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3,087,119

NOISE REDUCTION SYSTEM FOR PARAMETRIC AMPLIFIERS

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FIG. 1

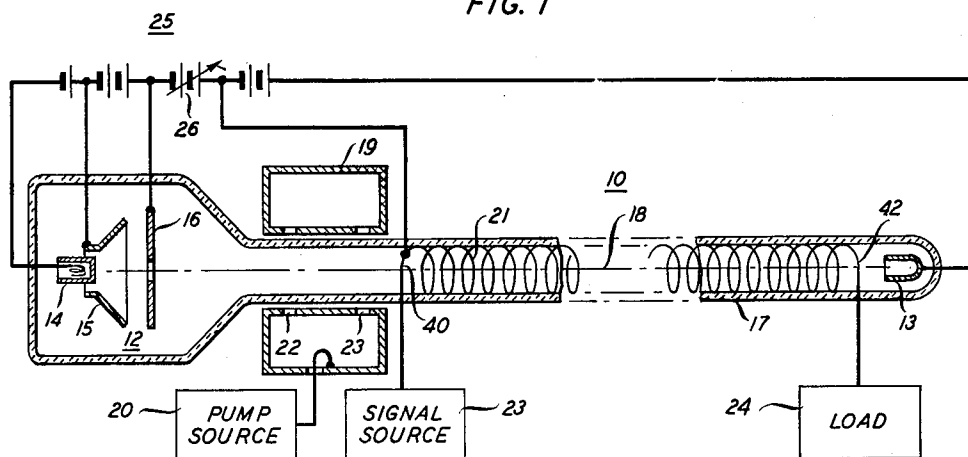


FIG. 2

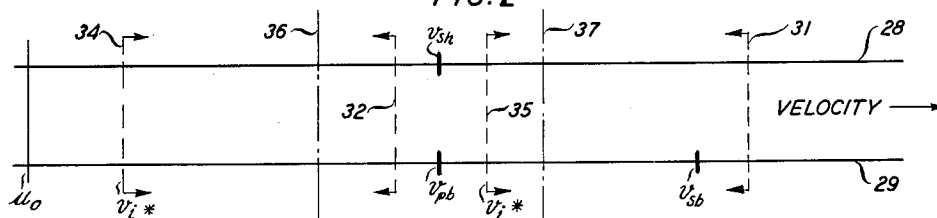


FIG. 4

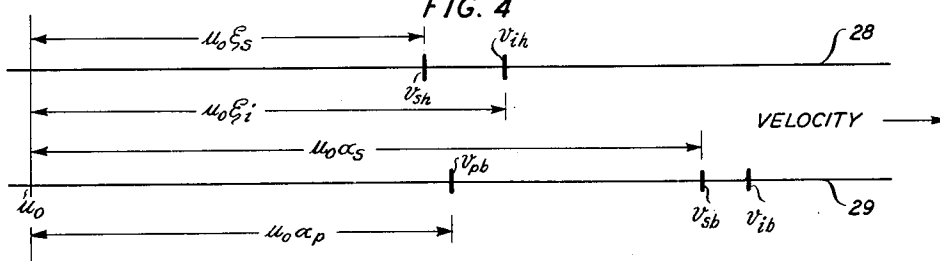
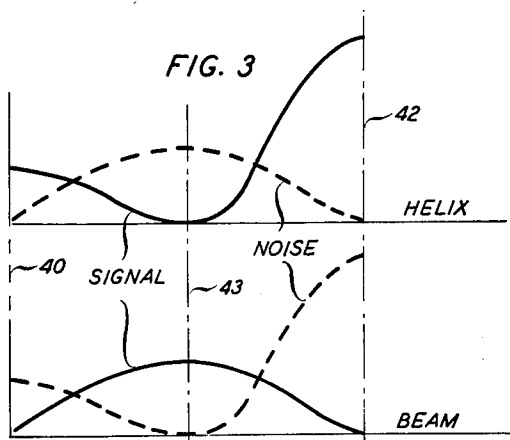


FIG. 3



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3,087,119 NOISE REDUCTION SYSTEM FOR PARAMETRIC AMPLIFIERS

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5 Claims. (Cl. 330-4.7)

This invention relates to high frequency electron discharge devices and more particularly to noise reduction in velocity modulation devices which utilize the principles of parametric amplification.

