June 16, 1959 H. HEFFNER ET AL 2,891,191

BACKWARD WAVE TUBE

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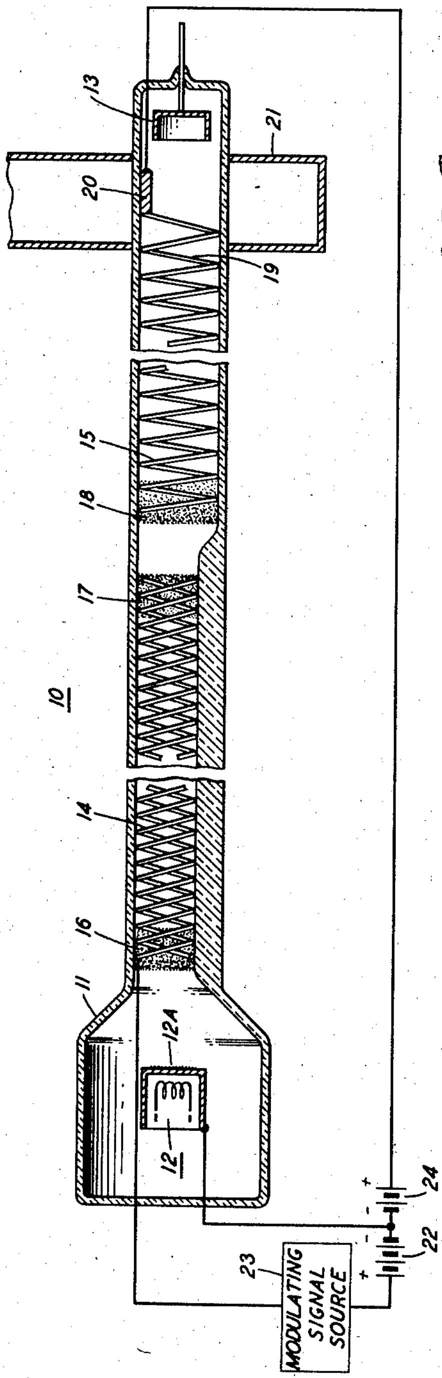

