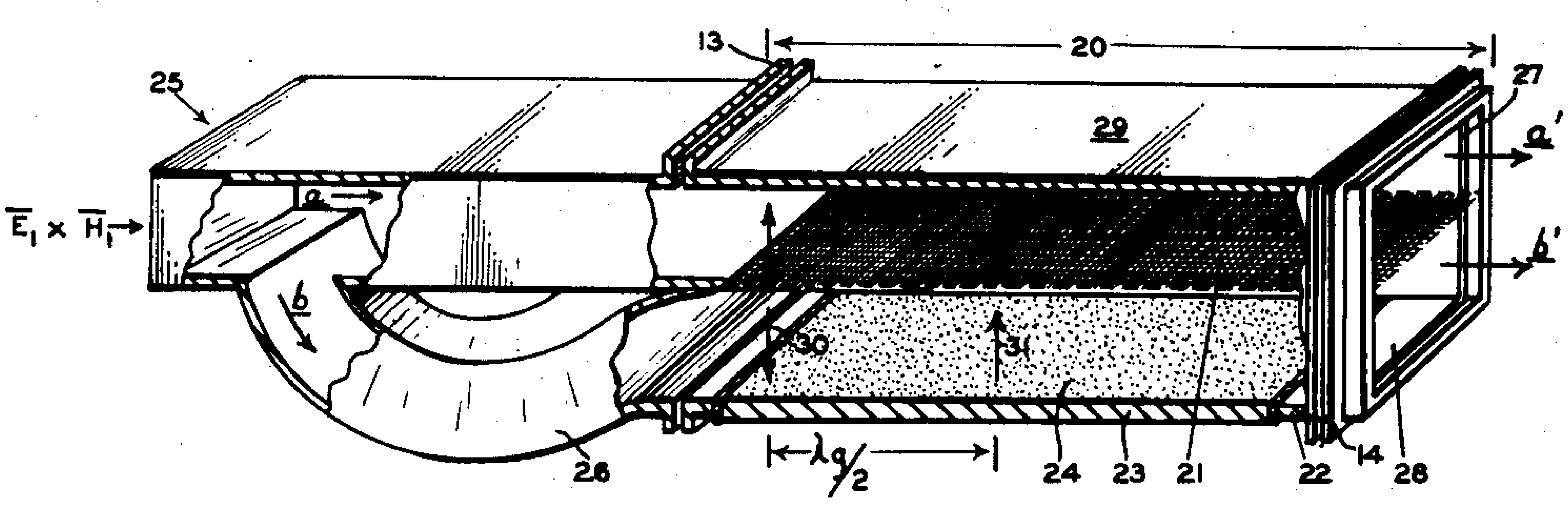

FIG. 3

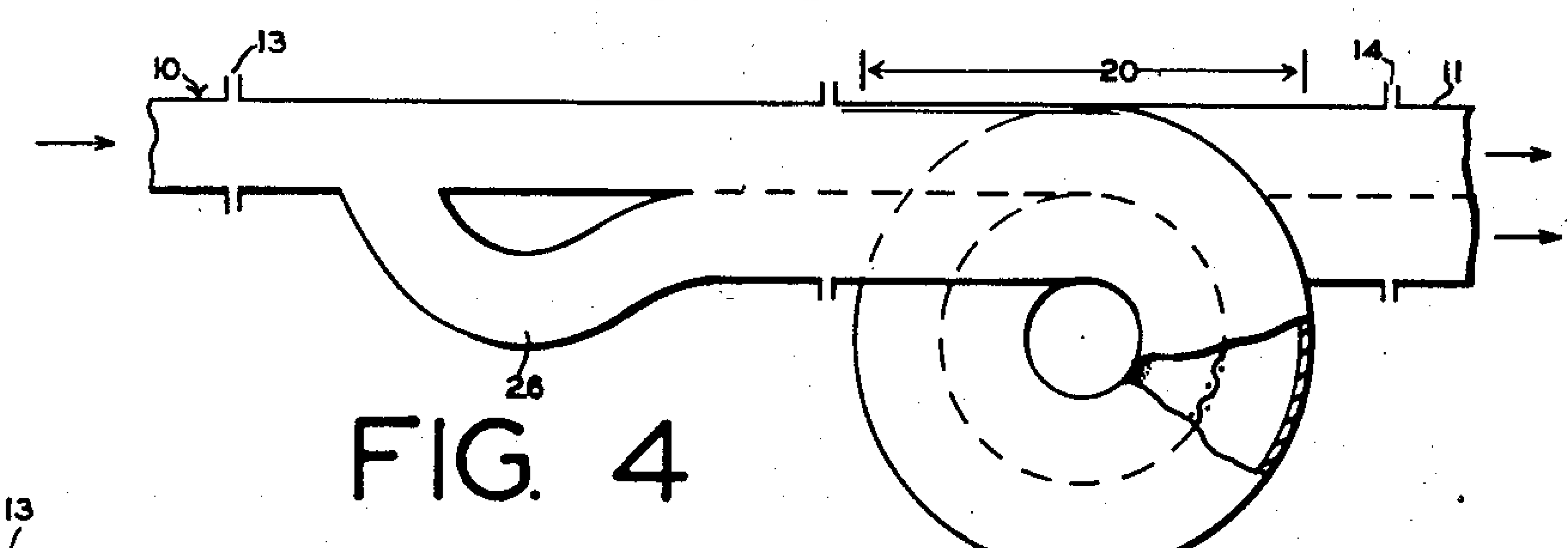

FIG. 4

