

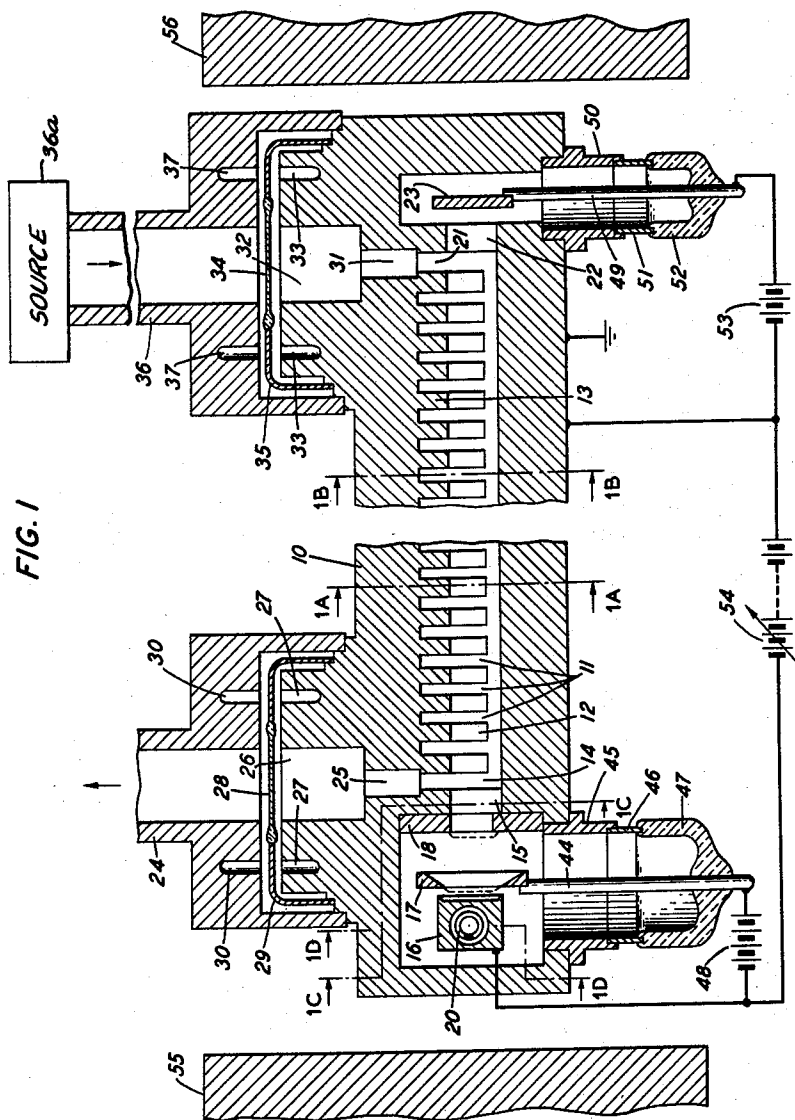
Dec. 8, 1959

R. KOMPNER ET AL
BACKWARD WAVE AMPLIFIER

2,916,657

Filed May 17, 1952

3 Sheets-Sheet 1



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FIG. 1C

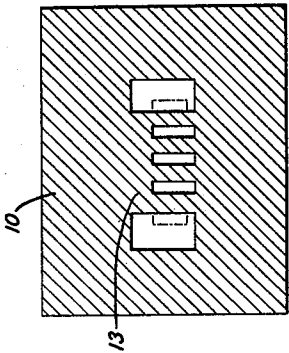


FIG. 1B

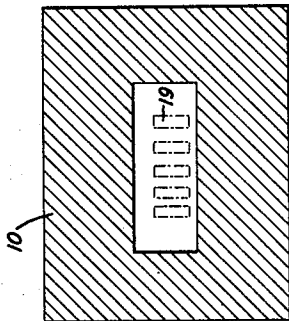


FIG. 1A

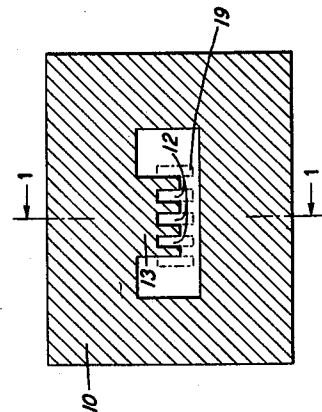
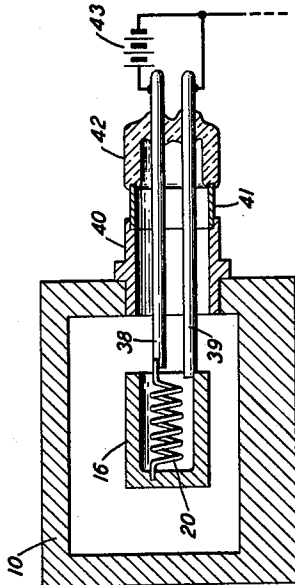