FIG. 1

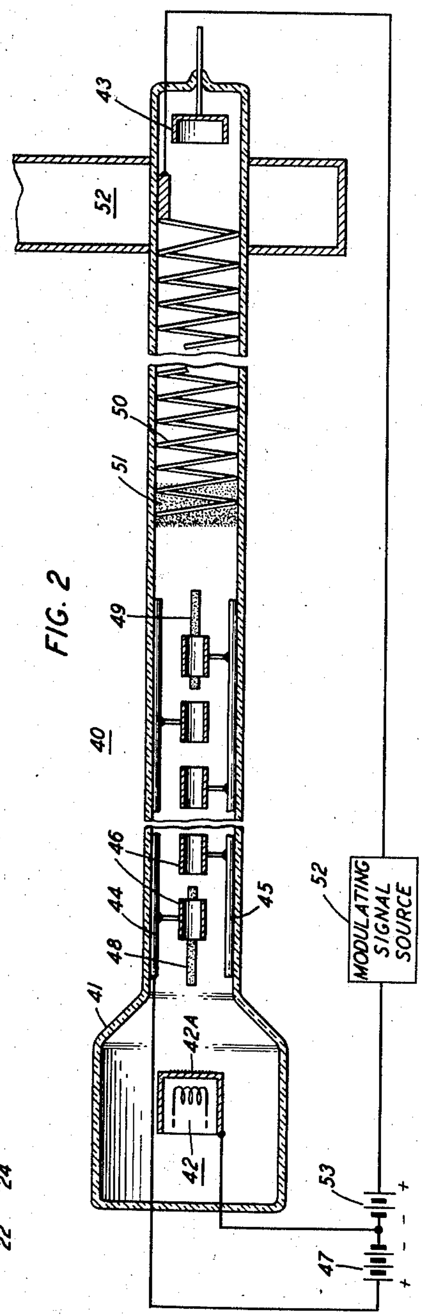

FIG. 2

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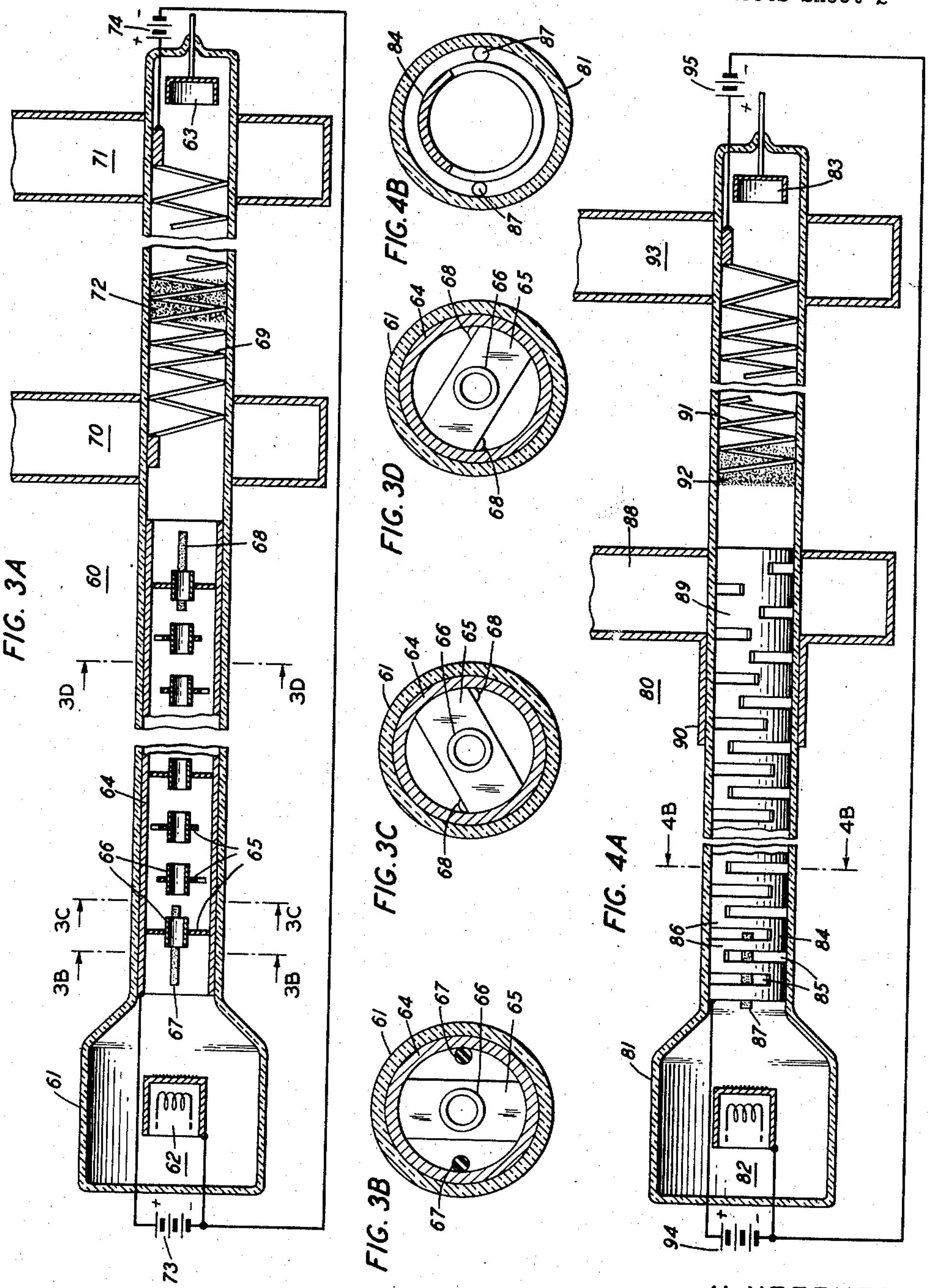

FIG. 3A FIG. 3B FIG. 3C FIG. 3D FIG. 4A FIG. 4B

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BACKWARD WAVE TUBE

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17 Claims. (Cl. 315—3.6)

This invention relates to electronic apparatus of the kind now generally designated as traveling wave tubes which utilize the interaction between a traveling electromagnetic wave and an electron stream.

An important class of such tubes utilizes the interaction between an electron stream and an oppositely directed or backward traveling wave. For operation in this way, there is employed an interaction circuit for propagating the traveling wave which has the characteristic that a wave traveling with the group velocity therealong in a given direction will give rise to components which have a phase velocity in the opposite direction. (It will be convenient to term such an interaction circuit as a backward wave circuit.) The electron beam in turn is adjusted to have a velocity substantially equal to the phase velocity of one of such components, whereby cumulative interaction between the beam and the wave component is made possible and amplification of the wave is achieved.

Operation in this way has two primary applications. Most importantly, operation in this way has formed the basis of backward wave oscillators. In the usual form of such oscillators, an electron stream is projected past a dispersive backward wave circuit which is made substantially reflectionless at its downstream end and from which oscillatory energy is abstracted at the upstream end. In this application, the terms "upstream" and "downstream" are used with reference to the relative separation along the path of flow from the electron source, upstream indicating proximity and downstream remoteness from the electron source. Thus the direction of electron flow from the electron source is the downstream direction and the upstream direction is opposite. Because the directions of wave energy propagation and electron flow are opposite, the electron beam provides positive feedback coupling, acting to return energy from points of higher level to points of lower level along the path of flow for sustaining oscillations. An important advantage of such backward wave oscillators is that the frequency of the oscillations can be tuned electronically over a wide continuous band of frequencies, this property making such oscillators well suited as frequency modulators. However, the full advantage of this property of backward wave oscillators has not readily been realizable hitherto because of the difficulty in abstracting the oscillatory energy from the backward wave circuit efficiently and without reflections over a wide band of frequencies. This has been so to a considerable degree because the nature of efficient backward wave circuits is such that broad band coupling connections thereto are difficult and awkwark. Additionally, the problem is complicated because the impedance of the most efficient backward wave circuits known varies widely over the oscillation band, making it difficult to keep the load well matched to the circuit continuously as is important for good coupling.

Accordingly, one object of the present invention is to

facilitate the efficient abstraction of oscillatory energy from a backward wave oscillator.

Another object is to increase the frequency band over which a backward wave oscillator may be conveniently and efficiently operated.

Another object is to make practical in traveling wave tubes the use of backward wave circuits which although of high impedance and thus well suited for propagating waves for interaction with an electron beam cannot readily be coupled to the more usual forms of wave transmission lines.

Another object is to make the output level of a backward wave oscillator more uniform with frequency over its operating range.