Velocity modulation devices such as the traveling wave tube have proven capable of amplification with reasonably high efficiency and stability over an exceedingly wide band of frequencies. Detracting from the significant advantages realized by such devices, however, is noise resulting from the utilization of an electron beam. In the conventional traveling wave tube six decibels is the theoretical minimum noise figure, as is established in an article entitled "The Minimum Noise Figure of Microwave Beam Amplifiers," by H. A. Haus and F. N. H. Robinson, Proceedings of The Institute of Radio Engineers, volume 43, pages 981-991, August 1955. Further discussion as to how this minimum noise figure may be reduced and indeed be made to approach zero, requires a brief discussion of the nature of an electron beam.

Because a beam transmits space charge waves much the same way as a transmission line transmits electromagnetic waves, and because the kinetic energy of the beam particles is an important consideration in beam analysis, the electron beam may be considered as being an electromechanical transmission line. Any modulation frequency or space charge wave which inherently exists on the beam or is introduced onto the beam from some outside source may propagate along the beam at either of at least two possible phase velocities. From this standpoint the electron beam is analogous to a wave guide transmission line which may transmit a wave of a particular frequency at any of a plurality of phase velocities, depending upon the mode at which it propagates. It can be shown that the faster of these two phase velocities at any given frequency is higher than the average or D.-C. velocity of the unmodulated beam, whereas the slower phase velocity is less than the beam's D.-C. velocity. Another characteristic of the beam is that it is dispersive. We therefore find that the entire frequency spectrum of waves which may propagate along the beam represents at least two spectra of possible phase velocities, one existing above and one existing below the D.-C. velocity of the beam. The spectrum of phase velocities which represents possible space charge wave propagation at a velocity higher than the D.-C. velocity is usually referred to as the fast space charge mode, while the spectrum of phase velocities which represents wave propagation at a velocity lower than the D.-C. velocity is referred to as the slow space charge mode.

A conventional traveling wave tube effects amplification of an electromagnetic wave through interaction with the slow space charge mode of an electron beam. The unique characteristic of the slow space charge mode which permits wave amplification is, however, disadvantageous in that spurious noise power which is inherent on the beam cannot be extracted. Because kinetic power is proportional to velocity, any power transmitted in a slow space charge mode is negative with respect to the unmodulated D.-C. power of the beam. This means that in order to compensate for noise power in the slow mode, or, in other words, spurious noise power fluctuations below the

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level of the D.-C. beam power, one would have to add power to the beam at the proper phase, frequency and amplitude relationship to the noise power components. Since the inherent noise waves are produced by such unpredictable as random emission, the impracticability of such a method is obvious. In a conventional traveling wave tube one is therefore, in general, limited to methods of reducing noise power in the region adjacent to the electron gun. These methods of reducing slow space charge mode noise power are limited, in general, by the minimum noise figure mentioned previously.

In the patent of C. F. Quate, No. 2,974,252, granted March 7, 1961, there is disclosed a completely different approach to the problem of reducing noise in a beam type device. By making use of the principles of parametric amplification, the disclosed device effects interaction between a signal and the beam's fast space charge mode thereby achieving desired amplification of the signal. Because the fast mode noise power is at a higher level than the D.-C. power, it can be extracted from the beam through any of a number of well-known devices.

Although various forms of beam type parametric amplifiers have achieved electromagnetic wave amplification with noise figures of less than six decibels, a zero decibel noise figure has not yet been realized. This is due to various second order effects, some of which have been isolated and others of which are still under study. For example, it is very difficult, if not impossible, to "strip" completely all of the deleterious fast mode noise power from the beam. For reasons of compactness and economy, it is usually desirable to combine the input section and the noise stripping apparatus into a single unit. However, when this is done, no provision is made for removing "input" noise which is introduced on the beam at the input section by crosscoupling. Further, the mixing of the pump and signal waves generates an "idler" wave of a frequency equal to the difference of frequencies of the pump and signal waves. Noise existing at this idler frequency must be stripped from the beam since the idler wave also couples with the signal wave. Therefore, the band of noise frequencies which must be stripped from the beam is often so wide as to require a plurality of stripping devices, thereby further complicating tube structure.

Accordingly, it is an object of this invention to eliminate the effects of noise power existing on an electron beam of a velocity modulation device.

It is another object of this device to obviate the necessity of noise stripping apparatus in a velocity modulation device of the parametric amplifier type.

