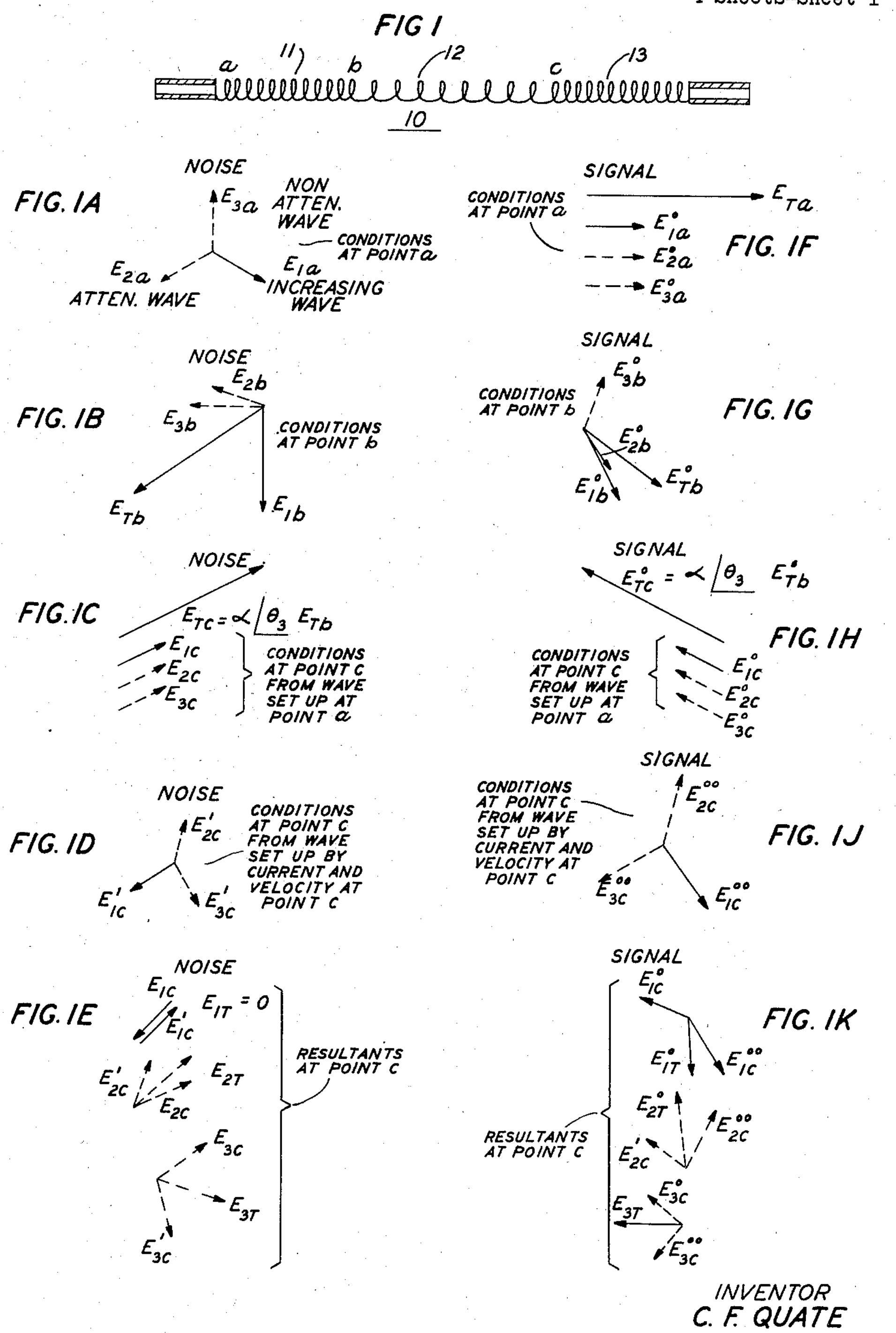
Oct. 13, 1959 C. F. QUATE 2,908,844

LOW NOISE TRAVELING WAVE TUBES

Filed April 11, 1951 4 Sheets-Sheet 1



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LOW NOISE TRAVELING WAVE TUBES

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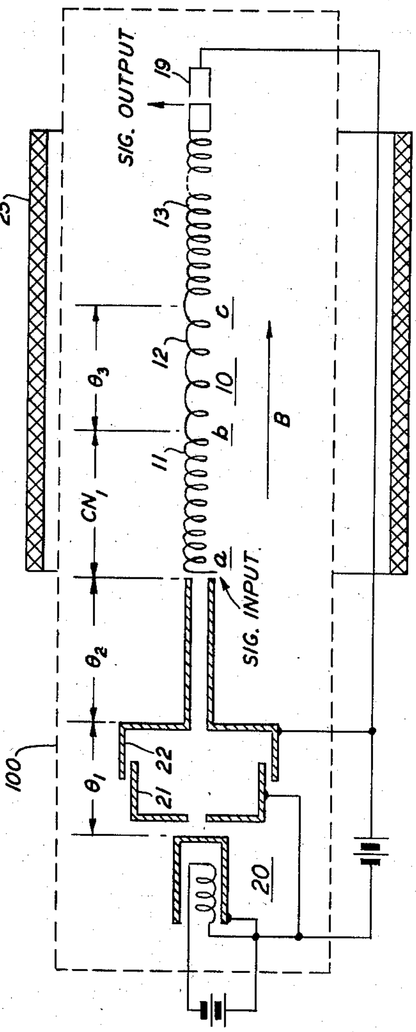