To these ends, a backward wave oscillator in accordance with the invention is modified to include in addition to its wide range backward wave circuit a separate broad brand forward wave type interaction circuit, for example, a helix, to which an efficient broad band coupling connection can be made readily and which is positioned downtsream relative to the backward wave circuit. In such an oscillator, the electron stream along which have been established modulations in the form of electron bunches as a result of backward wave interaction is permitted to travel past the forward wave type circuit on which the electron bunches induce a forward traveling wave with which they in turn interact. This forward wave is then abstracted at the downstream end of the forward wave circuit. The inclusion of the forward wave circuit in this fashion serves first to provide a broad band means for converting the oscillatory space charge wave set up on the electron beam in the form of electron bunches into an electromagnetic wave. Additionally, it serves to amplify the space charge wave on the stream and permits the eventual abstraction of a higher level signal than could have been abstracted originally in the region immediately past the region of backward wave interaction.

This latter characteristic offers further important advantages. It makes possible the realization of oscillatory waves of high level with short regions of backward wave interaction. Moreover, since the speed with which the oscillatory frequency of a backward wave oscillator can be varied for frequency modulation applications is related to the length of this backward wave region, it is usually desirable for such applications to have the backward wave interaction region as short as possible. Accordingly, an oscillator in accordance with the invention will be well suited for use as a fraquency modulator.

Additionally, an oscillator in accordance with the invention can be made to have a more nearly constant power output over its operating band than previously known backward wave oscillators by making internally both ends of the backward wave circuit substantially reflectionless, and operating the forward wave circuit at a constant voltage. Alternatively, amplitude modulation may be impressed on the oscillatory wave by varying in accordance with modulating intelligence either the voltage on the forward wave circuit around the value which results in maximum amplification or the current in the electron beam.

Additionally, the oscillator can be modified to mix a radio frequency signal with the oscillatory wave by applying such a signal as an input to the upstream end of the forward wave circuit for interaction with the electron beam on which already exists an oscillatory space charge wave.

The other important application of backward wave interaction is in a backward wave amplifier. In the usual form of such an amplifier, input waves to be amplified are applied to the downstream end of a backward wave circuit and the amplified output wave is abstracted at the upstream end of the circuit. An important advantage of such an amplifier is that while the frequency band over which amplification may be secured for a given electron beam velocity is small this pass band can be readily shifted over a wide region merely by varying the velocity of the electron beam. Accordingly, such an amplifier is well suited for use as an electronically tunable filter. However, one of the problems in the use of such an amplifier is the strong tendency it has to oscillate in a backward wave mode when high gains are sought, which tendency restricts the gain which can be achieved stably.

Accordingly, another object of the present invention is to increase the stability of backward wave amplifiers and so make possible increased amplification.

To this end, a backward wave amplifier in accordance with the invention includes a separate forward wave circuit along the path of flow positioned downstream relative to the backward wave interaction region. In operation, input waves to be amplified are applied to the downstream end of the backward wave circuit for travel therealong for impressing a relatively low level space charge wave on the electron stream which, in turn, induces a forward traveling wave in the forward wave circuit which is further amplified and then abstracted at the downstream end of the forward wave circuit. Such an amplifier retains the useful electronically tunable filter properties of the backward wave amplifiers known hitherto and yet permits high and relatively uniform stable gain in the pass band. Stability is enhanced by utilizing the backward wave interaction circuit to excite a space charge wave on the electron beam which although of sufficient level to induce a forward traveling wave on the forward wave circuit is of insufficient level to initiate and sustain backward wave oscillations.

Moreover, in the course of illustration of the principles of the invention, several novel forms of backward wave circuits will be described.

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

Fig. 1 shows a frequency modulator in accordance with the invention which utilizes a bifilar helix as the backward wave circuit;

Fig. 2 shows an amplitude modulator in accordance with the invention which utilizes a loaded Lecher-line as the backward wave circuit;

Figs. 3A through 3D show a radio frequency mixer in accordance with the invention which utilizes a loaded wave guide as the interaction circuit; and

Figs. 4A and 4B show a backward wave amplifier which employs a slotted hollow cylindrical conductor as the backward wave circuit.

Referring now more particularly to the drawings, in the tube **10** shown in Fig. 1 the various tube elements are enclosed in an evacuated glass envelope **11**. At opposite ends of the envelope are positioned an electron source which is the cathode **12A** of an electron gun **12** and the collector electrode **13** positioned in target relation with the source. The electron flow is focused by suitable means, not shown here, to be coaxial with the axis of the tube envelope. Positioned along the upstream portion of the path of flow is the backward wave circuit comprising a bifilar helix **14** which serves effectively as a helically coiled balanced transmission line. The general principles of the use of a bifilar helix as a backward wave circuit are described in detail in U.S. Patent 2,843,792, issued July 15, 1958, of J. R. Pierce. Positioned downstream along the path of flow is the forward wave circuit comprising the single wire helix **15**. The helix **15** is positioned coaxial with the tube envelope and with the path of flow. The bifilar helix **14** on the other hand is positioned to have its axis parallel to but displaced from the tube axis and the axis of the path of flow. The reasons for this will be discussed hereinafter.