These and other objects of the present invention are attained in one illustrative embodiment thereof which comprises an electron discharge device having an evacuated envelope with an electron gun therein for forming and projecting an electron beam along an extended path. A slow wave circuit such as a helix is positioned along the path of flow for propagating signal energy in interacting relationship with the fast space charge mode of the beam. A device is also positioned along the electron beam path for modulating the electron beam with "pump" energy which is at a frequency higher than the signal frequency. As signal energy is transferred from the slow wave circuit to the beam, it "mixes" with the pump energy which is traveling thereon and becomes parametrically amplified, as generally described in the aforementioned Quate application. Subsequently, the amplified signal energy is transferred back to the slow wave circuit where it is thereafter transmitted to an appropriate load.

In beam type parametric amplifiers such as that disclosed in the aforementioned Quate application, it has generally been understood that space charge waves at the

pump, signal and idler frequencies and various noise waves at these and other frequencies couple together to form a single growing wave. In order to prevent the undesirable coupling of noise waves to the signal wave, noise stripping apparatus is included as previously mentioned. We have found that, under certain conditions, two growing waves may be induced on an electron beam. These growing waves can be made to "beat" together in such a way that the signal energy can be removed from the beam while leaving substantially all of the inherent beam noise energy on the beam. In accordance with one aspect of this invention, there are, therefore, induced two growing waves on the electron beam of a beam type parametric amplifier.

In accordance with another aspect of this invention, these two growing waves propagate at different phase velocities but grow at the same rate. Under these conditions noise energy and signal energy can be made to be alternately transferred between the beam and the slow wave circuit which is properly coupled thereto. In other words, at some given distance along the beam signal energy will exist substantially completely on the slow wave circuit while noise energy exists substantially completely on the beam. At this point the signal wave can be removed from the slow wave circuit with substantially no noise content included therewith. In order that these conditions be fulfilled it is necessary that the slow wave circuit have a number of specific characteristics with respect to the beam.

It is a feature of this invention that the slow wave circuit have such propagation characteristics that an uncoupled electromagnetic wave of the signal frequency traveling thereon has a phase velocity which is a predetermined function of the phase velocities of uncoupled fast space charge waves propagating along the beam, respectively, at the signal, pump and idler frequencies and also a predetermined function of the ratio of the signal frequency to the idler frequency.

It is another feature of this invention that the slow wave circuit have such propagation characteristics that an uncoupled electromagnetic wave traveling thereon at the idler frequency have a phase velocity which is a predetermined function of the phase velocity of an uncoupled fast space charge wave of the pump frequency propagating along the beam, the phase velocity of an uncoupled electromagnetic wave of the signal frequency traveling on the slow wave circuit and the ratio of the signal frequency to the idler frequency.

It is still another feature of this invention that the ratio of the signal frequency to the idler frequency be a predetermined function of the gain parameter and the space charge parameter of the device.

It is yet another feature of this invention that the fraction of the beam current modulation at the pump frequency be a predetermined function of the following: the phase velocity of an uncoupled electromagnetic wave of the signal frequency traveling on the slow wave circuit; the phase velocities, respectively, of uncoupled fast space charge waves of the signal, idler, and pump frequencies propagating along the beam; the ratio of the signal frequency to the idler frequency; the gain parameter at the signal frequency; the space charge parameter at the signal frequency.

It is still another feature of this invention that the electromagnetic signal wave be extracted from the slow wave structure at a point at which substantially all of the signal has been transferred to the slow wave circuit and substantially all of the beam noise energy has been retransferred to the beam.

These and other features of this invention will be understood more fully from the following detailed description taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a schematic view of one illustrative embodiment of this invention;

FIG. 2 is a graph illustrating the correlation of the velocity spectra which may exist, respectively, on the slow wave circuit and electron beam of a device of the type shown in FIG. 1;

FIG. 3 is a graph illustrating the transfer of energy which may take place between the slow wave circuit and the electron beam of a device of the type shown in FIG. 1; and

FIG. 4 is a graph, similar to that of FIG. 2, illustrating other correlations of the velocity spectra which may exist, respectively, on the slow wave circuit and electron beam of a device of the type shown in FIG. 1.

Referring now to the drawing, the specific illustrative embodiment depicted in FIG. 1 comprises a traveling wave tube 10 having an electron gun 12 and a collector 13 at opposite ends thereof. For purposes of illustration, electron gun 12 is shown as comprising a cathode 14, a beam forming electrode 15, and an accelerating electrode 16, which jointly coax to form and project an electron beam, schematically shown as 18, toward the collector 13. Battery 25 maintains the various electrodes at proper potentials as is well known in the art. A vacuum is maintained within tube 10 by an envelope 17. Suitable means for focusing the electron beam are used. Such focusing means are well known in the art and are not shown for purposes of simplicity.