FIG. 2

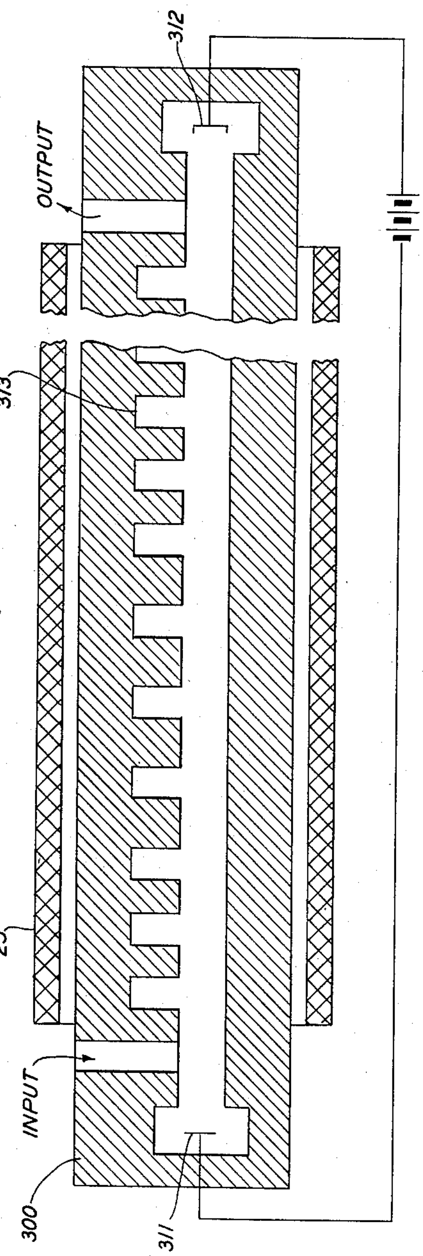

FIG. 5

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FIG. 3

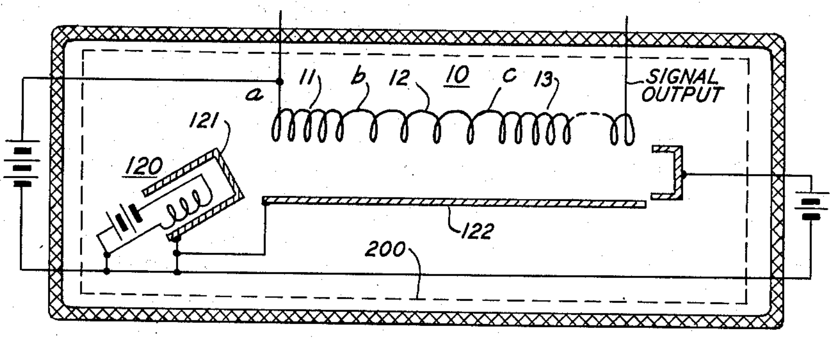

FIG. 4A

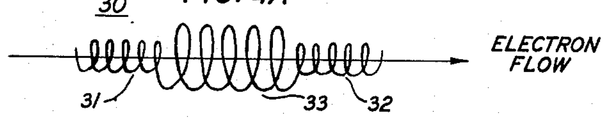

FIG. 4B

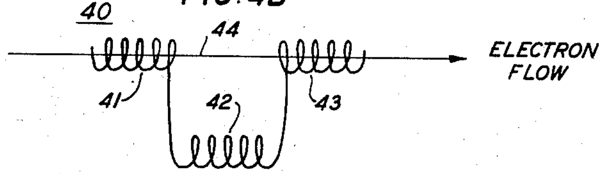

FIG. 4C

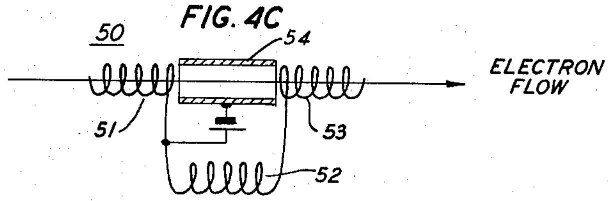

FIG. 4D

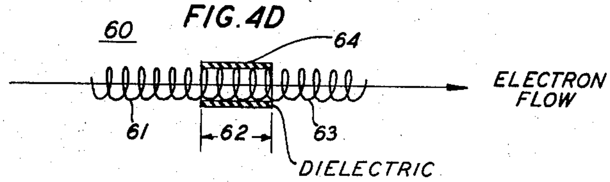

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FIG. 6A

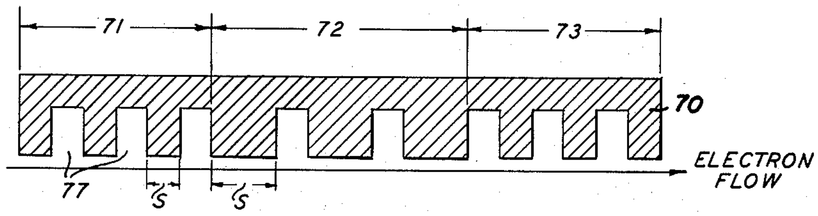


FIG. 6B

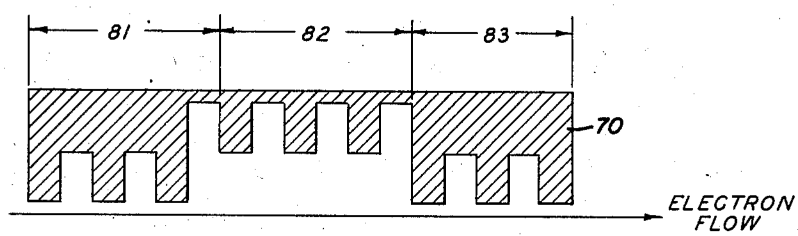


FIG. 6C

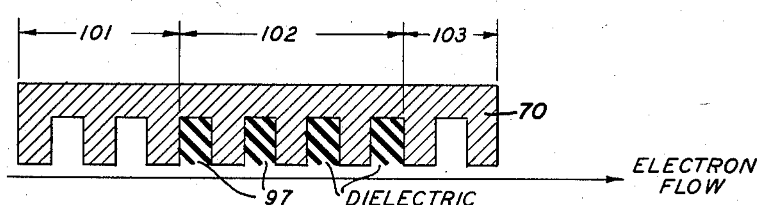
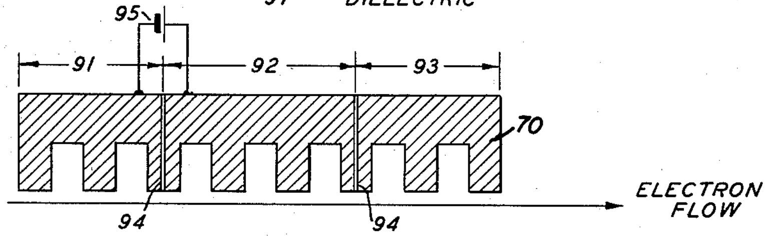


FIG. 6D



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LOW NOISE TRAVELING WAVE TUBES

Calvin F. Quate, Berkeley Heights, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application April 11, 1951, Serial No. 220,416

23 Claims. (Cl. 315—3.6)

This invention relates to space charge devices and more particularly to microwave amplifying devices which utilize the cumulative interaction between an electron stream and an electromagnetic wave to secure gain to the electromagnetic wave.

It is the principal object of this invention to reduce the effect of noise fluctuations in the electron streams of such devices.

Several kinds of devices are known which utilize the cumulative interaction between an electron stream and an electromagnetic wave to secure gain for the wave. Among the most important of these are the traveling wave tube (of which some representative types are described in the copending applications Serial No. 640,597, filed January 11, 1946, by J. R. Pierce now Patent 2,636,948 and Serial No. 99,757, filed June 17, 1949 by S. Millman now Patent 2,683,238) and the magnetron amplifier (of which some representative types are described in the copending application Serial No. 707,812 filed November 5, 1946 by J. R. Pierce, now Patent 2,768,328, issued October 23, 1956.

For the purposes of analysis, it will be convenient to describe the invention more particularly with reference to traveling wave tubes, but it will be appreciated that the principles thereof are applicable as well to other arrangements which utilize cumulative interaction of this sort to produce an increasing wave.

The traveling wave tube can be described as a vacuum tube which contains an electric circuit propagating radio frequency electromagnetic waves therethrough at velocities lower than the velocity of light and an electron stream passing through the electric field set up by the electric circuit in the direction of wave propagation. By proper adjustment of the velocities of the propagated wave and the electron stream, the two can be made to interact cumulatively whereby gain can be secured. In such operation, the radio frequency wave of the electric circuit accelerates electrons in the beam, giving rise therein to an alternating-current velocity component which sets up an A.-C. convection current component. This A.-C. current component in turn sets up a radio frequency field of its own which combines with the radio frequency field of the electric circuit. When the radio frequency wave and electron stream are properly synchronized, the cumulative action and reaction between the radio frequency field of the circuit and the A.-C. current component in the stream result in a wave which grows in magnitude as it travels along the electric circuit. By utilization of this property, such a tube can serve as an amplifier.

