

March 7, 1961

C. F. QUATE

2,974,252

LOW NOISE AMPLIFIER

Filed Nov. 25, 1957

2 Sheets-Sheet 1

FIG. 1

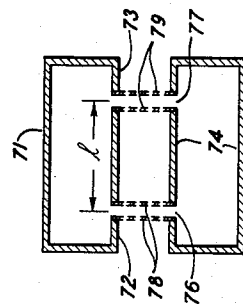
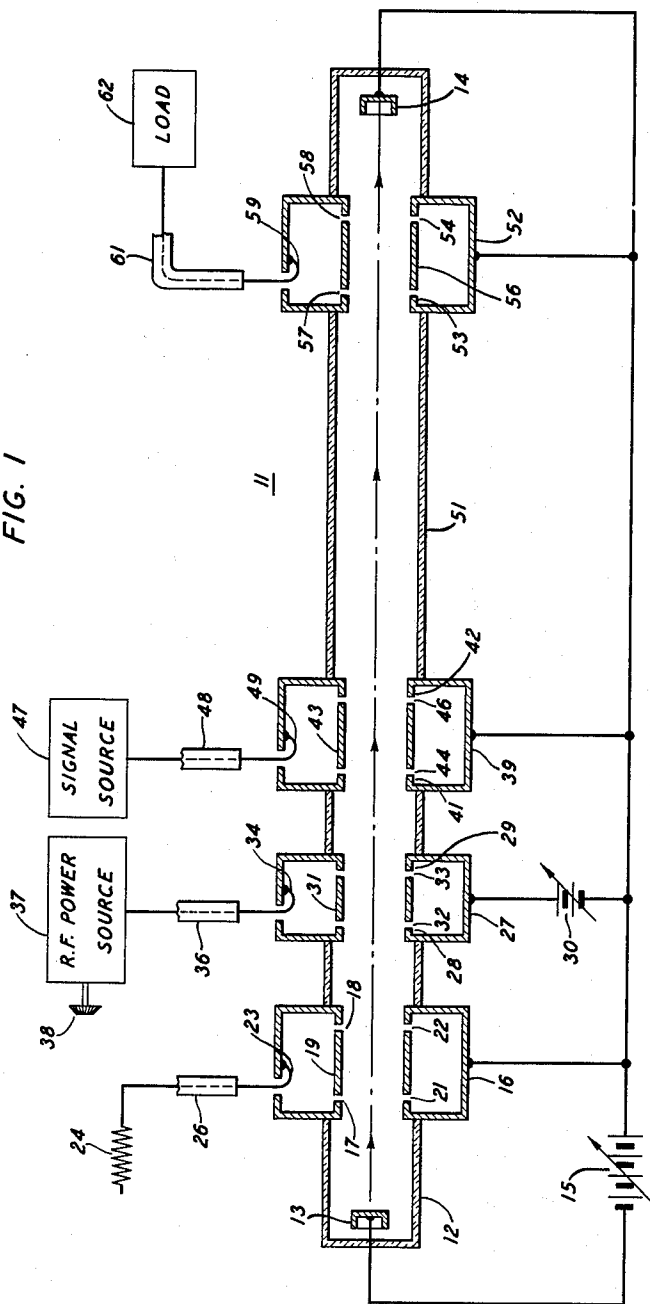


FIG. 2

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FIG. 3

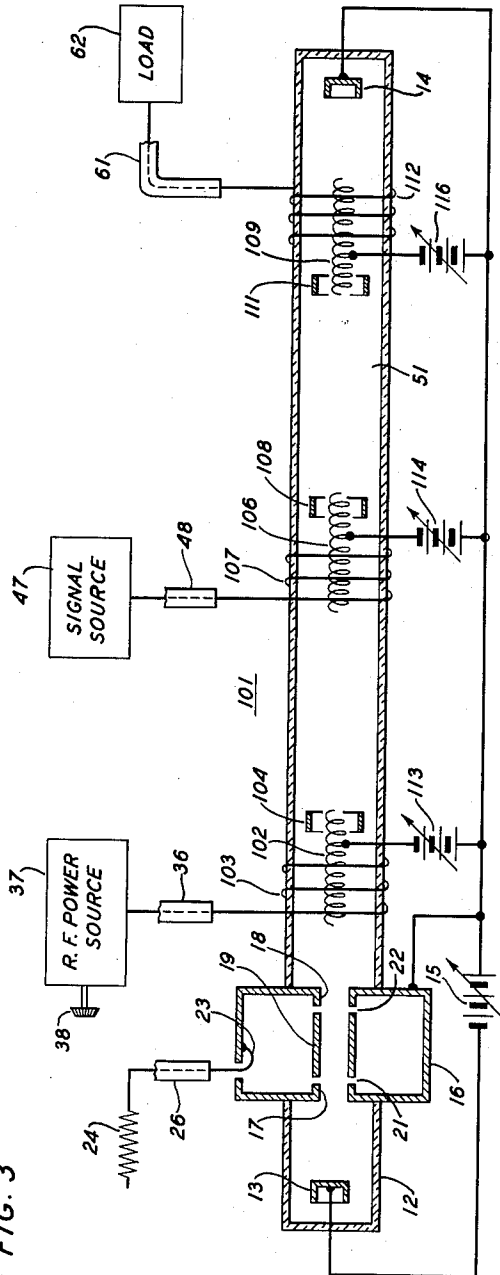
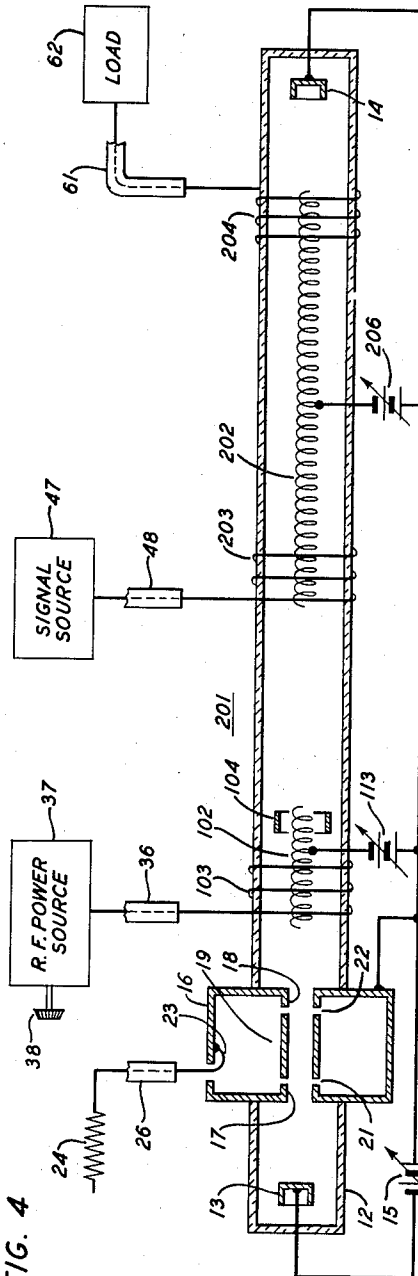


FIG. 4



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LOW NOISE AMPLIFIER

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28 Claims. (Cl. 315—3)

This invention relates to electron discharge devices and more particularly to such devices which utilize the interaction between an electron beam and an electromagnetic wave to produce signal amplification.