Electron beam 18 is characterized by two modes of propagation at any given frequency: a fast velocity space charge mode and a slow velocity space charge mode, hereinafter referred to respectively as the fast mode and the slow mode. Another characteristic of the beam is its dispersion, that is, the phase velocity of any wave propagating thereon will vary with frequency. As is well known, waves which propagate in the fast mode have a higher phase velocity than the mean, or D.C., velocity of the beam, while those propagating in the slow mode are of a lower phase velocity. Also characteristic of the beam are its inherent current density fluctuations. These fluctuations give rise to spurious space charge waves, hereinafter referred to as noise waves, which propagate at virtually all frequencies in both the fast and slow modes.

Downstream from the electron gun 12, that is, a point closer than the electron gun to the collector, is a cavity resonator 19 which surrounds a portion of the envelope. Resonator 19 is excited by electromagnetic wave energy from pump source 20. Re-entrant portions 22 and 23 are positioned to produce synchronism between the pump wave and the fast mode of beam 18. Resonator 19 thereby modulates the beam in the fast mode and causes the pump energy to propagate along the beam as a fast space charge wave.

Downstream from resonator 19 there extends a conductive helix 21 which serves to propagate an electromagnetic wave from signal source 23. Helix 21 is also biased positively with respect to cathode 14 by variable bias 26 of battery 25. By adjusting the D.C.- bias on helix 21, one can thereby adjust the mean velocity of the beam flowing therethrough as is well known in the art. Signal energy on the helix is transferred to the beam where it mixes with fast mode pump energy and thereby becomes parametrically amplified, as will be described presently. After being amplified, the signal energy is transmitted to an appropriate load 24. It is to be understood that both resonator 19 and helix 21 are only illustrative of numerous devices which could be used for desired beam modulation. For example, resonator 19 could be replaced by a Kompfner-Dip helix, while helix 21 could be replaced by any of numerous well-known slow wave circuits.

In the patent of Ashkin et al. No. 2,958,001, granted October 25, 1960, parametric amplification is analyzed from the "coupled mode" point of view. This method of analysis is useful in gaining a physical understanding of the rather complicated phenomenon of beam type

parametric amplification. As is pointed out therein, an electron beam can be considered as being an electro-mechanical transmission line. As such, other transmission lines can be coupled thereto by the familiar processes of inductive or electric coupling. This "ordinary" coupling will be referred to as passive coupling. In addition, however, two waves may also couple together in such a way as to produce growth, or amplification, of the coupled wave. This "extraordinary" coupling is referred to as active coupling. Active coupling between the slow mode and forward circuit mode is the unique phenomenon which produces amplification in a conventional traveling wave tube. Active coupling in the fast mode can be induced only by the use of beam parameter variations as are induced by a pump frequency wave. The mixing of the signal wave with the higher frequency pump wave results in the production of an idler wave having a frequency equal to the difference of the frequencies of the pump and signal waves. Under certain conditions active coupling can be induced between the fast mode signal wave and the fast mode idler wave, thereby producing growth of the coupled wave.

When waves on two dispersive transmission lines are coupled passively, the coupled wave will propagate at some new phase velocity which is different than the phase velocity of either of the uncoupled waves. If the two transmission lines each propagate in only one mode, it can be shown that the coupled wave will propagate at a velocity which is higher than either of the independent uncoupled waves, or at a velocity which is lower than either of the uncoupled waves, depending upon the additive or subtractive effect of mutual inductance or mutual capacitance. In the case of an electron beam, this coupling action is somewhat more complicated due to the presence of both fast and slow space charge modes. However, for purposes of this discussion, only fast mode beam propagation will be considered, and the effects of the slow mode will be neglected.

In terms of phase velocity, active coupling produces different results than passive coupling. When two waves are actively coupled, the coupled wave propagates at some velocity which is intermediate the velocities of the two uncoupled waves. Active coupling can therefore be represented as the merger, in terms of phase velocity, of two waves. In the aforementioned application of Ashkin et al., it was shown how two space charge waves can actively couple to produce a growing wave. We have found that, under certain conditions, two growing waves may be produced. If these two waves grow at the same rate and propagate at slightly different velocities, the noise figure of the tube can appreciably be reduced, as will be explained hereinafter.

