

**July 15, 1958**

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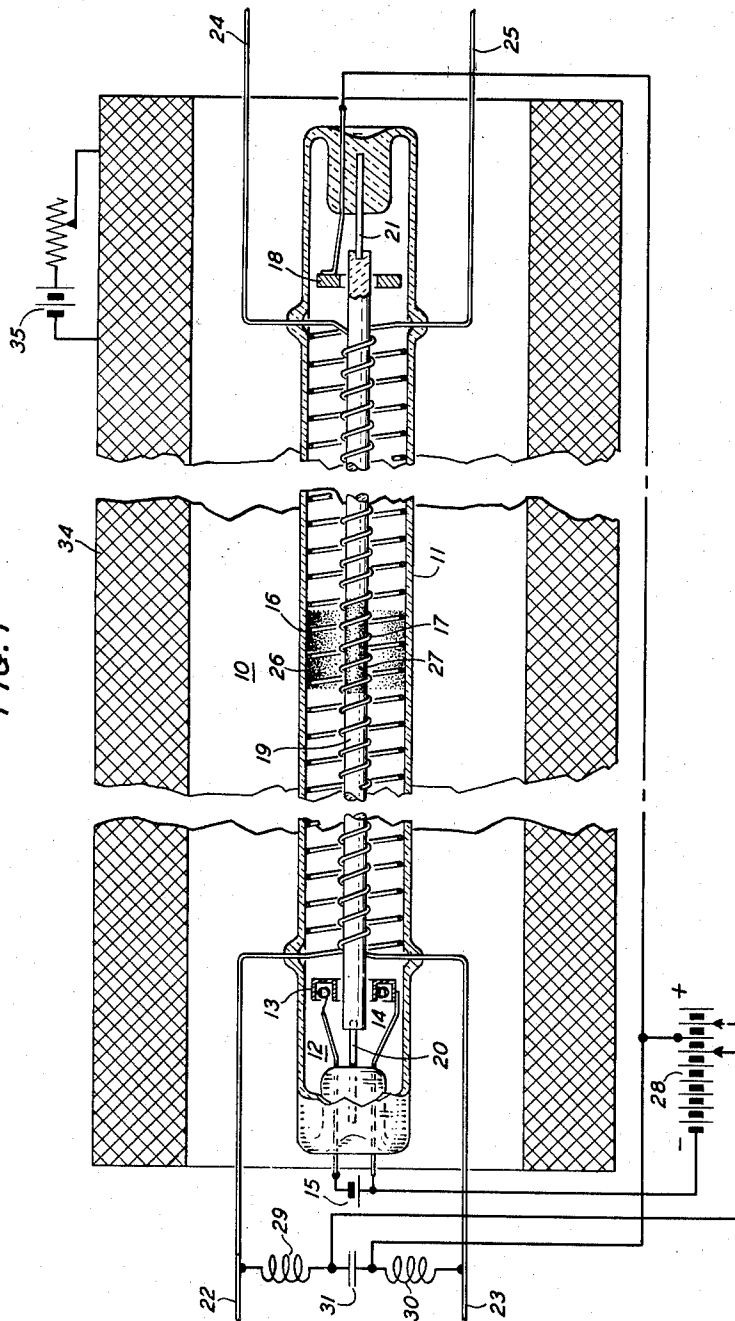
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TRAVELING WAVE TUBE