In general, electron discharge devices of this type, which are commonly called velocity modulation devices, depend, for amplification, upon the interchange of energy between the beam and the wave, which impresses alternating current components of electric velocity on the beam, some of the electrons in the beam being slowed down and others speeded up, producing in turn bunching of electrons in the beam. The bunched beam interacts with the wave energy in the circuit or induces wave energy in another circuit to give an amplified signal which is then extracted for utilization.

One well-known type of velocity modulation device is the klystron, which utilizes a resonant cavity into which is introduced the signal to be amplified. An electron beam is passed through the cavity and is velocity modulated through interaction with the electric field in a narrow gap in the cavity. The beam, after emerging from the cavity, passes through the drift region where the velocity modulation is converted to density modulation and then passes through a gap in a second cavity, giving up its energy thereto. The signal extracted from the second cavity is a greatly amplified version of the signal introduced into the first cavity.

Another well-known type of velocity modulation device is the traveling wave tube, which utilizes a wave propagation circuit along which is propagated the signal to be amplified. An electron beam is projected in coupling relation to the wave propagation circuit along the length thereof and the velocities of the beam and the wave are synchronized so that the beam gives up energy to the wave on the circuit, resulting in amplification of the wave.

Such velocity modulation devices as just described give, in general, high gain at exceedingly high frequencies and, particularly in the case of the traveling wave tube, deliver this gain over an extremely wide band of frequencies. However, inasmuch as an electron beam is utilized, these devices are inherently quite noisy, and much effort has been directed to reducing the noise characteristics without sacrificing the advantages of high gain and high frequency operation.

An electron beam which has been modulated by a high frequency electromagnetic wave in effect propagates two space charge waves as a result of the modulation. One of the space charge waves travels at a velocity less than the direct-current velocity of the beam and is generally referred to as the slow wave. The other space charge wave travels faster than the direct-current beam velocity and is referred to as the fast wave. It has long been known to workers in the art that the kinetic power of the beam in the presence of the slow wave is less than the direct-current power of the beam and, therefore, in order to modulate the beam with the slow space charge wave, it is necessary to abstract radio-frequency power

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from the beam. If this abstraction of radio-frequency power is accomplished over a distance as is done in the aforementioned traveling wave tube, for instance, the radio-frequency power in the wave propagation circuit grows and the kinetic power of the beam decreases resulting in amplification of the wave. One disadvantage of such operation is that the noise in the beam which is propagating as a slow space charge wave can never be completely eliminated since it would be necessary to deliver power to the beam at the correct frequencies and phase to exactly cancel the noise. It has been pointed out in an article entitled "The Minimum Noise Figure of Microwave Beam Amplifiers" by H. A. Haus and F. N. H. Robinson, Proceedings of the I.R.E., vol. 43, pages 981-991, August 1955, that there is a minimum noise figure of approximately 6 decibels beyond which further noise reduction is impossible. Heretofore workers in the art, in their efforts to reduce the noise figure of velocity modulation devices, have been unable to cross this barrier.

When the fast space charge wave propagates on the electron beam, the kinetic power of the beam is greater than the direct-current power, which means that in order to excite the fast space charge wave radio-frequency power must be delivered to the beam. Under such a condition the noise on the electron beam which is propagating in the fast space charge wave may be substantially completely eliminated from the beam by the simple expedient of abstracting the excess radio-frequency power representative of the noise waves from the beam. However, amplification heretofore has not been successfully achieved by operation with the fast space charge waves for the reason that radio-frequency energy must be given up to the beam in order to propagate the fast space charge wave, and, as a consequence, signal attenuation results.

It is accordingly an object of this invention to achieve high signal amplification in a velocity modulation type device with a minimum of noise in the amplified signal.

It is another object of this invention to achieve low noise amplification in a velocity modulation device through operation with an electron beam propagating energy in the fast space charge wave mode.

My invention is based upon the discovery that if certain conditions are met it is possible to achieve exponential gain of a signal to be amplified through the use of an electron beam operating in the fast space charge wave mode. More particularly, I have discovered that if a radio-frequency power source is utilized to modulate the beam in the fast wave mode, then the kinetic power of the beam will be increased above the direct-current power to the extent of the radio-frequency power input. If then a signal to be amplified is introduced onto the beam in the fast space charge wave mode, exponential gain will be realized to the extent of the excess of kinetic power on the beam over and above the direct-current power. It is then possible to abstract this amplified wave for utilization. Inasmuch as the operation is in the fast mode, the noise velocity modulations on the beam in the fast mode may be abstracted prior to the introduction of the signal to be amplified, in the manner pointed out in the foregoing, and substantially completely noise free amplification of the signal is achieved.

In one illustrative embodiment of this invention an electron discharge device comprises an evacuated envelope having first, second, third, and fourth hollow cavity resonators separated from each other by drift spaces, an electron gun and a collector electrode for forming and directing an electron beam through the cavity resonators, a signal input means to the second and third cavities, and signal output means to the fourth of said cavities.

In other illustrative embodiments of this invention one or more of the four cavities are replaced by a slow

wave circuit such as a helix having signal input or output means thereto and which is terminated to be substantially reflectionless, or having both signal input and output means thereto, or a combination of such helix arrangements.

Accordingly it is a feature of this invention that high frequency electromagnetic wave energy be amplified by removing from an electron beam the fast wave mode noise energy in the frequency range of the signal wave to be amplified, modulating the electron beam in the fast wave mode only with energy at a frequency different from that of the signal wave to be amplified, and further modulating the electron beam in the fast wave mode only with the signal to be amplified.