However, in the operation of such tubes, any nonhomogeneity of the electron stream at the point of injection into the circuit field serves to introduce a noise level in the output wave. Initial thermal fluctuations inherent in conventional electron beam sources and partition effects introduced by accelerating electrodes are among the most significant factors which prevent complete homogeneity of the electron stream at the point of

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injection into the region of interaction with the electric field. In practice it has been found that the electron stream can be represented, for purposes of analysis, as having average or D.-C. velocity and current components about which fluctuate noise velocity and current components. Such noise components interact with radio frequency fields in the electric circuit and thereby produce spurious or noise components in the amplified wave. In practice, it is important to minimize this noise if operation at low signal level is desired.

Accordingly, another object of this invention is to improve the performance of microwave devices of the type which utilizes the cumulative interaction between an electron stream and an electromagnetic wave and, more particularly, to minimize in tubes of this type the noise in their operation resulting in each case from the non-homogeneity of the electron stream.

Analysis of traveling wave interaction in a traveling wave tube shows that the propagation characteristics of the traveling wave when in cumulative interaction with the electron stream can be represented by four natural modes of propagation along the electric circuit and electron stream. Of these, three are forward traveling waves, and the fourth a backward traveling wave. If reflections are avoided, it is possible to disregard the effect of the backward traveling wave and confine attention to the three forward modes. Of these, one is an increasing wave which travels a little more slowly than the electrons, a second is a decreasing wave which also travels a little more slowly than the electrons, and the third is an unattenuated wave which travels a bit faster than the electrons.

In operation, the noise velocity and current components in the electron stream set up perturbations in the electric circuit which may be represented as three forward traveling waves which have the characteristics set forth hereinabove as characteristic of those set up by an input signal wave. As a result, any significant noise level in the stream at the point of injection into the electric field will ordinarily result in a corresponding noise level in the amplified wave output. However, in the practice of the present invention, substantial diminution of the effect of this noise in the electron stream is realized at the wave output by providing cancellation of the increasing wave mode of the traveling wave set up by the noise components of the stream.

To this end, a feature of the present invention is an electric circuit for propagation of the radio frequency wave which includes a preliminary section and a main section in both of which the electron stream and the traveling waves interact to produce a cumulative exchange of energy and also includes a cancellation section intermediate therewith in which there is substantially no cumulative exchange of energy between the stream and waves, but instead this intermediate section is designed to provide cancellation of the increasing wave component of the noise wave in the main section.

As explained above, at the point of injection into the region of interaction with the electric circuit, the nonhomogeneous electron stream can be represented by components of direct-current or average velocity and current about which fluctuate components of noise velocity and current. In a traveling wave tube designed in accordance with the present invention, there is consequently set up in the preliminary section by the noise components, three forward waves which will travel therethrough in cumulative interaction to the beginning of the cancellation section. Then, since cumulative interaction is there inhibited, the three waves will travel as ordinary waves along the electric circuit and hence can conveniently be represented by the composite wave which is their vector sum and which will travel therethrough and be attenuated in accordance with the attenuation characteristics of this section. However, at the beginning of the main section where cumulative interaction again results, this composite wave will act in the manner of a signal input wave applied thereto and will accordingly set up three forward waves, in the manner characteristic of cumulative interaction. Additionally, at the origin of the main section, the noise components there in the electron stream have the effect of setting up three additional forward traveling waves. In the practice of the present invention, the tube characteristics are chosen to provide at the start of the main section cancellation between the increasing wave component set up by the noise wave which has traversed the preliminary and intermediate sections and the increasing wave component of the new noise wave set up originally at this point by the noise fluctuations in the electron stream. In particular, the attenuation and phase shift characteristics of the cancellation section are chosen to make these two increasing waves equal in magnitude but opposite in phase. More particularly, the desired phase shift characteristics of the cancellation section are achieved by making the electrical length of the section relative to the increasing wave component of the noise wave different from the electrical length of the section relative to the noise fluctuations on the electron stream. It will be seen that, because of the dissimilarities in the manner of injection between the signal and noise waves, the condition for noise cancellation will not at the same time seriously affect the amplification of the signal. By suppression of the increasing wave of the noise components in this way at the commencement of the main section of the circuit, and by making the main section of sufficient length so that the other waves of the noise components become unimportant, relatively noise-free operation can be achieved over a considerable range of frequencies.

By way of example, the invention will be described with particular reference to a noise cancellation arrangement for a helix-type traveling wave tube, although as already pointed out hereinabove the invention can be adapted to provide noise cancellation in other tube types which utilize the cumulative interaction between an electron stream and an electromagnetic wave.

In the helix-type tube as known hitherto, the wave transmission circuit comprises a helix continuously and uniformly wound to a pitch which produces a slow wave having an axial velocity in the direction of the electron stream suitable for producing cumulative interaction between the stream and the slow wave. In the practice of the present invention, the helix circuit comprises a preliminary and a main section, uniformly wound to the necessary pitch and properly positioned in the path of the electron stream so that cumulative interaction results, and a cancellation section intermediate therewith wherein cumulative interaction is inhibited. A preferred embodiment utilizes a cancellation section in which the helix is wound to a pitch which results in the velocity of the traveling wave in the direction of the electron beam being sufficiently dissimilar to the velocity of the electron stream that there is substantially no cumulative interaction therebetween. The characteristics of this section are chosen to provide the cancellation effects described.

The invention will be better understood with reference to the following more detailed description taken in connection with the accompanying drawings forming a part thereof, in which:

Fig. 1 shows schematically an electric circuit of a kind which can be used in the practice of the invention; Figs. 1A through 1E are a series of vector diagrams illustrating at the designated points of the circuit of Fig. 1 the relative magnitude and phase of the noise wave components characteristic of traveling wave tube operation; and

Figs. 1F, 1G, 1H, 1J and 1K, respectively show the corresponding components of a signal wave;

Figs. 2 and 3 show, in schematic form, respectively, a traveling wave tube and a magnetron amplifier in each of which there is incorporated a helix-type circuit which has been modified for the practice of the invention;

Figs. 4A through 4D show, in schematic form, various modifications possible with helix-type circuits to inhibit cumulative interaction between the electromagnetic wave and the electron stream for the practice of the invention;

Fig. 5 shows in schematic form a filter type traveling wave tube which can be adapted for the practice of the invention; and

Figs. 6A through 6D show various modifications possible for adapting a filter type circuit for the practice of the invention.

Before describing specifically illustrative embodiments of the invention, it will be helpful first to analyze in a qualitative sense the principles underlying the invention. In this analysis reference will be made to Fig. 1 and its associated vector diagrams, Figs. 1A to 1K, inclusive.

The circuit **10**, which for purposes of exposition is shown as a helix, comprises a preliminary section **11** which is adapted to provide cumulative interaction between the traveling wave and the electron stream, an intermediate cancellation section **12** which is adapted to inhibit cumulative interaction so that it serves as a drift section, and a main section **13** which is also adapted for cumulative interaction. An electron gun (not shown in Fig. 1 but shown in Figs. 2 and 3) provides an electron stream which flows parallel to the axis of the helix in coupled relation therewith. For traveling wave tube operation, the circuit is immersed in a longitudinal magnetic field. In such an arrangement, the total electric field is composed of two parts; one is associated with carrying radio frequency power along the circuit and is strong near the circuit and the other part results from local space charge within the beam and is strong near the beam.

