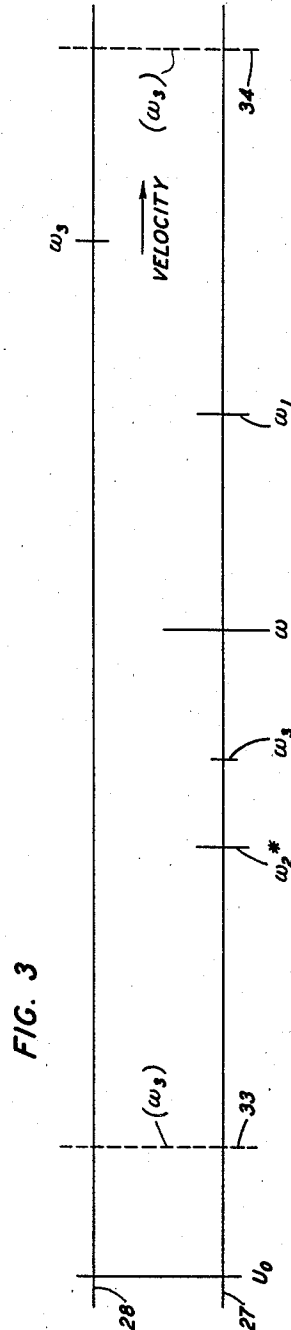
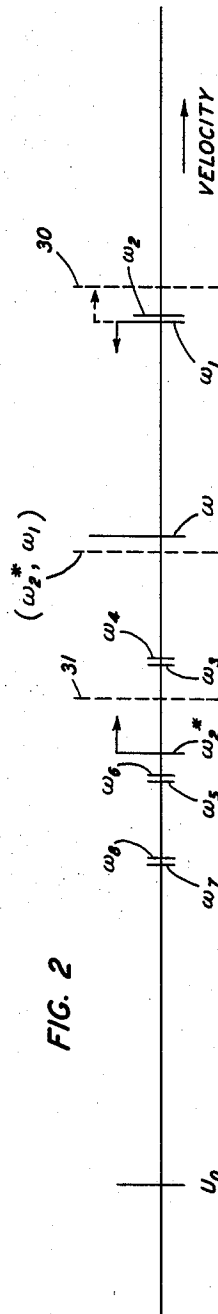
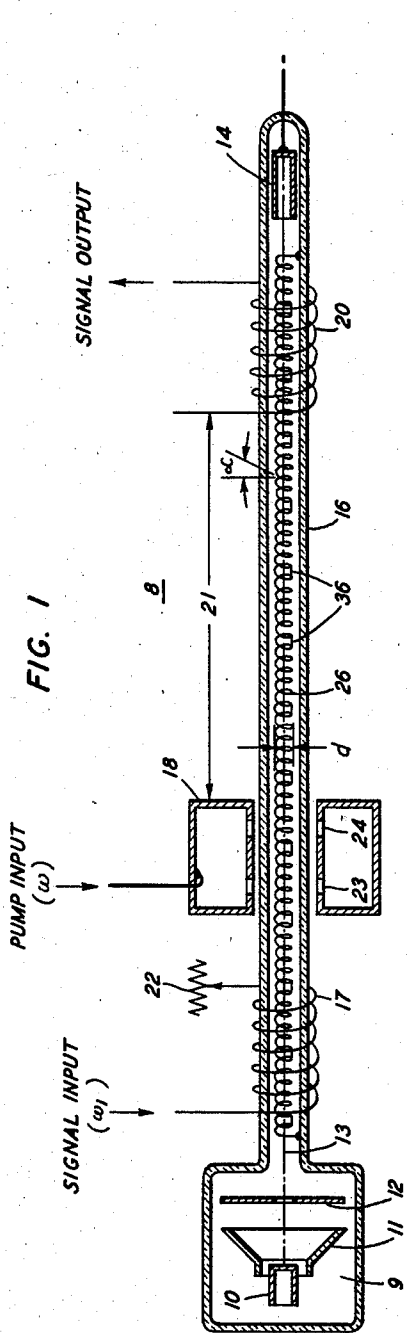


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A. ASHKIN ET AL
PARAMETRIC AMPLIFIER
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INVENTORS: A. ASHKIN
J. S. COOK
W. H. LOUISELL
C. F. QUATE
BY *David P. Kelley*
ATTORNEY

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2,958,001

PARAMETRIC AMPLIFIER

Arthur Ashkin, Bernardsville, John S. Cook, New Providence, and William H. Louisell, Summit, N.J., and Calvin F. Quate, Albuquerque, N. Mex., assignors to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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This invention relates to high frequency electron discharge devices and more particularly to 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 the 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 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., 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 is often referred to as 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 two possible phase velocities. In other words, the transmission line that is being considered, the electron beam, presents two possible propagation constants to each wave of a particular frequency which independently propagates therealong. 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 in which it propagates. Another characteristic of the beam is that it is dispersive, e.g., the "fast" space charge wave phase velocity varies in inverse proportion to its frequency. It can further be shown that the "fast" phase velocity at any given frequency is higher than the average or D.C. velocity of the unmodulated beam, whereas the "slow" phase velocity is less than the beam's D.C. velocity. We therefore find that the entire frequency spectrum of waves which may propagate along the beam represents 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 wave propagation at a velocity higher than the D.C. velocity is often referred to as the fast space charge mode, while the spectrum of phase velocities which represent wave propagation at a velocity lower than the D.C. velocity is referred to as the slow space charge mode.

