

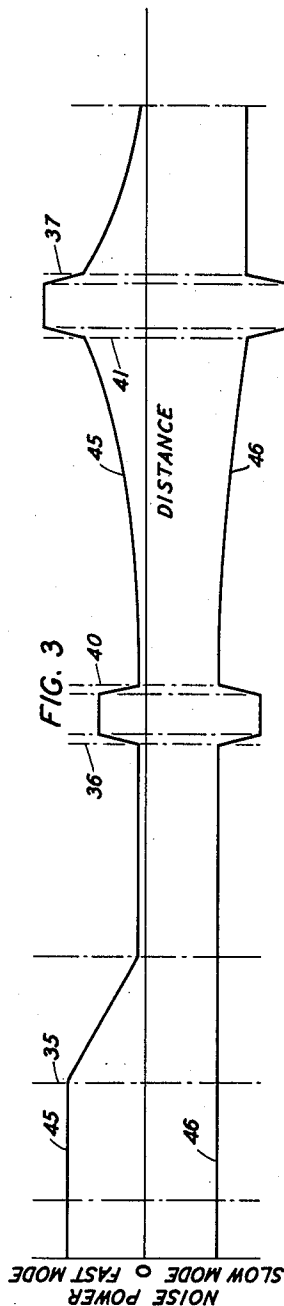
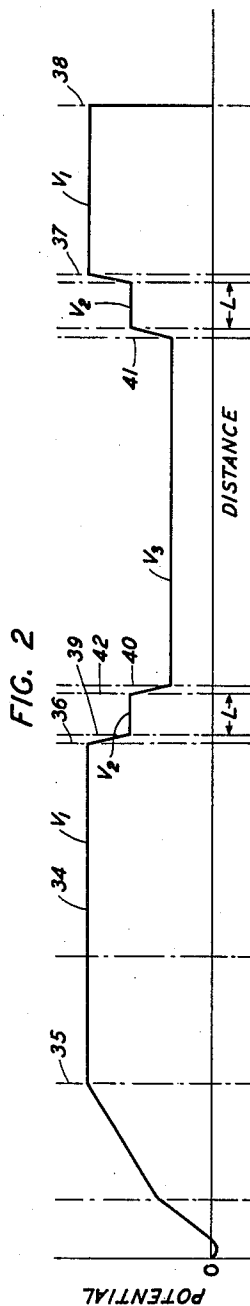
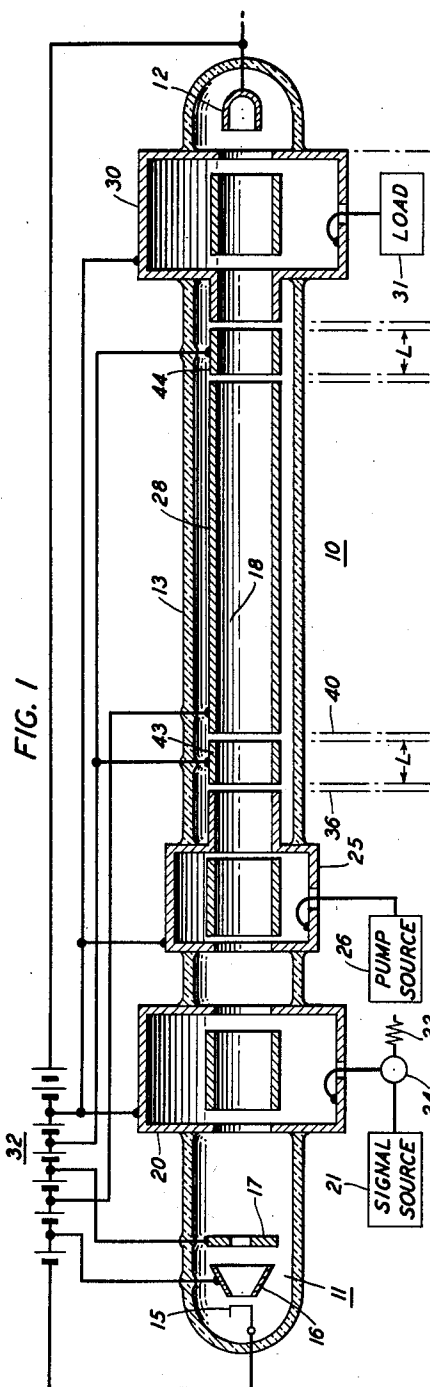
Feb. 25, 1964

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3,122,709

ELECTRON BEAM PARAMETRIC AMPLIFIER WITH QUARTER WAVE SECTIONS

Filed Oct. 20, 1960



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3,122,709

**ELECTRON BEAM PARAMETRIC AMPLIFIER
WITH QUARTER WAVE SECTIONS**

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Filed Oct. 20, 1960, Ser. No. 63,738

2 Claims. (Cl. 330-4.7)

This invention relates to electron beam devices and, more particularly, to velocity modulation devices that employ the principles of electron beam parametric amplification.