In the more quantitative analysis which will be set forth with reference to Fig. 2, both fields are accounted for, but in the qualitative discussion which follows here, it will be sufficient to discuss only the power carrying component of the field. At the input to the circuit **10**, point a, there is a certain noise velocity v_{na} and a given noise current q_{na} (the noise current and velocity being entirely correlated with one another). Due to the noise current and velocity, there are excited on the circuit three noise components of electric field as illustrated in Fig. 1A. Here E_{1a} represents the field component of the increasing wave, E_{2a} the field component of the decreasing wave, and E_{3a} the field component of the unattenuated wave. Since the resultant noise field at point a is zero, the three waves are necessarily out of phase. Moving down the electric circuit at the direct-current velocity of the electron stream, the three electric field vectors rotate in phase and change in magnitude. At point b between the preliminary section **11** and cancellation section **12**, the three components will be as shown in Fig. 1B. Since section **12** acts as a drift section, the three waves designated E_{1b}, E_{2b}, and E_{3b}, corresponding to the waves E_{1a}, E_{2a}, E_{3a}, respectively, can be represented by their sum at that point E_{Tb}. This wave will be propagated through section **12**, being attenuated by the factor α, and having its phase shifted through the angle θ_3 with respect to a frame of reference moving with electron stream. Therefore, at point c, which is the end of section **12** and the start of the main section **13**, the electric field E_{Tc} resulting from the noise wave set up at point a will be given by the expression

$$E_{Tc}=\alpha|\theta_3 E_{Tb}$$

At point c cumulative interaction reoccurs and hence the electric field E_{Tc} may be represented as the three waves E_{1c}, E_{2c}, and E_{3c}, as shown in Fig. 1C, in phase with the field E_{TC}. Additionally, at point c the noise current q_{nc} and noise velocity v_{nc} in the electron stream there set up three additional waves E'_{1c}, E'_{c2}, and E'_{3c}, of which the first is the increasing wave, the second the decreasing wave and the third is the unattenuated wave. These are shown in Fig. 1D and again the sum of these three waves is zero since the noise electric field at this point resulting from noise velocity and noise current is zero. For optimum realization of the advantages of the invention, the attenuation α and phase shift θ must be chosen so that the increasing wave component E_{1c} of the wave E_{TC} is equal and opposite to the increasing wave component E'_{1c} of the electric field set up by the noise current and velocity in the stream as shown in Fig. 1E. In practice, in order to realize cancellation it may also be necessary to adjust parameters characteristic of the electron gun and preliminary region of the electric circuit. This will be made evident in the quantitative analysis to follow. Finally, it is important to make the length of the main section **13** beyond the point c of sufficient length so that only the single increasing wave is of importance.

The vector diagrams of Figs. 1F through 1K correspond respectively, to the diagrams of Figs. 1A through 1E which are used to illustrate that noise cancellation can be effected without appreciable disturbance of the amplification of the input signal. The basic factor that makes noise cancellation independent of signal amplification is the dissimilarity in input boundary conditions between the noise and signal waves. At point a, the electric field resulting from the signal wave is necessarily equal thereto while signal velocity and current components have not yet been set up in the electron stream. This is in contrast with the input noise conditions which include noise velocity and current components in the electron stream but no noise field. Consequently, it can be appreciated that ordinarily the signal field and the signal velocity and current components in the stream at point c will be unrelated to the corresponding noise components. Accordingly, since a point of cancellation for a given electric circuit can only occur for particular relationships between the several input components of electric field, if this point is chosen to cancel the noise, it will not ordinarily cancel the signal.

It may be convenient to think of the preliminary section and intermediate noise cancellation section as integral parts of the electron gun stream source independent of the input signal source since it is possible to insert the input signal wave at a point further along in the electric circuit, as, for example, at the start of the main section. However, when the input signal is inserted at a point other than the input end of the electric circuit, measures should be taken to insure that this signal will be propagated through the circuit only in the direction of electron stream flow.

It can be appreciated that these principles of noise cancellation are applicable to other devices, as, for example the magnetron amplifier, which similarly utilizes the cumulative interaction between an electron stream and an electromagnetic wave. It is characteristic of such devices that cumulative interaction may be represented as setting up a plurality of waves at the origin of such interaction. In the magnetron amplifier, there are set up two principal waves of which one is an increasing wave in the manner of the traveling wave tube. To reduce the effect of noise variations in the electron stream in these devices, there can be obtained cancellation of this increasing wave in accordance with the principles set forth for the traveling wave tube.

Fig. 2 shows, in schematic form, a helix-type traveling wave tube in which there is incorporated a noise cancellation section of the kind described with reference to Fig. 1. The traveling wave tube **100** utilizes a slow wave electric interaction circuit **10** along which is transmitted an electromagnetic wave supplied from an input source at

point a at the input or upstream end of the circuit. It will be convenient to use the terms "upstream" and "downstream" to denote relative separation from the electron source. An electron gun structure **20** positioned beyond the input end of the circuit projects an electron stream therethrough parallel to the circuit axis and in the direction of wave propagation. The electron gun is characterized by a direct-current transit angle θ_1 between its cathode **21** and anode **22**. The anode **22** is separated from the input end of the circuit, point a, by a direct-current transit angle θ_2. At the opposite end of the electric circuit, the electromagnetic wave is supplied to an output wave circuit for utilization. Beyond the output end of the electric circuit, there is positioned a collector anode **17** in target relation to the electron stream source. To insure alignment of the electron flow, the solenoid **25** provides the longitudinal magnet field B.

As is well known, if the electron velocity supplied by the electron stream source is adjusted to be substantially the same as the wave velocity in the electric circuit in the absence of the electron stream, the presence of and interaction with the electron stream produces amplification of the electromagnetic wave propagated in the electric circuit in the direction of electron motion. In helix-type traveling wave tubes known hitherto, the electric interaction circuit has comprised a helix which, with the possible exception of modifications at the terminals for broad-band matching purposes, as, for example, tapering the pitch, has been substantially uniformly and continuously wound to a pitch which sought to achieve cumulative interaction between the electron stream and the traveling electromagnetic wave along the entire length of the helix. However, in accordance with the invention, the electric circuit shown in the tube of Fig. 2 as discussed with reference to Fig. 1, comprises a relatively short preliminary amplifier section **11** and a relatively longer main amplifier section **13** in which the helix is uniformly wound to provide cumulative interaction therealong, and a relatively shorter intermediate cancellation section **12** connected therebetween from point b to point c in which the uniformity of the helix is changed sufficiently so that there is no cumulative interaction between the electron stream and the traveling wave. Such an interaction circuit can be described as one having a relatively short preliminary section **11** and a relatively long main section **13** of both of which the retardation characteristic is suited for cumulative interaction between the traveling wave and stream and a relatively short intermediate section **12** where the retardation characteristic is unsuited for cumulative interaction between the traveling wave and stream. This uniformity can be changed either by varying the pitch to disturb the synchronization between the traveling wave and electron stream necessary for cumulative interaction and/or by displacement of this section of the helix to negative coupling between the stream and traveling wave. It is a characteristic of such an electric circuit that by suitable positioning and design, this intermediate section can be utilized to effect substantial cancellation of spurious noise components in the traveling wave arising from noise fluctuations in the electron stream. More particularly, if the electrical length of the wave propagation circuit in the cancellation or intermediate section is made to differ from the electrical length of the stream path in the cancellation section by a sufficient amount, the noise components of the wave on the wave propagation circuit will be approximately 180° out of phase with the noise wave induced on the main section by the electron stream and substantial cancellation of the noise wave results.