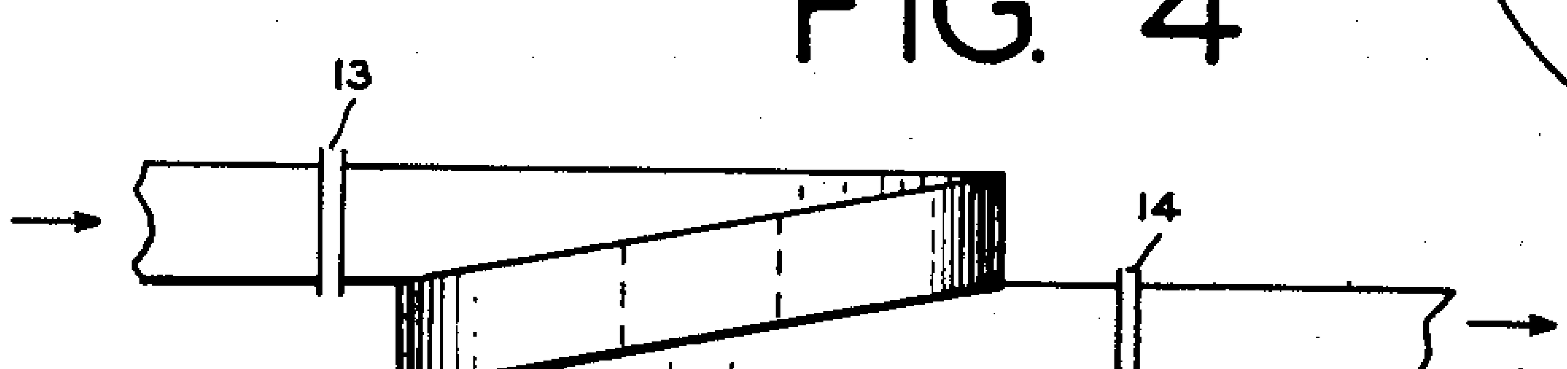

FIG. 5

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TRAVELING WAVE AMPLIFIER DEVICE