An important advance in the microwave art in recent years is the discovery that the principles of parametric amplification can be used to achieve unprecedented low noise figures. As applied to electron beam devices, the term parametric amplifier generally refers to a device wherein a signal wave is used to modulate an electron beam, the signal modulations being subsequently amplified through periodic variations of certain beam parameters by a pump frequency wave.

Space-charge waves of a given frequency can propagate on an electron beam in either of two modes, the fast or the slow mode. Fast mode propagation denotes propagation at a faster velocity than the mean or D.-C. velocity of the beam and results from an excess of kinetic energy of the space-charge wave over that of the D.-C. unmodulated beam; slow mode propagation is at a lower velocity than the D.-C. velocity of the beam and results from an extraction of kinetic energy from the unmodulated beam during the modulation process. Whereas conventional beam type amplifiers are limited to slow mode operation, parametric type amplification permits operation in the fast mode. This is significant in that fast mode noise waves, which are actually excess spurious kinetic energy, can be removed, or "stripped," from the beam, whereas such removal is, generally speaking, extremely difficult with respect to the negative energy slow mode noise waves.

Accordingly, a common form of space-charge wave parametric amplifier has the following placed in axial order along an electron beam: an input coupler for causing signal energy to modulate the beam and thereby propagate along the beam as a fast mode space-charge wave and for extracting fast mode noise waves from the beam; a pump coupler for causing pump energy, at a higher frequency than the signal frequency, to modulate the beam and to propagate along the beam as a fast mode space-charge wave; a drift region wherein the signal wave is allowed to mix with the pump wave and thereby become parametrically amplified; and an output coupler which extracts the amplified fast mode signal wave from the beam. Each of these elements is biased with a D.-C. potential that maintains the electron beam at a predetermined D.-C. velocity so that these elements essentially act as beam accelerating electrodes.

Recent study has shown the desirability of biasing the various structural elements at different D.-C. potentials. One of the primary purposes for such differences in potential is to vary the plasma wavelength of the beam along the various regions, the plasma wavelength being a function of beam velocity or beam potential. For example, the gain in the drift region is directly proportional to the number of plasma wavelengths therealong. It is therefore desirable to have a short plasma wavelength in the drift region so that maximum gain can be obtained without unduly increasing the actual length of the device. On the other hand, the couplers must generally be shorter than a plasma wavelength. Consequently, if the plasma wavelength in the coupler regions is very short, the size

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of the couplers must necessarily be so small that serious mechanical fabrication problems obtain.

Unfortunately, it has been found that the beam discontinuity resulting from an abrupt potential change may convert slow mode noise energy to the fast mode and fast mode energy to the slow mode. The transforming action of such a potential change or "velocity jump" is treated in an article by Ashkin et al., "Fast Wave Couplers for Longitudinal Beam Parametric Amplifiers," Journal of Electronics and Control (Brit.), vol 7, No. 1, pages 1-31, July 1959, and in my Patent Number 3,009,078, granted November 14, 1961. Although it may be possible to avoid mode conversions by making the potential change very gradual, this would again undesirably increase tube length. Obviously, if slow mode noise at the signal frequency is converted to fast mode noise, it will deleteriously couple to the growing signal wave and appear at the output. Further, the conversion of fast signal wave energy to the slow mode will degrade tube efficiency.

It is a specific object of this invention to produce changes of electron beam potential in a beam type parametric amplifier without thereby coupling noise to the signal wave which is to be amplified, and without degrading tube efficiency.