FIG. 1D



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FIG. 3C

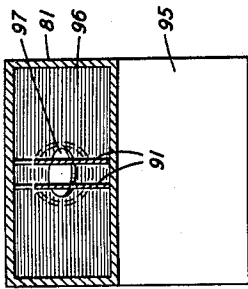


FIG. 2

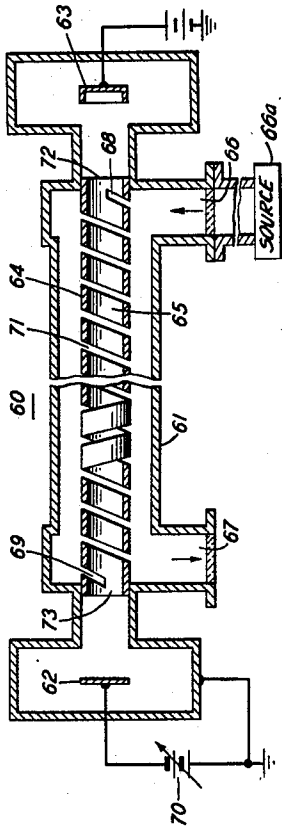


FIG. 3A

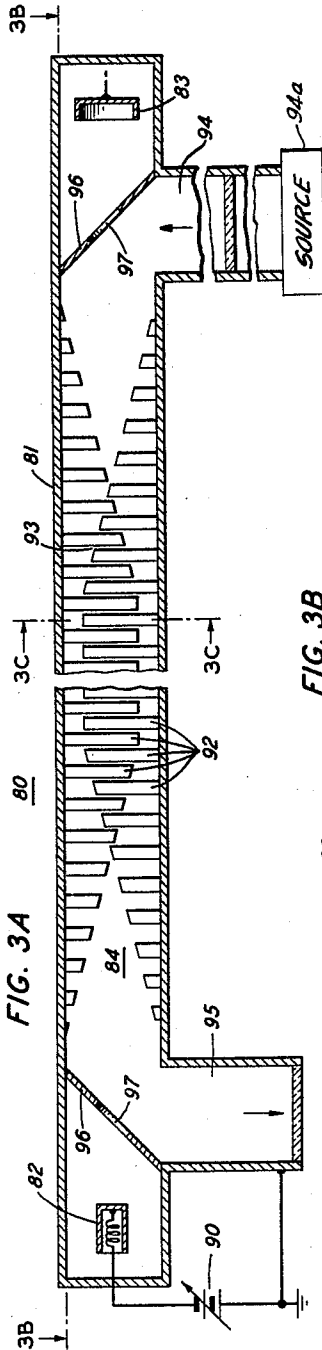
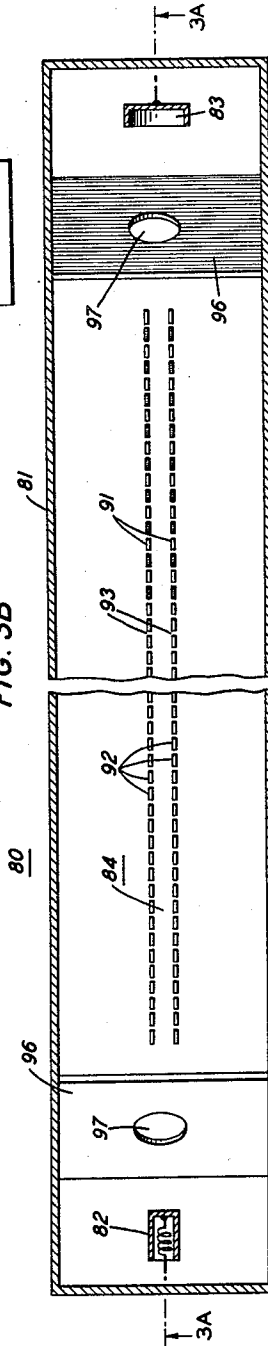


FIG. 3B



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2,916,657

BACKWARD WAVE AMPLIFIER

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Application May 17, 1952, Serial No. 288,438

13 Claims. (Cl. 315—3.6)

This invention relates to microwave amplifiers and more particularly to such amplifiers which utilize for amplification the interaction between an electron stream and an oppositely directed or backward traveling electromagnetic wave.

The traveling wave tube can be described as a vacuum tube which contains a wave circuit propagating electromagnetic waves therethrough and an electron stream passing through the electric field set up by the wave circuit. The electric field of the wave accelerates electrons in the stream, giving rise therein to an A.-C. velocity component which sets up an A.-C. current component. This A.-C. current component sets up an electric field of its own which combines with the electric field of the wave. For amplification, it is important that a given group of electrons interact with corresponding portions of the electric field as it progresses along the tube. In the most common type of traveling wave tube, as for example that which utilizes a wire helix as the wave guiding structure, interaction of this kind occurs continuously as the electron stream and wave progress along the tube. To this end, the electrons are caused to travel along in substantial synchronism with the wave, a particular group of electrons interacting with substantially the same portion of the wave at all times. In another type of traveling wave tube, of which a representative form is described in copending application Serial No. 99,757, filed June 17, 1947, by S. Millman, and which issued July 6, 1954, as U.S. Patent 2,683,238, the electron stream and the electromagnetic wave do not move along in substantial synchronism, but instead a discontinuous or intermittent type of interaction is employed. In operation of this sort, the electromagnetic wave is transmitted over a guiding structure in which the strength of the interacting component of the field associated with the wave is made alternately large and small at successive fixed intervals along the guiding structure and a stream of electrons is projected in the direction of wave propagation in an interacting relationship with the wave and at a velocity considerably lower than the phase velocity of the wave. The velocity of the electron flow is adjusted so that while an electron traverses the average distance between adjacent intervals in which the interacting component of the field is high, the wave traverses substantially the same distance plus an integral number (e.g., one) of wavelengths. In this way, a given group of electrons interacts with like portions of the wave as it traverses successive intervals in which interacting field strength is high. The intervening intervals in which interacting field strength is low prevent the electron bunching produced by the interaction in the high field intervals from being subsequently counteracted by interaction with out-of-phase portions of the wave. Wave guiding structures of this kind can be termed discontinuous or intermittent interaction type structures and operation of the kind described above in which a group of electrons interacts with like portions of the wave instead of the same

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portion of the wave can be termed spatial harmonic operation.