In the backward wave oscillators known hitherto, it is the practice to terminate the downstream end of the backward wave circuit to make it substantially reflectionless and to abstract the oscillatory wave at the upstream end of the circuit by a suitable external coupling connection. In the present tube, both ends of the backward wave circuit are terminated internally to be substantially reflectionless. For this purpose, for example, dissipative material, such as aquadag, is coated along the inner surface of the envelope along portions adjacent the end turns of the bifilar helix, the thicknesses of the end coatings **16** and **17** being tapered to provide a broad band dissipative termination. Additionally, the upstream end of the forward wave circuit is terminated in a similar manner by the coating **18** deposited along the inner surface of the envelope along portions adjacent its upstream end turns. The useful energy is abstracted at the downstream end of the helix **15** by suitable coupling means. In the coupling means illustrated, the downstream end of the helix **15** is connected by way of the impedance matching section **19** to the coupling strip **20**. The impedance matching section **19** comprises a section of helix in which the helix pitch increases gradually. The coupling strip **20** is positioned to couple to the electric vector in the rectangular wave guide **21** which is closed at one end and leads to the utilization means at its other end. Various other arrangements are known to workers in the art for coupling an external wave transmission line to a single wire helix. Although the interaction of the beam and the wave on the forward wave circuit results in forward wave type amplification, in general, it should be unnecessary to distribute dissipative material along the intermediate portion of the forward wave circuit to minimize the tendency to self-oscillation as is characteristic in the conventional forward wave traveling wave amplifier, inasmuch as the internal termination of the helix should result in little reflection from the upstream end of the forward wave circuit. However, in the case that reflections are unavoidable, any of the various arrangements known to the art for avoiding self-oscillation may be employed.

In operation as a backward wave oscillator, the velocity of the electron beam past the backward wave circuit is adjusted to be in synchronism with the phase velocity of a spatial harmonic component of a wave of the desired frequency set up by noise components on the beam at the downstream end of the backward wave circuit for travel upstream therealong. As is set forth in the Pierce patent, in a tube which uses a bifilar helix as the backward wave circuit the velocity of the electrons should be adjusted to be approximately

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

where ω is the radian frequency of the oscillations desired, p is the separation between adjacent turns of the bifilar helix, d is the diameter of the helix, and v is the velocity of the wave along the bifilar helix. Of course, for stable oscillations, the beam current should be kept at a value larger than the starting current needed to initiate oscillations.

The velocity of the electron beam past the backward wave circuit is controlled by the accelerating voltage which exists between the electron source and the backward wave circuit. A suitable potential difference is maintained by lead-in conductors from voltage source **22**. In some arrangements, it will be convenient to maintain a D.-C. voltage difference between the two conductors forming the bifilar helix for electrostatic focusing, but in the interest of simplicity the two conductors of the bifilar helix are here shown at the same positive D.-C. potential with respect to the electron source as is the case where magnetic focusing of the beam is employed.

For use as a frequency modulator, the modulating intelligence is used to vary the velocity of the electron beam past the backward wave circuit, thereby changing correspondingly the oscillatory frequency. To this end, a source 23 of modulating voltage under control of the modulating intelligence is inserted serially in the conductive path between the electron source and the backward wave circuit.

In operation, the backward traveling growing oscillatory wave bunches the forward flowing electron beam which may be considered as giving rise thereon to a forward traveling space charge wave. This space charge wave subsequently in its passage past the forward wave circuit induces a forward traveling electromagnetic wave in the forward wave circuit which travels therealong. By properly choosing the retardation characteristics of this forward wave circuit, this traveling wave can be made to interact with the electron beam whereby it is amplified. The amplified wave is abstracted for utilization at the downstream end of the forward wave circuit by the output coupling means. For interaction, the velocity of the electron beam past the forward wave circuit is adjusted to be approximately equal to the phase velocity of the forward traveling wave along the helix 15 in accordance with the usual practice in helix-type traveling wave tubes. This velocity can either be equal to or different from the velocity of the beam past the backward wave circuit. The relative velocities past the two circuits are dependent on the relative voltages on the two circuits. For controlling the electron velocity a potential difference is maintained between the electron source and the helix 15 by suitable lead-in conductors from the voltage source 24. Because of the broad band characteristics of a single wire helix as a forward wave interaction circuit, good amplification of the forward traveling wave induced by the space charge oscillatory waves can be achieved over the wide band of frequencies over which the oscillatory wave can be modulated.

It is important to displace the axis of the bifilar helix relative to the axis of the single wire helix to secure electron beam bunching by the bifilar helix of a kind which is best adapted to induce a forward traveling wave on the single wire helix. Because of spatial harmonic components of a wave traveling along the bifilar helix are quite small along the helix axis, for good spatial harmonic interaction it is advantageous to displace the path of flow of the beam from the helix axis to a region of stronger spatial harmonic components. However, in the case of the single wire helix, interaction with the fundamental mode of the traveling wave which is strong along the helix axis is usually preferable to spatial harmonic interaction, and, accordingly, it is desirable to have the path of electron flow past the single wire helix along the helix axis.

To improve the uniformity of the output level with changes in frequency, the forward wave circuit can be operated to have a frequency response which is complementary to the frequency response to the backward wave circuit. Alternatively, the frequency responses of the backward and forward wave circuits may be chosen to provide an output of any desired frequency characteristic.

In the amplitude modulator 40 shown in Fig. 2, the various tube elements are housed in a glass envelope 41. An electron gun 42 including a cathode 42A and a collector 43 define a path of longitudinal electron flow coaxial with the longitudinal tube axis. Suitable means not shown are employed to maintain the electron beam aligned with the tube axis. Such means may include either magnetic focusing equipment or means for achieving a spatially alternating time-constant field along the path of flow. The backward wave circuit utilized to modulate the electron beam and set up space charge oscillatory waves thereon comprises a Lecher system including the two parallel straight conductors 44 and 45 positioned diametrically opposite along the tube axis alternately from which is conductively supported a linear array of annular conductive cylinders 46 which are spaced apart coaxial with the longitudinal axis of the tube and surrounding the path of electron flow. A wave traveling along the parallel conductors will because of the presence of the cylinders 46 set up strong spatial harmonic components along with the tube axis which can be made to interact with the electron beam whereby backward traveling wave oscillations may be set up on the Lecher system and forward traveling space charge waves set up on the electron beam. The phase velocity of the spatial harmonic components may be adjusted by the periodicity and length of the cylinders. The velocity of the electron beam may be adjusted by the accelerating voltage provided between the succession of annular cylinders and the electron source. A suitable potential difference is maintained by lead-in conductors from the voltage supply 47. The frequency of the oscillatory wave is controlled by this potential difference which may be varied to tune the oscillatory frequency. To make possible oscillations of relatively uniform amplitude over a wide range, the two ends of the backward wave circuit are made substantially reflectionless by the insertion internally of dissipative terminations.