This and other objects of this invention are attained in an illustrative embodiment thereof comprising an electron discharge device having an evacuated envelope which encloses an electron gun for forming and projecting an electron beam along a path to a collector. A coupler such as a cavity resonator is positioned along the path for extracting fast mode noise energy from the beam and for causing signal wave energy to modulate the beam and to propagate therealong as a fast mode space-charge wave. Downstream from the signal wave coupler is a pump coupler for modulating the beam in the fast space-charge mode with pump energy. At the collector end of the device is an output coupler for extracting fast mode signal energy from the beam. Between the pump coupler and the output coupler there extends an elongated drift tube cylinder which defines a drift region wherein the signal and pump space-charge waves are allowed to mix to produce parametric amplification.

It is known that the plasma wavelength of the beam along the various regions of a device of this type varies directly with the square root of the D.-C. accelerating potentials applied to the beam along those regions. The drift tube cylinder is therefore biased at a relatively low D.-C. potential while the couplers are biased at a relatively high potential. Hence, the beam plasma wavelength in the drift region is relatively short, thereby resulting in a large gain per unit of actual length, while the beam plasma wavelength in the coupler regions is long, thereby permitting the use of relatively large couplers.

It is a feature of this invention that short electrode cylinders be interposed between the drift tube cylinder and the pump coupler and between the drift tube cylinder and the output coupler. I have found, as will be explained more fully hereinafter, that if the short electrode cylinders are of a particular length and are biased at a particular potential, which is intermediate that of the drift tube cylinder and the couplers, undesired energy conversion between the slow and fast modes can be prevented.

It is another feature of this invention that the voltages on the short electrode cylinders be defined by the following relationship:

$$V_2^2 \omega_{q2}^2 = V_1 V_3 \omega_{q1} \omega_{q3} \quad (1)$$

where V_1 is the voltage on the couplers, V_3 is the voltage on the drift tube cylinder, V_2 is the voltage on the short electrode cylinders, and $\omega_{q(1, 2, 3)}$ are the reduced plasma frequencies at voltages V_1 , V_2 and V_3 , respectively.

It is still another feature of this invention that the

short electrode cylinders be closely adjacent to the drift tube and the pump and output couplers, respectively, and that they each be substantially one-quarter of a reduced plasma wavelength long at the voltage V_2 of the electrode cylinders. The beam will therefore experience two voltage drops or jumps as it passes through each electrode cylinder. I have found that under these conditions a certain quantity of energy will be transferred between the slow and fast modes due to the first voltage jump, but that this same energy will be retransferred by the second voltage jump. Hence, there will be no net interchange of energy resulting from the voltage changes.

These and other objects and features of the present invention will be more clearly understood from a consideration of the following detailed description, taken in conjunction with the accompanying drawing in which:

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

FIG. 2 is a graph illustrating the voltages on various elements of the device of FIG. 1; and

FIG. 3 is a graph illustrating mode interchange of energy in the device of FIG. 1.

Referring now to the drawing, the illustrative embodiment of FIG. 1 comprises an electron discharge device 10 having an electron gun 11 and an electron beam collector 12 at opposite ends of an evacuated envelope 13. For purposes of illustration, electron gun 11 is shown as comprising an emissive cathode 15, a beam forming electrode 16, and an accelerating electrode 17, which jointly coact to form and project an electron beam, schematically shown by dashed line 18, toward collector 12. Suitable means for focusing the beam is used which, for the sake of clarity, is not shown. Any of the known beam focusing systems commonly used in space-charge wave devices, such as longitudinal magnetic, electrostatic, and periodic magnetic or electrostatic systems could be used to focus beam 18.

Downstream from the electron gun is a noise extraction and signal input coupler 20. Coupler 20 is designed, in accordance with principles known in the art, to cause electromagnetic energy from a signal source 21 to propagate along beam 18 as a fast space-charge wave. Coupler 20 also serves to extract fast mode space-charge noise waves from the beam which are thereafter transmitted to, and dissipated by, impedance 22. A circulator 24, which may take any of a number of well known forms, prevents signal energy from being transmitted to impedance 22 and noise energy from being transmitted to source 21. Adjacent the signal coupler 20 is a pump input coupler 25 which causes electromagnetic energy from a pump source 26 to propagate along beam 18 as a fast space-charge wave. Downstream from the pump coupler 25 is a drift region defined by a drift tube cylinder 28. In the drift region the fast mode signal and pump space-charge waves mix to produce, through the known phenomenon of parametric amplification, a space-charge wave of the signal frequency that grows with distance. At the collector end of the device is an output coupler 30 that extracts the amplified signal energy from beam 18 whereupon it is transmitted to an appropriate load 31. The various couplers are shown as being cavity resonators only for illustrative purposes; various other known devices such as helices or coupled resonators, for example, could alternatively be used.