It is another feature of this invention that a high frequency amplifier comprise an electron gun for projecting a beam of electrons to an electron collector and positioned between the gun and collector four coupling arrangements for coupling only to the fast wave mode of the electron beam, the first two of the coupling arrangements serving to remove fast mode noise waves from the electron beam in the frequency range of the signal to be amplified and to supply high energy power at a frequency removed from that frequency range and the last two of the coupling arrangements serving to modulate the fast wave mode with the input signal to be amplified and to remove the amplified signal therefrom. In accordance with this feature of my invention the last two coupling arrangements may be separated solely by a drift space or by a delay line transmission circuit.

In accordance with a further feature of my invention in specific illustrative embodiments thereof the coupling arrangements may comprise resonant cavities having two interaction gaps spaced apart so as to attain coupling to the fast mode wave energy only and/or wave propagation circuits, such as helical conductors, operated in the Kompfner Dip condition.

In accordance with features of one illustrative embodiment of this invention, a first cavity is made resonant at the midband frequency of the signals to be amplified. The electron beam, in passing through a narrow gap in the cavity, gives up energy at this frequency to the cavity. After emergence from the first cavity the beam passes through a second cavity, which is resonant at and has introduced therein through the signal input means, wave energy at a frequency which is approximately twice the midband frequency of the signals to be amplified. In passing through a narrow gap in the cavity the electron beam is velocity modulated at this frequency. After emergence from the second cavity the modulated beam passes through a third cavity, which is resonant at and has introduced therein through the signal input means wave energy representative of the signal to be amplified. The electron beam, in passing through a narrow gap in the cavity, is velocity modulated at the signal frequency. After emergence from the third cavity the modulated beam passes through a drift region where it becomes density modulated, and it then passes through a fourth cavity which is resonant at the signal frequencies. The electron beam gives up energy to the fourth cavity in the form of an amplified signal which is then abstracted for utilization.

In accordance with other features of this illustrative embodiment of my invention each of the four cavities is provided with two gaps which are spaced from each other a distance such that the energy which is applied to, or abstracted from, the electron beam is energy in the fast space charge wave mode only. As a result the first cavity abstracts any noise energy present on the beam in the signal frequency band which is propagating in the fast wave mode. The second cavity introduces radio-frequency power onto the beam for propagation in the fast space charge wave mode, and the third cavity introduces the signal wave onto the beam for propagation in the fast

space charge wave mode. The fourth cavity abstracts only that energy on the beam which is propagating in the fast space charge wave mode at the signal frequencies.

The invention and the above-noted and other features will be understood more clearly and fully from the following detailed description taken in conjunction with the accompanying drawings, in which:

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

Fig. 2 is a schematic view of a resonant cavity as used in the embodiment of Fig. 1;

Fig. 3 is a schematic view of another illustrative embodiment of the invention; and

Fig. 4 is a schematic view of still another illustrative embodiment of the invention.

Referring now to Fig. 1 there is shown schematically a velocity modulation type device 11 embodying the principles of the present invention. Located at opposite ends of an evacuated elongated envelope 12 which, for example, is of glass or any suitable material, are a source 13 of a beam of electrons and a target or collector electrode 14. The electron source 13 is shown schematically and will, in general, comprise an electron emissive cathode, a heater unit, an intensity control element, and an electrode arrangement for shaping and accelerating the electron beam. For the sake of simplicity these elements have been omitted from the figure. The target 14 serves as a collector of electrons and is, accordingly, maintained at a suitable potential positive with respect to the electron emissive cathode of source 13 by means of suitable lead-in connections from an adjustable voltage source 15. In general such a device is provided with a magnetic assembly or other suitable means not here shown, for focusing the electron beam throughout its travel along the path from the cathode 13 to the collector 14. Located intermediate the ends of the elongated envelope 12 is a first cavity resonator 16 which is preferably of highly conductive material. The resonator 16 may, as shown in Fig. 1, be incorporated into the elongated envelope 12 as a part thereof or it may be mounted externally in the envelope in a manner well known in the art. Cavity resonator 16 is provided with a first hollow reentrant portion 17 open at both ends, and a second hollow reentrant portion 18 also open at both ends. Between the interior ends of the two reentrant portions is located a hollow conductive member 19 defining a drift space within the resonator, the function and dimension of which will be discussed more fully hereinafter. The interior end of reentrant portion 17 and one end of member 19 are in close proximity to each other, thereby defining a narrow gap 21 past which the electron beam is projected. The interior end of reentrant portion 18 and the end of member 19 adjacent thereto are likewise in close proximity and define a narrow gap 22, past which the electron beam is projected. It is to be understood that while cavity 16 has here been shown as comprising reentrant portions for defining a narrow gap, other suitable geometric configurations might be used, and the arrangement here shown for resonator 16, as well as for the remaining resonators to be discussed hereinafter, is intended merely to be by way of illustration. An output coupling means 23 for abstracting energy from the resonator 16 communicates with the interior of the resonator and is connected to a dissipative load 24 through a suitable transmission line 26.

Downstream of cavity 16, that is to say at a point along the axis of the beam more remote from the electron gun than cavity 16, is a second resonant cavity 27 which, like cavity 16, may form a part of the evacuated envelope 12 or may be mounted externally thereof. Cavity 27, which structurally is quite similar to cavity 16, is provided with first and second hollow reentrant portions 28 and 29 and a hollow conductive member 31 which, with reentrant portions 28 and 29, defines a pair of spaced gaps 32 and

33. As was the case with resonator 16, the length of the member 31 and hence the spacing between the gaps will be explained more fully hereinafter. Resonator 27 is provided with an input means 34 which is connected through a suitable transmission line 36 to a source of radio-frequency power 37, which is provided with an adjusting member 38 for varying the phase of the power which is delivered from source 37 to resonator 27.

Downstream of resonator 27 is located a third resonator 39 which, as was the case with resonator 16 and 27, may form a part of envelope 12 or may be mounted externally thereof. Resonator 39 comprises first and second hollow reentrant portions 41 and 42 which, with a hollow conducting member 43, form a pair of gaps 44 and 46. Resonator cavity 39 is supplied with signals to be amplified from a signal source 47 through a suitable transmission line 48 and an input coupling means 49.