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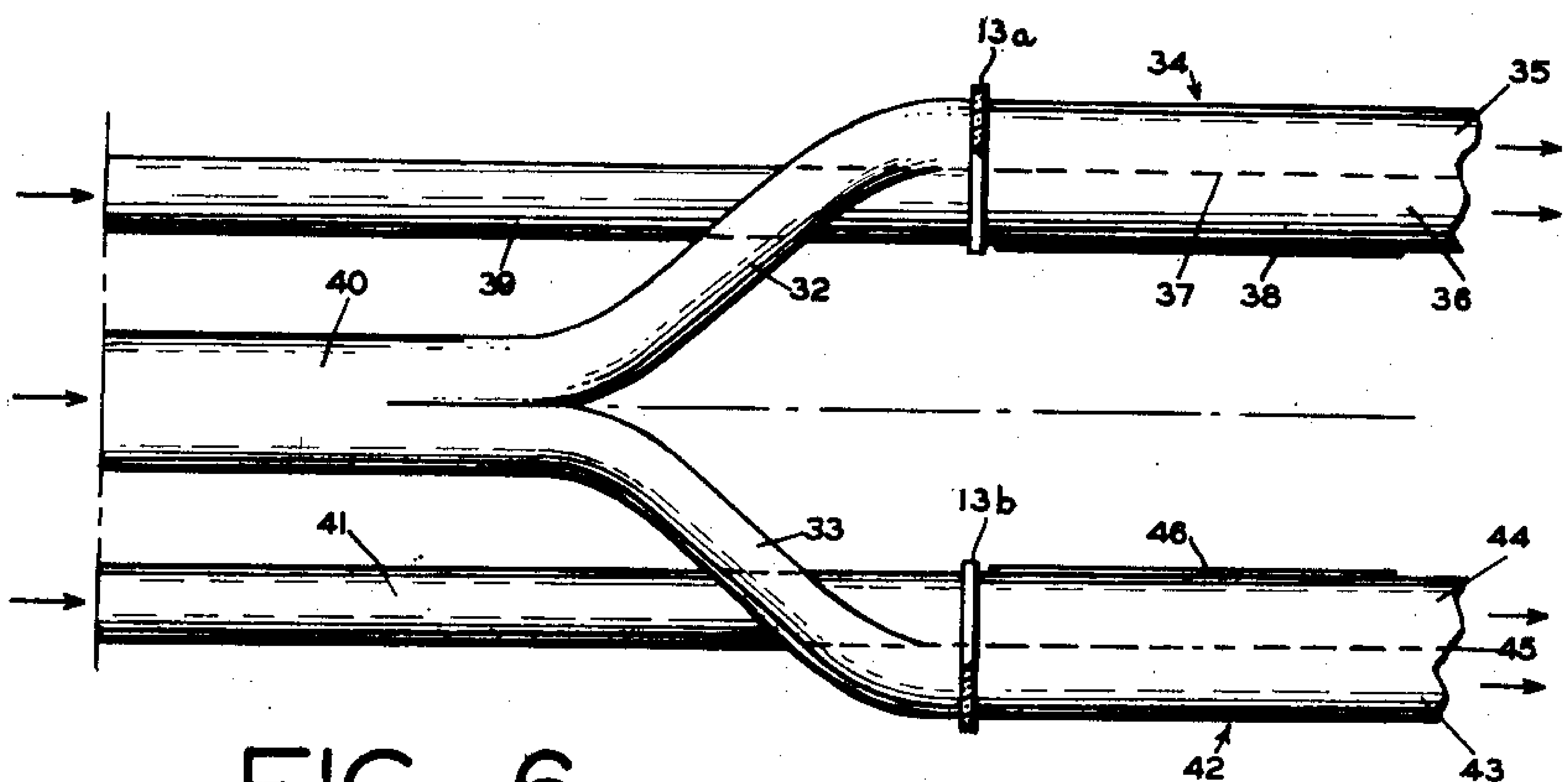
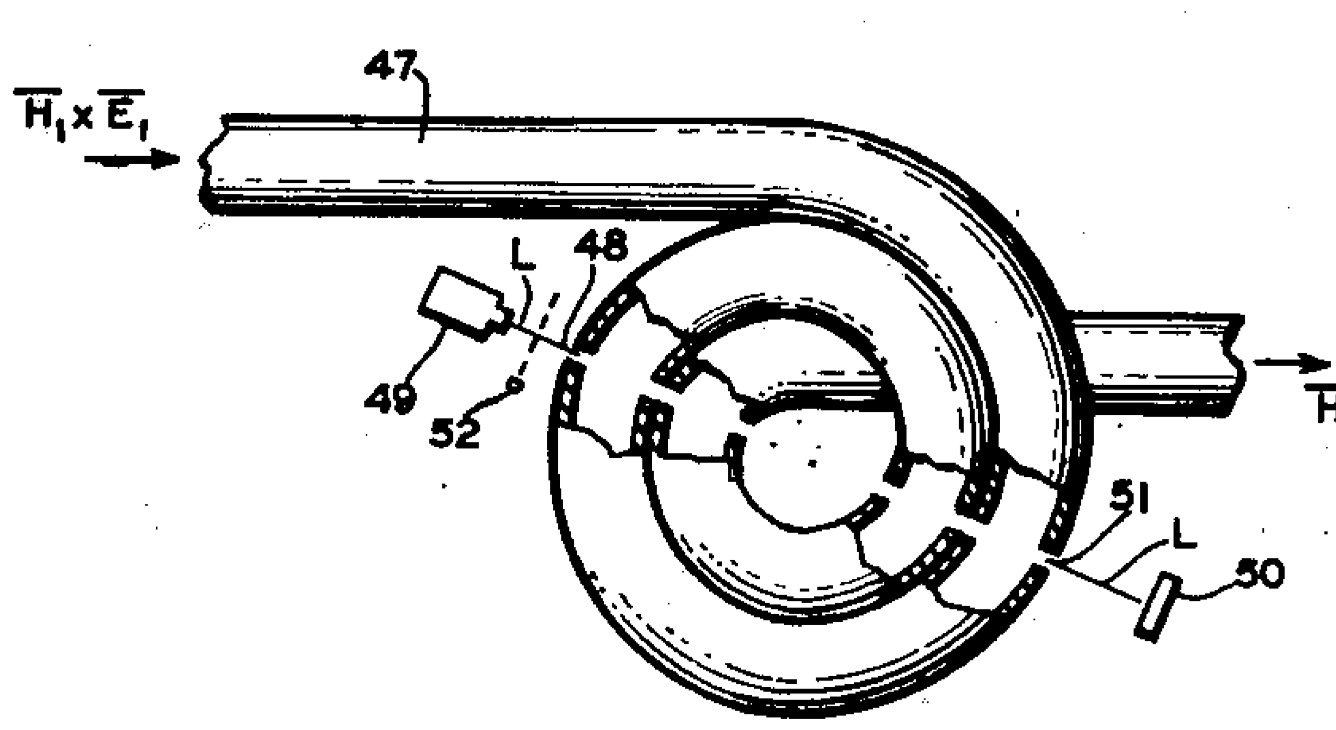