The present invention is directed primarily at a traveling wave tube which utilizes for amplification a discontinuous interaction type circuit to provide interaction between an electron stream and the spatial harmonics of an oppositely directed traveling wave.

In the literature, there is found speculation about the possibility of backward wave amplification, i.e., amplification between an electron stream and a wave traveling in opposite directions. However, it has not hitherto been appreciated that such amplification can in fact be conveniently secured if there be provided a discontinuous interaction type circuit for spatial harmonic operation in a backward wave mode so that a given group of electrons can be made to interact with like portions of the wave although the stream and the wave travel in opposite directions.

It has been found characteristic of backward wave operation of this kind that high factors of amplification can be obtained over a relatively narrow pass band of frequencies, and more importantly that this pass band of frequencies can to a considerable extent be shifted electronically by varying the electron stream velocity, as by changing the beam accelerating voltage. This characteristic makes a backward wave amplifier of this kind particularly suitable for special applications where it is desired to vary the pass band of an amplifier automatically over a wide range.

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

Fig. 1 represents a longitudinal cross section of a backward wave amplifier in accordance with the invention which employs an intermittent interaction type circuit which comprises a periodic series of lateral slots;

Figs. 1A, 1B, 1C and 1D are cross sections taken along the lines 1A—1A, 1B—1B, 1C—1C, and 1D—1D, respectively, of the amplifier shown in Fig. 1;

Fig. 2 is a side section of a second embodiment of the invention in which a ribbon helix is utilized as the wave guiding circuit; and

Figs. 3A, 3B, and 3C are a side section, a top section, and a cross section, respectively, of a traveling wave tube embodiment of the invention incorporating an interdigital type wave guiding circuit.

With reference particularly to Fig. 1, the traveling-wave tube shown is constructed largely of non-magnetic conducting material (e.g., copper). An elongated copper block 10 forms the main portion of the tube and has an evacuated hollow interior to guide electromagnetic waves. The wave-guiding path includes a series of lateral slots 11 which are regularly spaced for most of the length of the tube. Three longitudinal slots 12 cross lateral slots 11 and extend for substantially the whole length of the tube.

Details of the wave-guiding path are shown in the cross-sectional views of Figs. 1A and 1B. Fig. 1A is a section taken between two slots 11, along the line 1A—1A, while Fig. 1B is a section taken through a slot 11, along the line 1B—1B.

As shown in Fig. 1B, the cross-section of the hollow interior of the block 10 is rectangular at each slot 11, with the short dimension vertical. The cross-section of the hollow interior of the block 10 between slots 11 is much the same, as shown in Fig. 1A, except that a rectangular fin 13 extends down into the interior from the center of the top of the hollow interior. The spaces between adjacent fins 13 form the slots 11. The bottom edges of the fins 13 contain three spaced longitudinal slots 12 which extend for substantially the whole length of the tube. The slots 11 are in the nature of resonators

and serve to increase the field strength of waves propagating in the structure of their vicinity. Between slots 11, the effect of the projecting conductive fins is to reduce the strength of the interacting component of the field. The effect is to make the strength of the interacting component of the field of the traveling wave alternately large and small along the guiding structure. The longitudinal slots 12 serve to increase the space in which the electron stream can interact with the traveling wave.

Just to the left of the fin 13 farthest to the left, is an end slot 14. To the left of slot 14 is a short connecting section 15, a cross-section, taken along the line 1C—1C, being shown in Fig. 1C. The connecting section is of the same cross-section as the between-the-slot cross-section of Fig. 1A, except that the sections of the fin between longitudinal slots 12 extend to the bottom of the opening to provide a radio frequency short at the end of the wave-guiding path.

To the left of connecting section 15, block 10 has a hollow interior of rectangular cross-section to provide space for a cathode 16 and a control grid 17. An accelerator grid 18 also occupies part of the space to the left of connecting section 15 comprising a flat molybdenum plate of rectangular cross-section with a central screened rectangular aperture. The molybdenum plate is flush against the right-hand end of the open space and the aperture is aligned with passage 15 and fins 13. The aperture and the previously described end section determine the shape of an electron stream which is projected past fins 13, the shape being approximately that shown by the dotted outlines 19 in Fig. 1A.

An oxide coated nickel cathode 16 is located in the left-hand portion of the open space. Cathode 16 is rectangular in cross-section and its oxide coated surface faces to the right and is aligned with the aperture in the plate comprising accelerator grid 18. Cathode 16 has a hollow interior and contains a heating coil 20 which will be described later.