To this end, at each end of the backward wave circuit there is inserted a pair of dielectric rods 48, 49, each of which rods is coated with lossy material, the thickness of the coating increasing gradually to make reflectionless terminations of each pair of rods. The rods extend preferably for a distance of several operating wavelengths along the backward wave circuit, but in the interest of simplicity in the drawing they are shown of abbreviated length. The two rods of each pair preferably are disposed diametrically opposite one another and adjacent to the glass envelope 41 in the regions between conductors 44 and 45.

The forward wave circuit comprising the single wire helix 50 is positioned along the path of flow coaxial with the tube axis downstream of the forward wave circuit whereby the oscillatory spaced charge waves set up on the electron beam by the backward wave circuit induce a forward traveling electromagnetic wave on the helix. The helix 50 is made substantially reflectionless at its upstream end by a dissipative coating 51 along the inner surface of that portion of the tube envelope adjacent to its end turns as described above. The output wave is abstracted at the downstream end of the helix by a suitable coupling means 52 which, for example, is of the kind described above in the tube shown in Fig. 1.

The retardation characteristics of the helix are in this case also chosen so that the phase velocity of the fundamental component of a forward traveling wave therealong is approximately equal to the velocity of the beam therepast, which beam velocity is controlled by the voltage difference between the electron source and the helix. However, it is a well-known characteristic of helix-type traveling wave tubes that there exists an optimum beam voltage, dependent on various parameters, for which there results maximum interaction between the beam and the wave and hence maximum amplification of the wave. Accordingly, in the tube shown in Fig. 2, by utilizing the modulating intelligence to vary the voltage on the helix 50 which determines the beam velocity therepast from its optimum value, there can be provided at the downstream end of the helix 50 an oscillatory wave which is amplitude modulated in accordance with given modulating intelligence. To this end, a source 52 of modulating voltage is inserted in series with the voltage supply 53 to establish by suitable lead-in conductors the accelerating potentials on the helix 50.

It can be seen that by the principles of the invention there can be combined in a single tube both the oscillatory and amplitude modulating functions in a cooperative manner which results in no mutual interference.

Alternatively, amplitude modulation may be achieved by modulating in accordance with signal intelligence the current of the electron beam, provided only that precautions are taken to insure that the current never falls below the amount needed to sustain oscillations on the backward wave circuit.

In the radio frequency mixer 60 shown in Figs. 3A through 3D, the various tube elements are enclosed in an evacuated glass envelope 61. At opposite ends, an electron source 62 and a target electrode 63 define a path of electron flow coaxial with the longitudinal axis of the tube. The backward wave circuit in this tube comprises a conductive cylindrical wave guide 64 which extends along an upstream portion of the path of flow and which is loaded by a succession of transverse slat members 65 which extend across the wave guide in a diametric fashion. The slat members are spaced apart along the path of flow, and each successive member is rotated about the longitudinal axis a predetermined angle with reference to the immediately preceding member. Each of the slat members is apertured and the apertures are aligned in a linear array coaxial with the tube axis for passage of the electron flow therethrough. Moreover, from each slat there is supported a short conductive cylinder 66 for surrounding the path of flow. A voltage source 73 is connected between the wave guide 64 and the electron source 62. It is found characteristic of such a wave circuit that a wave propagating in a direction opposite to that of electron flow will set up along the tube axis strong spatial harmonic components. In particular, it is characteristic that the fundamental or lowest order spatial harmonic mode of a wave whose group velocity is in a direction opposite to that of electron flow will have a phase velocity in the direction of electron flow. A circuit of this kind is analogous to an artificial line made up of a ladder network of shunt inductances and series capacitances, the successive slat members acting as inductive posts for forming a series of shunt inductances and the spaced array of cylinders serving to introduce the intermediate series capacitances. In such an artificial line, the phase shift advances in a direction opposite to the direction of wave propagation along the line.

To terminate internally the two ends of the backward wave circuit, there are inserted pairs of dielectric rods 67 and 68 coated with dissipative material which resemble those inserted in the tube shown in Fig. 2.

The forward wave circuit which again comprises a single wire helix 69 is disposed along the path of flow downstream of the backward wave circuit for utilizing the oscillatory space charge waves set up on the beam in the manner described above. For operation as a radio frequency mixer, an input wave which is to be mixed with the oscillatory wave is inserted into the forward wave circuit at its upstream end by coupling means 70, and the mixed signal is available at the downstream end of the forward wave circuit for abstraction by output coupling means 71. In this instance, it is desirable to distribute dissipative material in a coating 72 along the forward wave circuit to minimize the tendency towards self oscillation of this circuit resulting from wave energy reflections at the input and output connections to this circuit. Alternatively, the tendency to self oscillations may be curbed by making this helix substantially nonreciprocal in its attenuation properties by the insertion therealong of a magnetically biased ferrite element, as is described in copending application Ser. No. 362,177, filed June 17, 1953, by R. Kompfner and H. Suhl. For accelerating the electron flow past the forward wave circuit, the helix is maintained at a suitable positive potential with respect to the electron source by lead-in conductors connected to the voltage supply 74. The retardation characteristics of the helix and the velocity of beam are adjusted for interaction between the beam and the wave.