Beam velocity along device 10 is controlled by a voltage source 32 which supplies D.-C. voltages to the various elements as shown. These voltages are graphically illustrated in FIG. 2 wherein curve 34 represents beam potential with respect to distance. The distance abscissa is of the same scale as the illustration of FIG. 1 so that relative potentials of the various biased elements of FIG. 1 can be appreciated by simple projection to curve 34.

It is known that the gain in the drift region of a space-charge wave parametric amplifier is a function of the

number of beam plasma wavelengths along that drift region. It is also known that the beam plasma wavelength along any given region is a function of beam potential along that region. To minimize tube length, it is therefore often desirable to bias the drift tube cylinder at a fairly low potential so that maximum parametric gain per unit of tube length can be attained. On the other hand, the sizes of the signal, pump and output couplers are also a function of the beam plasma wavelength. If they are biased at low potential, the resulting short plasma wavelength may result in undesirably small coupler requirements. Accordingly, couplers 20, 25 and 30 are biased at a high potential V_1 as illustrated by the portion of curve 34 between ordinates 35 and 36 and between ordinates 37 and 38. Drift tube cylinder 28 is biased at a low potential V_3 as shown by the portion of curve 34 between ordinates 40 and 41.

When an abrupt voltage change is made in an electron beam, slow mode energy is converted to fast mode energy, and fast mode energy is converted to slow mode energy. In a device of the type shown in FIG. 1, this effect can be seriously degrading because slow mode noise energy, which ordinarily would not couple to the fast mode signal, is thereby transferred to the fast mode, which, of course, is intended to be noiseless. To counteract this effect, in accordance with the present invention, short electrode cylinders 43 and 44 are inserted, respectively, between pump coupler 25 and drift tube cylinder 28 and between the drift tube cylinder and output coupler 30. As will be shown hereinafter, there will be no net interchange of energy between the fast and slow modes if the following conditions are fulfilled:

$$V_2^2 \omega_{q3}^2 = V_1 \cdot V_3 \omega_{q1} \omega_{q3} \quad (2)$$

$$L = (2n+1) \frac{\lambda_{q2}}{4} \quad (3)$$

where V_1 is the potential on the pump and output couplers 25 and 30, V_2 is the potential on cylindrical electrodes 43 and 44, V_3 is the potential on the drift tube cylinder 28, $\omega_{q(1, 2, 3)}$ are the reduced plasma frequencies at voltages V_1 , V_2 and V_3 , respectively, L is the length of the cylindrical electrodes 43 and 44, n is an integer, preferably zero, and λ_{q2} is the reduced plasma wavelength at voltage V_2 .

The utility of my invention can perhaps be better appreciated with reference to FIG. 3 wherein curve 45 is a representation of fast mode noise power with respect to distance and curve 46 represents slow mode noise power with respect to distance. The distance scale is the same as that of FIG. 2.

As the beam passes through signal coupler 20, fast mode noise power is extracted from the beam as shown by the slope of curve 45 from ordinate 35. The voltage drop between pump coupler 25 and electrode cylinder 43 constitutes a beam discontinuity which causes a transfer of slow mode noise power to the fast mode as shown by the steep rise of curve 45 at ordinate 36. As is known, fast wave power is positive power, while slow wave power is negative with respect to the average, or D.-C. kinetic power of the beam. The conversion of slow mode power to positive fast mode power is therefore manifested by a corresponding increase in negative slow mode power as shown by curve 46 at ordinate 36. Curve 46 is included merely to illustrate the conservation of beam power when acted upon by a voltage jump or drop.

As the beam passes through the voltage drop at ordinate 40, between electrode 43 and drift tube cylinder 28, energy conversion between the slow and fast modes again occurs. In accordance with my invention, however, this conversion compensates for the conversion that occurred at the voltage drop of ordinate 36. Hence, the energy that was transferred from the slow mode to the fast mode at ordinate 36 is retransferred to the slow mode at ordinate 40. The proof of this phenomenon presupposes a true voltage drop, that is, the distances between cylin-

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drical electrode 43 and both the pump coupler 25 and the drift cylinder 28 are small with respect to a reduced plasma wavelength.