Control grid 17 is located between cathode 16 and accelerator grid 18. It comprises a thin molybdenum plate with a rectangular screened aperture which is also aligned with the aperture in the plate comprising accelerator grid 18. The manner in which both cathode 16 and control grid 17 are supported will also be described later.

Just to the right of the fin 13 farthest to the right is an end slot 21 which corresponds to slot 14 on the left. A short connecting section 22, corresponding to section 15 on the left, extends between slot 21 and a rectangular hollow portion at the right-hand end of block 10 which contains a collector electrode 23. Collector 23 is a flat rectangular molybdenum plate and is aligned with section 22 and fins 13 to intercept the electrons which are projected past fins 13. The manner in which collector 23 is supported will be described later.

With reference first to the electron source, or output, end of the tube shown in Fig. 1, end slot 14 is connected to an output wave guide 24 by a wave-guide transformer 25. Output guide 24 is of standard rectangular cross-section and its long dimension is normal to the plane of the drawing. Transformer 25 is also of rectangular cross-section, but its transverse dimensions are smaller than those of guide 24. Transformer 25 comprises a rectangular hole, substantially a quarter of a wavelength (i.e., a quarter of a wavelength in the wave-guiding path) deep, formed in block 10 just above end slot 14. Above transformer 25 is a rectangular wave guide 26, which is of the same cross-section as the interior of wave guide 24. A short distance above the base of rectangular guide 26, block 10 terminates in a flat circular face which is raised somewhat from the rest of block 10.

An annular slot 27 opens on the flat circular face of block 10 and surrounds guide 26, serving as a radio frequency choke. The interior of block 10 is sealed off by a glass window 28, which is separated slightly from the

face of block 10 and situated directly over guide 26. Window 28 is held in place by a molybdenum cup 29 which surrounds the raised portion of block 10 and is brazed to block 10 outside of choke 27.

The end of output wave guide 24 is enlarged to fit over the raised portion of block 10 and make contact with block 10 without touching molybdenum cup 29. Except for a circular flange which surrounds cup 29, guide 24 is terminated in a flat circular face which is parallel to the face of block 10 and is located just above it on the other side of glass window 28. The rectangular interior of guide 24 is aligned with guide 26 and is similarly surrounded by an annular slot 30, which serves as a radio frequency choke.

The collector, or input, end of the tube is substantially identical to the electron source or output end. A wave-guide transformer 31, corresponding to transformer 25, is located just above end slot 21 and communicates with it. A rectangular wave guide 32, corresponding to guide 26, is just above transformer 31, which opens into it. As at the output end, block 10 terminates a short distance above the bottom of guide 32 in a flat circular face which is raised from the rest of block 10.

An annular slot 33, corresponding to slot 27, opens into the face and surrounds guide 32, serving as a radio frequency choke. A glass window 34, held in place by a molybdenum cup 35, is placed over the opening of guide 32, cup 35 holding window 34 slightly apart from the face of block 10. Cup 35 surrounds the raised portion of block 10 and is soldered to it outside of choke 33, sealing the interior of the tube.

An input wave guide 36, corresponding to guide 24, has an enlarged end from which an annular flange extends around the periphery of molybdenum cup 35, making contact with block 10 outside of the raised portion. Guide 36 terminates in a circular face which is parallel to the face of block 10, and the interior of guide 36 is aligned with guide 31. Input guide 36 has an annular slot 37, corresponding to slot 30, which surrounds the opening in the face of guide 36 and serves as a radio frequency choke.

Fig. 1D shows a section of the tube taken through cathode 16, along the line 1D—1D, illustrating the manner in which cathode 16 is supported and the manner in which it is heated. As shown, one end of heating coil 20 is imbedded in cathode 16. The other end of coil 20 is attached to a tungsten rod 38. Cathode 16 is attached to another parallel tungsten rod 39, both rods extending out of the tube, to the right in Fig. 1C and out normal to the plane of the drawing in Fig. 1. A copper sleeve 40 surrounds rods 38 and 39 and fits tightly into the side wall of block 10, forming a passage out of the tube. A short molybdenum sleeve 41 is brazed to the end of sleeve 40 and a glass cap 42 is sealed to the end of sleeve 41. Rods 38 and 39 extend through the end of glass cap 42. A heater potential source 43 is connected between rods 38 and 39, causing cathode 16 to be heated and its oxide coated face to emit a stream of electrons.

As shown in Fig. 1, control grid 17 is attached to a tungsten rod 44 which extends downward out of the tube. A copper sleeve 45 fits tightly into the bottom wall of block 10 to form a passage out of the tube. A short molybdenum sleeve 46 is brazed to the end of sleeve 45 and a glass cap 47 is sealed to the end of sleeve 46. Rod 44 extends through the end of glass cap 47 and is connected to the positive terminal of a biasing battery 48, the negative terminal of which is connected to rod 39, which is shown in Fig. 1D.

It should be noted that while Fig. 1 shows a connection from the negative terminal of voltage supply 48 passing through the left end wall of the tube, such a representation is only schematic, and is for the purpose of depicting a complete circuit. The actual connection is to the end of rod 39 as shown in Fig. 1D.

The collector electrode 23 at the right-hand end of the

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tube is attached to a tungsten rod 49 which extends through an opening in the bottom of block 10. A copper sleeve 50 surrounds rod 49 and fits snugly into block 10 to form a passageway out of the tube. A short molybdenum sleeve 51 is brazed to the end of sleeve 50, and a glass cap 52 is sealed to the end of molybdenum sleeve 51. Rod 49 extends through the end of glass cap 52 and is connected to the positive side of a voltage supply 53.