In operation, the oscillatory space charge wave on the electron beam sets up a forward traveling wave in the forward wave circuit which is mixed with the input wave also applied thereto. Then when the levels of the two signals become sufficiently high to result in operation in the nonlinear region of the tube's amplifying characteristics, there result the modulation products of the two waves of which a particular one may be favored by operation in a dispersive region of the circuit's phase velocity versus frequency characteristic. Additionally, it may be desirable to filter the output to remove the fundamental frequencies and undesired modulation product frequencies.

With reference now to Figs. 4A and 4B, the various elements of the backward wave amplifier 80 are enclosed in the evacuated glass envelope 81. At opposite ends an electron source 82 and a target electrode 83 define a path of flow of an electron beam along the longitudinal axis of the tube. Suitable focusing means not shown are utilized to keep the electron flow straight. Positioned upstream along the path of electron flow is the backward wave circuit which in this instance comprises the annular conductive cylinder 84 which has a succession of lateral slots or cuts 85 spaced apart longitudinally therealong. The slots are cut in an interleaved pattern, adjacent slots being on diametrically opposite sides of the cylindrical surface. The slots are relatively deep, leaving only relatively small conductive strips 86 integral with the conductive surface in the regions of the slots. Such a structure exhibits along its axis strong spatial harmonic components of a wave propagating therethrough. Accordingly, the cylinder 84 is positioned to have its axis parallel to the longitudinal axis of the tube along which flows the electron beam. An input wave guide 88 of rectangular cross section is used to supply input signals to the downstream end of the backward wave circuit. To this end, the wave guide 88 has its narrow side walls apertured for passage therethrough of the tube envelope and the wave guide is positioned along the tube envelope so that the downstream end of the cylinder is bridged across the apertured side walls of the guide. Toward the downstream portion of the cylinder the depth of the slots decreases gradually forming a tapered transition region 89 to which the wave guide is coupled. Additionally, a conductive sleeve 90 extends from the wave guide wall for shielding that portion of the transition region not included within the wave guide. One end of the wave guide is closed and the other end leads off to a signal source. The upstream end of the backward wave circuit is made substantially reflectionless by the insertion of a dissipative termination 87 comprising a pair of coated dielectric rods of the kind shown for terminating the backward wave circuit shown in Figs. 2 and 3. In this case the rods are positioned intermediate the glass envelope 81 and the conductive cylinder 84, as shown in Fig. 4B.

The forward wave circuit again comprises a helically wound conductor 91 disposed downstream along the path of flow coaxial with the tube axis whereby the electron beam passes axially therethrough. The upstream end of the forward wave circuit is made substantially reflectionless by the insertion of a resistive termination in the form of a coating 92 of dissipative material on the portion of the inner surface of the envelope adjacent the upstream end turns of the helix 91. It should not be necessary to insert loss along the intermediate portion of the forward wave circuit for tube stability if the upstream end of the forward wave circuit is made sufficiently reflectionless. The amplified output wave is abstracted at the downstream end of the forward wave circuit by coupling means 93.

In backward wave amplification operation, it is important to make the backward wave circuit sufficiently short and the electron beam current therepast sufficiently low that oscillations in the backward wave mode are not initiated. The backward wave circuit portion of the tube serves primarily as a narrow pass band filter whose pass band can be varied electronically. The pass band is controlled by the velocity of the electron beam past the backward wave circuit which can be varied by changing the voltage difference provided between the electron source 82 and the conductive cylinder 85. This voltage difference is established by lead-in connections from the voltage source 94. In operation, the backward wave circuit establishes on the electron beam a forward traveling space charge wave corresponding to the signal input wave and this space charge wave in turn excites a forward traveling wave in the forward wave circuit. Amplification of this new forward traveling wave is achieved in its travel along the forward wave circuit. To this end, the retardation characteristics of the forward wave circuit are chosen so that the phase velocity of the traveling wave is sufficiently near to the velocity of the electron beam whereby good interaction between the beam and wave results. The velocity of the beam is controlled by the voltage supply 95 used to establish a potential difference between the helix and the electron source.

As has been indicated above, in backward wave amplifiers it is important that the backward wave gain be insufficient to initiate oscillations in a backward wave mode. This has proved one of the limitations which have made it difficult to exploit fully the desirable properties of such amplifiers. In the embodiment described this problem is avoided by making the backward wave circuit no longer than necessary to bunch the electron beam in accordance with the input signal, and deriving amplification primarily from the action of the forward wave circuit. However, this embodiment still retains the advantages of a conventional backward wave amplifier in that the electron bunching process will be controlled by the velocity of the electron beam, the velocity of the beam having to be such as to permit interaction between the beam and a forward traveling spatial harmonic of the backward traveling signal wave. This makes possible electronic control of the pass band properties of the amplifier. Additionally, where high output powers are desired measures may be taken to increase the beam current past the forward wave circuit as, for example, by the provision of an additional electron source in the region intermediate the backward and forward wave circuits.