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2 Sheets-Sheet 1

**FIG. 1**



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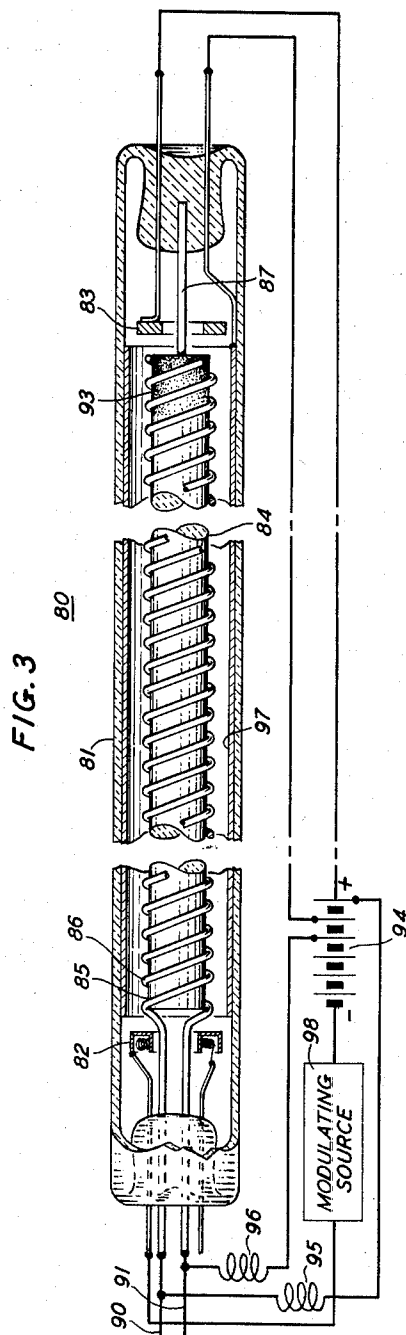
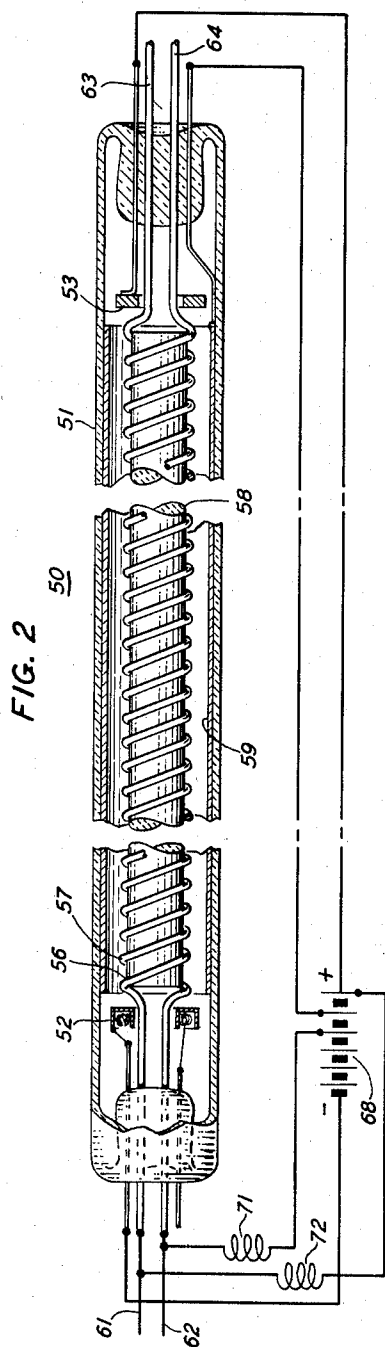
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## TRAVELING WAVE TUBE

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Application March 30, 1953, Serial No. 345,503

12 Claims. (Cl. 315—3.6)

This invention relates to radio frequency apparatus of the kind generally designated as traveling wave tubes, in which an electron stream and a traveling electromagnetic wave interact over a plurality of operating wavelengths to secure gain to the traveling wave.

In part, this application forms a continuation of my Patents 2,707,759, issued May 3, 1955, and 2,801,361, issued July 30, 1957.

In a traveling wave tube, an electromagnetic wave propagates along a wave interaction circuit and an electron stream flows past the wave interaction circuit in coupling relation with the electric field of the wave. By proper adjustment of the velocity of the electron stream and the phase velocity of the wave, the stream and wave may be made to interact cumulatively. In the first of the above-mentioned applications, there is described a traveling wave tube in which two concentric helices of different diameters and directly connected to external balanced circuits are employed as the interaction circuit and a tubular electron beam is projected concentric with and between the two helices. The two helices are wound to have separately the same phase velocities which are approximately the same as the velocity of the electron beam and are operated essentially in parallel.