Downstream of resonator 39 and spaced therefrom by a drift space 51 is located a fourth cavity resonator 52 which is designed to resonate at the signal frequency. Resonator 52, which may be mounted externally of the envelope or made integral therewith, comprises first and second hollow reentrant portions 53 and 54 which, with a hollow conducting member 56, form a pair of gaps 57 and 58. An output coupling means 59 communicates with the interior of the cavity 52 and abstracts energy therefrom which is fed through a suitable transmission line 61 to a utilization device such as load 62.

In operation an electron beam is formed and projected from the source 13 to the collector 14, and passes axially through each of the cavity resonators in turn. As was explained in the foregoing, the electron beam is characterized by having noise modulation both in the fast and slow mode after it leaves the source 13. Cavity 16 is made resonant at the midband frequency of the signals to be amplified, and in a manner which will be more fully explained hereinafter, as the beam passes through cavity 16 it gives up noise energy in the signal frequency range and in the fast wave mode to the cavity 16. This noise energy is then extracted from the cavity through the output coupling means 23 and is dissipated by member 24. The beam upon emerging from cavity 16 is then substantially completely free of noise modulations in the fast mode within the frequency range of the signal to be amplified, although there still remain on the beam noise modulations in the slow wave mode and in the fast wave mode outside of the signal frequency range. As the beam passes through cavity 27, which is made resonant at the radio-frequency power frequency which in the present embodiment is twice the signal frequency, it is modulated in a manner which will be explained more fully hereinafter, in the fast wave mode by the radio-frequency power frequency so that when the beam emerges from cavity 27 it has impressed thereon radio-frequency energy in the form of velocity modulations over and above the energy of the beam prior to its entry into cavity 27. As the beam passes through cavity 39 is it modulated in the same manner as it was modulated in cavity 27 by the signal to be amplified, cavity 39 being resonant at the signal frequency, so that when it emerges from cavity 39 it has impressed thereon, in addition to the radio-frequency modulations at twice the signal frequency, modulations at the signal frequency, all in the form of velocity modulations. In passing along the drift region 51 the radio-frequency modulations on the beam are converted into density modulations and, as will be explained more fully hereinafter, the radio-frequency modulations at the signal frequency grow exponentially during passage along the drift region 51 so that as the beam enters cavity 52 it has greatly increased signal energy in the form of density modulations on the beam. In passing through cavity 52 the beam gives up this amplified signal energy to the cavity in a manner to be explained more fully hereinafter. This amplified sig-

nal energy is then abstracted through output means 59 and applied for utilization to the load 62.

For a more complete understanding of the amplification phenomenon, which occurs in the operation just described, the following analysis will be helpful.

In the arrangement of Fig. 1, for simplicity we assume that the velocity on the electron beam of the fast wave at twice the signal frequency is the same as for the fast wave at the signal frequency, and that the modulation on the beam is large, but can be analyzed with the linear theory.

The well-known equations which relate velocity and current in an electron stream, as derived from Poisson's equation, the equation of continuity, and the equation of motion are

$$\frac{\partial^2}{\partial t \partial z} \left(\frac{v^2}{2} \right) + \frac{\partial^2 v}{\partial t^2} = \frac{\mu_0}{I_0} \omega_q^2 i \quad (1)$$

and

$$v^2 \frac{\partial i}{\partial v} = -v \frac{\partial i}{\partial t} + i \frac{\partial v}{\partial t} \quad (2)$$

where

v is the electron stream velocity

i is the electron stream current

t is time

z is distance along the stream

μ_0 is the direct-current velocity of the stream

I_0 is the direct-current of the stream, and

ω_q is the plasma frequency for a cylindrical beam.

Solving Equations 1 and 2 for v and i , and assuming only a single modulation frequency we obtain

$$i = -I_0 + i e^{-j\beta_e \left(1 \mp \frac{\omega_q}{\omega} \right) Z + j\omega t} \quad (3)$$

$$v = \mu_0 \mp \frac{\omega_q}{\omega} \frac{\mu_0}{I_0} i e^{-j\beta_e \left(1 \mp \frac{\omega_q}{\omega} \right) Z + j\omega t} \quad (4)$$

where

$$\beta_e = \frac{\omega}{\mu_0}$$

and $\omega = 2\pi f$ where f is the signal frequency.

From Equations 3 and 4 it can be seen that the alternating current and velocity are related in the past wave by

$$v_{\text{fast}} = -\frac{\omega_q}{\omega} \frac{\mu_0}{I_0} i_{\text{fast}} \quad (5)$$

It is well known that the kinetic power carried by an electron beam is given by

$$P = I_0 V_0 - \frac{\mu_0}{\eta} v i \quad (6)$$

where η is the ratio of charge to mass of the electron and V_0 is direct-current beam voltage and therefore, for a beam carrying the fast wave, the kinetic power becomes

$$P_{\text{fast}} = I_0 V_0 + \frac{\omega_q}{\omega} \frac{2V_0}{I_0} i_{\text{fast}}^2 \quad (7)$$

which bears out the previous statement that in the presence of the fast wave the kinetic power of the beam is increased.

Equations 3 through 7 and the analysis pertaining thereto may be found in the aforementioned article by Haus and Robinson.

Considering now the case where the beam is modulated with radio-frequency power at a frequency $2f$ at a high level in the fast wave mode, and with a low level

signal at a frequency f in the fast wave mode, from Equations 1 through 4 we obtain

$$i = -I_0 + \frac{m}{2} I_0 e^{-2j\beta_q \left(1 - \frac{\omega_q}{\omega}\right) Z + 2j\omega t} + i_{01} e^{\mu\beta_q Z - j\beta_q \left(1 - \frac{\omega_q}{\omega}\right) Z + j\omega t} + \text{c.c.} \quad (8)$$

and

$$v = \mu_0 - \frac{\omega_q}{\omega} \frac{m}{2} e^{-2j\beta_q \left(1 - \frac{\omega_q}{\omega}\right) Z + 2j\omega t} + v_{01} e^{\mu\beta_q Z - j\beta_q \left(1 - \frac{\omega_q}{\omega}\right) Z + j\omega t} + \text{c.c.} \quad (9)$$

where c.c. is the complex conjugate, m is an expression for the depth of modulation and is a complex term of the form $m = |m|e^{j\Phi}$, $i_{01}e^{\mu\beta_q Z}$ is an expression for the signal current, μ is the propagation constant in the presence of the pump, β_q is equal to ω_q/μ_0 , and $v_{01}e^{\mu\beta_q Z}$ is an expression for the signal velocity.

