

July 15, 1958

J. R. PIERCE

2,843,791

TRAVELING WAVE TUBE

Filed March 30, 1953

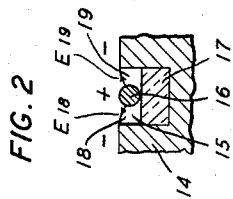
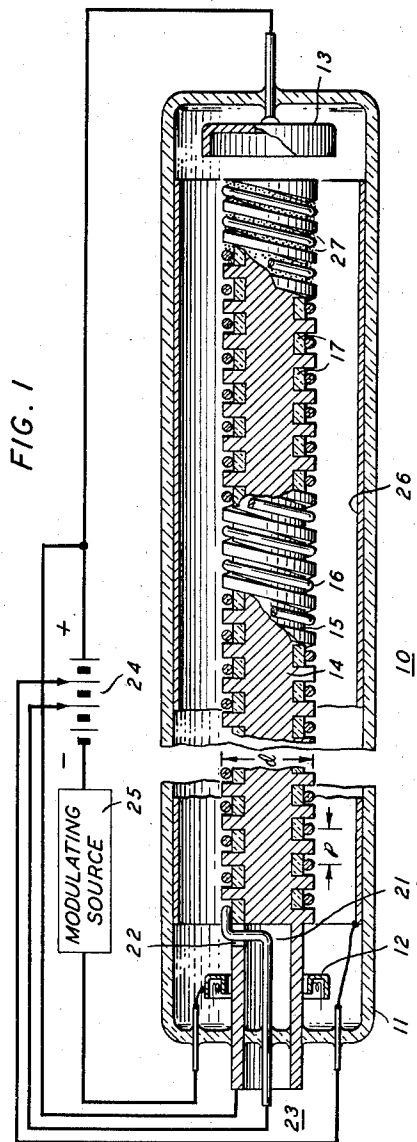
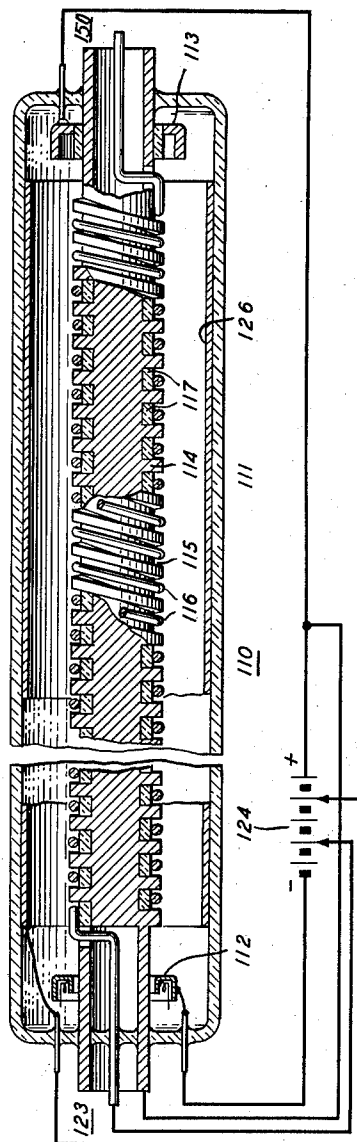


FIG. 3



INVENTOR
J. R. PIERCE
BY *Hugh S. Wentz*
ATTORNEY

1

2,843,791

TRAVELING WAVE TUBE

John R. Pierce, Berkeley Heights, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application March 30, 1953, Serial No. 345,502

14 Claims. (Cl. 315—3.6)

This invention relates to radio frequency apparatus and more particularly to such apparatus which employs the interaction between a traveling electromagnetic wave and an electron stream over a plurality of wavelengths to secure gain to the electromagnetic wave. Such apparatus is now generally designated as a traveling wave tube.

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 can be made to interact whereby the stream is bunched and the wave is amplified. In early traveling wave tubes, this relationship was satisfied by making the velocity of the electron stream substantially equal to the phase velocity of the fundamental component of the traveling wave. However, more recently there have been devised traveling wave tubes, characterized by operation designated as spatial harmonic, in which the phase velocity of the fundamental component of the traveling 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 so that a particular group of electrons, nevertheless, sees the same phase conditions of the electric field at successive regions of wave interaction in its traversal through the tube. Such operation may be viewed as characterized by a wave circuit conducive to establishing spatial harmonic components of the traveling wave of which one has a phase velocity sufficiently close to the velocity of the electron stream for cumulative interaction. In such a tube of the 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, vol. 39, pages 1035 through 1043 (September 1951); the desired relationships are met by utilization of a wave circuit along which the electric field of the wave is intermittently large and small along the stream path, the relative velocities being adjusted so that a particular group of electron sees the same in-phase condition at each interval of high electric field. Alternatively, it is also found possible to achieve spatial harmonic operation by the utilization of wave circuits which introduce periodic reversals of the direction of the electric field of the wave. 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 wave circuit in which the direction of the longitudinal electric field component with which the electron stream interacts reverses between adjacent finger elements because of the interdigital pattern. Circuits of this kind are generally more economical of tube length than circuits of the intermittent interaction type.