In the drift region between ordinates 40 and 41, the parametric pumping will amplify the fast mode noise power as shown by the exponential increase of curve 45. A certain amount of pump power will probably couple to the slow mode as well, which results in a smaller growth of the slow mode noise power as shown by curve 46. It should be pointed out, however, that the amplified fast mode noise power is in most cases negligible with respect to the amplified signal wave power which has not been shown.

The same process occurs at the voltage jumps of cylindrical electrode 44 as at electrode 43. The noise power which unavoidably transferred to the fast mode at the beam discontinuity of ordinate 41 is retransferred back to the slow mode at ordinate 37. It can be seen that substantially no net signal frequency noise power is introduced to the fast mode, in spite of the abrupt voltage changes occurring along the device.

The following is a derivation of Equations 2 and 3, the conditions which define my invention and by which the introduction of slow mode noise energy to the fast mode is prohibited:

In a velocity jump or drop occurring in a distance which is short compared to a space-charge wavelength, there are two conditions which quite accurately describe the discontinuity. First, the R.F. current across the discontinuity is continuous because it occurs in such a short length that it cannot change. Secondly, if the energy in the beam is to be conserved, the ratio of the R.F. velocities must be in the ratio of the D.-C. velocities. We may express these conditions as:

$$v_2 = \frac{u_1}{u_2} v_1 \quad (4)$$

$$i_2 = i_1 \quad (5)$$

where v_1 is the R.F. velocity at voltage V_1 between ordinates 35 and 36, v_2 is the R.F. (signal frequency) velocity at voltage V_2 , $u_{(1,2)}$ is the D.-C. beam velocity at voltages V_1 and V_2 , respectively, and $i_{(1,2)}$ is the instantaneous R.F. current at ordinates 36 and 39, respectively. In terms of fast and slow waves, we can write:

$$i_1 = i_{f1} + i_{s1} \quad (6)$$

and

$$i_2 = i_{f2} + i_{s2} \quad (7)$$

where i_f is the fast space-charge wave current and i_s is slow space-charge wave current.

Similarly:

$$v_1 = v_{f1} + v_{s1} \quad (8)$$

$$v_2 = v_{f2} + v_{s2} \quad (9)$$

where the relationship between the velocity and current in these waves is given by:

$$v_i = \mp \frac{u_1}{I_0} \frac{\omega_{q1}}{\omega} i_i \quad (10)$$

where I_0 is the D.-C. beam, ω_{q1} is the reduced plasma frequency at voltage V_0 , and ω is the R.F. (signal) frequency. Rewriting Equations 4 and 5 in terms of the corresponding fast and slow waves using Equation 10:

$$i_{f2} + i_{s2} = i_{f1} + i_{s1} \quad (11)$$

and

$$-\frac{u_2}{I_0} \frac{\omega_{q2}}{\omega} i_{f2} + \frac{u_2}{I_0} \frac{\omega_{q2}}{\omega} i_{s2} = \frac{u_1}{I_0} \left[-\frac{u_1}{I_0} \frac{\omega_{q1}}{\omega} i_{f1} + \frac{u_1}{I_0} \frac{\omega_{q1}}{\omega} i_{s1} \right] \quad (12)$$

Rewriting Equation 12:

$$-i_{f2} + i_{s2} = \frac{u_1^2}{u_2^2} \frac{\omega_{q1}}{\omega_{q2}} [-i_{f1} + i_{s1}] \quad (13)$$

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Adding and subtracting Equations 11 and 13 gives:

$$i_{f2} = \frac{1}{2} \left[i_{f1} \left\{ 1 + \frac{u_1^2}{u_2^2} \frac{\omega_{q1}}{\omega_{q2}} \right\} + i_{s1} \left\{ 1 - \frac{u_1^2}{u_2^2} \frac{\omega_{q1}}{\omega_{q2}} \right\} \right] \quad (14)$$

$$i_{s2} = \frac{1}{2} \left[i_{f1} \left\{ 1 - \frac{u_1^2}{u_2^2} \frac{\omega_{q1}}{\omega_{q2}} \right\} + i_{s1} \left\{ 1 + \frac{u_1^2}{u_2^2} \frac{\omega_{q1}}{\omega_{q2}} \right\} \right] \quad (15)$$