Substituting Equations 8 and 9 into Equations 1 and 2, combining and simplifying, we obtain an expression for μ , which is

$$\mu^4 + 4\left(1 - \frac{|m|^2}{8}\right)\mu^2 - \frac{9|m|^2}{4} = 0 \quad (10)$$

from which we obtain

$$\mu_1 = \frac{3|m|}{4} \quad (11)$$

$$\mu_2 = -\frac{3|m|}{4} \quad (12)$$

$$\mu_3 = -j2 \quad (13)$$

$$\mu_4 = +j2 \quad (14)$$

Of primary interest to us are the expressions for μ_1 and μ_2 , which represent waves traveling at the velocity of the fast wave, μ_1 being a wave which grows exponentially, and μ_2 a wave which decreases exponentially. Thus, from Equations 10 and 11, it is clearly evident that there is an exponentially growing wave at the signal frequency when the beam is modulated in the fast wave mode with frequencies f and $2f$.

From Equations 10 through 14, it can be seen that at $z=0$, the beam velocity is made up of four components, thus

$$v_{01} + v_{02} + v_{03} + v_{04} = v_{in} \quad (15)$$

By substituting Equations 8 and 9 into 1 and 2, and by use of Equations 10 through 14, we can obtain expressions for each of these velocity components. However, components v_{01} and v_{02} , which represent the growing and attenuating fast waves are of primary interest. It can be shown, then, by the above-mentioned steps, that

$$v_{01} = \frac{1}{2} \left(1 - j \frac{m}{|m|}\right) v_{in} = \frac{1}{2} (1 - je^{j\Phi}) v_{in} \quad (16)$$

$$v_{02} = \frac{1}{2} \left(1 + j \frac{m}{|m|}\right) v_{in} = \frac{1}{2} (1 + je^{j\Phi}) v_{in} \quad (17)$$

from which it is readily apparent that an amplified wave or an attenuated wave may be set up depending upon the phase of the modulation. If Φ is made equal to

$3\pi/2$, then, by use of Equations 9 through 14, it can be shown that

$$v_{out} = v_{in} e^{\frac{3|m|}{4} \omega_q L - j\beta_q \left(1 - \frac{\omega_q}{\omega}\right) L + j\omega t} \quad (18)$$

where L is the length of the electron beam, and

$$\text{Gain} = \left(\frac{v_{out}}{v_{in}}\right)^2 = 8.68 \frac{3|m|}{4} \beta_q L = 41 N_q \text{ db} \quad (19)$$

where N_q is the number of plasma wavelengths along the beam of length L .

The foregoing analysis clearly demonstrates that high gain is possible with the arrangement of Fig. 1, and that this gain becomes greater the longer the length of drift region 51, when the phase of the modulation is properly adjusted as by member 38 on the source 37. Although the analysis was based upon the assumption that the fast wave on the beam at frequency $2f$ travels at the same velocity as the fast wave on the beam at frequency f , this condition in practice does not generally obtain. However, it can readily be shown that for a wide range of velocity differences, high noise-free gain is still attainable if the principles of the present invention are followed.

In the foregoing discussion, it was assumed that energy in the fast wave mode was launched onto and extracted from the beam. In the case of the embodiment of Fig. 1, this is accomplished by resonant cavities 16, 27, 39, and 52. It is now necessary to consider how this is accomplished. In Fig. 2 there is shown a resonant cavity 71 which comprises first and second hollow reentrant portions 72 and 73 which form in conjunction with a hollow conductive member 74 a pair of interaction gaps 76 and 77. It can be seen that cavity 71 is substantially identical with cavities 16, 27, 39, and 52 in configuration. In practice there may be a pair of electron permeable members 78 on either side of gap 76 and members 79 on either side of gap 77 although these members are not necessary. These members aid in the establishment of an electric field across the gaps, thereby facilitating interaction with the beam.

If cavity 71 is excited so that there is a voltage V across each gap 76 and 77, the beam, after crossing the first gap is velocity modulated such that the radio-frequency velocity is given by

$$v_1 = \frac{\mu_0}{2V_0} (V + i_2 R) \quad (20)$$

where R is the shunt impedance of the gap. As a result of this velocity modulation, there will be at the second gap

$$v_2 = v_1 \cos \beta_q Z e^{-j\beta_q Z} \quad (21)$$

and

$$i_2 = -j \frac{I_0}{\mu_0} \frac{\omega}{\omega_q} v_1 \sin \beta_q Z e^{-j\beta_q Z} \quad (22)$$

beyond the second gap will be

$$i_3 = i_2 \quad (23)$$

$$v_3 = v_2 + v_1 \quad (24)$$

If the fast wave only is to be excited, it can be seen from Equation 5 that the following condition must obtain

$$\frac{\mu_0}{I_0} \frac{\omega_q}{\omega} i_3 = -v_3 \quad (25)$$

Combining Equations 21 and 22 with Equations 24 and 25, we obtain

$$\cos \beta_q Z - j \sin \beta_q Z = -e^{j\beta_q Z} \quad (26)$$

which holds for

$$\beta_q Z = \frac{\pi}{2} \quad (27)$$

and

$$\beta_e Z = \frac{\pi}{2} \quad (28)$$

Equations 27 and 28 clearly show that the spacing l between gaps 76 and 77 in cavity 71 must be one-quarter of a plasma wavelength and, since the electrical wavelength, that is, the exciting frequency wavelength is so much shorter than the plasma wavelength, l , to satisfy Equations 26, 27, and 28, must be $(4n+1)$ quarter wavelength of the exciting frequency, where n is an integer, if the fast wave is to be excited by cavity 71.

In a like manner it can readily be shown that to remove energy in the fast wave mode from the beam, the same spacing between gaps 76 and 77 must exist. It can further be shown that with this critical spacing, the slow wave on the beam will be unaffected by the cavity and will simply pass straight through.