In the conventional traveling wave tube, interaction takes place between an electromagnetic wave propagating along a slow wave structure and the electron beam with resulting amplification of the electromagnetic wave. Such

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interaction is the result of strong coupling between the electromagnetic wave and the beam in the slow space charge mode. This coupling phenomenon, which may be referred to as active coupling, is extensively treated in the book entitled "Traveling-Wave Tubes," by J. R. Pierce, D. Van Nostrand & Company, Incorporated, 1950. If the wave couples to the beam in the fast space charge mode, no amplification takes place in the conventional tube. This form of coupling may be referred to as passive coupling and is analogous to ordinary inductive or capacitive coupling between transmission lines. The Pierce book, for obvious reasons, refers to the fast space charge mode as the passive mode, and the slow space charge mode as the active mode.

The unique characteristics of the slow space charge mode which permit active coupling and, hence, amplification are, however, also disadvantageous in that they do not permit spurious noise frequencies which are inherent in the beam to be extracted. Since kinetic power is proportional to velocity, any power transmitted in the 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 power fluctuations below the level of the D.C. power one would have to add power to the beam in proper phase, frequency and amplitude relationship to the noise frequency components. Since the inherent noise waves are produced by such unpredictables as random emission, the impracticability of such a method is obvious. Once such spurious noise waves have coupled with the signal wave on the beam, they are inseparable therefrom; therefore one is limited, in general, to methods of reducing noise power in the region adjacent the electron gun. These methods of reducing slow space charge mode noise power are limited by the minimum noise figure mentioned previously.

In the copending application of C. F. Quate, Serial No. 698,854, filed November 25, 1957, there is disclosed a completely different approach to the problem of reducing noise in a traveling wave tube. 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 level higher than the D.C. power, it can be conveniently extracted from the beam through the use of any of a number of devices which permit total transfer of power between two transmission lines.

There are numerous ways, through familiar analogies etc., by which the phenomenon of parametric amplification in a traveling wave tube may be analyzed. Suffice it to say that if one mixes a particular predetermined "pump" frequency with a lower frequency signal propagating in the fast space charge mode of a beam, a lower sideband "idle" frequency will be produced which is of a frequency equal to the difference between the pump and signal frequencies. Under certain conditions strong active coupling may be induced between the signal and the fast space charge mode "idle" frequency which results from signal modulation and, hence, amplification may be attained. One embodiment of the device disclosed in the aforementioned Quate application therefore has the following placed axially along the electron beam: Apparatus for extracting fast mode noise waves from the beam; apparatus for coupling pump power at a predetermined frequency onto the beam; apparatus for coupling a signal to be amplified onto the beam; a drift region for allowing the signal and pump frequencies to mix, thereby effecting parametric amplification of the signal wave; and apparatus for extracting fast mode signal power from the beam.

Although the aforementioned device offers many obvi-

ous advantages over the conventional traveling wave tube, certain deleterious second order effects have become apparent. Devices such as resonant cavities or Kompfner-Dip helices, which can be used for removing or "stripping" fast mode noise energy, inherently present limited bandwidth characteristics and therefore can be effective in removing fast mode noise waves only over a predetermined bandwidth corresponding to that of the signal frequencies to be amplified. It has been found, however, that certain noise frequencies above the signal band unfortunately tend to couple inseparably with the signal wave.

For purpose of illustration, the mixing of the pump and signal frequencies can be considered as being analogous to the mixing of carrier and signal frequencies in the familiar case of amplitude modulation. The "first lower sideband" which is produced by this mixing is generally referred to as the idle frequency and, as previously pointed out, it is this idle frequency which actively couples to the signal frequency to provide parametric amplification. As will be explained hereinafter, other "lower sideband frequencies" are not produced. A spectrum of higher frequencies is also produced by the mixing of signal and pump frequencies and, inasmuch as these frequencies correspond to those produced through amplitude modulation, they will be hereinafter referred to as "upper sideband frequencies." It should be pointed out that recent literature in the art has referred to these "upper sideband frequencies" as "higher harmonics"; this term will not be used since, as will become obvious hereinafter, it is clearly a misnomer.

Although the first upper sideband, with a frequency equal to the sum of the pump and signal frequencies, will not ordinarily couple actively with the signal it does, however, represent a frequency which will passively couple with the signal frequency under normal conditions. In many practical cases, the first upper sideband also represents a frequency which is above the band of fast mode noise frequencies which have been "stripped" from the beam. Fast mode noise energy at the first upper sideband frequency will, therefore, normally couple to the signal wave and be parametrically amplified therewith. It is also found that the second upper sideband couples with the first, the third upper sideband with the second, and through like successive coupling according to frequency, all of the upper sideband frequencies are effectively coupled to the signal wave. In some cases the coupling between the upper sideband frequencies may not be very strong. It can be appreciated, however, that the amplification of spurious noise waves at all of these upper sideband frequencies, most of which are above the signal frequency bandwidth, may result in a very significant quantity of undesired noise power at the output.

Another disadvantage of the aforementioned device is the production of upper sidebands through the mixing of the pump and idle frequencies. The sideband frequencies thereby produced couple passively to the idle frequency and introduce spurious noise energy thereto in the same manner by which the previously discussed sidebands introduce noise energy to the signal wave. As will be explained, the upper sideband frequencies resulting from the mixing of pump and signal waves are usually approximately equal in frequency to the upper sidebands resulting from the mixing of pump and idle waves. The unqualified phrase "upper sideband frequency" will therefore hereinafter refer to both of these series of upper sideband frequencies.