Additionally, in a tube of the kind described the two helices can be operated as a coiled balanced line, adjacent points along the two helices being at substantially equal and opposite radio frequency potentials just as in a parallel balanced line adjacent points of the two wires are at equal and opposite radio frequency potentials. A helically coiled balanced line of this kind propagates a wave therealong in which the electric field between the two helices is substantially transverse. For amplification, the electron stream is projected between the two helices with a velocity substantially equal to the phase velocity of the transverse wave along the line.

There have been devised recently traveling wave tubes characterized by operation, designated as spatial harmonic, in which the phase velocity of the fundamental component of the wave is considerably different from the velocity of the electron stream but in which the relationships for useful interaction are met by special circuit arrangements such that a particular group of electrons sees effectively the same phase conditions of the electric field in successive regions of wave interaction in its traversal through the tube. Viewed in one aspect, in such operation there is employed a wave circuit conducive to the setting up of spatial harmonic components of which one has a phase velocity sufficiently equal to the electron velocity for cumulative interaction. In one tube of this kind described in an article entitled "A Spatial Harmonic Traveling Wave Amplifier for Six Millimeters Wavelength" by S. Millman published in the Proceedings of the Institute of Radio Engineers, pages 1035-1043 (September 1951) the spatial harmonic wave components are set up by an interaction circuit along which the electric field of the wave is intermittently large and small along the stream path, the relative velocities being adjusted

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so that a particular group of electrons sees the same in-phase condition at each interval of high electric field. Alternatively, it is also found possible to set up spatial harmonic wave components by an interaction circuit which introduces spatially a succession of reversals of the direction of the electric field of a wave traveling therealong. In a copending application Serial No. 327,566, filed December 23, 1952 by R. Kompfner, there is disclosed a tube which employs an interdigital type interaction circuit in which the direction of the longitudinal electric field with which the electron stream interacts reverses between adjacent finger elements because of the interdigital pattern and, accordingly, there are set up spatial harmonic components having diverse velocities. For spatial harmonic operation, circuits of this kind are generally more economical of tube length than circuits of the intermittent interaction type.

An important feature of the present invention is a novel interaction circuit of the kind in which the direction of the longitudinal component of the electric field of a wave traveling therealong reverses spatially with a periodicity high relative to the frequency of the wave. To this end, the interaction circuit comprises a balanced pair transmission line which is helically coiled, the two helices being of equal diameter and wound in the same sense to form a bifilar helix. However, unlike bifilar helix circuit arrangements of the prior art in which the two component helices are operated so that the radio frequency polarities of contiguous turns are substantially in phase and the electron stream is projected therepast at a velocity substantially equal to the phase velocity of the fundamental component of the electromagnetic wave along the helices, in the practice of the present invention each of the two helices serves effectively as a different one of two conductors of a balanced line, so that the radio frequency polarities of contiguous turns are maintained substantially 180° apart whereby the direction of the longitudinal electric field between successive gaps reverses, and additionally the electron stream is projected therepast at a velocity substantially equal to the phase velocity of a spatial harmonic component of the electromagnetic wave along the line. An interaction circuit of this kind is easy to construct and reproduce, of high impedance which makes possible high gain, and conducive to convenient input and output coupling connections for the supplying and abstracting of radio frequency energy.

Another distinct feature of the invention is a focusing arrangement in which the two interwound conductors are adjacent a third member and each is operated at different D.-C. potential in order to achieve a succession of regions of longitudinal and radial electrostatic fields between contiguous turns along the path of flow, the direction of the electrostatic fields reversing with successive regions. This focusing arrangement can be characterized as establishing along the path of flow time-constant spatially alternating longitudinal radial and electrostatic fields. By this expedient, electrostatic focusing of the electron stream can be achieved so that there can be avoided the necessity of establishing a longitudinal magnetic field for focusing, as is characteristic of the usual traveling wave tube. Such an arrangement can be viewed as comprising a first electrode means which defines an equipotential envelope or surface and a second electrode means disposed opposite said first electrode means for defining an envelope or surface along which the potential varies periodically with distance, the electron flow being in the interspace between the first and second electrode means.