Referring again to Fig. 1, each of the cavities 16, 39, and 52, which are resonant at the signal frequency, are maintained at a positive potential with respect to the cathode 13 by source 15. Source 15 is made adjustable so that the transit time of the beam between the gaps in each of cavities 16, 39, and 52 may be regulated. In this manner each of these cavities may be constructed so that the spacing between the gaps satisfies Equation 27 and then the direct-current velocity of the beam may be adjusted to satisfy Equation 28. Alternatively, each of these cavities may be maintained at the proper potential by means of a separate power supply or by other suitable means, the arrangement shown in Fig. 1 being intended merely by way of example. Additionally, a small power source may be inserted in series with the collector to permit maintaining it at a different potential if desired. Inasmuch as cavity 27 is made resonant at a frequency $2f$, the transit time of the beam between gaps 32 and 33 must be adjusted separately from that for cavities 16, 39, and 52, inasmuch as it will differ therefrom. To this end, cavity 27 is supplied from an adjustable potential source 30 so that it may be maintained at a different potential relative to the remaining cavities. As the electron beam enters each cavity in turn it will be accelerated or decelerated, depending upon the direct-current potential of the cavity, and, consequently, its transit time between the gaps in the cavity is determined by this direct-current potential.

In the embodiment of Fig. 1, resonant cavities were utilized to impress upon and extract from the beam energy in the fast wave mode. The use of resonant cavities may, under certain conditions, be disadvantageous where, for instance, broad band operation is desired. Thus, under certain conditions the use of slow wave circuits such as helices might be more desirable. In Fig. 3 there is shown an electron discharge device 101 which is basically similar in operation to the device 11 in Fig. 1 but which uses helices instead of resonant cavities to excite and extract the fast wave mode. For simplicity those elements in the device of Fig. 3 which are the same as the corresponding elements in the device 11 of Fig. 1 have been given the same reference numerals. The device 101 of Fig. 3 comprises an elongated evacuated envelope 12 having an electron gun 13 and a collector electrode 14 for forming and projecting an electron beam. A first cavity 16 is utilized, as was the case with the embodiment of Fig. 1, to extract noise energy in the fast wave mode from the beam. Axially disposed in the envelope 12 downstream of cavity 16 is an elongated conducting helix 102 for propagating an electromagnetic wave in interacting relationship with the beam. Radio-frequency power at a frequency $2f$ is applied from the power source 37 through a suitable coupling arrangement 103 to helix 102 for propagation therealong. It is to be understood that while the wave propagation circuit 102 is shown as a helix and the input coupling means 103 is shown as a helix, other types of wave propagation

circuits and input coupling means well known in the art may be used with equal effectiveness, those here shown being by way of illustration only. The downstream end of helix 102, that is, the end remote from the input coupling means 103, is terminated by a resistive termination 104 which may take any one of the forms well known in the art, being shown here as a ring of lossy material surrounding the helix. Termination 104 serves to suppress or dissipate any energy which may exist on the helix at its downstream end, thereby preventing reflections. Downstream of the helix 102 and axially disposed within envelope 12 is a helix 106 for propagating a wave in interacting relationship with the electron beam. Helix 106 is supplied through a suitable input coupling connection 107 with signal energy from signal source 47. The downstream end of helix 106 is terminated so as to be substantially reflectionless by a suitable termination 108. Downstream of helix 106 and spaced therefrom by a drift region 51 is a helix 109 for propagating a wave in interacting relation with the electron beam. The upstream end of helix 109 is terminated so as to be substantially reflectionless by a suitable termination 111. The downstream end of helix 109 is coupled to a suitable output coupling means 112 which in turn is connected through a suitable transmission line 61 to a load 62.

The operation of the device of Fig. 3 is quite similar to the operation of the device 11 in Fig. 1. The electron beam is projected through cavity 16 where the noise energy in the signal frequency range and in the fast wave mode is extracted from the beam and dissipated in dissipative member 24. After emergence from cavity 16 the beam passes in interacting relationship with helix 102 which has propagating therealong radio-frequency energy at a frequency $2f$. In a manner which will be explained more fully hereinafter helix 102 excites upon the beam energy at the frequency $2f$ in the fast wave mode. After emergence from helix 102 the beam passes through helix 106 and has excited thereon signal energy at a frequency f in the fast wave mode. In passing through the drift region 51 the velocity modulations on the beam are transformed to density modulations and the signal wave increases exponentially, and as the beam passes through helix 109 in interacting relationship therewith it gives up increased signal energy at a frequency f in the fast wave mode to the helix 109, from which the amplified signal is extracted and utilized.

In order that helices 102, 106, and 109 may excite on the beam and extract from the beam only energy in the fast wave mode it is necessary that these helices be designed to meet certain conditions. In an article entitled "A Coupled Mode Description of the Backward-Wave Oscillator and the Kompfner Dip Condition," by R. W. Gould, IRE Transactions on Electron Devices, vol. ED-2, No. 4, October 1955, pages 37-42, there is a discussion of a phenomenon known as the Kompfner Dip condition. This phenomenon occurs when a helix is propagating wave energy in the same direction as an electron beam is traveling in interacting relationship therewith. Where the helix voltage and length are properly chosen there will be no wave energy propagating on the helix at the downstream end thereof, all of the energy having been transferred to the beam in the fast wave mode. From the article it is readily seen that the Kompfner Dip occurs when the helix has a length such that CN is approximately equal to .314 and Cb is approximately equal to -1.515, where N is the length of the helix in wave lengths of the wave propagating therealong, C is a normalizing factor and

$$Cb = \frac{V_B - V_0}{2V_0}$$

where V_B is the voltage on the helix and V_0 is the beam voltage required to make the beam direct-current velocity synchronous with the velocity of propagation of the circuit. It can readily be seen that the Kompfner Dip con-

dition may be obtained for a given length of helix by adjusting the voltage on the helix and thereby the beam velocity and the beam current inasmuch as the factor C is dependent upon the beam current. To this end helix 102 is maintained at the proper potential by means of an adjustable potential source 113. Helices 106 and 109 are likewise maintained at the proper potentials by means of potential sources 114 and 116 respectively. These potential sources are adjusted until helices 102 and 106 will excite the fast wave mode on the beam at frequencies $2f$ and f , respectively and helix 109 will extract from the beam energy in the fast wave mode at a frequency f . It is to be understood that while the potential sources 113, 114, and 116 are shown as applying potential at a certain polarity to the helices, under certain conditions some or all of these polarities might be reversed and the arrangement shown is not intended to be restrictive. Likewise other suitable means for applying the proper potentials to the helices might be used, those here shown being merely by way of illustration.