Besides the coupling of noise onto the signal, the presence of upper sideband frequency waves results in other deleterious effects. The passive coupling of one upper sideband to the idle frequency and another upper sideband to the signal frequency tends to weaken the effect of active coupling between the idle and signal frequencies which is necessary for desired parametric amplification. The stronger the upper sideband passive coupling be-

comes, the less effective becomes the active coupling between idle and signal. As will be explained hereinafter, amplification will not occur unless the active coupling between the signal and idle waves is very strong. Therefore, it becomes necessary, in the Quate device, to employ other means for strengthening the necessary active coupling and compensating for the degrading effects of the upper sideband frequency waves.

Generally speaking, one may induce stronger active coupling between the idle and signal waves in a traveling wave tube parametric amplifier by increasing the pump power. When the pump frequency is introduced on the beam, however, pump harmonic frequencies are produced due to the nonlinear characteristics of the beam. Increasing the power of the pump frequency also increases the power of these higher frequency harmonics. As the pump harmonics are increased in power, they may, in turn, induce active coupling between the upper sideband frequencies and the signal and/or idle frequencies according to the same phenomenon by which the pump fundamental induces active coupling between the idle and signal frequencies. Of course such spurious interaction may seriously hamper desired operation of the tube.

Accordingly, it is an object of this invention to reduce the pump power required for operation of a velocity modulation device of the parametric amplifier type.

It is another object of this invention to increase the gain of a velocity modulation device of the parametric amplifier type.

It is still another object of this invention to eliminate the effects of noise power on the electron beam of a velocity modulation device.

It is a further object of this invention to eliminate the effects of upper sideband frequency power on the beam of a velocity modulation device of the parametric amplifier type.

It is a corollary object of this invention to prevent upper sideband power from coupling to the signal wave on the beam of a velocity modulation device of the parametric amplifier type.

Since, as previously pointed out, the upper sideband frequencies couple successively, each to the next lower frequency, one may eliminate their deleterious effects by preventing the first upper sideband from coupling to the signal wave. We have found that this may be accomplished by creating a large difference in the phase velocities of the first upper sideband frequency and the signal frequency.

Accordingly, it is still another object of this invention to separate, in terms of phase velocity, the first upper sideband frequency wave from the signal wave on the beam of 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 and collector at opposite ends for projecting an electron beam along an extended path therebetween. An input device such as a "Kompfner-Dip" helix is positioned along the path of flow for transferring signal energy from an outside source to the beam and for extracting the fast mode noise content of the beam in the band of frequencies to be amplified. Downstream from this helix is positioned a device such as a cavity resonator for modulating the electron beam with "pump" energy which is at a frequency higher than the signal frequency. Adjacent the cavity resonator, and downstream therefrom, is a "drift" region where the pump wave is allowed to mix with the signal wave. The signal wave is thereby amplified in the drift region through the parametric amplification process as described in the aforementioned Quate application. Downstream from the drift region is an output device such as a "Kompfner-Dip" helix for transforming ampli-

fied fast space charge mode signal energy on the beam into electromagnetic wave energy at the helix output. As the pump and signal frequencies mix in the drift region, upper sideband frequencies are produced which are potentially deleterious for the reasons given above.

It is a feature of this invention to utilize in the "drift" region an auxiliary slow wave structure in passive coupling relationship to the beam for the purpose of eliminating the deleterious effects of the upper sideband frequencies.

It is another feature of this invention that the auxiliary slow wave structure have such predetermined propagation characteristics as to allow coupling with the beam in the fast space charge mode at a frequency representative of the previously mentioned first upper sideband. This is accomplished by providing the structure with a propagation constant at the first upper sideband frequency which approaches the propagation constant of the first upper sideband frequency in the fast space charge mode of the beam. As previously mentioned, coupling to the fast space charge mode is passive coupling and is analogous to electric or inductive coupling to an ordinary transmission line. The closer that the propagation constants at the first upper sideband frequency of the structure and the fast space charge mode of the beam approach coincidence, the stronger the effective coupling between the two will be.

It is not intended that any energy be transmitted along the auxiliary slow wave structure. If, however, any transmission line is placed in coupling relationship with a second transmission line, the propagation characteristics of the second transmission line, at the frequency at which coupling occurs, is changed. This can be appreciated by bearing in mind the following: If two transmission lines are inductively coupled together at a particular frequency, a wave at that frequency will propagate on the coupled system at a velocity either greater or less than the uncoupled velocity of either line, depending upon the additive or subtractive effect of mutual inductance. Hence, the propagation constant of both lines, at that particular frequency, is effectively changed. In the present invention the deleterious effect of upper sideband noise is a result of the coupling between the first upper sideband and the signal in the fast mode of the beam. By radically changing the velocity of the first upper sideband in the fast mode on the beam, through coupling with the auxiliary slow wave structure, the signal and first upper sideband frequencies can be thrown so far out of synchronism as to make the effective coupling therebetween negligible. Accordingly, it is another feature of this invention that the auxiliary slow wave structure be effective in separating, in terms of fast mode phase velocity, the first upper sideband from the signal wave.

While the utility of the instant invention requires strong coupling between the auxiliary slow wave structure and the beam at the first upper sideband frequency, it is not desirable that such coupling take place at the pump, signal or idle frequencies. If coupling at these frequencies does take place, it can be appreciated that the velocities of the waves traveling at these frequencies on the beam will be changed such that the active coupling necessary for amplification might be seriously degraded. It is accordingly a feature of one embodiment of this invention that the slow wave structure be of the filter type and include stop-bands at the pump, signal and idle frequencies.