FIG. 6



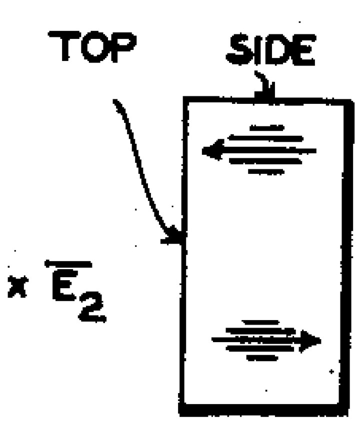


FIG. 9a

FIG. 7

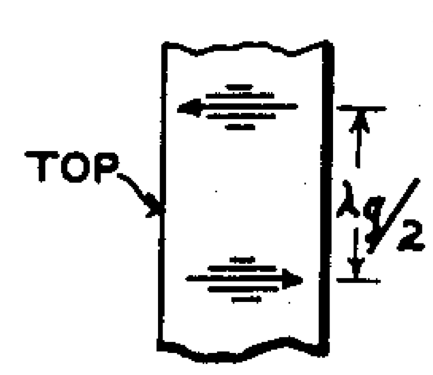
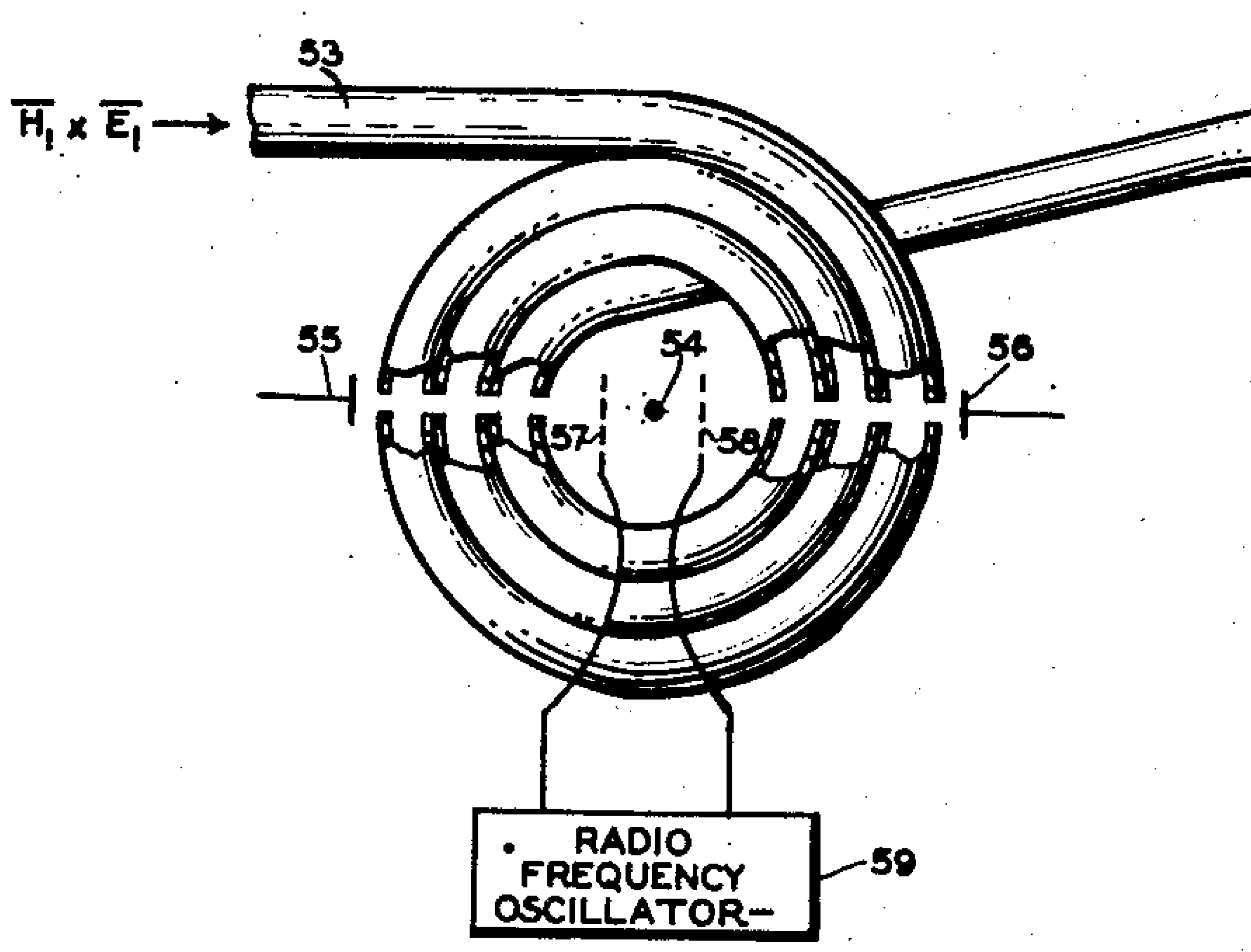


FIG. 9b



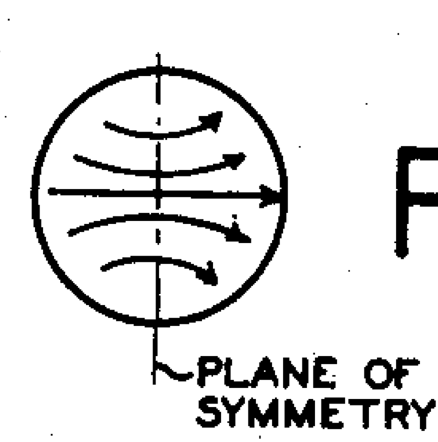


FIG. 10

FIG. 8

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UNITED STATES PATENT OFFICE

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TRAVELING WAVE AMPLIFIER DEVICE

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Application August 14, 1947, Serial No. 768,577

9 Claims. (Cl. 179—171)

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This invention relates to wave energy amplifiers and more particularly to amplifiers of the high frequency traveling wave type.

A principal object of the invention is to provide a novel form of electromagnetic wave energy amplifier employing the interaction between free electrons and a traveling wave.

Another object is to provide a more efficient amplifier of the traveling wave type.

A further object is to provide a wave energy amplifier employing a wave guide and means for producing an electron stream transversely of the wave guide for correlating the phases of the traveling waves at various points along the guide, with the electron emission, so that a high energy transfer is supplied to the traveling waves by the emitted electrons.

A feature of the invention relates to a traveling wave amplifier employing a main wave guide section and an auxiliary wave guide section both of which have a common wave energy input end and a common wave energy output end, the auxiliary section being proportioned so as to produce a predetermined time delay in the auxiliary section, the two sections merging into a common section which has means to produce therein electron emission under joint control of the waves from both sections in such a way as to achieve a high percentage of energy transfer from the electrons to the traveling wave.

Another feature relates to a traveling wave amplifier employing a main wave guide section with an auxiliary or shunt wave guide section, both of said sections having common input and common output ends with the output end having means to develop a stream of electrons therein and correlated with the phase of the electrical vector of the traveling wave so as to impart thereto a high energy transfer from the electrons.