The primary object of this invention is to provide a wave circuit suitable for operation in this way which is easily constructed and readily lends itself to connection to a two conductor transmission line.

2

In accordance with the invention, the wave interaction circuit comprises a coiled conductor and a conductive member extending adjacent the coiled conductor and including a succession of projections extending into the region between successive turns of the coiled conductor for dividing each of these regions into two distinct gaps across which the direction of the electric field of waves propagating along the circuit reverses. In a preferred embodiment, the wave interaction circuit comprises a conductive core member which is helically grooved and into whose groovings is wound a conductor which is kept insulated from the groovings. In such a circuit the longitudinal component of the fringing electric field existing between the conductor and the side walls of the grooving reverses direction for each of the two side walls. In operation, the electron beam is made to interact with this fringing electric field. A wave circuit of this kind can be sturdy and readily adaptable for the dissipation of high powers, easy to construct and to reproduce, efficient in operation, and conducive to good input and output matches for the supplying and abstracting of radio frequency energy. In particular, in this preferred embodiment, for effecting energy transfers to external connections, the conductive core member and the helix can be formed as extensions of the outer and inner conductors, respectively, of a coaxial line.

Wave circuits of this kind are conducive both to forward wave type of operation of the kind described in the above-mentioned S. Millman article or backward wave type of operation of the kind described in this Millman article or backward wave type of operation of the kind described in the above-mentioned Kompfner application in which the electron stream interacts with forward-traveling spatial harmonics of a backward traveling wave. In backward wave operation, the interaction circuit is chosen to set up strong spatial harmonic components of a wave propagating along the circuit which have a phase velocity in a direction opposite to that of the group velocity of the wave. The electron beam is projected past the wave circuit in the direction opposite to that of the group velocity of the wave for interaction with a spatial harmonic component traveling in the direction of the beam. The electron stream moving in the direction opposite to that of the energy propagation serves to couple regions of high level more proximate to the electron source to regions of low level more remote from the source. Such positive regeneration produces oscillations when the density of the stream and the coupling between the stream and the circuit are sufficiently high, at a frequency which provides synchronism between the electron stream and the spatial harmonic component with which it interacts. A more detailed description of the theory of backward wave traveling wave tubes is set forth in the Proc. of the I. R. E., vol. 41, pps. 1602-1611, in an article entitled, "Backward Wave Tubes," by R. Kompfner and N. T. Williams.

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

Fig. 1 shows schematically as one embodiment of the invention a backward wave type oscillator;

Fig. 2 shows on an enlarged scale a fragment of the interaction circuit of the oscillator shown in Fig. 1; and

Fig. 3 shows schematically as another embodiment an amplifier which can be employed to secure gain either to a forward or backward traveling wave.

For the sake of simplicity, various details, such as spacer and support elements, whose need will be apparent to workers in the art, have been omitted from the drawing.

In the backward wave oscillator 10 shown in Fig. 1, an evacuated elongated envelope 11 which, for example,

3

is of glass, houses the various tube elements. At opposite ends of the envelope are positioned a source of electrons and a target electrode. A conventional electron gun, shown schematically merely as an annular cathode 12, furnishes a tubular electron stream for projection parallel to the longitudinal axis of the tube. At the opposite end, a cup-shaped electrode 13 having its open end facing the electron gun serves as a collector for the electrons at the end of their paths of flow.