A preferred embodiment of the invention is a backward wave oscillator in which the interaction circuit comprises a balanced line coiled for forming a bifilar helix whose source or upstream end is connected to an external balanced line output coupling connection and whose

target or downstream end is terminated resistively in the characteristic impedance of the line, and in which the two conductors of the line are operated at different D.-C. potentials for effecting electrostatic focusing.

Fig. 1 illustrates an amplifier embodiment in which two concentric helices of different diameter directly connected to balanced external circuits are employed as the interaction circuit and a tubular electron stream is projected concentric with and between the two helices, this embodiment is shown as Fig. 3 in the first-mentioned parent application;

Fig. 2 illustrates an amplifier embodiment in which a balanced line helically coiled to form a bifilar helix is employed as the interaction circuit for spatial harmonic operation either in a forward or backward wave mode; and

Fig. 3 illustrates, as a preferred embodiment, a backward wave oscillator in which a balanced line helically coiled to form a bifilar helix serves as the interaction circuit.

In the amplifier 10 shown in Fig. 1 a vacuum-tight evacuated glass envelope is designated 11. The ring cathode 12 with an emissive coating 13 is utilized to produce a tubular beam extending between the two coaxial helices 16 and 17 to the collector 18. The cathode is heated by heater 14 energized from the voltage source 15. The outer helix 16 rests against and is supported by the inner surface of the envelope 11. The inner helix 17 is wound upon the ceramic support 19 which is supported at the ends by the pins 20 and 21. The balanced signal input line 22, 23 is connected directly to the input ends of the two helices 16 and 17 and the balanced output line 24, 25, is connected directly to the output ends of the two helices. Loss material 26 is deposited on the inside surface of the envelope 11 near the center of the helix 16 and loss material 27 is deposited on the ceramic support 23 near the center of the helix 17. This loss material provides attenuation in the wave transmission circuit desirable to avoid oscillations. Electron beam accelerating voltage is derived from the voltage source 28 which is connected to the helices 16 and 17 through the high impedance choke coils 29 and 30, respectively, and to the electron collector 18. 31 is a high-frequency bypass condenser. The two helices are maintained at different direct-current potentials and either one may be the higher as indicated by the tap connections to the battery 28. With the helices at different potentials a radial electric field, transverse to the direction of the electron beam, is produced in the region of the electron beam between the two helices. This field tends to move any positive ions in the beam toward the lower potential one of the helices where they are collected and thereby prevented from accumulating in the beam to a degree where noise oscillations are produced. The solenoid 34 energized from a direct-current source such as the battery 35 provides an axial magnetic focussing field along the path of the electron beam.

The helices are wound to have about the same phase velocities separately and to have phase velocities approximately the same as the velocity of the electron beam. For this reason since the diameters of the helices are different the turn spacings may be quite different though for convenience they are here shown nearly the same. Under this condition the high frequency wave receives energy from the electron beam and is amplified as it travels along the helices.

All slow electromagnetic waves have both longitudinal and transverse electric field components. Sometimes either the longitudinal or the transverse field may go to zero along a line or plane parallel to the direction of propagation. For instance, for the slow mode of propagation there is substantially no transverse field on the axis of a helically-conducting sheet. Still, over any plane normal to the direction of propagation there are bound to be both longitudinal and transverse field components.

If a very strong longitudinal magnetic field is used in connection with a traveling wave tube, the transverse motions of electrons may be so restricted as to be of little importance. With weak focusing fields, however, the transverse motion of electrons may be important in producing gain. The transverse fields can force the electrons sidewise, and thus change the longitudinal fields acting on them in such a way as to abstract energy from the electron stream. This is closely analogous to the action of the longitudinal fields in displacing electrons forward or backward into regions of greater or lesser longitudinal field.