Another feature relates to a traveling wave amplifier employing a wave guide which is coiled intermediate its ends and having means to inject free electrons through the respective coiled turns so as to achieve a high order of amplification of the traveling wave energy by interaction between the electrons and the correlated phases of the traveling wave.

Another feature relates to a traveling wave amplifier constituted of a wave guide which is divided into two wave guide sections by a foraminous wall and having means to produce electron streams transversely of both sections. Both said sections are supplied with high frequency energy from a suitable source in such a way that the waves traveling through one section are time

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delayed with respect to the waves traveling through the other section so that the phase of the electrical vectors of the waves along the length of the sections is in proper relation to provide the maximum energy transfer between the electrons and the traveling wave.

Another feature relates to an arrangement for amplifying high frequency traveling waves comprising a wave guide having input and output ends with the intervening length of the wave guide coiled to a substantially planar spiral in conjunction with an electron emitting cathode which is mounted symmetrically at the center of the spiral and with a pair of electron collector electrodes mounted outside the spiral but in alignment with the cathode. Located between the cathode and the spiral are electron control electrodes which are alternately energized to cause the electrons to travel transversely, first through the sections of the coil on one side of the cathode, and then through the sections of the coil on the opposite side of the cathode, for the purpose of transferring a maximum amount of energy from the electrons to the high frequency waves traveling through the guide.

A further feature relates to the novel organization, and arrangement of parts, which cooperate to provide an improved high frequency wave energy amplifier of the traveling wave type.

Other features and advantages will appear from the ensuing descriptions and the appended claims.

In the drawing which shows, by way of example, certain preferred embodiments, Fig. 1 is a generalized view of a traveling wave amplifier of known construction employing a wave guide section used in explaining the invention.

Fig. 2 is a graph of the electric vector of the traveling wave in the amplifier of Fig. 1.

Fig. 3 is a perspective view of an amplifier or a wave repeater according to the invention.

Fig. 4 is a side view of a modification of the arrangement of Fig. 3.

Fig. 5 is a top plan view of Fig. 4.

Figs. 6, 7 and 8 represent respective further modifications of the invention.

Figs. 9*a* and 9*b* are diagrammatic views explanatory of an amplifier or repeater according to the invention employing a rectangular wave guide using the $TE_{0,2}$ mode of transmission.

Fig. 10 is a diagrammatic view explanatory of the operation of an amplifier according to the invention, employing a circular wave guide.

Referring to Fig. 1, there is illustrated a conventional rectangular wave guide system comprising an input section 10, and output section 11, and an intervening amplifier section 12. It will be assumed that a high frequency wave energy is received through the input section 10 so that the various sections are excited in the $TE_{0,1}$ mode. The sections 10, 11, are conductively isolated or insulated from the section 12 by suitable insulators or insulator joints 13, 14, so that the section 12 is insulated from sections 10 and 11 for direct current flow, but without disturbing the alternating current field. In accordance with known theory of traveling wave amplifiers, the section 12 should have a length which is equal to one or more wavelengths of the excitation energy which is supplied thereto from the input section 10. Merely for purposes of reference, it will be assumed that the wall 15 is the top wall of the wave guide, and therefore the electrical field will exist between this top wall and the opposite or bottom wall of the guide. Suitably mounted or carried by the bottom wall of the guide section 12 is an electron emitting cathode surface 16. Preferably this cathode surface is D. C. insulated from the walls of the guide section 12, for example the bottom wall of section 12 may have a window or opening into which is insulatingly fitted a metal strip carrying on its inner surface a suitable electron emissive coating which can be raised to emissive temperature by any well-known means. The remaining walls of the guide section 12 can be positively biassed by any suitable D. C. potential source. Preferably, the length of the cathode coating 16, in the direction of the wave propagation is equal to one or more wavelengths of the excitation energy. The $\bar{E}$ vector groupings of the propagated energy are schematically represented in Fig. 1 by the line groups 17, 18, 19, etc. The Poynting's vector $\bar{E}_1$ and $\bar{H}_1$ indicate the direction of propagation of high frequency energy through the system. The $\bar{E}$ vectors at odd maxima, for example at 17 and 19, may be considered positive, while at the even maxima, for example 18, they may be considered negative.

With the wall 15 at a suitable positive D. C. potential the electrons from the emitted surface 16 will drift along the Y axis. When no high frequency or radio frequency wave energy is present in the section 12, and for values E_p of the D. C. potential applied to wall 15, at which potential it is assumed that the relativity effect does not enter, these electrons from surface 16 will absorb energy from the positive electric field and will give it up at the surface of wall 15 in the form of heat and current flow. Under such conditions the electrons will, as is well-known, arrive at wall 15 with a velocity

$$\sqrt{\frac{2e/E_p}{m}}$$

However when radio frequency waves are being propagated through the section 12, they will modulate the stream of electrons in so far as their velocity is concerned, alternately accelerating and decelerating them. If the net effect of the traveling wave field is a deceleration of the electrons, then energy is supplied to the radio frequency field from the D. C. field, and amplification of the wave energy takes place. For example, assuming that amplification takes place, the magnitude of the $\bar{E}$ vector in the guide can be represented by an increasing quasi-sinusoid, as shown for example in Fig. 2. If the positive, that is the upper halves of $\bar{E}$ in Fig. 2 are considered as accelerating with respect to the electrons, the negative or lower halves of $\bar{E}$ are decelerating in action. Since the negative halves are larger in amplitude than the next preceding positive halves, there occurs a net deceleration over an integral number of cycles.