It may be helpful to analyze the noise cancellation scheme of the present invention in a more quantitative fashion for the case of a traveling wave tube of the kind illustrated in Fig. 2. The theoretical noise figure for a conventional traveling wave tube has already been evaluated for the case where the space charge effects may be ignored in the region beyond the anode of the electron gun of the stream source by J. R. Pierce and is set forth on pages 145–156 of his book entitled "Traveling Wave Tubes," published in 1950 by D. Van Nostrand Company, Inc., New York.

In the present analysis the space charge effect will be considered, although partition effects introduced by the tube elements will be ignored, and so the analysis is begun with the expressions obtained by Pierce (supra) for the noise current and velocity at the anode, namely

$$v_{anode} = -v_n e^{-\theta_1} \quad (1)$$

$$q_{anode} = -j\frac{I\theta_1}{u_0} v_n e^{-\theta_1} \quad (2)$$

where

$$\frac{2}{v_n} = (4-\Pi) n \frac{kTc}{I_0} B \quad (3)$$

and

v_{anode}=noise velocity at the anode
q_{anode}=noise at the anode
v_n=root mean square of the thermal velocity fluctuations at the potential minimum just off the cathode surface
I_0=average beam current
u_0=average velocity of the electrons at the anode
θ_1=direct-current transit angle from cathode to anode
T_c=temperature of cathode in degrees Kelvin
k=Boltzmann's constant
B=noise band width of the receiving system

Equations 1 and 2 express the input boundary conditions for the drift region between the anode of the gun and the input of the electric circuit. In such a drift region the alternating current phenomena is characterized by two space charge waves which propagate as

$$e^{j\omega t - j\beta z \pm \delta z} \quad (4)$$

where

$\delta = j\beta\sqrt{4QC^3}$
$4QC^3$=the space charge parameter of the beam defined by Pierce (supra)
$\beta = \omega/u_0$, and
z=the distance along the circuit in the direction of electron flow

The electric field associated with each of the space charge waves has been evaluated in terms of the velocity and current as expressed by the relations

$$v = \frac{\eta}{u_0} E/\delta \quad (5)$$

$$q = j\frac{\beta I_0}{2u_0}\frac{E}{\delta}2 \quad (6)$$

With Equations 5 and 6 the electric field set up in each wave by the input boundary conditions of Equations 1 and 2 can be readily obtained. Equation 4 then expresses the manner in which the field propagates along the beam. With the value of the electric field at the output of the first drift region there can be utilized Equations 5 and 6 to find the noise current and velocity at the input to the circuit, point a of Fig. 2, and they can be written as

$$v_{na} = v_a\sqrt{1+\theta_1^2 4QC^3}\cos\varphi e^{-j(\theta_1+\theta_2)} \quad (7)$$

$$q_{na} = j\frac{I_0}{u_0}\frac{\alpha 1}{C} v_{na} \quad (8)$$

$$\varphi = -\theta_2\sqrt{4QC^3} + \tan^{-1}\theta_1\sqrt{4QC^3} \quad (9)$$

where

$\alpha_1 = \tan\varphi$
θ_2=direct-current transit angle from the anode to the circuit input point a

With the input boundary conditions of Equations 7 and 8 the three waves set up on the circuit can be written for the velocity

$$v_{1a} = \frac{v_n}{\text{C.D.}}[\delta_1(\delta_2-\delta_3)][(\delta_2+\delta_3)+\alpha_1(\delta_2\delta_3-4QC)] \quad (10)$$

$$v_{2a} = -\frac{v_n}{\text{C.D.}}[\delta_2(\delta_3-\delta_1)][(\delta_1+\delta_3)+\alpha_1(\delta_1\delta_3-4QC)] \quad (11)$$

$$v_{3a} = -\frac{v_n}{\text{C.D.}}[\delta_3(\delta_1-\delta_2)][(\delta_1+\delta_2)+\alpha_1(\delta_1\delta_2-4QC)] \quad (12)$$

where

$$\text{C.D.} = (\delta_1-\delta_2)(\delta_1-\delta_3)(\delta_2-\delta_3) \quad (13)$$

Incidentally, it should be pointed out that originally Pierce defined

$$\delta_n = (x_n + jy_n)\beta C$$

but later changed to the notation employed here where

$$\delta_n = x_n + jy_n$$

Also

$$q_{1a} = -j\frac{I_0}{u_0}\frac{1}{C}\frac{v_{1a}}{\delta_1} \quad (14)$$

with corresponding expressions for q_{2a} and q_{3a}.

Also

$$E_{1a} = -\frac{u_0}{\eta}\beta C\delta_1 v_{1a} \quad (15)$$

with corresponding expressions for E_{2a} and E_{3a}.

Now again note that E_{1a} represents the total field associated with the amplified wave and, as is described in an article by J. R. Pierce, entitled "Effect of Passive Modes in TW Tubes," Proceedings of Institute of Radio Engineers, volume 36, pages 993 through 997 (1948), the relation between E_{1a} and the power carrying component, E_{1p}, is

$$E_{1p} = \frac{E_{1a}}{(1+4QC(b-j\delta_1))} \quad (16)$$

Now at point b, the input to the cancellation section

$$q_{1b} = q_{1a}e^{2\pi\delta_1 CN_1} \quad (17)$$

with corresponding expression for q_{2b} and q_{3b}.

There can be written for the total components at point b

$$q_b = j\frac{I_0}{u_0}\frac{1}{C}\frac{v_n}{\text{C.D.}}A_1 \quad (18)$$

$$v_b = \frac{v_n}{\text{C.D.}}B_1 \quad (19)$$

$$E_{bp} = \frac{u_0}{\eta}\beta C\frac{v_n}{\text{C.D.}}C_1 \quad (20)$$

where

$$\begin{aligned} A_1 = {} & (\delta_2-\delta_3)[(\delta_2+\delta_3)+\alpha_1(\delta_2\delta_3-4QC)]e^{2\pi\delta_1 CN_1} \\ & +(\delta_3-\delta_1)[(\delta_1+\delta_3)+\alpha_1(\delta_1\delta_3-4QC)]e^{2\pi\delta_2 CN_1} \\ & +(\delta_1-\delta_2)[(\delta_1+\delta_2)+\alpha_1(\delta_1\delta_2-4QC)]e^{2\pi\delta_3 CN_1} \end{aligned} \quad (21)$$