FIG. 2 illustrates a method by which two growing waves can be produced in device 10. Graph 28 illustrates the spectrum of phase velocities of waves which may propagate along helix 21, while graph 29 illustrates a similar spectrum with reference to beam 18. Both graphs are one-dimensional and show increases of phase velocity from left to right as indicated by the arrow labelled "velocity." The D.-C. velocity u_0 of the electron beam is used as a reference for both graphs because all fast mode space charge waves propagate at a faster velocity than u_0 .

For purposes of simplicity, consider first the situation in which the pump frequency ω_p is twice the signal frequency ω_s . In this case the idler frequency ω_i will be equal to the signal frequency ($\omega_i = \omega_p - \omega_s$). The uncoupled phase velocity of the pump wave ω_p is shown on graph 29 by v_{pb} , the subscript b being included to indicate beam propagation. Because of the dispersive nature of the beam, uncoupled space charge waves of the signal frequency ω_s will propagate along the beam at a higher velocity v_{sb} .

Consider the signal wave as traveling along the helix at a velocity v_{sh} which is equal to v_{pb} . The signal wave

on the helix is not quite in synchronism with the fast space charge mode velocity v_{sb} , but it is close enough to synchronism to permit fairly strong passive coupling to the beam. When the signal wave on the helix couples with the fast mode of the beam, two normal modes 31 and 32 are produced. The lines representing the velocities of these normal modes extend through both graphs 28 and 29 to indicate that signal energy propagates at these velocities on the coupled system, that is, on both the helix and the beam.

Since the idler frequency equals the signal frequency, normal modes 31 and 32 are also indicative of the coupled phase velocities of the idler wave. As is pointed out in the aforementioned Ashkin et al. application, idler frequency energy ordinarily propagates at two velocities symmetrically disposed about the pump wave velocity, one being its original velocity and the other being its "image" velocity. In the situation portrayed in FIG. 2, idler frequency energy at the velocities indicated by v_i^* is produced as images of idler energy existing at both normal modes 31 and 32. Idler energy at velocity 34 is the image wave of the idler at normal mode 31, while idler energy at velocity 35 is the image wave of the idler at normal mode 32. Note that in each case the original and image velocities are substantially equidistant from the pump velocity.

As pointed out in the aforementioned Ashkin et al. application, beam type parametric amplification is produced through active coupling between the signal wave and the idler image wave. In this case, it can be shown that signal energy at normal mode 32 couples actively with idler energy at velocity 34, while signal energy at normal mode 31 couples actively with idler energy at velocity 35. When such active coupling takes place, the two coupled waves propagate, respectively, at velocities 36 and 37. The small arrowheads on velocity lines 31 and 35 indicate that they couple together to form the wave 37, while similar arrowheads on velocity lines 32 and 34 indicate the formation of a wave at the velocity 36. The waves at velocities 36 and 37 are growing waves.

As seen from FIG. 2, two growing waves are produced which travel at different phase velocities. If these two waves grow at the same rate they will interfere with each other, thereby setting up standing waves along the interaction region whose amplitudes increase exponentially with distance. Due to this interference, signal energy on helix 21 will be transferred entirely to the beam, and farther down the tube it will be transferred back to the helix, growing exponentially with distance. On the other hand, fast mode space charge wave energy within the signal bandwidth entering the interaction region on the beam will transfer periodically between the beam and the helix, also growing exponentially.

This process is illustrated in FIG. 3. The upper graph represents electromagnetic wave energy on the helix versus distance, while the lower graph represents space charge wave energy on the beam versus distance. The solid curves represent signal energy, while the dotted curves represent energy which is inherent on the beam, i.e., noise energy. Position 40 represents the point at which signal energy is introduced into the tube, while position 42 represents the point at which signal energy is extracted. These points are shown in FIG. 1 for reference purposes.

At position 40 all of the signal energy is on the helix and all of the noise energy is on the beam. Further down the tube, at position 43, all of the signal energy is transferred to the beam and all of the noise energy is transferred to the helix. At position 42 all of the signal energy has been retransferred back to the helix and all of the noise energy is on the beam. At this point the amplified signal energy is advantageously removed from the beam with substantially no noise content. It is to be noted that the energy transfer is periodic; the distance between 40 and 43 is the same as the distance between 43 and 42.