From the foregoing, it will be seen that if the electrons are moving in the same coordinate system as that of the traveling wave and at the same velocity in this system (that is if the electrons are injected at the same velocity as the wave guide velocity), then only those electrons which are emitted at a negative or decelerating $\bar{E}$-space-time position, will give up energy to the radio frequency field. However, those electrons emitted from 16 at accelerating $\bar{E}$-space time positions will take less energy from the radio frequency waves under either of the following conditions:

(1) The number of electrons at these accelerating positions are fewer; or

(2) The E_p field is opposite to that which exists at a point $\lambda g/2$ away.

Under these conditions, the dimensions of the wave guide are not critical when the electrons move with the wave.

One of the principal difficulties of the foregoing described type of amplifier is in making sure that the electron injection from the surface 16 is effected at the speed of the traveling radio frequency wave. Various attempts have been made to achieve this result, for example by slowing down the radio frequency wave by means of a coil. This known type of expedient is not predicated mainly on either of the above-mentioned alternatives. I have found that this slowing down effect can be greatly increased by purposely arranging the system so that fewer electrons are emitted from the cathode 16 at the undesired time instant. One typical arrangement for accomplishing this result is shown in Fig. 3. In this figure the amplifier section 20 of the wave guide corresponding to the section 12 of Fig. 1, is divided longitudinally into two parts by means of an open-work metal wall or grid 21. The section 20 is preferably closed at its ends for example by glass walls, and the interior of section 20 is highly evacuated. The coupling for A. C. wave energy between section 20 and sections 10 and 11 can therefore be effected electrostatically as is well-known in wave guide systems. The lower wall 22 of this guide has a window or opening in which is insulatingly fitted the metal plate 23 having its inner face provided with an electron emissive coating 24 which can be raised to emitting temperature by any well-known heating means (not shown). The input section 25 of the guide communicates with a branch 26, so that the input wave energy is divided into two guide paths designated respectively by the arrows a and b. The length of the branch 26 from the point of its coupling to the input section 25 and to the point of its coupling to the amplifier section 20, is designed so that at the common region where the sections 25 and 26 couple to the amplifier section 20, the waves arriving over branch 26 are delayed by $\lambda g/2$ with respect to the waves arriving directly from section 25. Thus the section 20 may be considered as made up of two wave guides having a common foraminous dividing wall 21, the upper portion 27 of section 20 receiving the wave propagation directly through section 25, and the lower portion 28 receiving the propagation through the branch 26. Thus in the section 28, the radio frequency field of the traveling wave causes electron emission only at favorable points for insertion into the section 27 through the grid

21, namely at those points where the electric field of the traveling waves in section 27 have a decelerating action on the electrons which emerge through the grid 21. On the other hand, when the electric field of the traveling waves in section 27 are in the accelerating phase, the traveling waves in the section 28 are in a decelerating phase, thus reducing considerably the number of electrons which emerge through the grid 21 at this region. The section 28 may be terminated by a suitable termination or preferably its output can by a suitable coupling be added to the output from the section 27. While there may be some wave amplification in the section 28, it is only to a slight degree as compared with the resultant wave amplification in section 27.

It will be understood of course that the section 20 is D. C. insulated from the input and output sections, such as sections 10, 11 (Fig. 1), without affecting the A. C. field. Likewise, as described above in connection with Fig. 1, the upper wall 29 can be connected to a suitable positive D. C. potential with respect to the cathode. If the work function of the cathode 24 is E_w, a small positive D. C. potential E_{bb} should exist between the cathode 24 and the foraminous wall 21, so that during the deceleration cycles of the traveling waves the fields of these waves just cut off the electron current at the deceleration half-cycle, represented schematically by the arrow 30. If the electron transit time between 23 and 21 is negligible, or if the length of section 26 is designed to take into account this transit time, the electrons from cathode 24 will emerge through the grid 21 into guide section 27 in the presence of a strong D. C. accelerating field, as represented schematically by the arrow 31. But at this instant, the field in the section 27 at the region represented by arrow 31 will be strongly decelerating. In other words, the field of the traveling wave in section 27 has its $\bar{E}$ vector decelerating at the same instant the electrons are being highly accelerated into the section 27 by the simultaneous accelerating action of the $\bar{E}$ vector in section 28. The positive D. C. potential applied across wall 29 and grid 21 should be such as to cause the average electron to give up the maximum of its energy before it is collected by the surface 29.

There will of course be some wave amplification in the section 28 and theoretically this amplification may be of the order of 50%. However, in section 27 theoretically the maximum amplification will be nearly 90% resulting in a greatly increased over-all amplification efficiency, particularly when the amplified output of section 28 is added to the amplified output of section 27. In order further to increase the amplifying efficiency, the section 20 instead of being straight, can be coiled into a helix, as illustrated in Figs. 4 and 5, providing the radius of this helix is not made too small. With a sufficiently large helix, the above-described amplifying action can be obtained without disturbance of the radio frequency waves traveling through the guide. While Figs. 4 and 5 show the amplifying section formed with a single helical turn, it will be understood that it may be formed with two or more helical turns. In effect, by coiling the amplifying section as shown in Fig. 4, the rectangular cathode 24 of Fig. 3 is now of cylindrical shape. Therefore, this cylindrical cathode can be conveniently provided with a central heater (not shown) of any suitable design, so as to raise it to emitting temperature.