The double helix structure shown in Fig. 1 will support both a longitudinal wave in which the electric field mid-way between the helices is substantially longitudinal, and a transverse wave in which the electric field mid-way between the helices is substantially transverse. The two waves will have slightly different phase velocities. Either wave may be used in producing amplification. If, for example, the transverse wave is to be used the electron velocity should be made substantially equal to the phase velocity of the transverse wave, and the coupling at the ends of the helix should be made such as to couple efficiently to the transverse wave. This adjustment can be made by varying the pitch of one helix near the end so as to add or subtract wire. For instance, if the coupling is initially good for exciting a longitudinal wave, adding or subtracting approximately a half free-space wavelength of wire at the end of either helix will make the coupling good for the transverse wave.

It is desirable that the differences in velocity between the longitudinal and the transverse wave be made as great as possible, so that the desired wave can be clearly chosen by adjusting electron speed. For a given separation of helices, the separation in wave velocity will be greater if the helices are wound in opposite senses than if they are wound in the same sense, and hence they should ordinarily be wound in opposite senses in the manner shown here.

In the amplifier 50 shown schematically in Fig. 2, the glass envelope 51 encloses the various tube elements. The ring cathode 52 positioned at one end of the envelope is utilized to produce a tubular beam for travel to the collector 53 at the opposite end. The interaction circuit comprises conductors 56, 57 interwound to form a bifilar helix on the ceramic support 58 which is supported at the two ends by rigid-straight extensions of the conductors through the envelope. At the upstream end, the two conductors 56, 57 extend in straight sections through the tube envelope to form a balanced line coupling connection 61, 62 and at the downstream end, the two conductors similarly are extended in straight sections to form a balanced line coupling connection 63, 64.

A cylindrical electrode 59 surrounds the interaction circuit flush with the inner surface of the envelope. This serves to minimize the radiation from the interaction circuit and plays a part in focusing the electron stream. This electrode can simply be a suitable resistive coating on the envelope. For accelerating the beam, the two conductors are each maintained at different positive potentials with respect to the cathode 52 by being connected to separate taps on the voltage source 68. Radio frequency chokes 71 and 72 are used to block the radio frequency signals. The electrode 59 is maintained at a potential intermediate between those on conductors 56 and 57 by being connected to an appropriate tap on voltage source 68. The collector 53 is maintained at the higher of the potentials on conductors 56 and 57 to minimize secondary electron emission. By maintaining a D.-C. potential difference between contiguous turns of the interwound conductors, there is established along the path of flow a succession of regions of longitudinal and radial electrostatic field and characterized in that the direction of these electrostatic fields reverses with successive regions. Such a succession of electrostatic

field regions together with an appropriate radial field produced by means of electrode 59 serve to maintain the flow cylindrical and to minimize transverse components of flow. Electrostatic focusing of this kind can, in some instances, obviate the need for the longitudinal magnetic field customarily used in traveling wave tubes to minimize transverse components of flow and maintain the beam cylindrical.

This focusing arrangement can be viewed as one in which the cylindrical electrode 59 defines an equipotential boundary or surface along the path of flow and in which the bifilar helix including the high potential conductor 56 and the low potential conductor 57 defines a boundary or surface along which the potential varies periodically with distance, the equipotential surface being at a potential intermediate the potentials on the two conductors 56 and 57.

In accordance with another important feature of the invention, the bifilar helix formed by the two interwound conductors can be operated as a helically coiled balanced line, a balanced line being understood to be a two conductor line in which the radio frequency potentials at any two corresponding points are equal but opposite with respect to a reference level. The distance around one turn of each conductor is made relatively short with respect to the wavelength at the operating frequency along the balanced line so that the instantaneous radio frequency potentials of points along adjacent turns of the two conductors differ in phase by approximately  $\pi$  radians. Accordingly, at a given instant, there exists between contiguous turns a radio frequency longitudinal electric field whose direction reverses with successive gaps between contiguous turns. It is this characteristic that adapts this form of interaction circuit for spatial harmonic operation.