The circuit along which the electromagnetic waves travel for interaction with the electron stream is positioned, coaxial with the tube's longitudinal axis, between the electron gun 12 and the target electrode 13. As a preferred embodiment of the invention, the interaction circuit comprises a conductive core member 14 which, for example, is a solid cylinder of a non-magnetic metal such as copper and which has its outer surface corrugated for forming a helical grooving 15 which extends along its length with a substantially uniform pitch and a conductor 16 helically wound in the grooving but spaced therefrom by a dielectric layer 17. The details may be seen with greater clarity in the fragment of the circuit shown in Fig. 2. The outer diameter of the helix 16 is substantially equal to the transverse dimension or diameter of the core member 14 whereby there results an outer surface for the interaction circuit which is smooth except for the succession of pairs of gaps 18 and 19 formed between the conductor 16 and the side walls of the grooving. The electron stream is projected close past this surface. To minimize transverse components of flow, in traveling wave tubes, one expedient has been to establish a longitudinal magnetic field along the path of flow by suitable means, such as a solenoid. However, in the tube shown, the electron beam is confined by electrostatic focusing in a manner which is described below. When a radio frequency wave propagates along the circuit a fringing electric field is set up across each of the pair of gaps 18 and 19. This field has a longitudinal component parallel to the axis of the core member and to the direction of electron flow. It is characteristic of the two longitudinal electric fields set up in pairs of gaps 18 and 19 that their respective directions are reversed as is shown in Fig. 2. The electric fields E_{18} and E_{19} associated with gaps 18 and 19, respectively, are reversed in direction inasmuch as the electric field extends radially from the conductor 16 to the walls of the grooving. By way of example, the condition shown in Fig. 2 is for that in which the instantaneous radio frequency polarity of the fragment of conductor is positive with respect to the adjacent walls of its grooving. It is with these fringing electric fields across the series of gaps 18 and 19 that the electron flow primarily interacts, and it is the reversal in direction of electric fields across the two gaps of a pair that provides advantages to this form of interaction circuit for spatial harmonic type operation.

It is characteristic of backward wave oscillators that the useful energy is abstracted at the upstream or electron source end of the interaction circuit while the downstream or collector end of the circuit is made substantially reflectionless, as for example by the insertion of a dissipative termination. Advantages of this circuit of the invention are that it lends itself readily to the abstraction of output wave energy and to the insertion of a reflectionless termination.

For the abstraction of oscillatory energy, the core member is bored at the electron gun end for forming a tubular end section 21 which is extended out through the glass envelope past the electron gun to form the outer member of a coaxial coupling connection 23 and an aperture 22 is cut in its outer surface through to the hollow of the end section through which is passed the conductor 16 which thereafter is made to extend coaxial within this tubular end section 21 through the glass envelope to form the inner member of the coaxial coupling connection 23. By means of this coupling connection 23, output

4

oscillatory energy can be led off by a coaxial line to wherever it is to be utilized.

For the reflectionless termination of the interaction circuit, it is sufficient at the collector end to fill the interspace between the conductor 16 and the adjacent walls of the grooving 15 with dissipative material 27, such as Aquadag. For a broadband termination it is preferable to increase the amount of the filling gradually over several turns.

For oscillations at a desired frequency, two basic conditions must be satisfied. First, the electron current must be made sufficiently large to insure that the backward gain at such frequency is sufficient to initiate and sustain oscillations. To this end, it is important to utilize an electron gun which supplies enough current and a focusing system which permits efficient passage of the current past the interaction circuit. Additionally, it is important that the velocity of the electron stream is adjusted relative to the phase velocity of a spatial harmonic of the wave of the desired frequency traveling along the interaction circuit that a particular group of electrons see substantially the same phase of the electric field with which it is interacting throughout its travel past the interaction circuit.

To this end, if v is the velocity of a wave traveling along the conductor 16 of the interaction circuit, which velocity usually will be close to the velocity of light, d is the diameter of the helix formed by the conductor and p is the pitch distance of this helix, for useful interaction with an electromagnetic wave of radian frequency ω traveling upstream (i. e. towards the electron gun) along the interaction circuit, it can be shown that the electron velocity v_e should be approximately

$$\frac{\omega p}{\Pi \left(2n - \frac{\omega}{v} d \right)}$$

where n is any positive integer.

The velocity of the electron stream can be readily adjusted as desired by controlling the accelerating D.-C. potential provided between the cathode of the electron gun and the core member 14. To this end, a voltage source 24 is connected by means of suitable lead-in conductors between the cathode 12 and the core member 14.

It is also generally desirable for minimizing secondary electron emission to maintain the collector electrode 13 at substantially the same potential of the core member. Moreover, electrostatic focusing can be achieved by maintaining a D.-C. potential difference between the conductor 16 and the core 14, as shown. To this end it is also useful to surround the interaction circuit with a cylindrical conductive electrode 26 which is maintained at a D.-C. potential intermediate that of core 14 and the helix 16.

In operation, noise components of the electron stream excite backward traveling circuit waves which tend to interact with the electron stream. When the basic conditions described above are met, oscillations at the frequency determined by the velocity of the electron stream are set up which can be abstracted for utilization.