The negative side of supply 53 is connected directly to copper block 10, which is also grounded. The negative side of supply 53 is also connected to the positive pole of a main beam accelerating voltage supply 54 which can be varied. The negative pole of supply 54 is connected to the negative terminal of supply 48. The potential supplied by battery 48 is preferably chosen for a value of beam current suited for stable operation. The entire tube extends lengthwise between two poles 55 and 56 of an electromagnet which supplies a longitudinal beam focusing field.

In the operation of the amplifier shown in Fig. 1, an electromagnetic wave to be amplified is supplied to the transmission path through input guide 36, from a source 36a. Source 36a, shown schematically, may be any suitable source of electromagnetic waves such as an oscillator, an antenna, or even another traveling wave tube, the output of which it is desirable to amplify. As the wave of the dominant mode travels through input guide 36, it has no longitudinal electric field. The nature of the slotted wave-guiding structure is such that the wave propagates along its length with a longitudinal electric field. The slotted structure transmits the wave at a predetermined phase velocity which is to some extent dependent on the wave frequency. An electron beam is projected lengthwise past the slotted structure at a predetermined velocity and interacts with spatial harmonics of the wave in the manner to be described below, causing the wave to grow in amplitude as it progresses to the left. The amplified wave is taken off through output guide 24, with no longitudinal electric field.

For gain, it is important that a particular group of electrons which have been bunched in accordance with the signal upstream along the path by interaction there with the longitudinal fields in the slots 11 see substantially similar longitudinal fields at succeeding slots as it moves down stream. By "upstream" is meant a point or position in the circuit which is closer to the cathode than a point with which it is being compared. Conversely, "downstream" denotes a point or position closer to the collector than a point with which it is being compared. "Downstream" is also used to denote the direction of electron travel, whereas "upstream" denotes the direction opposite to that of the electron travel. To this end, the relative velocities of the traveling wave and the group of electrons are made such that the wave has progressed in a direction upstream a distance of one wavelength less the distance between the centers of two adjacent slots 11 in the time taken for the electron group to progress downstream the distance between the centers of these two slots. In this way the condition called for is met and the interaction becomes cumulative and gain is achieved. The immediate presence of the conducting fins 13 between the slots prevents interaction with out-of-phase portions of the waves from counteracting gain already secured. From these considerations, it is evident that the gain of the amplifier will be to some extent dependent on the intensity of the electron beam current.

It should be borne in mind that the process is continuous and that many electrons are involved. It should also be remembered that the analysis is strictly accurate only when the boundary conditions just off the metal fins 13 obtain. In general, electrons traveling farther away from the fins 13 interact somewhat with out-of-phase field components and are thereby less effective in producing gain. For simplicity, however, the boundary condi-

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tions will be considered to exist in the analyses which follow.

In obtaining a thorough understanding of the invention, it is helpful to consider the relationship between electron and field from a mathematical standpoint. The following mathematical analysis applies when the above-mentioned boundary condition exist.

The array of slots 11 shown in Fig. 1 considered to be a filter-type iterative structure. Assume that there is set up in the circuit a traveling electromagnetic wave moving lengthwise, in the tube, which will be designated the z direction, with a phase velocity v . Let β be the phase displacement between the centers of adjacent slots separated by a distance d , so that

$$\beta = 2\pi \frac{d}{\lambda} \quad (1)$$

where λ is the wavelength in the wave guiding structure at the frequency of operation. The time taken for the wave to move a distance d is

$$\frac{\beta}{2\pi} T$$

where T is the period of oscillation of the wave. Therefore

$$v = \frac{d}{\beta T} 2\pi = \frac{\omega d}{\beta} \quad (2)$$

where ω is equal to 2π times the frequency of wave oscillation.

In a conventional traveling-wave tube in which the electrons interact directly with the wave, the electron velocity would have to be approximately equal to v . The time taken for an electron to move from one slot to an adjacent slot would have to be

$$\frac{\beta}{\omega}$$

or the same as that taken for the wave to travel the same distance.

In accordance with a principal feature of the present invention, the electron flow is oppositely directed to the traveling wave, and the time required for an electron to move a distance d is

$$T - \frac{\beta}{\omega}$$

or the same time that is required for the wave to advance a distance equal to $\lambda - d$.

Assuming now that a peak in the electromagnetic wave at a slot is the optimum condition for some type of interaction between the electrons and the wave, such as would be the case when the peak represents the maximum retarding force on a bunched electron beam, synchronism is maintained by having a peak of the electromagnetic wave at a slot whenever the bunched electrons pass the slot. The electron speed required for this synchronism is

$$v_c = \frac{d}{T - \frac{\beta}{\omega}} = \frac{\omega d}{2\pi - \beta} \quad (3)$$

instead of

$$\frac{\omega d}{\beta}$$

for the case when the electrons are in synchronism with what might be called the forward wave. Adverse interaction between the bunched electrons and the wave, during the part of the cycle for which the phase is exactly wrong, is minimized by having the electrons at that part of the cycle close to the metal walls where the axial component of the electric field vanishes.