The amplifier 50 shown can be adapted for either forward or backward wave interaction. Suppose there is first considered the case where the input wave to be amplified is applied to coupling connection 61, 62 for forward wave operation and the output wave is abstracted at coupling connection 63, 64. Then if  $v$  be the velocity of the wave along the wire of the helix, which will generally be close to the velocity of light,  $\omega$  be the radian frequency of the wave,  $d$  be the diameter of the helix and  $p$  be the separation between the two helical conductors, the phase lag  $\theta_F$  going the distance  $p$  in the direction of electron flow will be given by

$$\theta_F = \pi + \frac{\omega p}{v} = \pi \left( 1 + \frac{\omega d}{v} \right) \quad (1)$$

Let  $V$  be the phase velocity of a spatial harmonic component of the helix field. Then

$$\theta_F = \frac{\omega p}{V} = \pi \left( 1 + \frac{\omega d}{v} \right) \quad (2)$$

$$V = \frac{\omega p}{\pi \left( 1 + \frac{\omega d}{v} \right)} \quad (3)$$

If the electrons are given a velocity near to  $V$ , then the beam will interact with this spatial harmonic component of the wave. Accordingly for operation in the forward wave mode, the beam accelerating voltage supplied by source 68 is adjusted to give a velocity to the electrons substantially equal to

$$\frac{\omega p}{\pi \left( 1 + \frac{\omega d}{v} \right)}$$

For amplification in backward wave mode, input waves to be amplified are applied to coupling connection 63, 64 and the output wave is abstracted at coupling connection 61, 62. In this case, the phase lag  $\theta_B$  going the distance  $p$  in the direction of flow is given by

$$\theta_B = \pi - \frac{\omega p}{v} = \pi \left( 1 - \frac{\omega d}{v} \right) \quad (4)$$

and for interaction, the velocity of the electrons should be adjusted to be approximately

$$\frac{\omega p}{\pi \left( 1 - \frac{\omega d}{v} \right)} \quad (5)$$

In addition to the differences in beam velocities characteristic for interaction, forward and backward wave operation are distinguished in other respects. In particular when the operation is in a backward wave mode, the electron stream intensity should be adjusted to a value insufficient to initiate backward wave type oscillations of the kind described below. On the other hand, when the operation is in a forward wave mode, loss material preferably is inserted along the interaction circuit to minimize any tendency towards oscillation in the manner characteristic of conventional forward wave type traveling wave tubes.

Moreover, it should be evident that arrangements can be devised in which the electrode member 59 is positioned in the interior of the region enclosed by the bifilar helix and the electron beam is similarly projected in the space between the electrode member and the bifilar helix. In such a case, the bifilar helix can be supported by dielectric rods extending axially along the tube disposed around the periphery of the helix.

The backward wave oscillator 80 shown in Fig. 3 resembles in many respects the amplifier 50 shown in Fig. 2. It is characteristic of backward wave oscillators, however, that the downstream end of the interaction circuit is terminated while the useful output is abstracted from the upstream end of the interaction circuit. An evacuated envelope 81 houses at opposite ends an annular cathode 82 for forming a tubular electron stream and a collector electrode 83 in target relation with the cathode 82. Extending coaxially within the tubular stream is a ceramic support 84 on which is uniformly wound the conductors 85 and 86 to form a bifilar helix. The support 84 is supported at its collector end by pin 87. At the cathode end, the support 84 is supported by two straight sections of conductors 85 and 86. At the upstream or electron source end of the interaction circuit, the straight sections of the two conductors 85 and 86 extend through the glass envelope to form a balanced line output coupling connection 90, 91 from which oscillatory energy can be abstracted for utilization. At the downstream or collector end, the bifilar helix is terminated in its characteristic impedance by a resistive connection 93 designed to provide a substantially reflectionless termination over a broad frequency band. The resistive connection 93 is preferably lossy material sprayed on the ceramic support 84 in such a manner as to give large R.-F. dissipation without causing a D.-C. short between the wires. For a broad band termination, the dissipation effect is increased gradually over several turns.

The electron flow is accelerated substantially in the same manner as in the amplifier 50 shown in Fig. 2. The interaction circuit is surrounded by a cylindrical electrode 97 which is maintained at a positive potential with respect to the cathode 82 by means of voltage source 94. For focusing, the conductors 85 and 86 are maintained, respectively, at positive and negative D.-C. potentials with respect to this electrode by connections to suitable taps on voltage source 94 thereby creating a series of regions of longitudinal and radial electrostatic fields between contiguous turns of the two conductors, the direction of the fields reversing with successive sections. In this way, there can be achieved electrostatic focusing of the electron beam for cylindrical flow past the interaction circuit. Alternatively, cylindrical flow can be achieved by magneto-static focusing in the manner usual to traveling wave tubes.