We have found that in some cases it may be more desirable to limit the aforementioned deleterious coupling at the signal, pump and idle frequencies by other methods. By making the auxiliary slow wave structure highly dispersive with respect to the beam, one can effect a large separation of the propagation constants of the structure at the signal, pump, idle and first upper sideband frequencies. In such a case, the close correspond-

ence of propagation constants of the beam and structure at the first upper sideband frequency necessarily results in a large difference between the propagation constants of the structure and the beam at the other frequencies. Since the effective coupling between the beam and slow wave structure at a given frequency is inversely proportional to the difference between the propagation constants at that frequency, it can be seen that one can substantially eliminate undesired coupling through the use of a highly dispersive slow wave structure which creates a large separation between the propagation constants of the various frequencies.

It is accordingly a feature of another embodiment of this invention that the slow wave structure be highly dispersive with respect to the dispersive nature of the beam.

It is yet another feature of this invention that the auxiliary slow wave structure be of such a high resistance as to prohibit any electromagnetic wave from propagating along the entire length thereof. As previously mentioned, it is not intended that any wave be transmitted along the auxiliary helix, since its sole purpose is to prevent, by velocity separation, the coupling between upper sideband frequency noise waves and the signal wave. The structure is therefore made highly resistive to insure that the waves induced therein may be attenuated and thereby prevent undesired oscillation in the forward or backward traveling wave tube modes.

These and other features of the present invention will be understood more clearly and 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 spectrum of velocities which may exist on an electron beam of a device of the type shown in Fig. 1; and

Fig. 3 is a pair of graphs which illustrate the correlation of the velocity spectra which may exist respectively on the electron beam and the slow wave structure 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 8 including an electron gun 9. For purposes of illustration, electron gun 9 is shown as comprising a cathode 10, a beam forming electrode 11, and an accelerating anode 12, which jointly coact to form and project an electron beam, schematically shown as 13, toward a collector 14. A vacuum is maintained within tube 8 by envelope 16 which is shown as being made of glass, but may be of any of a number of other suitable materials. Suitable means for focusing the electron beam is used but, for the sake of clarity, is not shown. Downstream from the electron gun, that is, at a point closer than the gun to collector 14, is a noise extraction and signal input helix 17, the function of which will be explained hereinafter. Downstream from helix 17 is a pump resonator 18 for introducing a pump frequency, shown by the pump input arrow, onto the beam 13. Downstream from resonator 18 and adjacent collector 14 is a signal output helix 20. Output helix 20 and resonator 18 define a drift region 21 therebetween. Voltage sources are, of course, employed to maintain predetermined potentials on certain described elements but, since such circuitry is well known in the art, it has been omitted in interest of clarity.

Electron beam 13 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 respectively referred to as the fast mode and the slow mode. Although the electron gun 9 is designed to project a beam of electrons which approaches a constant, unvarying current density, certain fluctuations in current density are inherent. These fluctuations propagate in both the fast and slow modes and will be hereinafter referred to as noise waves.

Input helix 17 is designed according to the principles of the well-known Kompfner-Dip and, as such, is effective in completely transferring signal energy, designated by the signal input arrow, onto the beam. The propagation characteristics of helix 17 are so chosen that any input signal, within a predetermined bandwidth, will modulate the electron beam in the fast mode. Helix 17 performs a dual function in that it is also effective in removing fast mode noise waves from the beam which exist within the aforementioned bandwidth. The extracted noise energy is then transmitted to, and dissipated by, resistor 22. Various other structures such as velocity pump transducers can be advantageously used in conjunction with helix 17 as disclosed in the copending application of A. Ashkin, Serial No. 743,672, filed June 23, 1958. It is to be understood also that other different schemes and combinations can be used for the purposes of introducing a signal wave and extracting noise from the beam. For example, a separate resonator may be used for each of these functions as is disclosed in the aforementioned Quate application. Further, separate Kompfner-Dip helices can be used, or a combination of a helix and a resonator.

Pump energy, which is at a frequency higher than the signal frequency, is used to modulate the beam in the fast mode through the use of cavity resonator 18, which is resonant at the pump frequency. Reentrant portions 23 and 24 are advantageously positioned to insure a proper predetermined synchronism with the signal wave propagating on the fast mode of the beam as is fully explained in the aforementioned Quate application. Again, it is to be understood that the pump input circuit is shown as a resonator only for purposes of illustration.

Subsequent to the introduction of the pump wave onto the fast mode of the beam, parametric amplification begins to take place. In the drift region 21 the signal wave is mixed with the pump wave which results in the production of an idle wave having a frequency equal to the difference in frequency of the pump and signal waves. The parametric amplification phenomenon is rigorously treated in the aforementioned Quate application. For purposes of the present disclosure one may state that the pump wave induces strong active coupling between the signal and idle frequencies, such coupling resulting in exponential growth of the coupled wave.

The signal wave is therefore allowed to grow, or be amplified, in the drift region 21 and is thereafter extracted through the use of Kompfner-Dip helix 20. A resonator for this purpose is disclosed in the aforementioned Quate application and could equally well be used in the present embodiment.

The mixing of the pump and signal frequencies and the pump and idle frequencies in the drift region 21 results in the production of two spectra of upper sideband frequencies which are potentially deleterious since they may reduce desired gain and introduce spurious noise. To eliminate these undesired effects an auxiliary filter helix 26 is included in drift region 21. The function of auxiliary helix 21 can be better understood after a brief discussion of the nature of electron beam 13.

Fig. 2 is a graph which illustrates, among other things, the dispersive nature of the electron beam. It is a one-dimensional graph of phase velocity which increases from left to right as shown by the arrow labelled "velocity." U_0 is the average, or D.-C. velocity of the electron beam, and is a convenient reference point since all space charge waves in the fast mode propagate at a faster velocity than U_0 and all space charge waves in the slow mode propagate at a slower velocity. That portion of the graph to the left of U_0 therefore represents slow mode propagation, while that portion to the right thereof represents fast mode propagation.