While in Figs. 3 and 4 there is provided an auxiliary path or T-junction 26 for obtaining the phase change of $\lambda g/2$ (or odd multiple thereof), other well-known arrangements may be provided for obtaining this relative phase delay between the waves entering the section 28, as compared with the waves entering the section 27, thus allowing the T-junction to become a matched Y-junction.

Referring to Fig. 6, there is shown a further modification wherein the wave guide is split along its plane of symmetry represented by the dot-dash line, so as to form Y branches 32, 33. The branch 32 merges into an amplifier section 34 similar to section 20 (Fig. 3) comprised of two adjacent wave guides 35, 36, having a common foraminous boundary wall or grid 37. The wall of section 36 which is opposite to wall 37 carries an electron emitting cathode 38 for injecting electrons into the wave guide section 35 under control of grid 37 and the electric field of the traveling waves in guide section 36. It will be understood that the cathode 38 is suitably D. C. insulated from the wall 37 and from the remainder of guide 34. It will also be understood that the amplifier section 34 is D. C. insulated from the remainder of the wave guide system without affecting the A. C. fields within the guide. As mentioned above, the upper wall of guide 34 can be suitably biassed positively with respect to the cathode 38. Coupled for wave propagation to the section 36, but D. C. insulated therefrom, is an input wave guide 39. The Y branch 32 which is coupled to the section 35 is also coupled to a wave guide section 40 both of which are excited by the input waves, for example in the $TE_{0,1}$ mode, from a suitable source.

Likewise the Y branch 33 and the corresponding wave guide section 41 are coupled for A. C. propagation to an amplifier wave guide section 42 similar to section 34, having two wave guide sections 43, 44, with a common foraminous conductive separating wall or grid 45. The wall of section 44 opposite to grid 45 carries an electron emitting cathode 46 which is suitably D. C. insulated from the guide 42 and is arranged to be raised to emission temperature by any suitable means which may be the same means that heats the cathode 38 as above described. The sections 35, 36 can be suitably phased with respect to each other as described above in connection with Fig. 3 by properly designing the length of the Y branch 32. Likewise the sections 43 and 44 can be properly phased by designing the appropriate length for the section 33. The outputs from the amplifier sections 34 and 46 can be appropriately combined so as to increase the over-all amplification of the system.

By correctly matching all the wave guide junctions in known manner, reflection losses can be avoided. In the case of the coiled wave line embodiment of Fig. 4, and in the subsequent coiled embodiments to be described, reflection losses can be minimized if the constants of the guides are preserved while forming the helices. This will result in large propagational velocities, but since the helix can be installed economically in relatively small space, sufficient D. C. potential can be used to transfer a substantial part of the energy from the electrons into the traveling wave. If the velocity of the wave propagation is too high, for example greater than the velocity of light, the wave guides above described should have their diameters or transverse dimensions correspondingly changed to lower the propagational velocity, and by also using appropriate matching means at each end.

Referring to Fig. 7, there is shown a further modification wherein wave amplification is obtained by employing for example a circular wave guide **47** which is rolled up into a spiral, so that all the turns are in substantially the same plane and preferably with the walls of the adjacent turns in contact. With such an arrangement, along the line L—L, the wall-to-wall radio frequency voltage of the guide is in phase. In accordance with the invention, the walls of the turns are provided with windows or openings all of which are in alignment along the line L—L. Adjacent the outer window **48** is an electron gun **49** or any other well-known means for developing a beam of high velocity electrons which can be focussed or directed so as to move along the line L—L. If desired, a high potential anode **50** can be located adjacent the opposite window **51** to facilitate the acceleration of the electrons in the beam. By appropriate means, for example by the grid **52** the electron beam can be blanked off at an appropriate rate by any well-known source of periodic blanking potentials. The passage of the electron beam serially through the several turns of the coiled wave guide is timed so that they pass transversely through each turn only at the instants when the $\bar{E}$ vector of the traveling wave propagated through the guide **47** has a decelerating action on the electrons emanating from the gun **49**. The energy of these electrons is then transferred to the radio frequency field and the amplitude of the traveling wave in the guide is correspondingly increased.

Referring to Fig. 8, there is shown a modification of the traveling wave amplifier embodiment of Fig. 7, but wherein easier control is obtainable over the proper phase relation between the traveling waves and the electron emission. In this embodiment, the wave guide **53** which may be a circular wave guide, is coiled to substantially spiral form, as in the case of Fig. 7. Likewise, the walls of the adjacent turns of the spiral have aligned windows. Centrally mounted within the spiral is another suitable electron emitting cathode **54**, and located on opposite sides of the cathode **54** externally of the spiral wave guide and in alignment with the windows, are respective anodes **55**, **56** which are suitably biassed positively with respect to the cathode **54**. Located between the cathode and the inner turn of the spiral wave guide, are two accelerating grids **57**, **58**. The grids **57** and **58** are connected respectively to a radio frequency oscillator **59** in push-pull relation so that when one grid is biassed positively with respect to the cathode **54**, the other grid is biassed to plate current cutoff. The oscillator **59** is adjusted to operate at the same frequency as the frequency of the waves propagated through the guide **53**. By this arrangement, the electrons from cathode **54** are alternately accelerated, first in one direction through the coil turns towards the anode **55**, and then in the opposite direction through the coil turns towards the anode **56**. The spirally formed wave guide **53** is so dimensioned, that regardless of whether the electrons are flowing to anode **55** or to anode **56**, the electric field of the traveling waves within the guide are always in decelerating phase with respect to the electrons passing through the guide from the cathode **54**, resulting in a greatly increased overall wave amplification at the output end **60** of the guide.