In operation, the electron beam current is made sufficiently high to initiate oscillations, and the frequency

of the oscillations is adjusted by control of the electron velocity. For oscillations of radian frequency  $\omega$ , the beam accelerating voltage is adjusted to provide a beam velocity approximately equal to

$$\frac{\omega p}{\left(1 - \frac{\omega d}{v}\right)\pi}$$

where  $p$  is the separation between the two helical conductors,  $d$  is the diameter of the bifilar helix, and  $v$  is the velocity of a wave along the bifilar helix. It can be seen that this condition on the electron velocity resembles that in the backward wave amplifier described in connection with Fig. 2. Accordingly, in amplifier operation, it is important to keep the beam current sufficiently low not to initiate oscillations.

An oscillator of this kind since it can be tuned electronically is well adapted for use as a frequency modulator. To this end, a modulating source 93 is inserted in series between the cathode 82 and the negative terminal of source 94 for modulating the accelerating potentials acting on the electron flow. By modulating the accelerating potentials, and hence the beam velocity, by signal intelligence in this way, there is effected signal modulation of the oscillatory frequency.

It is to be understood that the particular embodiments shown were intended to be merely illustrative of the general principles of the invention. Various other arrangements can be devised by one skilled in the art without departing from the spirit and scope of the invention. In particular, although the two interwound conductors have been shown as wires of circular cross section, for some applications it may be advantageous to interwind ribbon-type or tape conductors. Reference is made to my copending application Serial No. 345,502, filed March 30, 1953 which relates to traveling wave tubes similarly comprising two conductor type interaction circuits.

What is claimed is:

1. In radio frequency apparatus, means for forming and projecting an electron stream, two conductors helically interwound to form a bifilar helix axially disposed parallel to the path of the electron stream, an electrode member disposed along the path coaxial with the bifilar helix, and means for maintaining said conductors and electrode member at different direct-current potentials to focus said electron stream projected between said conductors and said electrode member.

2. In radio frequency apparatus, two conductors helically interwound to form a bifilar helix, an electrode member coaxially disposed and surrounding said bifilar helix, means for forming and projecting an electron stream in a direction parallel to the axis of the helix and in the interspace between the helix and the electrode member, and means for maintaining said electrode member and said conductors at different direct-current potentials electrostatically to focus said electron stream projected in said interspace between said helix and said electrode member.

3. In combination, an electron source and target electrode spaced apart for defining therebetween a path of electron flow, an interaction circuit in the path of said flow comprising two coaxially interwound conductors forming a bifilar helix, means for maintaining said interwound conductors at different direct-current voltages, a cylindrical electrode surrounding the interaction circuit, and means for maintaining the direct-current voltage of said cylindrical electrode intermediate the two different direct-current voltages on said two interwound conductors.

4. In a microwave oscillator, two conductors helically interwound to form a bifilar helix, an electrode member surrounding said bifilar helix, an electron source for forming an electron stream for projection along the direction of the axis of the bifilar helix and in the interspace between the helix and electrode member, means for main-

taining the electrode member at a direct-current potential intermediate the direct-current potentials of the two conductors, means coupled at the electron source end of the bifilar helix for abstracting oscillatory energy, and resistive means for terminating the other end of the bifilar helix.

5. An oscillator according to claim 4 characterized in that the velocity of the electron stream is adjusted for interaction with a backward traveling wave along the bifilar helix.

6. In a device which utilizes the interaction between an electron stream and a traveling wave, first cylindrical electrode means comprising periodic high and low direct-current potential portions for forming a surface along which the direct-current potential varies periodically with distance, second cylindrical electrode means disposed coaxial with said first electrode means for forming therewith an annular interspace region and defining direct-current equipotential surface of potential intermediate that of the high and low potential portions of said first electrode means, one of said electrode means being adapted for propagating a slow electromagnetic wave in said annular interspace region, and means for propagating an annular electron beam through said annular interspace region for interaction with the slow electro-magnetic wave.