Consider first the signal wave ω_1 which is introduced on the beam in the fast mode. Since ω_1 propagates in the fast mode, it will represent a higher velocity than the D.-C. velocity U_0 , as shown on the graph. The pump

frequency ω is at a higher frequency than the signal ω_1 and will therefore propagate at a lower velocity due to the dispersive nature of the beam. The mixing of the pump and signal waves in drift region 21 results in the production of an idle frequency ω_2 which is equal to ω minus ω_1 and therefore propagates at a velocity higher than the pump frequency.

The mixing of the pump and signal frequencies also results in the production of a series of upper sideband frequencies designated on the graph by odd-numbered subscripts. The first upper sideband frequency ω_3 is equal to the sum of the pump and signal frequencies, while the second upper sideband frequency ω_5 is equal to the sum of the pump and first upper sideband frequencies. More convenient definitions of the upper sideband frequencies are as follows:

$$\omega_3 = \omega_1 + \omega$$

$$\omega_5 = \omega_3 + \omega$$

$$\omega_7 = \omega_5 + \omega$$

Other upper sideband frequencies such as ω_9 , ω_{11} , ω_{13} , etc., have not been shown for the sake of clarity.

The mixing of pump and idle frequencies results in the production of another series of upper sideband frequencies designated on the graph by even-numbered subscripts. The first upper sideband frequency ω_4 is equal to the sum of the pump and idle frequencies, while the second upper sideband frequency ω_6 is equal to the sum of the pump and first upper sideband frequencies. More convenient definitions of these upper sideband frequencies are as follows:

$$\omega_4 = \omega_2 + \omega$$

$$\omega_6 = \omega_4 + \omega$$

$$\omega_8 = \omega_6 + \omega$$

Other upper sideband frequencies, such as ω_{10} , ω_{12} , ω_{14} , etc., also have not been shown for reasons of clarity.

For purposes of the present discussion, it will be helpful to discuss the parametric amplification process from the standpoint of relative velocities of space charge waves on the beam and the beam-to-beam coupling which exists between certain of these space charge waves. The idle frequency which is produced by the mixing of the signal and pump waves would normally be expected to propagate at the velocity illustrated in the graph of Fig. 2 as ω_2 . It can be shown, however, that when the amplitude of the pump wave is very much larger than that of the signal wave, energy at the idle frequency may propagate at two velocities symmetrically disposed about the pump wave velocity, one being its original velocity, and the other its image designated on the graph of Fig. 2 as ω_2^* . The existence and nature of the idle frequency image ω_2^* can be proven by a rather lengthy mathematical treatment. Such rigorous proof has not been included herein in the interest of brevity.

In a conventional traveling wave tube, amplification is attained by the active coupling of an electromagnetic wave on a helix with a slow mode space charge wave on the tube's electron beam. Active coupling between two such waves is manifested by coupled velocities of propagation of the waves which are intermediate those of the independent uncoupled waves. Gain results when the coupled waves reach a coincident velocity. Parametric amplification in the fast mode is analogous in that it can be considered as resulting from the active coupling of the signal and idle fast space charge waves. With reference to Fig. 2 active coupling between ω_2^* and ω_1 results in a coupled velocity which is intermediate the uncoupled velocities of the two frequencies. Hence, active coupling with resultant gain may be represented as the merger, in terms of velocity, of the idle frequency ω_2^* and signal frequency ω_1 . This requires an increase in velocity of ω_2^* and a decrease in velocity of ω_1 as shown by the solid

arrows of ω_2^* and ω_1 . Amplification of the coupled waves will not occur until such coupling has been manifested by the production of a coupled wave propagating at a velocity near that of the pump and indicated on the velocity graph as (ω_2^* , ω_1).

Consider next passive coupling which may exist between space charge waves on the fast mode of the beam. As previously mentioned, it can be shown that the first upper sideband ω_3 will couple passively with a signal ω_1 . Any wave which propagates due to passive coupling between two independent waves will propagate at a velocity which is higher than either of the independent uncoupled velocities, or at a velocity which is lower than either of the independent uncoupled velocities, depending upon the additive or subtractive effect of mutual inductance or mutual capacitance. Propagation at the slower velocity is a result of coupling which produces a 180 degree difference in phase between the fields associated with the two lines, such coupling being generally referred to as out-of-phase coupling, or coupling in the out-of-phase normal mode. Propagation at the faster velocity is a result of coupling which produces an in-phase condition between the two fields, such coupling being generally known as coupling in the in-phase normal mode. Hence, passive coupling between ω_3 and ω_1 , which is independent of other forces, will result in a velocity of the coupled wave (ω_3 , ω_1) at the dashed line 31 indicating the out-of-phase normal mode, or at the velocity indicated by the in-phase normal mode 30, or a combination of these two velocities. The in-phase condition, represented by the velocity of propagation at 30 represents an effective increase of the velocity of the signal wave ω_1 , as is shown by the dashed arrow of ω_1 . Such a condition is opposed to the desired condition of decreased signal velocity shown by the solid arrow of ω_1 which is necessary for parametric amplification and, hence, desired gain may be impeded.