It should be evident from the preceding description that the various specific embodiments illustrated are merely illustrative of the general principles of the invention. Various modifications may be devised by one skilled in the art without departing from the spirit and scope of the invention. In particular, various forms of both backward and forward wave interaction circuits may be employed. Additionally, the path of flow of the electron beam need not be straight, but may be circular as is characteristic of some forms of traveling wave tubes, particularly those of the magnetron type which employ crossed electric and magnetic fields. Additionally, pulsed operation may be achieved by the insertion of suitable deflecting means interposed between the backward and forward wave circuits for making the flow past the forward wave circuit intermittent without disturbing the oscillatory behavior of the backward wave circuit. Such a modification in the tube of Fig. 1, for example, makes available at the output a train of pulses, each of which is frequency modulated but whose phase is continuous from pulse to pulse.

What is claimed is:

1. In an electron discharge device in combination, an electron source and a target electrode for defining a path of flow for an electron beam, a backward wave interaction circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of electron flow for impressing space charge waves on the electron beam, dissipative termination means located solely within said device for making the upstream end of the backward wave circuit substantially reflectionless, a forward wave interaction circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the space charge waves on the electron beam induce forward traveling electromagnetic waves, and means to couple output wave energy from the downstream end of the forward wave circuit.

2. In an oscillator, an electron source and a target electrode defining a path of flow for an electron beam, a backward wave interaction circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow for exciting oscillatory space charge waves on the electron beam, dissipative termination means located solely within said oscillator for making the upstream end of the backward wave circuit substantially reflectionless, a forward wave interaction circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the oscillatory space charge waves excite forward traveling waves, and means to couple oscillatory wave energy from the downstream end of the forward wave circuit.

3. In a frequency modulator, an electron source and a target electrode for defining a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow for exciting space charge waves on the electron beam, dissipative termination means located solely within said modulator for making the upstream end of the backward wave circuit substantially reflectionless, means controlled by modulating intelligence for varying the velocity of the electron beam past the backward wave circuit, a forward wave circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the space charge waves excite forward traveling electromagnetic waves, and means for coupling out the wave energy at the downstream end of the forward wave circuit.

4. In an amplitude modulator, an electron source and a target electrode defining a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow for impressing space charge waves on the electron beam, dissipative termination means located solely within said modulator for making the upstream end of the backward wave circuit substantially reflectionless, a forward wave circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the space charge waves excite forward traveling electromagnetic waves, means under the control of modulating intelligence for varying the velocity of the electron beam past the forward wave circuit, and means for coupling output wave energy from the downstream end of the forward wave circuit.

5. In a radio frequency mixer, an electron source and a target electrode defining a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow for impressing space charge waves on the electron beam, dissipative termination means located solely within said mixer for making the upstream end of the backward wave circuit substantially reflectionless, a forward wave circuit spaced downstream along the path of flow with respect to said backward wave circuit in which the space

charge waves excite forward traveling electromagnetic waves, means for applying a mixing signal to the upstream end of the forward wave circuit, and means for abstracting the mixed wave signal at the downstream end of the forward wave circuit.

6. In an electron discharge device in combination, an electron source and a target electrode defining a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow for propagating therealong an electromagnetic wave in a direction opposite to the path of electron flow and inducing a space charge wave on the electron beam which travels in the direction of electron flow, dissipative termination means located solely within said device for making the two ends of the backward wave circuit substantially reflectionless, a forward wave circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the space charge wave excites a wave traveling in the direction of electron flow, dissipative termination means for making the upstream end of the forward wave circuit reflectionless, and means for coupling wave energy from the downstream end of the forward wave circuit.

7. In a frequency modulator, an electron source and a target electrode defining a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow for establishing a forward traveling space charge wave on the electron beam, dissipative termination means located solely within said modulator for making the two ends of the backward wave circuit substantially reflectionless, means under the control of modulating intelligence for varying the velocity of the electron beam past the backward wave circuit for varying the frequency of the space charge wave on the electron beam, a forward wave circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the forward traveling space charge wave excites a forward traveling electromagnetic wave, dissipative termination means for making the upstream end of the forward wave circuit substantially reflectionless, and means for coupling wave energy from the downstream end of the forward wave circuit.

8. In an amplitude modulator, an electron source and a target electrode for defining a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction for inducing a forward traveling oscillatory space charge wave on the electron beam, dissipative termination means located solely within said modulator for making both ends of the backward wave circuit substantially reflectionless, a forward wave circuit positioned downstream along the path of electron flow with respect to said backward wave circuit in which the forward traveling space charge wave excites a forward traveling electromagnetic wave, means under the control of modulating intelligence for varying the velocity of the electron beam past the forward wave circuit, dissipative termination means for making the upstream end of the forward wave circuit substantially reflectionless, and means for coupling output wave energy from the downstream end of the forward wave circuit.

9. In a backward wave amplifier, an electron source and a target electrode for defining therebetween a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow, means for applying an input signal to be amplified to the downstream end of the backward wave circuit for propagation therealong in a direction opposite to that of electron flow for establishing on the electron beam a forward traveling space charge wave, dissipative termination means located solely within said amplifier for making the upstream end of said backward wave circuit substantially reflectionless, a forward wave circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the forward traveling space charge wave on the electron beam induces a forward traveling electromagnetic wave, and means for abstracting the amplified electromagnetic wave at the downstream end of the forward wave circuit.

10. In an electron discharge device in combination, an electron source and a target electrode for defining therebetween a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction positioned upstream along the path of flow, means coupled to the downstream end of the backward wave circuit for inducing a wave to be amplified for propagation therealong in a direction opposite to that of electron flow for establishing a forward traveling space charge wave on the electron beam, dissipative means located solely within said device for making the upstream end of the backward wave circuit substantially reflectionless, a forward wave circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the space charge wave on the beam induces a forward traveling electromagnetic wave, dissipative means for making the upstream end of the forward wave circuit substantially reflectionless, and means coupled to the downstream end of the forward wave circuit for abstracting for utilization the amplified electromagnetic wave.