The foregoing discussion illustrates the general basic concept of how two growing waves can be produced in a parametric amplifier and how they can be made to interfere with each other to produce low noise amplification. In order to discuss the specific conditions under which such interfering growing waves can be produced, it is necessary to define certain beam and helix parameters. In determining the necessary relative velocities of the various waves on the beam and helix, the beam parameter α_p , the reduced plasma frequency, is useful. The plasma frequency is the rate at which an electron in an infinitely extending beam will oscillate about its equilibrium position if it is displaced by a small force. The reduced plasma frequency, on the other hand, is the rate at which an electron will oscillate about equilibrium in a finite beam which has been modulated by some other large frequency. Unlike the plasma frequency, α_p is a function of the frequency of a given space charge wave propagating along the beam. In determining a beam velocity parameter, let:

$$\alpha = \frac{\omega_q}{\omega} = \frac{\text{reduced plasma frequency at } \omega}{\text{modulation frequency}} \quad (1)$$

Applying this relationship to the pump, signal, and idler waves propagating along the beam:

$$\alpha_{(p, s, i)} = \frac{\omega_{q(p, s, i)}}{\omega_{(p, s, i)}} \quad (2)$$

where the subscripts (p, s, i) refer alternatively to the pump, or signal, or idler waves on the beam. With the use of the beam velocity parameter α , it can be shown that the necessary velocity of the uncoupled fast space charge pump wave is:

$$v_{pb} = u_0(1 + \alpha_p) \quad (3)$$

Likewise, the velocities of the uncoupled fast mode signal and idler waves are:

$$v_{sb} = u_0(1 + \alpha_s) \quad (4)$$

$$v_{ib} = u_0(1 + \alpha_i) \quad (5)$$

Simple algebraic manipulation shows that the difference of these space charge wave velocities and the beam $d-c$ velocity is:

$$v_{(p, s, i)b} - u_0 = u_0 \alpha_{(p, s, i)} \quad (6)$$

A physical illustration of beam velocity parameters α_s and α_p is shown on FIG. 4. FIG. 4 illustrates beam and helix velocity spectra as explained with reference to FIG. 2. Whereas FIG. 2 illustrates the particular situation in which the pump frequency is twice the signal frequency, FIG. 4 illustrates the more general situation in which the pump frequency is merely higher than the signal frequency. Since the reduced plasma frequency ω_q is fairly easy to determine by methods well known in the art, it is seen that the velocities of the various space charge waves on the beam are readily predictable.

The beam velocity parameter is a useful indication of beam dispersion. As will be shown hereinafter, it is generally necessary that helix 21 also be dispersive. At this point it will therefore be helpful to define a helix velocity parameter ξ which is analogous to α :

$$v_{(p, s, i)h} - u_0 = u_0 \xi_{(p, s, i)} \quad (7)$$

A physical representation of helix velocity parameters ξ_s and ξ_i is also shown on FIG. 4. v_{ih} is, of course, the uncoupled phase velocity of an electromagnetic wave traveling along helix 21 at the idler frequency.

Another parameter which is useful is the ratio of the signal frequency to the idler frequency. This will be represented by:

$$p = \frac{\omega_s}{\omega_i}$$

Having defined these parameters, we can discuss the specific conditions under which two growing waves will be produced which interfere in such a way as to produce

two standing waves which are 180 degrees out-of-phase as shown in FIG. 3. The derivations of these conditions are the result of a great number of mathematical calculations, many of which are made with the aid of an electronic computer. For purposes of simplicity and clarity, these derivations will not be shown. In terms of the foregoing parameters, it can be shown that the first condition is given by the relationship:

$$\xi_s = \frac{\alpha_p + \alpha_s}{2} + \frac{\alpha_p - \alpha_i}{2p} \quad (7)$$

The second condition for optimum noise reduction through the interference of two growing waves can be shown as being:

$$\xi_i = \alpha_p - p(\xi_s - \alpha_p) \quad (8)$$

It can be shown that the third condition is:

$$p^2 = \left(\frac{C_i}{C_s} \right)^2 \sqrt{\frac{(QC)_s}{(QC)_i}} \quad (9)$$

where $C_{s, i}$ is the gain parameter at the signal and idler frequencies, respectively, and $(QC)_{s, i}$ is the space charge parameter at these two respective frequencies. The gain parameter and the space charge parameter are widely used in the art and are defined in the book entitled "Traveling Wave Tubes," by J. R. Pierce, D. Van Nostrand and Company, Inc., 1950.