As previously mentioned, gain may be increased by increasing the amplitude of the pump wave introduced onto the beam. Due to the non-linear characteristics of the beam, however, harmonics of the pump frequency 2ω , 3ω , 4ω , etc., are produced which become increasingly more significant as the pump power is increased. Just as the pump frequency induces active coupling between the idle and signal waves, so may a pump harmonic of sufficient amplitude induce active coupling between certain fast mode upper sideband frequencies and the lower fast mode frequencies. It can be shown, for example, that 2ω may induce active coupling between ω_3 and ω_2^* , thereby parametrically amplifying ω_3 . The undesirability of amplifying the first upper sideband frequency wave ω_3 can be appreciated by considering the noise energy that may exist on the beam at that frequency.

As previously pointed out, fast mode noise can be extracted from the beam by helix 17 only over a relatively narrow bandwidth. For obvious reasons, this bandwidth is made to correspond with the bandwidth of the signals to be amplified. Noise which exists at much higher frequencies, for example, the frequency ω_7 , is not extracted. Since ω_7 couples with ω_5 , ω_5 with ω_3 , and ω_3 with ω_1 , it is seen that all of the noise existing at these upper sideband frequencies is effectively coupled with the signal wave ω_1 . Further, the noise existing at ω_8 , ω_6 , and ω_4 is likewise effectively coupled to the idle frequency ω_2 . It is therefore seen that still another disadvantage of the coupling of higher sideband frequencies to the signal and idle waves is the introduction of spurious noise.

Classic illustrations of the parametric amplification phenomenon usually show the pump frequency as being twice the signal frequency. When such is the case:

$$\omega = 2\omega_1$$

(1)

Therefore:

$$\begin{aligned}\omega_3 &= \omega + \omega_1 \\ &= 2\omega_1 + \omega_1 \\ &= 3\omega_1\end{aligned}\quad (2)$$

and

$$\begin{aligned}\omega_4 &= \omega + \omega_2 \\ &= \omega + (\omega - \omega_1) \\ &= 2\omega_1 + (2\omega_1 - \omega_1) \\ &= 3\omega_1\end{aligned}\quad (3)$$

Therefore:

$$\omega_3 = \omega_4 \quad (4)$$

It is not intended, in the present case, that this condition be fulfilled at all times during operation. As a matter of fact, in most practical cases, the signal frequency will be constantly varying within a predetermined bandwidth. The foregoing mathematical sequence is presented to illustrate that the two first upper sidebands ω_3 and ω_4 may have proximate frequencies as shown in Fig. 2 if, indeed, they do not coincide.

Fig. 3 is included to illustrate the effect of auxiliary helix 26 on certain space charge waves of beam 13. The lower graph 27 is similar to the graph of Fig. 2 and illustrates, in terms of relative velocities, the propagation constants of different frequency space charge waves on beam 13, while the upper graph 28 illustrates, in terms of relative velocity, the propagation constant of the auxiliary helix 26 at the first upper sideband frequency ω_3 . The line representing the velocity U_0 extends through both of the graphs 27 and 28 to indicate that it serves as a reference velocity for both graphs. Velocity graph 27, for purposes of clarity, shows only the upper sideband frequencies resulting from the mixing of the pump and signal frequencies. As previously pointed out, the spectrum of upper side band frequencies resulting from the mixing of pump and idle frequencies will closely correspond to the upper sideband frequencies shown such that any change affecting say, ω_3 , will likewise affect ω_4 . For purposes of simplicity, therefore, one may consider ω_4 as coinciding with ω_3 , ω_6 as coinciding with ω_5 , ω_8 as coinciding with ω_7 , etc. Further, it should be borne in mind that:

$$\omega_2 = \omega - \omega_1 \quad (5)$$

and since

$$\omega \approx 2\omega_1 \quad (6)$$

Then:

$$\begin{aligned}\omega_2 &\approx 2\omega_1 - \omega_1 \\ \omega_2 &\approx \omega_1\end{aligned}\quad (7)$$

One may therefore likewise consider ω_2 as coinciding with ω_1 .

We have found that the degrading effects of the upper sideband frequencies can be eliminated by greatly augmenting the difference in velocity which exists between the signal frequency ω_1 and the first upper sideband frequency ω_3 . A corollary to this statement, of course, is that the aforementioned degrading effects are reduced by augmenting the difference in velocity between ω_2 and ω_4 . Increased velocity separation between ω_1 and ω_3 necessarily results in increased velocity separation between ω_2 and ω_4 . If a large velocity separation is effected between ω_1 and ω_3 , they will be thrown so far out of synchronism with each other as to make the effective coupling therebetween negligible.

Filter helix 26 is designed to present a propagation constant at the first upper sideband ω_3 as shown on graph 28. In other words, helix 26 is designed such that if ω_3 was transmitted thereon, it would propagate at the phase velocity shown on the graph 28. The velocity spectra shown on graphs 27 and 28 can be considered to be of a greatly expanded scale. Because of the close proximity of the helix to the beam and because the propagation constants of the beam and helix closely correspond at the

frequency ω_3 , the helix and the beam will couple passively at frequency ω_3 . Such passive coupling will result in two normal modes of propagation as previously described. The velocity of the out-of-phase coupling condition is shown as the dotted line 33, while the velocity of the in-phase normal mode is shown at 34. It can be seen that such coupling is effective in producing a desirably wide velocity separation between ω_1 and ω_3 , and hence the effective coupling therebetween is substantially eliminated.