11. In combination, an evacuated envelope, an electron source and a target electrode at opposite ends of said envelope for defining therein a path of flow for an electron beam, a backward wave circuit characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction within said envelope positioned upstream along the path of flow for propagating therealong a backward traveling wave which establishes a forward traveling space charge wave on the electron beam, dissipative termination means located solely within asid envelope for making the two ends of the backward wave circuit substantially reflectionless, a forward wave circuit within said envelope positioned downstream along the path of flow with respect to said backward wave circuit in which the forward traveling space charge wave induces a forward traveling electromagnetic wave, dissipative termination means within said envelope for making the upstream end of the forward wave circuit substantially reflectionless, and means external to the envelope coupled to the downstream end of the forward wave circuit for abstracting wave energy for utilization.

12. In combination, an electron source and a target electrode for defining therebetween a longitudinal path of flow for an electron beam, a bifilar helix positioned upstream along the path of flow for propagating therealong an electromagnetic wave traveling in the direction opposite to that of electron flow and inducing a forward traveling space charge wave on the electron beam, a single conductor helix positioned downstream along the path of flow with respect to said backward wave circuit in which the space charge wave on the electron beam induces a forward traveling electromagnetic wave, and means at the downstream end of the single conductor

helix for abstracting the forward traveling wave for utilization.

13. In an electron discharge device in combination, an electron source and a target electrode for defining a longitudinal path of flow for an electron beam, a Lecher system positioned upstream along the path of flow for propagating therealong an electromagnetic wave traveling in a direction opposite to that of electron flow and inducing a forward traveling space charge wave on the electron beam, dissipative termination means located solely within said device for making the upstream end of the Lecher system substantially reflectionless, said Lecher system comprising a pair of parallel conductors from which extend a linear array of annular conductive cylinders through which flows the electron beam, alternate cylinders extending from the same conductor, adjacent cylinders extending from different conductors, a single conductor helix positioned downstream along the path of flow with respect to said backward wave circuit in which the forward traveling space charge wave induces a forward traveling electromagnetic wave, and means coupled to the downstream end of the single conductor helix for abstracting the forward traveling electromagnetic wave for utilization.

14. In an electron discharge device in combination, an electron source and a target electrode for defining therebetween a longitudinal path of flow for an electron beam, an annular conductive cylinder positioned for surrounding an upstream portion of the path of flow for propagating an electromagnetic wave traveling in a direction opposite to that of electron flow and inducing a forward traveling space charge wave on the electron beam, dissipative termination means located solely within said device for making the upstream end of the propagating cylinder substantially reflectionless, a succession of transverse diametric slat members spaced apart longitudinally along the cylinder and apertured for passage of the electron flow, successive members being angularly displaced around the cylindrical axis, a single conductor helix positioned along a downstream portion of the path of electron flow in which the forward traveling space charge wave induces a forward traveling electromagnetic wave, and means coupled to the downstream end of the single conductor helix for abstracting the forward traveling wave for utilization.

15. In an electron discharge device in combination, an electron source and a target electrode for defining therebetween a longitudinal path of flow for an electron beam, a conductive annular cylinder positioned around the upstream portion of the path of electron flow for propagating an electromagnetic wave traveling in a direction opposite to that of electron flow and inducing a forward traveling space charge wave on the electron beam, dissipative termination means located solely within said device for making the upstream end of the propagating cylinder substantially reflectionless, said cylinder having successive transverse slots in its cylindrical surface, successive slots being on opposite sides of the cylindrical surface for forming an interleaved pattern of slots, a single conductor helix positioned around the downstream portion of the path of electron flow in which the forward traveling space charge wave induces a forward traveling electromagnetic wave, and means coupled to the downstream end of the single conductor helix for abstracting the forward traveling wave for utilization.

16. In an electron discharge device in combination an electron source and a target electrode for defining a path of flow for an electron beam, a backward wave interaction circuit positioned upstream along the path of electron flow for impressing space charge waves on the electron beam, the backward wave circuit being characterized in that a wave traveling with a group velocity therealong in a given direction will give rise to space harmonic components which have a phase velocity in the opposite direction and being adapted to provide an interaction between the electron beam and the space harmonic components to cause growth of said traveling wave, dissipative termination means located solely within said device for making the upstream end of the backward wave circuit substantially reflectionless, a forward wave interaction circuit positioned downstream along the path of flow with respect to said backward wave circuit in which the space charge waves on the electron beam induce forward traveling electromagnetic waves, and means to couple output wave energy from the downstream end of the forward wave circuit.

17. In an electron discharge device in combination an electron source and a target electrode for defining a path of flow for an electron beam, a backward wave interaction circuit positioned upstream along the path of electron flow and in which there is induced by the electron beam an electromagnetic wave which travels therealong in the direction opposite to that of electron flow and gives rise to space harmonic components which have a phase velocity substantially equal to that of the electron flow with which components the electron beam interacts, whereby the induced wave grows and space charge waves are impressed on the electron beam, dissipative termination means located solely within said device for making the upstream end of the backward wave circuit substantially reflectionless, a forward wave interaction circuit positioned downstream along the path of flow with respect to the backward wave circuit in which the space charge waves on the electron beam induce forward traveling electromagnetic waves, and means to couple output wave energy from the downstream end of the forward wave circuit.

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