The fourth requirement concerns the fraction of beam current modulation m at the pump frequency:

$$(\xi_s - \alpha_s)^2 < \left(\frac{m}{4} \right)^2 \frac{(\alpha_s \alpha_i + \alpha_s \alpha_p + \alpha_i \alpha_p)^2}{p \alpha_s \alpha_i} < (\xi_s - \alpha_s)^2 + \frac{C_s^2}{4 \sqrt{(QC)_s}} \quad (10)$$

where $m=1$ represents 100 percent modulation. Typical limits for m are:

$$.4 < m < .8 \quad (11)$$

When the foregoing conditions are fulfilled energy will transfer between helix 21 and beam 18 as illustrated in FIG. 3. It is usually desirable to extract the signal energy at its first peak on the helix, i.e., at position 42. Helix 21 could also be twice as long as that illustrated in FIG. 3, and the signal energy could thereby be extracted at the point of its second maximum on the helix. Although this would provide greater amplification, deleterious second order effects which will be explained herein-after, would become more pronounced. It can then be shown that the length of helix 21 for signal extraction at position 42 is given by:

$$L = \frac{1}{(2) \sqrt{\frac{\kappa_s^2}{\alpha_s} + \left(\frac{\xi_s - \alpha_s}{2\alpha_s} \right)^2 - \frac{M}{4}}} \quad (12)$$

where L is measured in reduced plasma wavelengths at the signal frequency. κ_s is given by:

$$\kappa_s = \frac{\alpha_s}{4(QC)_s^{3/4}} \quad (13)$$

M is given by:

$$M = \frac{m^2}{16} \left(\frac{\alpha_i}{\alpha_p} \right) \left(1 + \frac{\alpha_p}{\alpha_s} + \frac{\alpha_p}{\alpha_i} \right)^2 \quad (14)$$

Once the foregoing requirements are known, adjustment of tube parameters to conform to these requirements is a matter of design which is within the capabilities of workers skilled in the traveling wave tube art. The velocities of the helix waves are primarily a function of the number of turns per unit length of the helix. The helix dispersion, and hence the helix velocity parameters, is a function of the helix diameter and the capacitance between the helix and the envelope 17. Therefore the thickness and the dielectric constant of envelope 17 of the illustrative device of FIG. 1 must be predetermined. The gain parameters are a function of the interaction im-

pedance of the coupled beam and helix and the current and voltage of the unmodulated beam. The phase velocities of the waves on the beam are, of course, a function of the D.-C. beam velocity as well as the reduced plasma frequencies as mentioned previously. The D.-C. beam velocity is primarily a function of the D.-C. bias on helix 21. This can be regulated by adjusting variable bias 26 as mentioned previously. The space charge parameters are determined primarily by the strength of coupling between the beam and helix which, in turn, is a function of, among others, the distance between the helix and beam. Inasmuch as these design considerations are well-known, and because other slow wave structures such as coupled resonators, etc., could be used in place of helix 21, a more detailed discussion of the structural design of the various devices within the scope of the present invention will not be given.

It should be pointed out at this juncture that the foregoing requirements for tube operation in accordance with our invention apply to optimum tube performance. All of the conditions need not be fully met in order to achieve low noise operation in accordance with this invention. For example, if the two standing waves depicted in FIG. 3 are not exactly 180 degrees out of phase, the signal may still be removed at a point at which substantially all of the noise energy is on the beam. This is done, however, at the sacrifice of tube gain.

Further, certain second order effects may be present in embodiments of our invention. The most serious of these are caused by upper sideband frequency space charge waves which are produced as a result of the mixing of the pump and signal waves and the pump and idler waves on the beam. These higher frequency waves couple strongly to the signal wave and therefore appear at the output as part of the signal wave. Fortunately, the degrading effects of these waves can be overcome by methods explained in the copending application of Cook et al., Serial No. 854,076, filed November 19, 1959.

It is to be understood that the structures and methods discussed are presented only for purposes of illustration. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of this invention.

What is claimed is:

1. An electron beam device comprising means for forming and projecting a beam of electrons, means for causing pump frequency energy to propagate along the beam at a faster phase velocity than the average velocity of the beam, and means for transmitting signal frequency energy in coupling relationship with the beam, said transmitting means having such propagation characteristics with respect to the propagation characteristics of the beam that the following relationship is substantially fulfilled:

$$\xi_s = \frac{\alpha_p + \alpha_s}{2} + \frac{\alpha_p - \alpha_i}{2\nu}$$

where ξ_s is the transmitting means velocity parameter at the signal frequency, α_p is the beam velocity parameter at the pump frequency, α_s is the beam velocity parameter at the signal frequency, α_i is the beam velocity parameter at a frequency equal to the difference of the pump and signal frequencies, and ν is the ratio of the signal frequency to the idler frequency.