An equivalent analytical expression of the above may

be obtained by representing the axial component of the electric field of the traveling wave by the relation

$$E_z = F(z)e^{j\omega t} \quad (4)$$

where:

$$F(z) = \sum_{n=-\infty}^{\infty} A_n e^{-i(2\pi n + \beta)\frac{z}{d}} \quad (5)$$

Assuming the amplitude of E_z to be constant at the mouth of the slots, and denoting it by E_0 ,

$$A_n = \frac{E_0}{d} \int_{-\frac{w}{2}}^{+\frac{w}{2}} e^{j(2\pi n + \beta)\frac{z}{d}} dz = \frac{2E_0}{2\pi n + \beta} \sin \left[(2\pi n + \beta)\frac{w}{2d} \right]$$

where w is the width of the slot.

Combining (4), (5), and (6) gives

$$E_z = E_0 \sum_{n=-\infty}^{\infty} \frac{2 \sin \left[(2\pi n + \beta)\frac{w}{2d} \right]}{2\pi n + \beta} e^{j \left[\omega t - (2\pi n + \beta)\frac{z}{d} \right]}$$

Thus E_z is represented as a sum of Fourier component traveling waves with different phase velocities. The component wave corresponding to $n = -1$ may be termed the first backward spatial harmonic, and is given by

$$E_{z1} = E_0 \frac{2 \sin \left[(2\pi - \beta)\frac{w}{2d} \right]}{2\pi - \beta} e^{j \left[\omega t + (2\pi - \beta)\frac{z}{d} \right]}$$

This represents a wave moving in the direction of decreasing z with a phase velocity

$$\frac{\omega d}{2\pi - \beta}$$

which is the same as that given in Equation 3.

Thus, in the traveling-wave tube described, the electrons may be said to interact with the first Fourier spatial harmonic of the backward electromagnetic wave.

It should be pointed out that the spatial harmonic concept is for purposes of mathematical description only, and that the harmonics have no independent physical existence. A spatial harmonic is to be sharply distinguished from the usual frequency harmonic, in that the concept applies only in the case of traveling waves. The various spatial harmonics may be considered as being waves of the same frequency but of different wavelengths and phase velocities. A complex traveling wave, such as that which may travel along the wave guiding circuit in Fig. 1, may be completely described in mathematical terms by a series of such waves.

From Equation 7 it can be seen that gain-producing interaction may be obtained if the electron stream is synchronized with any Fourier spatial harmonic of the backward traveling wave. For such interaction to take place, the electron velocity should be substantially equal to

$$\frac{\omega d}{2\pi n + \beta}$$

where n is the number of the order of the harmonic with which the stream is to interact. It will be convenient to rewrite this expression as

$$\frac{\omega d}{2\pi n - \beta}$$

where n is now a positive integer.

It is a characteristic of an amplifier of this kind that high gain is achieved over a relatively narrow frequency band but that this frequency band of high gain can be shifted electronically by changing the beam voltage. Accordingly, variations in the potential supplied by the battery supply 54 can be made to vary the frequency-gain response of the amplifier for selective amplification. This frequency response can be varied in a periodic fashion by the insertion in series with the beam potential

of suitable voltages for changing the beam accelerating voltage.

From one point of view, the slotted structure of Fig. 1 may be considered to comprise an electromagnetic wave transmission path with means (i.e., the resonators or slots 11) for increasing the axial electric field at regular intervals along the tube. From a second point of view, the structure may be said to comprise a transmission path with means (i.e., the fins 13) for decreasing the axial electric field at regular intervals along the tube. From a third point of view, the structure may be considered as a transmission path in which fins 13 and slots 11 comprise means for alternately decreasing and increasing the axial electric field at successive intervals along the path.

From still another standpoint, the wave-guiding structure may be considered as a corrugated structure comprising regularly spaced sections having alternately different surge impedances. For example, the hollow interior of block 10 may be considered to be a wave guide comprising regularly spaced sections. The sections at each slot 11 may be considered to have a high surge impedance, while the sections at each fin 13 may be considered to have a low surge impedance.

From a still further point of view, the structure may be considered as being made up of a succession of iterative sections each of length d along the path of electron flow and introducing a phase displacement of β .

Various other forms of wave-guiding structures can similarly be utilized in backward wave amplifiers. Fig. 2 shows schematically such an amplifier 60 in which there is incorporated a ribbon helix wave circuit. The various tube elements are enclosed in an evacuated tubular envelope 61 which preferably is of copper. At one end of the envelope is the electron gun 62 which for purposes of convenience and simplicity in the drawings is shown simply as a cathode emissive surface. At the opposite end of the envelope, there is arranged the target electrode 63 which defines with the electron gun a longitudinal path of electron flow. Conventional magnetic focussing is employed to minimize radial components of electron flow. The electron source is maintained at a negative beam potential with respect to the envelope by means of the voltage source 70. Along this path there is disposed the wave transmission circuit which in this case comprises the helically wound, or otherwise fashioned, ribbon conductor 64 having its broad dimension extending in the direction of flow. Input waves which are to be amplified are applied by way of the wave guide 66 from a source 66a, shown schematically, coupled downstream along the circuit and output waves which are abstracted upstream along the circuit are derived by way of wave guide 67. One convenient technique for achieving a suitable wave transmission circuit of this kind is to groove a hollow metallic cylinder along a suitable helical path. In particular, the wave circuit shown is of this construction. A thin walled cylinder 65 of length sufficient to extend from the input and output wave guides 66 and 67, respectively, is grooved between points 68 and 69 in the helical path 71 which becomes the gap between turns. The pitch of this grooving determines the wave velocity along the circuit and accordingly is adjusted to provide a phase velocity suitable for interaction of the kind being described. By terminating the grooving in from the ends of the cylinder, there remain two ungrooved end sections by which the helix can be supported. For a better impedance match to the input and output wave guides, it is advantageous to taper the pitch of the grooving at each end.