$$\begin{aligned} -B_1 = {} & \delta_1(\delta_2-\delta_3)[(\delta_2+\delta_3)+\alpha_1(\delta_2\delta_3-4QC)]e^{2\pi\delta_1 CN_1} \\ & +\delta_2(\delta_3-\delta_1)[(\delta_1+\delta_3)+\alpha_1(\delta_1\delta_3-4QC)]e^{2\pi\delta_2 CN_1} \\ & +\delta_3(\delta_1-\delta_2)[(\delta_1+\delta_2)+\alpha_1(\delta_1\delta_2-4QC)]e^{2\pi\delta_3 CN_1} \end{aligned} \quad (22)$$

and

$$\begin{aligned} C_1 = {} & \frac{\delta_1^2(\mu_2-\delta_3)}{[1+4QC(b-j\delta_1)]}[(\delta_2+\delta_3)+\alpha_1(\delta_2\delta_3-4QC)]e^{2\pi\delta_1 CN_1} \\ & +\frac{\delta_2^2(\delta_3-\delta_1)}{[1+4QC(b-j\delta_2)]}[(\delta_1+\delta_3)+\alpha_1(\delta_1\delta_3-4QC)[e^{2\pi\delta_2 CN_1} \\ & +\frac{\delta_3^2(\delta_1-\delta_2)}{[1+4QC(b-j\delta_3)]}[(\delta_1+\delta_2)+\alpha_1(\delta_1\delta_2-4QC)]e^{2\pi\delta_3 CN_1} \end{aligned} \quad (23)$$

Now there can be computed the noise velocity v_c and current q_c at point "c" at the output of the cancellation section resulting from the noise components v_b and q_b.

At point "b" there can be written for the fields associated with the two space charge waves.

$$E_{Ib}=-\frac{1}{2}\beta\sqrt{4QC^3}\left[j\frac{u_0}{\eta}v_b+\beta\sqrt{4QC^3}\frac{2V_0}{j\beta I_0}q_b\right] \quad (24)$$

and

$$E_{IIb}=-\frac{1}{2}\beta\sqrt{4QC^3}\left[-j\frac{u_0}{\eta}v_b+\beta\sqrt{4QC^3}\frac{2V_0}{j\beta I_0}q_b\right] \quad (25)$$

and at point "c"

$$E_{Ic}=E_{Ib}e^{j2\pi\sqrt{4QC}CN_2} \quad (26)$$
$$=E_{Ib}e^{i\Phi}$$

where $\Phi=2\pi\sqrt{4QC}\,CN_2$

and

N_2=distance from "b" to "c" in wavelengths.

Also

$$E_{IIc}=E_{IIb}e^{-i\Phi} \quad (27)$$

and

$$v_c=-\frac{\eta}{ju_0\beta\sqrt{4QC^3}}(E_{Ic}-E_{IIc}) \quad (28)$$

$$q_c=-\frac{j\beta I_0}{2V_0\beta^2 4QC^3}(E_{Ic}+E_{IIc}) \quad (29)$$

from which

$$v_c=v_b\left[\cos\Phi+\sqrt{4QC}\frac{A_1}{B_1}\sin\Phi\right] \quad (30)$$

and

$$q_c=q_b\left[\cos\Phi-\frac{B_1}{\sqrt{4QC}A_1}\sin\Phi\right] \quad (31)$$

Consider now the electric field on the helix. At point "b" there is a field E_{bp}. This field will propagate to point "c" with slight regard for the presence of the stream and will be attenuated by the attenuation characteristics of the helix. Also, assume that the field will be shifted in phase with respect to a wave traveling at the velocity of the electron stream.

Hence, for the field on the helix at point "c" there can be written

$$E_{cp}=\alpha\underline{|\theta_3}E_{bp} \quad (32)$$

where α is less than unity and represents the attenuation between "b" and "c" and θ_3 is the phase shift of the wave with respect to a wave traveling at the velocity of the electron stream.

With v_c, q_c and E_{cp} determined, there can be derived an expression for the field excited on helix in the increasing wave.

$$E_{1np}=\sqrt{2}\frac{u_0}{\eta}\frac{v_n}{\text{C.D.}}\beta CB_1\left(\cos\Phi+\frac{\sqrt{4QC}A_1}{B_1}\sin\Phi\right)x\frac{[(\delta_2+\delta_3)+D_1(\delta_2\delta_3-4QC)+F_1]}{(1+4QC(b-j\delta_1))\left[1-\frac{\delta_3}{\delta_1}\right]\left[1-\frac{\delta_2}{\delta_1}\right]} \quad (33)$$

where

$$D_1=\frac{1}{\sqrt{4QC}}\frac{\left(\sqrt{4QC}\frac{A_1}{B_1}\cos\theta-\sin\theta\right)}{\left(\cos\Phi+\frac{B_1}{\sqrt{4QC}A_1}\sin\Phi\right)} \quad (34)$$

and

$$F_1=\frac{\alpha\underline{|\theta_3}C_1}{B_1\left(\cos\Phi+\sqrt{4QC}\frac{A_1}{B_1}\sin\Phi\right)} \quad (35)$$

Now in Equation 33 there is expressed the field set up by increasing wave on the helix output section. The cancellation scheme resolves into adjusting the pertinent parameters such that $E_{1np}=0$. Or

$$(\delta_2+\delta_3)+D_1(\delta_2\delta_3-4QC)+F_2=0 \quad (36)$$

This condition will result in a noise figure of zero decibels provided the conditions expressed by Equation 36 do not at the same time cancel the incoming radio frequency signal. By calculations similar to those just carried out, it can be shown that Equation 36 does not express the condition for signal cancellation.

In Fig. 3 there is shown schematically a magnetron amplifier **200** in which there is incorporated an electric circuit **10** of the kind described before with reference to Fig. 1. The electron stream which is supplied from the cathode **121** of the gun **120** has initially a component in a direction perpendicular to the direction of travel of the electromagnetic waves set up by the electric circuit but it is bent to the desired direction along that of wave propagation by means of a magnetic field B_T, not illustrated, which is transverse both to the wave propagation direction and to the direct-current electric field set up between the cathode **121** and electrode **122** and the electric circuit **10**. For a more detailed description of this and other forms of magnetron amplifiers, reference is made to the second-mentioned Pierce application. The principles of the invention, however, are little affected by the differences between the magnetron amplifier and traveling wave tube amplifier. As with the traveling wave tube, there is set up in the main section **13** by the noise fluctuations of the electron stream, a noise wave which includes an increasing component. In accordance with the invention, by means of the preliminary section **11** and the intermediate cancellation section **12**, there is set up in the main section another noise wave of which the increasing component is a wave equal in magnitude and opposite in phase to that of the other increasing wave whereby substantial reduction of the effect of noise fluctuations in the electron stream is realized, in the same manner described above in detail for the traveling wave tube amplifier.

It can be appreciated that there are numerous techniques which may be adapted for inhibiting the cumulative interaction between the electron stream and the electromagnetic wave for setting up a second cancelling wave and making possible thereby the practice of the present invention. In a preferred embodiment, this effect is realized by changing the axial velocity of wave propagation (i.e. retardation characteristic) in an intermediate region of the circuit. This can be done easily by modifications of the circuit geometry in the region affected. One instance of this technique has been used in the arrangement of Fig. 2 in which the pitch of the helix is changed in the cancellation section to vary the axial wave velocity. Additionally, the axial wave velocity can be changed in a particular region by varying the dielectric surrounding the circuit in that region. Conversely, cumulative interaction can be inhibited by modifying the average velocity of the electron stream in a particular region. Still another method is to displace the cancellation portion of the electric circuit sufficiently to remove its field from the region of effective coupling with the electron stream. However, it is important that the arrangement employed permit good matching between the several sections of the circuit so that reflections in the circuit are avoided.