2. An electron beam device comprising means for forming a beam of electrons, means for causing pump frequency energy to propagate along the beam at a faster phase velocity than the average velocity of the beam, and means for transmitting signal frequency energy in coupling relationship with the beam, said transmitting means having such propagation characteristics with respect to the propagation characteristics of the beam that the following relationship substantially exists:

$$\xi_i = \alpha_p - \nu(\xi_s - \alpha_p)$$

where ξ_i is the transmitting means velocity parameter at a

frequency equal to the difference of the pump and signal frequencies, ξ_s is the transmitting means velocity parameter at the signal frequency, α_p is the beam velocity parameter at the pump frequency, and ν is the ratio of the signal frequency to the difference of said pump and signal frequencies.

3. A low noise parametric amplifier comprising an electron gun for forming and projecting a beam of electrons, said beam being characterized by fast and slow modes of propagation and noise energy thereon, a source of signal energy, a source of pump energy, transmitting means extending along said beam for periodically with respect to distance introducing to and extracting from the fast mode of said beam said signal energy and for periodically extracting from and introducing to the fast mode of said beam certain of said noise energy, the transferrals of said signal energy and said noise energy between the beam and the transmitting means being substantially 180 degrees out-of-phase with respect to distance whereby substantially all of said noise energy exists on said beam at a position at which substantially all of said signal energy exists on said transmitting means, means for modulating said beam in the fast mode with pump energy, means including said beam for causing parametric amplification of said signal energy through the mixing of said signal energy with said pump energy, and means located at a position at which substantially all of said signal energy exists on said transmitting means and substantially all of said noise energy exists on said beam for extracting said signal energy from said transmitting means.

4. An electron discharge device comprising a coupled transmission system, said system comprising a cathode for forming an electron beam, means for projecting said beam along an extended path, and an elongated slow wave circuit in coupling relationship to said beam, a source of signal frequency wave energy connected to an input end of said slow wave circuit and a load device connected to an output end of said circuit, a source of pump wave energy of a higher frequency than the signal frequency, means included between said cathode and said slow wave circuit for causing pump energy to propagate along said beam as a fast space charge wave and mix with said signal wave energy, said mixing being characterized by the formation of a fast space charge idler wave, said coupled system being characterized by the following relationships:

$$(a) \quad \xi_s = \frac{\alpha_p + \alpha_s}{2} + \frac{\alpha_p - \alpha_i}{2\nu}$$

$$(b) \quad \xi_i = \alpha_p - \nu(\xi_s - \alpha_p)$$

$$(c) \quad \nu \left(\frac{C_i}{C_s} \right)^2 \sqrt{\frac{(QC)_s}{(QC)_i}}$$

$$(d) \quad (\xi_s - \alpha_s)^2 < \left(\frac{m}{4} \right)^2 \frac{(\alpha_s \alpha_i + \alpha_s \alpha_p + \alpha_i \alpha_p)^2}{\nu \alpha_s \alpha_b}$$

$$< (\xi_s - \alpha_s)^2 + \frac{C_s^2}{4\nu(QC)_s}$$

where ξ_s is the slow wave circuit velocity parameter at the signal frequency, ξ_i is the slow wave circuit velocity parameter at the idler frequency, α_p is the beam velocity parameter at the pump frequency, α_s is the beam velocity parameter at the signal frequency, α_i is the beam velocity parameter at the idler frequency, ν is the ratio of the signal frequency to the idler frequency, C_i is the gain parameter at the idler frequency, C_s is the gain parameter at the signal frequency, $(QC)_s$ is the space charge parameter at the signal frequency, $(QC)_i$ is the space

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charge parameter at the idler frequency, and m is the fraction of beam current modulation at the pump frequency.

5. The electron discharge device of claim 4 wherein the length of said slow wave circuit is substantially defined by:

$$L = \frac{1}{(2) \sqrt{\frac{\kappa_s^2}{\alpha_s} + \left(\frac{\xi_s - \alpha_s}{2\alpha_s} \right) - \frac{M}{4}}}$$

where L is measured in reduced plasma wavelengths at the signal frequency, κ_s is given by:

$$\kappa_s = \frac{\alpha_s}{4(QC)_s^{3/4}}$$

and M is given by:

$$M = \frac{m^2}{16} \left(\frac{\alpha_i}{\alpha_s \nu} \right) \left(1 + \frac{\alpha_n}{\alpha_s} + \frac{\alpha_p}{\alpha_i} \right)^2$$

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