The principles of operation are similar to those described in connection with the amplifier shown in Fig. 1. Electromagnetic waves are propagated along the circuit in interacting relation with oppositely directed electron flow. The broad dimension of the ribbon helix serves to shield electrons opposite thereto from the longitudinal electric field components of the propagating wave. Only

within the gap between turns will the axial electric field of the propagating wave be high. Accordingly, the path of travel for a particular group of electrons will comprise periodic intervals of high axial field strength interspersed with longer drift regions of low axial field strength in the manner described above. As before, for gain the velocity of the stream is made such that while a charged particle traverses the average distance between turns, the backward traveling wave traverses an integral number of wavelengths less the distance between turns. In this way, a given group of electrons interacts with successive like portions of the wave as it traverses successive gaps between turns.

Figs. 3A, 3B, and 3C show schematically a backward wave amplifier 80 which utilizes an interdigital type circuit as representative of a somewhat different form of wave guiding structure. The elongated evacuated envelope 81, for example, of rectangular cross section is of a non-magnetic metal, such as copper. At opposite ends an electron source 82 and a target electrode 83 define a longitudinal path of electron flow along the axis of the tube. This flow can be in the form of a hollow cylindrical electron beam. Magnetic focussing is employed to minimize transverse components of electron flow in the usual manner. Beam accelerating potential is supplied by the voltage supply 90. Electromagnetic waves to be amplified are made to propagate upstream along a slow wave transmission path as before. In this case, to serve as the slow wave guiding circuit there is provided a loaded wave guide 84 which comprises the portion of the envelope loaded by means of two rows or sets 91 of regularly spaced fins or fingers 92 extending in a linear array in an interdigital pattern from the two opposite broad inner surfaces of the envelope, each row parallel to and on opposite sides of the axis of the tube. Two rows are used to provide two parallel circuits to make more efficient use of the cylindrical electron beam. For broad band the lengths of the fins of each row increase at each end gradually towards the center section which comprises a multiplicity of fins of uniform length. This length is sufficient to have the fins projecting from one surface of the envelope interleave with the fins projecting from the opposite surface to form longitudinal gaps 93 between fins past which the electrons flow.

In this interleaved region along the path of flow there results a succession of relatively long region adjacent to the fins interspersed with shorter gaps between fins. Accordingly, as in the wave circuits described in connection with Figs. 1 and 2 when an appropriate electromagnetic wave propagates along the structure the longitudinal component of the field along the path of flow is made alternately large and small.

Input waves are applied to the downstream end of this circuit by way of an input circuit 94 which is a rectangular wave guide which can be a continuation by way of a glass window of a wave guide transmission system which includes a source 94a of electromagnetic waves, here shown schematically, and output waves are abstracted for utilization at the upstream end of the wave circuit 95 by way of an output circuit which is also a rectangular wave guide. Both the input and output circuits 94 and 95 make a right angle bend with the elongated portion of the tube envelope, and accordingly 45 degree deflection plates 96 are provided at the ends of the loaded guide section 84 obliquely across the elongated portion of the envelope diverting input waves for longitudinal travel along the slow wave circuit 84 and amplified output waves to the output circuit 95. These plates are provided with apertures 97 for the passage of electron flow therethrough.

The operation is as has been described above. The electron velocity is adjusted so that a particular group of electrons interacts with like portions of the backward traveling wave as it traverses successive gaps between fins where the interacting field component is high. In this case, however, the direction of the longitudinal field in

the gap between fins reverse with each successive gap. This is a characteristic well known for such interdigital structures which in effect are special forms of folded wave guides. To compensate for the π radians phase reversal between gaps, for interaction with the backward traveling electromagnetic wave, the electron velocity is made such that while an electron traverses the average distance between successive gaps, the wave traverses an integral number of half wavelengths less substantially this average distance. In a quantitative sense, the velocity of the electrons should be adjusted to be substantially equal to

$$\frac{\omega l}{n\pi - \theta}$$

where ω is the frequency of the backward traveling wave, l is the average distance along the path of electron flow between successive gaps, n is an integer, and θ is the wave phase displacement in between successive gaps.

However, if each interdigital structure be considered as a plurality of iterative filter sections, each section comprising a pair of adjacent fins and associated gaps, for interaction the velocity of the electron stream should be adjusted so that while a given electron travels along the electron path the length of one filter section, the backward traveling wave traverses an integral number of wavelengths less this same length. Quantitatively, for interaction, the velocity of the electron stream should be such that

$$\frac{\omega d}{2n\pi - \beta}$$

where d is the average length of a filter section i.e. the average distance between successive like gaps, and β is the phase displacement per filter section of the wave. It can be seen that this relationship is similar to that derived for the wave circuits shown in Figs. 1 and 2.