It is characteristic of an oscillator of the kind described that the frequency is tuned merely by varying the electron velocity which, in turn, is controlled by the accelerating voltages. Accordingly, such an oscillator can be readily adapted as a frequency modulator by utilizing signal intelligence to vary the accelerating voltage, as by the insertion of a source of modulating voltages 25 in series with the voltage source 24 between the electron source 12 and the core member 14.

The amplifier 110 shown in Fig. 3 resembles the oscillator 10 shown in Fig. 1 in most respects, the principal difference being in the provision of an additional external coupling connection 150, similar to coupling connection 123 at the upstream or electron source end of the interaction circuit, at the downstream or collector end

of the interaction circuit in place of a dissipative termination. In backward wave operation, input waves to be amplified are supplied to the interaction circuit for propagation therealong by way of this added connection. In forward wave operation, output waves which have been amplified are abstracted from the interaction circuit by way of this added connection.

In the interest of simplicity, reference numerals designating elements in the amplifier 110 which correspond to elements in the oscillator 10 are greater by one hundred than the reference numerals designating such oscillator elements. Accordingly, the amplifier tube envelope is designated as 111, the electron source 112, the collector 113 etc. The collector 113 is, however, annular for the passage therethrough of the connection to the downstream end of the interaction circuit.

The external coupling connection 150 at the downstream end resembles external coupling connection 123 at the upstream end, being a coaxial connection the inner member of which is a straight section extension of the conductor 116 and the outer member of which is an extension of a tubular end section of the core 114 through which has been passed the conductor 116.

For operation as a backward wave amplifier it is important that the voltage source 124 be adjusted to provide an electron velocity v_e which is approximately given by

$$\frac{\omega_c p}{\Pi \left(2n - \frac{\omega_c d}{v} \right)}$$

where ω_c is the center radian frequency of the operating band, p is the pitch distance of the helix formed by conductor 116, d is the diameter of the helix, and v is the velocity along the conductor 116 of the traveling wave to be amplified. To avoid oscillations, it is important to operate with a beam current less than that necessary to initiate backward wave oscillations.

For operation as a forward wave amplifier, the voltage source 124 is adjusted instead to provide an electron velocity v_e which is approximately given by

$$\frac{\omega_c p}{\Pi \left(2n + \frac{\omega_c d}{v} \right)}$$

It is similarly important here to keep the beam current sufficiently low that oscillations are not initiated. However, in this instance the tendency towards self-oscillation may be lessened by the insertion of lossy material along the interaction circuit.

It is to be understood that the specific embodiments described are merely illustrative of the principles of the invention. Various modifications will be apparent to one skilled in the art which do not depart from the spirit and scope of the invention. For example, the conductor wound in the helical grooving has been shown as a wire of circular cross section, whereas for some applications it may be preferable to utilize a ribbon-like flat conductor. Similarly, it may be desirable to vary the shape and width of the grooving to increase the longitudinal component of the fringing electric field. Additionally, although there has been disclosed a core member of which the outer surface has been grooved, alternatively it is possible to utilize a tubular member of which the inner surface is helically grooved for the insertion of a conductor. In general, a wave circuit in accordance with the invention can be defined as a two conductor transmission line of which one conductor is a coil and the other a member which extends between adjacent turns of the coil for dividing each of these regions into two distinct gaps.

Reference is made to my copending application Serial No. 345,503, filed March 30, 1953 which relates to a traveling wave tube in which the interaction circuit is

a balanced transmission line helically coiled to form a bifilar helix.

What is claimed is:

1. In a radio frequency apparatus, an interaction circuit comprising a conductive core member helically grooved and a conductor wound in the grooving to form a helix, said conductor being electrically insulated from said core member, means for projecting an electron stream past said interaction circuit parallel to the axis of the helix for interacting with radio frequency waves traveling therealong, and a coaxial connection coupled to each of the two ends of the interaction circuit comprising an inner member which is an extension of the conductor and an outer member which is an extension of the core member.

2. The radio frequency apparatus of claim 1 in which input waves to be amplified are applied to the coaxial connection coupled to the downstream end of the interaction circuit and output waves are abstracted at the coaxial connection coupled to the upstream end of the interaction circuit and the electron velocity is adjusted to be approximately equal to

$$\frac{\omega_c p}{\Pi \left(2 - \frac{\omega_c d}{v} \right)}$$

where ω_c is the radian frequency of the center of the operating band, p is the pitch distance of the helix, d is the diameter of the helix, and v is the velocity of wave propagation along the helix.