In the embodiment illustrated in Fig. 3 it is necessary to adjust the potentials on several different helices as well as the potential of the electron gun 13, cavity 16 and the collector 14. Such a large number of adjustments makes it difficult to achieve optimum performance. In Fig. 4 there is shown another embodiment of the invention where the number of potential adjustments is reduced without impairing the operating efficiency. In Fig. 4 there is illustrated a device 201 which is substantially similar in operation to the embodiments illustrated in Figs. 1 and 3. For simplicity those elements in the device 201, which are the same as those in the device 101 in Fig. 3, bear the same reference numerals. Device 201 comprises an evacuated envelope 12 having an electron gun 13 and collector electrode 14 for forming and projecting an electron beam. A resonant cavity 16 is located downstream of the electron gun for extracting from the electron beam wave energy in the signal frequency range in the fast wave mode, as was explained in connection with Fig. 1. Downstream of cavity 16 and axially positioned within the tube for propagating wave energy in interacting relationship with the beam is a helix 102, which has its downstream end terminated in a reflectionless termination 104. Helix 102 is designed to modulate the electron beam in the fast wave mode with wave energy at a frequency $2f$ from radio-frequency power source 37 in the manner explained in connection with the embodiment of Fig. 3. Downstream of helix 102 and axially positioned within the tube for propagating wave energy in interacting relationship with the electron beam is a conductive helix 202. Helix 202 has applied thereto through a suitable input coupling connection 203 signal energy to be amplified from a source 47. At the downstream end of helix 202 suitable output coupling means is supplied to extract energy from the helix 202 and apply it through a suitable transmission line 61 to a utilization device 62. In order that amplification in the fast wave mode may be achieved it is necessary that the wave energy propagating along the helix be synchronized with the fast wave mode on the electron beam. As was pointed out earlier, the fast wave mode propagates along an electron beam at a velocity greater than the direct-current velocity of the beam in contradistinction to the slow wave mode which propagates along the beam at a velocity less than the direct-current velocity of the beam. It is necessary, therefore, that the beam as it travels along helix 202 in interacting relationship therewith, travel at a velocity slower than the velocity of the wave propagating along the helix to the extent that the fast wave mode on the beam is in synchronization with the wave propagating on the helix. To this end helix 202 is maintained at a suitable potential by means of an adjustable source of potential 206.

As the beam enters the helix it is decelerated by the potential on the helix until it is traveling at a velocity

such that the fast wave mode propagating on the beam is in synchronism with the wave energy propagating along the helix, in which case interaction between the fast wave mode on the beam and the wave energy on the helix takes place and amplification of the signal occurs.

In all of the foregoing embodiments a resonant cavity 16 was utilized to extract the noise energy in the fast wave mode from the beam. It is to be understood that a wave propagation circuit operating at the Kompfner Dip condition might just as easily be used and applicant does not intend to limit himself to the use of the cavity only. In all of the embodiments disclosed herein, the radio-frequency power source was stated to be at twice the frequency of the signal to be amplified. While such a frequency relationship materially simplifies analysis of the amplification phenomenon, it is not necessary that that relationship obtain. It can readily be shown that a wide range of frequencies might be used for the power source, without materially impairing the amplification of the signal, and it is intended that such other frequencies fall within the scope of the present invention. Additionally, while the elements for performing the functions of modulating the beam with both radio-frequency power and a signal to be amplified have been shown in a certain sequential arrangement, the sequence of these functions is not critical and the positions of the elements may be interchanged. It is to be further understood that the foregoing embodiments utilizing the principles of the invention are by way of illustrating those principles and that other different embodiments will be apparent to those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, said beam being characterized by the presence of both fast and slow mode noise waves thereon, first means positioned along said path for extracting from said beam fast mode noise waves, second means positioned along said path for modulating said beam in the fast mode with radio frequency energy, input means disposed along said path for introducing into fast mode coupling relationship with said beam a signal wave to be amplified, and output means downstream of said input means for extracting from the fast mode of the beam an amplified signal.

2. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, said beam being characterized by the presence of both fast and slow mode noise space charge waves thereon, first means positioned along said path for extracting from said beam fast mode noise space charge waves, second means positioned along said path for modulating said beam in the fast space charge wave mode at a predetermined frequency, third means positioned along said path for modulating said beam in the fast space charge wave mode with a signal to be amplified, and means downstream of said second and third means for extracting from the fast mode of said beam the amplified signal.

3. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, said beam being characterized by the presence of both fast and slow mode noise space charge waves thereon, first means positioned along said path for extracting from said beam fast mode noise space charge waves, second means positioned along said path for modulating said beam solely in the fast space charge wave mode with radio-frequency energy, third means positioned along said path for modulating said beam solely in the fast space charge wave mode with a signal to be amplified, and means downstream of said second and third means and separated therefrom by a drift region for extracting from said beam the amplified signal in the fast space charge wave mode.

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4. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, said beam being characterized by the presence of both fast and slow mode noise waves thereon, a resonant cavity adjacent a portion of said path for extracting from said beam fast mode noise waves, said cavity being resonant at the midband frequency of the band of frequencies to be amplified, first means positioned along said path for modulating said beam in the fast mode with radio-frequency energy, second means positioned along said path for modulating said beam in the fast mode with a signal to be amplified, and means downstream of said first and second means for extracting from the fast mode of said beam the amplified signal.

5. A high frequency amplifier as claimed in claim 4 wherein said resonant cavity comprises means defining first and second interaction gaps, said gaps being spaced from each other a distance equal to a quarter of a plasma wavelength.

6. A high frequency amplifier as claimed in claim 4 wherein said first means comprises a resonant cavity having means defining a pair of spaced interaction gaps therein, the distance between said gaps being one-quarter plasma wavelength.

7. A high frequency amplifier as claimed in claim 4 wherein said first means comprises a wave propagation circuit in fast mode interacting relationship with the electron beam.

8. A high frequency amplifier as claimed in claim 4 wherein said second means comprises a resonant cavity resonant at the signal frequency, said cavity having means defining a pair of spaced interaction gaps, the distance between said gaps being one-quarter plasma wavelength.

9. A high frequency amplifier as claimed in claim 4 wherein said second means comprises a wave propagation circuit in fast mode interaction relationship with said electron beam.

10. A high frequency amplifier as claimed in claim 4 wherein said means downstream of said first and second means comprises a resonant cavity resonant at the signal frequency, said cavity having means defining a pair of spaced interaction gaps, the distance between said gaps being one-quarter plasma wavelength.

11. A high frequency amplifier as claimed in claim 4 wherein said means downstream of said first and second means comprises a wave propagation circuit in fast mode interaction relationship with said electron beam.

12. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, said beam being characterized by the presence of both fast and slow mode noise waves thereon, first means positioned along said path in interacting relationship with said beam for extracting from said beam noise energy in the fast wave mode, second means positioned along said path in interacting relationship with said beam for modulating said beam in the fast wave mode only at a predetermined frequency, third means positioned along said path in interacting relationship with said beam for modulating said beam in the fast mode only with a signal to be amplified, means positioned along said path downstream of said second and third means in interacting relationship with said beam for extracting from said beam the signal energy on said beam in the fast wave mode only, and means for controlling the transit time of electrons in the beam past each of said means.

13. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, said beam being characterized by the presence of both fast and slow mode noise waves thereon, first means positioned along said path in interacting relationship with said beam for extracting from said beam noise energy in the fast wave mode, second means positioned along said path in interacting relationship with said beam for modulating said beam in the fast wave mode only with radio frequency energy, third means positioned along said path

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in interacting relationship with said beam for modulating said beam in the fast mode only with a signal to be amplified, fourth means positioned along said path downstream of said first, second, and third means in interacting relationship with said beam for extracting from said beam a signal energy on said beam in the fast wave mode only, means for controlling the transit time of electrons in the beam past each of said first, third, and fourth means, and separate means for controlling the transit time of electrons in the beam past said second means.

14. A high frequency amplifier as claimed in claim 13 wherein said fourth means is separated from said third means by a drift region.

15. A high frequency amplifier as claimed in claim 14 wherein each of said first, second, third, and fourth means comprises a resonant cavity.

16. A high frequency amplifier as claimed in claim 14 wherein each of said second, third, and fourth means comprises a wave propagation circuit in fast mode interaction relationship with said beam.

17. An electron discharge device comprising an evacuated envelope, means at one end of said envelope for forming and projecting an electron beam axially of said envelope, target means at the other end of said envelope for collecting electrons in the beam, first means positioned downstream of said beam forming means in interacting relationship with said beam for extracting from said beam noise energy in the fast wave mode only, means connected to said first means for dissipating the energy thus extracted, second means positioned downstream of said first means in fast mode interacting relationship only with said beam, a source of high frequency energy, means applying said energy to said second means whereby said beam is modulated in the fast mode only with said high frequency energy, third means positioned downstream of said first means in fast mode interacting relationship only with said beam, a source of signals to be amplified, means for applying said signals to said third means whereby said beam is modulated in the fast mode only by the signals to be amplified, fourth means positioned downstream of said third means in fast mode interacting relationship only with said beam, and an output means coupled to said fourth means for extracting therefrom an amplified signal.

18. An electron discharge device as claimed in claim 17 wherein said first means comprises a resonant cavity resonant at the midband frequency of the signals to be amplified, said cavity comprising means forming first and second interaction gaps therein, said interaction gaps being spaced a quarter plasma wavelength apart, and means for controlling the transit time of electrons in the beam between said gaps.

19. An electron discharge device as claimed in claim 18 wherein each of said second, third, and fourth means comprises a resonant cavity, each of said cavities having means defining a pair of interaction gaps therein, the distance between each of the interaction gaps being a quarter plasma wavelength, said third and fourth means being resonant at the midband frequency of the signals to be amplified, and said second means being resonant at a different frequency.

20. An electron discharge device as claimed in claim 18 wherein each of said second, third, and fourth means comprises a wave propagation circuit in interacting relationship with said beam, and means for operating each of said circuits in the Kompfner Dip condition, including means for controlling the beam velocity past each of said propagation circuits.

21. An electron discharge device comprising an evacuated envelope, means within said envelope at one end thereof for forming and projecting an electron beam axially therealong, target means at the other end of said envelope for collecting electrons in the beam, first means positioned downstream of said beam forming means in interacting relationship with said beam for extracting

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from said beam noise energy in the fast wave mode only, means for dissipating the energy thus extracted, second means positioned downstream of said first means in fast wave mode interacting relationship only with said beam, a source of radio-frequency energy, means coupling energy from said source to said second means for modulating said beam in the fast wave mode only, wave propagation means downstream of said second means defining an interaction region with said electron beam, a source of signals to be amplified, means coupling signals from said source to said wave propagation means, means for maintaining the velocity of said beam as it passes through said interaction region at less than the velocity of the signal waves propagating along said circuit, and output means for extracting an amplified signal from said circuit.

22. The combination as claimed in claim 21 wherein said first means comprises a resonant cavity resonant at the midband frequency of the signals to be amplified, said cavity having means forming a pair of spaced interaction gaps therein, the distance between said gaps being a quarter plasma wavelength, and means for controlling the transit time of electrons in the beam between the two gaps.

23. The combination as claimed in claim 21 wherein said second means comprises a wave propagation circuit, and means for operating said circuit in the Kompfner Dip condition.

24. A high frequency amplifier comprising an electron gun for projecting a beam of electrons along a path to a collector, four coupling means for coupling to the fast space charge wave mode of the electron beam, the first two of said coupling means comprising means for removing fast mode noise space charge waves from said beam in the frequency range of the signal to be amplified and means for supplying high frequency energy in the fast space charge wave mode to said beam, and the last two of said coupling means comprising means for modulating said beam in the fast space charge wave mode with an input signal to be amplified and means for removing from the fast mode of the beam the amplified signal.

25. A high frequency amplifier as claimed in claim 24

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wherein said last two of said coupling means are spaced from each other by a drift region.

26. A high frequency amplifier as claimed in claim 24 wherein said last two of said coupling means are spaced from each other by a delay type transmission circuit.

27. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, first means positioned along said path for modulating said beam in the fast space charge wave mode with radio-frequency energy, input means disposed along said path for introducing into fast mode coupling relationship with said beam a signal wave to be amplified, and output means downstream of said input means for extracting from the fast space charge wave mode of the beam an amplified signal.

28. A high frequency amplifier comprising means for forming and projecting an electron beam along a path, first means positioned along said path for modulating said beam in the fast space charge wave mode with radio-frequency energy, second means positioned along said path for modulating said beam in the fast space charge wave mode with the signal to be amplified, and means downstream of said second means and separated therefrom by a drift region for extracting from the fast space charge wave mode of said beam the amplified signal.

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Notice of Adverse Decision in Interference

In Interference No. 92,484 involving Patent No. 2,974,252, C. F. Quate,
LOW NOISE AMPLIFIER, final judgment adverse to the patentee was rendered Mar. 4, 1965, as to claims 1 and 12.
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