The techniques described briefly above are all susceptible of many possible embodiments, depending on the type of amplifier and wave circuit employed. However, the same principles are generally applicable, regardless of the particular form of electric circuit employed or type of cumulative interaction operation utilized. It may be helpful to describe with some particularity, by way of illustration, a few representative embodiments, although it can be appreciated that a much larger variety is possible.

For the helix type electric circuit, the geometry may be changed in several ways to vary the axial velocity of wave propagation therethrough. As an alternative to changing the pitch with which the helix is wound as described hereinabove with reference to Fig. 2, the same result may be had by changing the radius and keeping the pitch uniform. In Fig. 4A there is shown a helix circuit **30** which comprises a preliminary section **31** and a main section **32** of a first radius and an intermediate cancellation section **33** of a larger radius to produce a decrease in axial wave velocity therethrough.

In Fig. 4B, there is shown a helix circuit **40** in which the intermediate cancellation section **42** has been displaced with respect to the preliminary section **41**, the main section **43**, and electron stream **44** to eliminate coupling with the stream. Within this section, the helix could be wound with various combinations of pitches and radii.

In Fig. 4C, there is shown a circuit **50** which is a variation of the circuit **40** of Fig. 4B. In this case, the beam within the cancellation section **52** between the preliminary section **51** and the main section **53** is surrounded by a conducting cylinder **54**. By providing a difference in direct-current potential between the cylinder and the circuit, the average velocity of the electron stream can be changed in the region of the cylinder. In this way, the average velocity of the electron stream can here be made to differ from the axial wave velocity in the electric circuit.

In Fig. 4D, there is shown an arrangement in which the axial wave velocity is modified by changes in the dielectric surrounding a particular section. To this end, dielectric **64** is added in the intermediate region **62** between the preliminary section **61** and the main section **63** in the helix circuit **60** to slow the velocity of wave propagation therethrough.

In addition to helix-type circuits, another common class of slow wave circuits is composed of wave-guiding structures generally known as of the filter type. Fig. 5 shows, in schematic form, a traveling wave tube **300** which employs a filter type circuit. An electron stream is projected from an electron gun **311** at one end of the tube to a collector electrode **312** at the opposite end of the tube. An electromagnetic wave is supplied for coupling to the electron stream by means of a wave-guiding circuit **313** which comprises a conductor having a series of lateral slots along the path of the stream. Wave energy is supplied as an input at one end of the circuit and derived for utilization at the opposite end. In operation this tube acts in the manner of a helix-type traveling wave tube. A more detailed explanation of the use of filter type circuits in traveling wave tubes may be found in the first-mentioned Pierce application. Also for the use of filter type circuits in magnetron amplifiers reference is made to the later-mentioned Pierce application.

It is well known, however, that such filter type tubes are merely modifications of the helix-type counterpart in which the helix slow wave circuit has been replaced by another form of slow wave structure. The techniques described above with reference to helix-type circuits for setting up a combination noise wave in accordance with the invention have their counterparts in the filter type circuits.

In Figs. 6A through 6D, there are shown illustrative arrangements for cancellation adapted to one typical circuit of the filter type. This particular circuit is a wave-guiding structure made up of a conductor **70** having a series of lateral slots **77** of the kind shown in the tube of Fig. 5. With such a circuit, one expedient for changing the wave velocity in the direction of the electron stream in a particular section, to make possible the practice of the invention, is to vary the geometry. In the circuit shown in Fig. 6A, the spacings between slots in the intermediate cancellation section **72** between the preliminary and main sections **71** and **73** is varied to achieve the desired effect.

In the arrangement of Fig. 6B, cumulative interaction is inhibited by displacing the cancellation section **82** between the preliminary section **81** and main section **82** to limit coupling with the electron stream.

In the arrangement of Fig. 6D, the cumulative interaction is inhibited by varying the velocity of the electron stream in the region of noise cancellation. To this end, the cancellation section **92** of the electric circuit **90** is insulated from the preliminary and main sections **91** and **93**, respectively, by insulating strip **94**. Additionally, it is operated at a direct-current potential different from that of the remainder of the circuit by means of source **95**, thereby providing a different accelerating voltage for the electron stream within the cancellation section, whereby a new average velocity results.

Fig. 6C shows another arrangement for varying the wave propagation velocity. In this instance, the slots **97** in the cancellation section **102** between the preliminary and main sections **101** and **103**, respectively, are filled with a dielectric to slow the wave velocity therethrough.

In all of the foregoing embodiments it will be readily apparent to one skilled in the art that cancellation is achieved by a variation in the electrical length of the wave propagation circuit in the cancellation section relative to the electrical length of the electron stream in the cancellation section by an amount sufficient to bring about a phase shift of approximately 180° between the first induced noise wave in the wave propagation circuit and the noise wave induced in the main section.

It should be apparent at this point that the above-described arrangements are merely a few of those available. Numerous other arrangements can be devised by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a device which utilizes the cumulative interaction between an electron stream and electromagnetic waves to secure gain, a source supplying an electron stream characterized by noise fluctuations about an average velocity, and a continuous wave propagation circuit having a preliminary section positioned in the path of said electron stream and having a retardation characteristic for slowing the velocity in the direction of the electron stream of waves traveling therethrough to substantially the average velocity of the electron stream thereby inducing a first growing noise wave in said section which is in cumulative interaction with the electron stream, signal input means at the upstream end of said section for introducing signal waves on to said section for interaction with the electron stream, said wave propagation circuit further having a main section positioned in the path of the electron stream downstream of said preliminary section and having a retardation characteristic for slowing the velocity in the direction of the electron stream of waves traveling therethrough to substantially the average velocity of the electron stream thereby inducing a second noise wave which is in cumulative interaction with the electron stream, signal output means at the downstream end of said main section, said wave propagation circuit further having an intermediate section between said preliminary and said main sections defining a region of substantial noninteraction between the electron stream and waves traveling along said section, the electrical length of the noninteraction region relative to noise fluctuations on said electron stream differing from the electrical length of the section relative to the growing noise wave on said section such that at the main section the first noise wave includes a mode of propagation which is an increasing wave equal in magnitude and opposite in phase to the

increasing wave which is a mode of propagation of the second noise wave.

2. A device according to claim 1 in which the intermediate wave circuit section is positioned so that the electric fields in the direction of electron flow of waves propagating therethrough are substantially negligible along the path of the electron stream.

3. A device according to claim 1 in which the intermediate wave circuit section is adapted for providing a wave propagation of velocity of waves traveling therealong substantially different from the average velocity of the electron stream therealong.

4. A device according to claim 1 which includes voltage supply means for changing the average velocity of the stream along the intermediate wave circuit section.