Equations 14 and 15 give the slow and fast wave R.F. currents at the downstream end of a single velocity jump or drop in terms of the slow and fast wave currents at the upstream end. To consider the effects of the voltage changes at electrode 43 on only a fast space-charge wave incident thereto, let i_{s1} be zero, that is, assume that there is no slow mode R.F. current at ordinate 36 and voltage V_1 . Equations 14 and 15 then reduce to:

$$i_{f2} = \frac{i_{f1}}{2} \left\{ 1 + \frac{u_1^2}{u_2^2} \frac{\omega_{q1}}{\omega_{q2}} \right\} \quad (16)$$

$$i_{s2} = \frac{i_{f1}}{2} \left\{ 1 - \frac{u_1^2}{u_2^2} \frac{\omega_{q1}}{\omega_{q2}} \right\} \quad (17)$$

By letting the subscript 3 denote current, frequency and velocity at voltage V_3 of ordinate 40, we can rewrite Equations 14 and 15, to describe the voltage drop at ordinates 42, 40:

$$i_{f3} = \frac{1}{2} i_{f2}' \left[\left\{ 1 + \frac{u_2^2}{u_3^2} \frac{\omega_{q2}}{\omega_{q3}} \right\} + i_{s2}' \left\{ 1 - \frac{u_2^2}{u_3^2} \frac{\omega_{q2}}{\omega_{q3}} \right\} \right] \quad (18)$$

$$i_{s3} = \frac{1}{2} i_{f2}' \left[\left\{ 1 - \frac{u_2^2}{u_3^2} \frac{\omega_{q2}}{\omega_{q3}} \right\} + i_{s2}' \left\{ 1 + \frac{u_2^2}{u_3^2} \frac{\omega_{q2}}{\omega_{q3}} \right\} \right] \quad (19)$$

where i_{f2}' and i_{s2}' are the fast and slow wave R.F. currents at ordinate 42. The object of the apparatus is to prevent conversion of energy from one mode to another. Thus, we seek the conditions under which $i_{s3} = 0$. From Equation 19, setting $i_{s3} = 0$ yields:

$$\frac{\left\{ 1 + \frac{u_2^2}{u_3^2} \frac{\omega_{q2}}{\omega_{q3}} \right\}}{\left\{ 1 - \frac{u_2^2}{u_3^2} \frac{\omega_{q2}}{\omega_{q3}} \right\}} = -\frac{i_{f2}'}{i_{s2}'} \quad (20)$$

or

$$\frac{\frac{i_{f2}'}{i_{s2}'} + 1}{\frac{i_{f2}'}{i_{s2}'} - 1} = \frac{u_2^2 \omega_{q2}}{u_3^2 \omega_{q3}} \quad (21)$$

R.F. space-charge wave current propagates as:

$$i = I e^{-j(\beta_e - \beta_q)z + j\omega t} \quad (22)$$

where I is the maximum amplitude of the R.F. current, β_e is

$$\frac{\omega}{u}$$

(R.F. frequency over D.-C. beam velocity), β_q is the reduced plasma wave phase constant, z is distance, and t is time. The relationship between the R.F. current at ordinate 39 and that at ordinate 42 is, therefore:

$$i_{f2}' = i_{f2} e^{-j(\beta_e - \beta_{q2})L} \quad (23)$$

where β_{q2} is the reduced plasma phase constant at voltage V_2 and L is the distance between ordinates 39 and 42.

From Equations 21 and 23:

$$\frac{u_2^2 \omega_{q2}}{u_3^2 \omega_{q3}} = \frac{\left\{ \frac{i_{f2}}{i_{s2}} e^{(2j\beta_{q2}L)} + 1 \right\}}{\left\{ \frac{i_{f2}}{i_{s2}} e^{(2j\beta_{q2}L)} - 1 \right\}} \quad (24)$$

The right side of Equation 5 must be real and less than 1.

Therefore:

$$e^{2\beta_{q2}L} = -1 \quad (25)$$

and:

$$2\beta_{q2}L = \pm(2n+1)\pi \quad (26)$$

where:

$$\beta_{q2} = \frac{2\pi}{\lambda_{q2}} \quad (27)$$

where n is an integer and λ_{q2} is the reduced plasma wavelength at voltage V_2 .

Equations 26 and 27 give:

$$L = \pm(2n+1)\frac{\lambda_{q2}}{4} \quad (28)$$

Q.E.D.