7. A traveling wave tube comprising an elongated envelope, an electron gun at one end of said envelope for projecting an electron beam having a pair of boundaries along said envelope, electron collector means at the other end of said envelope, means situated in said envelope along the path of said beam for maintaining one boundary of said beam constant, said means including a plurality of alternate electrode portions adjacent said one boundary and means for maintaining said alternate electrode portions at different potentials, and means situated in said envelope along the path of said beam for maintaining the other boundary of said beam constant, said last-mentioned means including a single electrode extending adjacent said other boundary and means for maintaining said single electrode at a potential intermediate the potentials of said alternate electrode portions.

8. A traveling wave tube comprising an elongated envelope and an electron gun at one end of said envelope for projecting a hollow electron beam along said envelope, electron means at the other end of said envelope, means situated in said envelope for maintaining one boundary of said hollow beam at a substantially constant diameter, said means including a plurality of electrode portions adjacent one boundary and arranged in alternate groups and means for maintaining said groups of electrode portions at different potentials, and means for maintaining the other boundary of said beam at a substantially constant diameter, said last-mentioned means including a single electrode adjacent said other boundary and means for maintaining said single electrode at a potential intermediate the potentials of said groups of electrode portions.

9. A traveling wave tube in accordance with claim 8 wherein said groups of electrode portions and said single electrode are coaxial and at opposite sides of said beam.

10. A traveling wave tube in accordance with claim 8 wherein said groups of electrode portions are defined by individual turns of a pair of interwound helices comprising a bifilar helix structure.

11. In a device which utilizes the interaction between an electron stream and a traveling wave, first electrode means defining a direct current equipotential surface, means for projecting an electron stream adjacent said surface, and second electrode means positioned adjacent said surface but to the opposite side of said electron stream for defining a surface along which the direct current potential varies periodically with distance, said second electrode means including at least a pair of electrodes insulated from each other with respect to direct current potentials, one of said electrode means serving to propa-

gate a slow electromagnetic wave in the interspace between said first and said second electrode means and said second electron stream being projected through that interspace for interaction with the slow electromagnetic wave.

12. In a device which utilizes the interaction between an electron stream and a traveling wave, first electrode means defining a direct current equipotential surface, means for projecting an electron stream along said surface, and second electrode means on the opposite side of said electron stream than said first electrode means and comprising at least a pair of electrodes insulated from each other with respect to direct current potentials and forming a succession of high and low direct current potential portions for defining opposite said equipotential surface a surface along which the direct current potential varies periodically with distance, one of said electrode means serving to propagate a slow electromagnetic wave in the interspace between said first and said second electrode means and said electron stream being projected between said first and second electrode means and through the

interspace for interaction with the slow electromagnetic wave.

#### References Cited in the file of this patent

##### UNITED STATES PATENTS

|           |                  |                |
|-----------|------------------|----------------|
| 2,233,126 | Haefl -----      | Feb. 25, 1941  |
| 2,541,843 | Tiley -----      | Feb. 13, 1951  |
| 2,559,581 | Bailey -----     | July 10, 1951  |
| 2,584,308 | Tiley -----      | Feb. 5, 1952   |
| 2,593,113 | Cutler -----     | Apr. 15, 1952  |
| 2,636,948 | Pierce -----     | Apr. 28, 1953  |
| 2,650,956 | Heising -----    | Sept. 1, 1953  |
| 2,652,513 | Hollenberg ----- | Sept. 15, 1953 |
| 2,725,499 | Field -----      | Nov. 29, 1955  |
| 2,742,588 | Hollenberg ----- | Apr. 17, 1956  |

##### FOREIGN PATENTS

|         |                     |               |
|---------|---------------------|---------------|
| 987,303 | France -----        | Apr. 11, 1951 |
| 668,017 | Great Britain ----- | Mar. 12, 1952 |