5. In an electron discharge device utilizing the interaction between an electron stream and an electromagnetic wave, in combination an electron stream source and a collector defining a path of electron flow, said stream being characterized by noise fluctuations about its average velocity, a continuous wave propagation circuit, signal input means and signal output means connected to the upstream and downstream ends respectively of said circuit, said circuit having a first section adjacent its upstream end defining an interaction region with said stream for inducing a first growing noise wave on said first section, a second section located downstream of said first section and defining an interaction region with said stream for inducing a noise wave on said second section, and means for canceling the noise wave induced on said second section comprising a third section between said first and second sections defining a region of substantial noninteraction with said stream, said third section being adapted to shift the phase relationship of the noise wave induced on said first section and the noise fluctuations in the stream.

6. In an electron discharge device, the combination as claimed in claim 5 wherein the velocity of the noise waves propagated in said third section differs from the velocity of the electrons in said stream.

7. In an electron discharge device, the combination as claimed in claim 5, in further combination with voltage supply means for projecting the electron stream past said third section at a velocity which differs from the velocity of said stream as it traverses said first and second sections.

8. In an electron discharge device, the combination as claimed in claim 5, wherein the velocity of propagation characteristic of said third section of said wave propagation circuit differs from the velocity of propagation of said first and second sections.

9. In an electron discharge device, the combination as claimed in claim 5, wherein said first and second sections are adjacent said electron stream and said third section is displaced from the path of said stream.

10. An electron discharge device comprising an envelope, an electron stream source and a collector for said stream defining a path of flow within said envelope, said stream being characterized by noise fluctuations about its average velocity, a continuous wave propagation circuit within said envelope adjacent said path of flow over at least a portion of its length, signal input means for launching a wave on said wave propagation circuit, signal output means at the downstream end of said wave propagation circuit, said wave propagation circuit having a first section adjacent the upstream end thereof defining an interaction region with said stream for inducing a first growing noise wave on said first section, a second section downstream of said first section defining an interaction region with said stream for inducing a second noise wave on said second section, and means for canceling the noise wave induced on said second section comprising a third section between said first and second sections, said third section defining a drift region of substantial noninteraction between the waves propagating therealong and said stream, the electrical length of said drift region relative to the waves propagating along said third section being different than the electrical length of said drift region relative to the electron stream.

11. The combination comprising an electron beam velocity modulation tube for signals at a predermined operating frequency having an electron gun to produce a beam of electrons along a path, a signal input coupling to said path, means coupled to said path intermediate said gun and said input coupling to derive a beam noise voltage, and a signal path including only passive elements and none other between said intermediate means and said input coupling to apply noise voltage to said input coupling, the path length differences between said signal path and said beam path from the means coupling and the input coupling being selected to provide at least some compensation by signals substantially in phase opposition at said operating frequency for signal to noise ratio at the output.

12. The combination comprising an electron beam tube for signals at a predetermined operating frequency having an electron gun to produce a beam of electrons along a path, an input coupling to said tube at a signal input coupling region along the beam path, an output coupling to said tube at a region along said beam path more remote from said gun than said input coupling region, means between said gun and said input coupling region to derive a beam noise voltage, and a signal path including only passive elements to apply said noise voltage at said input voltage region, said signal path being otherwise decoupled from the beam path, the path length difference between said signal path and said beam path from said noise voltage deriving means to said input region being a selected difference to provide signals substantially in phase opposition at said operating frequency whereby an improvement in signal to noise ratio at the output is secured in tube operation at the operating frequency.

13. The combination claimed in claim 12, said means to derive a beam noise voltage including a travelling wave helix having a voltage wave velocity substantially equal to the velocity of said electron beam adjacent to and in signal coupling relation with said beam path.

14. The combination claimed in claim 12, said tube including a travelling wave helix between said input and output couplings adjacent to and in coupling relation with said beam path to provide signal amplification.

15. The combination claimed in claim 12, said signal path including a helix adjacent the beam path but not coupled thereto, having a voltage wave velocity at a selected operating frequency substantially different from the beam velocity and intermediate said first mentioned helix and said input coupling.

16. The combination claimed in claim 13, further comprising a drift tube through which the beam path passes and intermediate said helix and said input coupling region.

17. The combination claimed in claim 12, said means comprising a helix adjacent to and in coupling relation with said beam path, and positioned intermediate said gun and said input coupling region, said signal path comprising a further helix adjacent said beam but in noncoupling relation thereto and having at least a portion of substantially different pitch from that of said first helix, said further helix being positioned intermediate said first helix and said input coupling region.

18. The combination claimed in claim 12, further comprising a drift tube through which the beam path passes and intermediate said gun and said input coupling region.

19. The combination comprising an amplifier having means to provide a beam of electrons along a path, beam velocity modulating means including an input coupling to the beam path and an output coupling to the beam path, whereby signals of a predetermined operating frequency applied to said input coupling may be amplified and made available at said output coupling, means between said beam providing means and said input cou-

pling to derive a noise voltage from said beam, a passive signal path to feed said noise voltage forward to said input coupling and otherwise decoupled from said beam path, the path lengths from the noise voltage deriving means to said input coupling being related to provide at said input coupling noise signals substantially in phase opposition at said operating frequency from said signal path for beam noise fluctuation compensation.

20. An electron beam device comprising: electron gun means for producing an electron beam along a path and containing noise fluctuations; input means, coupled to said path, for modulating said beam in accordance with an input signal at a predetermined operating frequency; means coupled to said path between said electron gun means and said input means, for extracting a noise voltage from said beam; and signal transmission means, coupled between said voltage extracting means and said input means, for applying said noise voltage to said beam at said input means substantially 180° out of phase at said operating frequency with the noise fluctuations present in said beam at that point, whereby the effect of said noise fluctuations on the operation of said device is minimized.

21. An electron beam velocity modulation device for operation at a predetermined frequency comprising: electron gun means for producing an electron beam along a path and containing noise fluctuations; input means, coupled to said path, for velocity modulating said beam in accordance with an input signal of said frequency; output means coupled to said path beyond said input means; means, coupled to said path between said electron gun means and said input means, for extracting a noise voltage from said beam; and signal transmission means, coupled between said voltage extracting means and said input means, for applying said noise voltage to said beam at said input means substantially in phase opposition at said frequency with the noise fluctuations present in said beam at said input means, whereby the effect of said noise fluctuations on the operation of said device is minimized.

22. A device as in claim 21, wherein all of the elements recited are contained within an evacuated envelope.

23. In an electron discharge device utilizing the interaction between an electron stream and an electromagnetic wave, in combination, an electron stream source and a collector defining a path of flow for the electron stream, a continuous circuit extending along the path of flow for a major portion of the length thereof for propagating electromagnetic waves adjacent the path of flow, said circuit having input and output coupling means at the ends thereof, said circuit comprising a coiled helical conductor having a first section adjacent the input coupling means of a helix pitch such that electromagnetic waves on said section are in coupling relationship with the electron beam, a second section adjacent the output coupling means of a helix pitch such that electromagnetic waves on said section are in coupling relationship with said electron beam, said first and second helix sections having substantially the same helix diameter, and an intermediate section between said first and second sections having the same helix diameter as said first and second sections but having a helix pitch differing from those of the first and second sections such that electromagnetic waves on said section are decoupled from said electron beam.

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