Combining Equations 24 and 25:

$$\frac{u_2^2\omega_{q2}}{u_3^2\omega_{q3}} = \frac{\left\{ \begin{array}{l} 1 + \frac{u_1^2\omega_{q1}}{u_2^2\omega_{q2}} \\ 1 - \frac{u_1^2\omega_{q1}}{u_2^2\omega_{q2}} \end{array} \right\} - 1}{\left\{ \begin{array}{l} 1 + \frac{u_1^2\omega_{q1}}{u_2^2\omega_{q2}} \\ 1 - \frac{u_1^2\omega_{q1}}{u_2^2\omega_{q2}} \end{array} \right\} + 1} \quad (30)$$

Solving for $u_2^2\omega_{q2}$:

$$(u_2^2\omega_{q2})^2 = (u_1^2\omega_{q1})(u_3^2\omega_{q3}) \quad (31)$$

Since beam velocity varies directly with the square root of beam voltage:

$$V_2^2\omega_{q2}^2 = V_1\omega_{q1}V_3\omega_{q3} \quad (32)$$

Q.E.D.

The foregoing is a derivation of the conditions for preventing the conversion of fast mode energy to the slow mode. The same conditions are necessary for preventing the conversion of slow mode energy to the fast mode as can be proved by setting equal to zero the incident fast wave energy at Equation 16 and the output fast wave energy at Equation 20.

It should be pointed out that the device of FIG. 1 is merely intended to be illustrative of the uses of my invention. Various other types of fast wave parametric amplifiers are known in the art. Further, fast wave noise stripping can be used in certain instances to enhance the noise characteristics of slow wave amplifiers. Thus the invention is useful in such devices whenever successful operation depends upon a substantially noise-free frequency band in the fast mode of the electron beam. 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 discharge device comprising means for forming and projecting along a path an electron beam which is characterized by fast and slow modes of wave propagation and a reduced plasma frequency which varies as a function of the D.-C. potential of electrodes acting thereon, means for modulating the beam in the fast space-charge mode, means for stripping noise from the fast mode of the beam, a first electrode biased at a first D.-C. potential positioned adjacent one portion of said path, a third electrode biased at a third D.-C. potential which is different from said first potential positioned adjacent another

portion of said path, and means located between and closely adjacent said first and third electrodes for preventing energy transfer between said fast and slow modes as a result of the change of D.-C. potential experienced by electrons traveling along said path, said last-mentioned means comprising a second electrode having a length L substantially determined by:

$$L = \pm(2n+1)\frac{\lambda_{q2}}{4}$$

and being biased at a D.-C. potential V_2 substantially determined by:

$$V_2^2\omega_{q2}^2 = V_1\omega_{q1}V_3\omega_{q3}$$

where n is any integer, λ_{q2} is the reduced plasma wavelength at voltage V_2 , V_1 is the D.-C. potential of the first electrode, V_3 is the D.-C. potential of the third electrode, and $\omega_{q(1, 2, 3)}$ are the reduced plasma frequencies at voltages V_1 , V_2 , and V_3 , respectively.

2. An electron discharge device comprising means for forming and projecting a beam of electrons characterized by fast and slow modes of propagation and noise energy thereon, a source of signal frequency energy, a source of pump frequency energy, signal input coupling means for causing signal energy to propagate along the beam as a fast mode space-charge wave, means for extracting fast mode noise energy from the beam, pump input coupling means for causing pump energy to propagate along the beam as a fast space-charge wave, a drift tube cylinder, an output coupler for extracting fast mode signal energy from the beam, a first cylindrical electrode interposed between and closely adjacent to said drift tube cylinder and one of said input coupling means, a second cylindrical electrode interposed between and closely adjacent to said drift tube cylinder and said output coupler, each of the cylindrical electrodes extending along the beam a distance equal to

$$(2n+1)\frac{\lambda_q}{4}$$

where n is any integer and λ_q is the reduced plasma wavelength at the potential of the cylindrical electrode, means for biasing both of said input coupling means and said output coupler at a first D.-C. potential, means for biasing said drift tube cylinder at a second D.-C. potential that is lower than said first potential, and means for biasing both of said cylindrical electrodes at a third D.-C. potential that is intermediate said first and second potentials, the square of the product of the third potential and the reduced plasma frequency at the third potential being substantially equal to the product of the first potential, the second potential, the reduced plasma frequency at the first potential, and the reduced plasma frequency at the second potential.

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