Accordingly, it is to be understood that the various embodiments described above are merely illustrative of the general principles of the invention. Various arrangements can be devised by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An amplifier comprising an electron source and target electrode defining a path of unidirectional electron flow, a wave guiding structure for propagating high frequency waves along said path in a direction opposite to that of electron flow and in interacting relationship with the electrons therein, a source of high frequency waves, input coupling means supplied by said wave source positioned downstream along the wave guiding structure between said source and said target electrode, and output coupling means positioned upstream along the wave guiding structure.

2. In combination, a source of electromagnetic waves, a wave guiding structure supplied at the input end with waves from said source for propagating therethrough and providing along a longitudinal path periodic gaps of high longitudinal fields separated by longer regions of substantially lower longitudinal fields, output means at the output end of the wave guiding structure for abstracting waves therefrom, and means for projecting a unidirectional electron stream along said path in interacting relationship with electromagnetic waves propagating along said wave guiding structure in a direction opposite to that of propagation of the electromagnetic waves, said input end being at the downstream end of said wave guiding structure and said output end being at the upstream end of said structure.

3. A combination according to claim 2 in which the wave guiding structure is a longitudinal conductor having a plurality of lateral slots.

4. A combination according to claim 2 in which the wave guiding structure is a ribbon conductor helically wound with its broad dimension parallel to the direction of electron flow.

5. A combination according to claim 2 in which the wave guiding structure is a wave guide loaded by an interdigital array of conductive elements.

6. In an amplifier, an electron source and a target electrode defining therebetween a path of electron flow, an intermittent interaction type of wave transmission circuit extending along said path for providing therealong periodic intervals of high electric field, a source of electromagnetic waves for applying input electromagnetic waves coupled to the downstream end of the wave transmission circuit, utilization means for abstracting output waves coupled to the upstream end of the wave transmission circuit and flow accelerating means for projecting the electron flow along said path at a velocity substantially equal to

$$\frac{\omega d}{2n\pi - \beta}$$

where ω is the angular frequency of the input waves, n is an integer, β is the phase difference in radians between the electric fields at two successive like intervals, and d is the distance along said path between the two successive like intervals.

7. In an amplifier, an electron source and a target electrode defining therebetween a path of unidirectional electron flow, a wave guiding structure which comprises a plurality of iterative sections positioned along said path, a source of signal waves, input coupling means at the downstream end of said structure and supplied from said source with signal waves for propagation upstream along said structure in interacting relationship with electrons in said path of flow, and output coupling means at the upstream end of said structure for deriving output waves said input and said output coupling means being situated between said electron source and said target electrode.

8. In electronic apparatus for amplifying electromagnetic waves, an electron source and a target electrode defining therebetween a path of electron flow, a wave guiding structure positioned along said path for providing therealong periodic intervals of high longitudinal fields separated by longer regions of substantially lower longitudinal fields, input means coupled to the downstream end of the path for applying electromagnetic waves for propagation along said structure, and output means coupled to the upstream end of the path for abstracting electromagnetic waves from the structure and flow accelerating means for projecting the electron flow along said path at a velocity substantially equal to

$$\frac{\omega d}{2n\pi - \beta}$$

where ω is the angular midband frequency of the propagating wave, n is an integer, β is the phase difference in radians between the electric fields of two successive like intervals of high longitudinal field, and d is the distance along said path between the two successive like intervals.

9. Electronic apparatus as in claim 8 in which the wave guiding structure is a longitudinal conductor with a plurality of transverse slots.

10. Electronic apparatus according to claim 8 in which the wave guiding structure is a ribbon helix having its broad dimension parallel to the direction of electron flow.

11. Electronic apparatus according to claim 8 in which the wave guiding structure is a wave guide loaded by means of an interdigital array of conductive elements.

12. In electronic apparatus, an electron source and a target electrode defining a longitudinal path of unidirectional electron flow, a source of electromagnetic waves, a dispersive wave circuit positioned along said path and supplied from said source for propagating the electromagnetic waves in a direction opposite to that of electron flow in interacting relationship with electrons therein and providing along said path periodic intervals of high longitudinal electric fields interspersed with drift regions of lower longitudinal electric fields, output means at the upstream end of said circuit for abstracting output waves, said input and said output means being situated between said electron source and said target electrode and beam accelerating means for varying the velocity of electron flow in the direction of forward travel along said path.

13. In combination, an electron source and a target electrode defining a longitudinal path of electron flow, a source of a band of electromagnetic waves, a dispersive wave circuit positioned along said path and supplied from said source for propagating the electromagnetic waves in a direction opposite to that of electron flow and providing along the path periodic intervals of high longitudinal field strength interspersed with longer regions of low longitudinal field strength, output coupling means at the upstream end of said circuit for abstracting output waves for utilization, beam accelerating means including voltage supply means for projecting the electron flow along said path at a velocity substantially equal to

$$\frac{\omega d}{2n\pi - \beta}$$

where ω is the angular frequency of the midband point of the band of electromagnetic waves, n is an integer, β is the phase difference in radians between the electric fields of two successive intervals of high longitudinal electric fields and d is the separation along the path of two successive intervals, and means for varying the voltage supply means for varying the velocity of the electron flow in the direction of forward travel along the path.

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