Several considerations must be taken into account in the determination of the proper propagation constant of the filter helix at ω_3 . If the helix is fabricated such that ω_3 represents a higher velocity than that shown, the in-phase normal mode 34 will also be increased in velocity (moved further to the right in Fig. 3). Although this will result in a greater separation between ω_1 and in-phase normal mode 34, it will also decrease the separation between ω_1 and the out-of-phase normal mode 33. Conversely, a decrease of the helix velocity at ω_3 will result in decreased separation between ω_1 and in-phase normal mode 34. It should be pointed out, however, that such a decrease of velocity at ω_3 of the helix will result in a desirably stronger helix-to-beam coupling at ω_3 because of the closer proximity of the helix and beam propagation constants. This advantage must be balanced not only with the disadvantage of a decreased velocity of in-phase normal mode 34, but also with the disadvantageous possibility of coupling with an ω_3 frequency wave which may exist on the slow space charge mode of the beam thereby causing undesired amplification of the ω_3 wave. For these and other reasons, we have found that the position of ω_3 on graph 28 represents the optimum propagation constant of the helix at that frequency.

The design of helix 26 is governed by principles which are well known in the art. Two of the essential variables which determine the propagation constant are the pitch of the helix, as represented by the angle α , and the helix diameter d . Other parameters may also be of necessary consideration depending upon the design of the tube, e.g., metallic shielding may give rise to a capacitance which might affect the propagation constant of the helix 26. For purposes of the present illustration, however, it may be stated that the desired propagation constant of the helix at ω_3 , as shown on graph 28, may be achieved through the proper dimensioning of the angle α and the helix diameter d .

In view of the foregoing, it can be appreciated that coupling between the beam 13 and helix 26 is desirable only at the frequency ω_3 . Helix-to-beam coupling at the frequencies ω and ω_1 might be particularly disadvantageous since the phase velocities of the space charge waves at these frequencies would be changed, and hence the desired parametric amplification process might be disrupted.

One method of preventing such coupling is to construct helix 26 such that it will filter out these frequencies or, in other words, to construct helix 26 such that it will not permit any propagation thereon of waves at frequencies ω and ω_1 . The design considerations necessary for desired filtering are well known in the art. Straps 36 are positioned approximately one-half wavelength apart at the signal frequency and, hence, approximately one wavelength apart at the pump frequency ($\omega \approx 2\omega_1$). Waves at the signal frequency will therefore be reflected at each half wavelength, while waves at the pump frequency will be reflected at each full wavelength. A comparison of the length of a strap 36 with the wavelength being reflected is a rough indication of the effectiveness of the filter at that frequency and of the bandwidth or "stop-band" which will be filtered. The lengths of straps 36 are fairly small by comparison to the wavelength of the signal frequency ω_1 and are therefore quite effective in filtering the frequency ω_1 over a comparatively large stop-band. The ratio between the strap length and the wavelength

at ω is larger than in the former case and one may consider the effectiveness of desired reflection at this frequency to be somewhat more crude. At the frequency ω_3 ($\omega_3 \approx 3\omega_1$), the strap is comparatively large with respect to the wavelength and hence the stop-band will be very small and shifted in frequency. Since the width of the stop-band decreases with increasing frequency, one may design helix 26 such that ω_1 and ω will always fall within a stop-band, while ω_3 will never fall within a stop-band.

Admittedly, the design of helix 26 is rather complicated since the pitch, diameter, number of turns per unit length, and position of the straps must be determined accurately to give both a desired propagation constant at ω_3 and desired stop-bands at ω_1 and ω .

An alternative method of restricting helix-to-beam coupling to the first upper sideband frequency is to make the helix 26 highly dispersive. Graph 27 of Fig. 3 illustrates the dispersive nature of the beam wherein the velocities of ω_3 , ω , and ω_1 vary in inverse proportion to frequency. If the helix 26 is made very dispersive, the propagation constants thereof at ω and ω_1 will represent phase velocities at those frequencies which are much higher than that at ω_3 . Hence, on graph 28 of Fig. 3, ω will exist at a point far to the right of ω_3 , and ω_1 will exist at a point even further to the right. When this is the case, the difference between the propagation constants of the helix and beam at the signal and pump frequencies is so large that substantially no helix-to-beam coupling at these frequencies can occur.

It can be shown that a helix can be made highly dispersive over a given band of frequencies by introducing stop-bands at certain higher frequencies. Helix 26 may therefore be made highly dispersive at the frequencies ω , ω_1 , and ω_3 by increasing the number of straps per unit length such that stop-bands result at frequencies higher than ω_3 .

As can be appreciated from the foregoing discussion, the sole purpose of helix 26 is to change the phase velocity of the first upper sideband ω_3 , which propagates on the beam or, more specifically, to augment the difference in velocity between ω_3 and ω_1 . Helix 26 must therefore be conductive only to such an extent as will allow coupling with the beam. If the helix is allowed to propagate a wave over its entire length, either forward or backward wave oscillation may occur. Filter helix 26 is therefore made sufficiently resistive to attenuate any wave before it can propagate along the entire length thereof.

Although the helix 26 performs its intended function only throughout drift region 21, it is shown as extending along substantially the entire length of the tube 10. We have found that such extension is advantageous both for convenience of fabrication and for shielding the beam from the dielectric envelope.

It is to be understood that the structure discussed are presented only for purposes of illustration. As previously pointed out, structures other than those shown could well be used for the signal input, pump input, and signal output. Likewise, the filter helix 26 is merely intended to be exemplary of many various slow wave structures which could be used. For example, coupled resonators could be used which would exhibit those desired propagation, filtering, dispersion and resistive characteristics described. 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 an electron gun for forming and projecting an electron beam having fast and slow modes of propagation and noise waves thereon, means for collecting said electron beam, means for removing certain fast mode noise waves from said beam and for modulating said beam with a signal frequency in the fast space charge mode, means for modulating said beam with a pump frequency in the fast space charge mode, a drift region for allowing the signal and

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pump frequencies to mix, the mixing of said pump and signal frequencies being characterized by the production of upper sideband frequency space charge waves on said beam which propagate along the beam in the fast space charge mode, means for changing the velocity of propagation on the beam of at least one of said upper sideband frequency waves comprising a slow wave structure extending along said drift region in passive coupling relationship with the fast mode waves on said beam, and means for extracting amplified signals from said beam.