While in Fig. 8 the electrons from the cathode **54** are subjected to alternate or two-phase control, it will be understood that the cathode **54** may be provided with three or more grids symmetrically surrounding the cathode, and each of these grids will then be in alignment with a corresponding aligned set of windows in the spiralized wave guide. These grids can then be connected to any well-known form of polyphase radio frequency oscillator so as further to increase the over-all wave amplification at the output end **60** of the guide.

In all of the foregoing embodiments, it will be understood that the interiors of the amplifier sections, for example section **20** (Figs. 3 and 4), sections **34**, **46** (Fig. 6), are evacuated in any suitable manner, for example these ends of these sections may be closed-off by suitable glass insulators, and these sections can be coupled to the input and output wave guides by capacitor couplings as is well-known in the wave guide art.

While in the foregoing descriptions reference has been made to the $TE_{0,1}$ mode of wave propagation, it will be understood that other modes can be employed to achieve the desired amplification. Thus there are shown schematically in Figs. 9*a* and 9*b* the distribution of the $\bar{E}$ vector in a rectangular wave guide excited in the $TE_{0,2}$ mode. In the case of circular wave guides as represented schematically in Fig. 10, the guide may be excited in the $TE_{1,1}$ mode. With this mode the $\bar{E}$ vector lines are symmetrical as illustrated in Fig. 10, in which case an electron emitting cathode, corresponding to cathode **24** (Fig. 3) can then be mounted within the guide in this plane of symmetry, without disturbance, and providing of course the cathode is maintained negative with respect to the guide walls. Furthermore the invention is not limited to wave guides of rectangular cross-section and therefore circular cross-section wave guides may also be employed.

While certain particular embodiments have been described, various changes and modifications may be made therein without departing from the spirit and scope of the invention.

What is claimed is:

1. Apparatus for amplifying high frequency wave energy, comprising a pair of wave guides each having an input end and an output end and the pair having a common electron permeable separating wall, means in one of said guides to emit electrons transversely thereacross through said dividing wall and thence transversely across the other wave guide, and means to introduce traveling wave energy into the input ends of said wave guides in opposite phase with respect to their action on the emitted electrons.

2. Apparatus for amplifying high frequency wave energy, comprising a pair of wave guides, means in one guide to emit electrons into the other guide, a wave guide coupled to both said wave guides on one side of said electron emitting means for applying high frequency energy thereto, a wave guide coupled to both said wave guides on the other side of said electron emitting means for extracting the amplified high frequency energy therefrom and means to delay the electric field of the wave energy in the first guide with respect to the field of the wave energy in the other guide whereby more electrons are emitted into said other guide when the electric fields in said other guide are in decelerative phase with respect to said electrons as compared with the number of electrons that are emitted into said other guide when the electric fields in said other

guide are in accelerative phase with respect to the electrons.

3. A wave amplifier of the traveling wave type, comprising a wave guide, means for emitting electrons interiorly of the guide and transversely thereacross, a foraminous conductive member dividing said guide into two sections, means for coupling one of said sections to a source of high frequency wave energy, and means for coupling the other of said sections also to said source, the last-mentioned means including means to delay the wave energy excitation of one of said sections with respect to the wave energy excitation of the other of said sections so that for corresponding regions of both said sections the electric fields are of substantially opposite phase.

4. A high frequency wave amplifier of the traveling wave type, comprising a wave guide, a foraminous conductive wall dividing said wave guide into two similar wave guide sections, an electron emitting cathode carried by one of said sections for emitting electrons transversely thereacross and thence through said dividing wall and transversely across the other section, a T-junction for coupling a source of high frequency wave energy respectively to said sections, one leg of the T-junction being of greater transmission length than the other so that at corresponding regions of said two sections the electric fields of the traveling waves are of substantially opposite phase with respect to the electrons from said cathode.

5. A traveling wave amplifier according to claim 4 in which said sections of the traveling wave amplifier are adapted to be coupled to said source through respective wave guides one of which delays the electric field by one-half the wave length of the traveling wave.

6. A traveling wave amplifier according to claim 4 in which said dividing wall is adapted to be biassed with respect to the cathode so that when the electric fields of the traveling waves in the first section are in decelerative phase with

respect to the electrons, the electron emission is substantially cut off from the other section.

7. A traveling wave amplifier according to claim 4 in which said wave guide is coiled to helical shape.

8. A traveling wave amplifier according to claim 4 in which said wave guide is of the rectangular type having said cathode forming one of the walls between which the electric fields are propagated, said guide being coiled to helical shape whereby said cathode assumes a substantially cylindrical formation around the interior of the coil.

9. A traveling wave amplifier comprising a pair of amplifier units, each unit consisting of a wave guide divided into two sections by a foraminous conductive wall, each unit also having means to emit electrons transversely across both sections and through the respective foraminous wall, means to couple both of said units to a source of high frequency energy, the last-mentioned means including a pair of linear wave guides for coupling the corresponding sections of said units to said source, and a Y-junction wave guide having the arms of the Y respectively coupled to the other sections of said units to cause the electric fields of the wave energy in the two sections of each unit to be of substantially opposite phase.

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