3. In combination, a helical conductor, a conductive member positioned adjacent to the axis of said helical conductor and having portions extending in the regions between adjacent turns of said helical conductor for dividing each of said regions into two gaps, said helical conductor and said conductive member being electrically insulated from each other, a cylindrical electrode extending axially around said helical conductor and conductive member, means for projecting an electron stream axially in the interspace between said electrode and helical conductor, and means for maintaining the helical conductor and conductive member at different potentials and the electrode at a potential intermediate said different potentials.

4. In radio frequency apparatus, a conductive core member which is helically grooved along a portion thereof, a conductor wound to form a helix in the helical grooving which is electrically insulated from the conductive core member and to divide each turn of the grooving into a pair of distinct gaps, means for forming an electron stream for flow past the successive gaps for interacting with the electric fields set up thereacross by a wave propagating along the circuit, connector means at at least one end of said interaction circuit for coupling the circuit to a transmission line, said connector means comprising a conductor which extends axially through a hollow end portion of said conductive core member electrically insulated therefrom and is electrically connected to the helically wound conductor.

5. In radio frequency apparatus, an interaction circuit comprising a cylindrical conductive core member which is helically grooved along a portion thereof, a conductor wound in the helical grooving electrically insulated from the conductive core member for forming a helix coaxial with the core member, a conductive cylindrical electrode coaxial with and surrounding the core member, and means for projecting an annular electron beam in the interspace between the core member and the electrode parallel to the axis of the core member for interacting with the electric fields of a wave traveling along the interaction circuit.

6. A traveling wave tube comprising a conductive member having a helically grooved surface, a wire helix positioned in the grooves of said surface but insulated from said conductive member, the portions of said surface defining said grooves extending between adjacent turns

7

of said helix whereby opposite direction longitudinal electric fields exist from each turn of said helix to the immediately adjacent surface portions, means for applying an electromagnetic wave to said conductive member and said helix for transmission therealong, and means for projecting an electron stream along said surface portions and said helix at a velocity for interaction with a spatial harmonic of the electromagnetic wave energy.

7. A traveling wave tube in accordance with claim 6 further comprising dissipative means for terminating the downstream end of said conductive member and said helix, and a coaxial connection coupled to the upstream end of said conductive member and said helix.

8. A traveling wave tube in accordance with claim 7 wherein said coaxial connection comprises an outer member which is an extension of said conductive member and an inner member which is an extension of said helix.

9. A traveling wave tube in accordance with claim 7 wherein said dissipative means includes lossy material inserted along the downstream end of the helical grooving.

10. A traveling wave tube comprising a conductive member having a helically grooved surface, a wire helix positioned in the grooves of said surface but insulated from said conductive member, the portions of said surface defining said grooves extending between adjacent turns of said helix whereby opposite direction longitudinal electric fields exist from each turn of said helix to the immediately adjacent surface portions, said conductive member and said helix serving to transmit electromagnetic wave energy therealong, and means for projecting an electron stream along said surface portions and said helix at a velocity for interaction with said wave energy.

11. A traveling wave tube in accordance with claim 10 wherein said surface portions extend between said adjacent turns as far as the outer surface of said helix.

12. A traveling wave tube in accordance with claim 11 further comprising a coaxial transmission line connection having outer and inner members in energy transfer rela-

8

tion with said conductive member and said helix, said outer member being an extension of said conductive member and said inner member being an extension of said helix.

13. A traveling wave tube in accordance with claim 10 further comprising dissipative means for terminating the downstream end of said conductive member and said helix, and a two-conductor connection coupled to the end of the interaction circuit adjacent said electron stream projecting means for abstracting oscillatory waves, said connection having one conductor integral with said helix and the other conductor integral with said conductive member.

14. A traveling wave tube in accordance with claim 13 in which the velocity of said electron stream along said surface portions is approximately equal to

$$\frac{\omega p}{\Pi \left(2 - \frac{\omega d}{v} \right)}$$

where ω is the radian frequency of the desired oscillatory waves, p is the pitch of the helix, d is the diameter of the helix, and v is the velocity of wave propagation along the helix.

References Cited in the file of this patent

UNITED STATES PATENTS

2,643,353	Dewey	June 23, 1953
2,725,499	Field	Nov. 29, 1955

OTHER REFERENCES

Extrait Des Comptes Rendus Des Seances L'Academie Des Sciences, pages 236-238 (Paris, France), July 21, 1952, Geunard et al.

35 "A Spatial Harmonic Traveling-Wave Amplifier for Six Millimeters Wavelength" by Millman from Proceedings of I. R. E., vol. 39, issue 9 pages 1035-1043, Sept. 1951.