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 modes of propagation and noise waves thereon, first means positioned along said path for extracting fast mode noise from said beam and for coupling a high frequency signal wave onto the fast mode of said beam, second means positioned along said path for coupling a high frequency pump wave onto the fast mode of said beam, third means positioned along said path in passive coupling relationship with the fast mode of said beam at a frequency equal to the sum of the frequencies of said pump and signal waves, and output means for extracting said signal wave from said fast mode of said beam.

3. A traveling wave tube comprising an electron gun for forming and projecting a dispersive electron beam, said beam being characterized by fast and slow modes of propagation and noise waves thereon, first means for extracting from said beam fast mode noise frequencies within a signal bandwidth and for coupling onto the fast mode of said beam signal frequencies within the range of said signal bandwidth, second means for modulating said beam with power at a pump frequency, third means for extracting said signal frequencies from said beam, and fourth means for preventing noise waves at a frequency higher than said signal bandwidth from coupling to said signal frequencies comprising a slow wave structure passively coupled to the fast mode of said beam at a frequency equal to the sum of said pump and signal frequencies and extending from said second means to said third means.

4. The traveling wave tube of claim 3 wherein said slow wave structure is more dispersive than said electron beam.

5. The traveling wave tube of claim 3 wherein said slow wave structure includes means providing stop-bands at said signal bandwidth and at said pump frequency.

6. A high frequency amplifier comprising means for forming and projecting a dispersive electron beam along a path, said electron beam being characterized by fast and slow modes of propagation and noise waves thereon, means for introducing a high frequency pump wave onto said beam, a drift region wherein said pump and signal waves are mixed, said mixing being characterized by the production of a first upper sideband wave having a frequency equal to the sum of said pump and signal and having a different phase velocity than said signal frequency, and means to augment the difference in phase velocity between said first upper sideband wave and said signal wave comprising a slow wave structure extending along said drift region in passive coupling relationship to said beam, the velocity of propagation characteristic of said slow wave structure being substantially different than the fast mode velocity of propagation characteristic of the beam at the pump and signal frequencies.

7. The high frequency amplifier of claim 6 wherein said slow wave structure has such predetermined propagation characteristics as to cause passive coupling between said slow wave structure and said first upper sideband wave on said beam.

8. The high frequency amplifier of claim 6 wherein said slow wave structure has a resistance high enough to prevent the propagation of an electromagnetic wave along the entire length thereof.

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9. A high frequency amplifier comprising an electron gun for projecting an electron beam along a path, said electron beam being characterized by fast and slow modes of propagation and noise waves thereon, means for modulating said beam in the fast modes with a signal frequency, means for modulating said beam in the fast mode with a pump frequency, a drift region wherein said pump and signal frequencies are mixed, said mixing being characterized by the production of a first upper sideband frequency which is equal to the sum of said pump and signal frequencies and having a different phase velocity than said signal frequency, and means to augment the difference in phase velocity between said first upper sideband frequency and said signal frequency comprising a filter-type slow wave structure extending along said drift region in passive coupling relationship with certain energy which propagates in the fast mode of said beam, said filter-type slow wave structure having stop-bands at said pump and signal frequencies.

10. The high frequency amplifier of claim 9 wherein said slow wave structure has such high attenuating properties as to prevent the propagation of an electromagnetic wave along the entire length thereof.

11. A parametric amplifier comprising means for forming and projecting an electron beam along a path, said electron beam being characterized by fast and slow modes of propagation, means for causing a signal space charge wave to propagate in the fast mode of said beam, means for causing a pump space charge wave to propagate in the fast mode of said beam concurrently with the propagation of said signal wave such that it will mix with said signal wave, the mixing of said pump and signal waves giving rise to a fast mode first upper sideband space charge wave on said beam having a frequency equal to the sum of the frequencies of said pump and signal waves, means substantially to prevent effective coupling between said first upper sideband space charge wave and said signal space charge wave comprising a slow wave structure in close proximity to said beam, said slow wave structure being characterized by a propagation constant at the first upper sideband frequency such as to cause the helix and the beam to couple strongly at the first upper sideband frequency, stop-bands at said signal and pump frequencies, and attenuating properties such as to prevent an electromagnetic wave from propagating along the entire length thereof, and means for extracting said signal wave from said beam.

12. A traveling wave tube comprising an electron gun for forming and projecting an electron beam along a path, said beam being characterized by fast and slow modes of propagation and noise energy thereon, first means positioned along said path for removing from said beam fast mode noise energy which exists within a predetermined frequency band, second means positioned along said path for modulating said beam in the fast mode at a signal frequency, third means positioned along said path for modulating said beam in the fast mode at a pump frequency, output means positioned along said path for extracting signal energy from said beam, fourth means positioned along said beam path between said third means and said output means for preventing the manifestation at said output of noise energy which exists without said frequency band comprising a helix having such a predetermined pitch and diameter as to cause coupling with energy of said beam which propagates in the fast mode at a frequency equal to the sum of said signal and pump frequencies, and straps positioned periodically along said helix, the distance between adjacent straps being equal to one wavelength of said pump frequency, said helix and straps being so constructed that any electromagnetic wave being transmitted thereon will be completely attenuated before it propagates along the entire distance thereof.

13. A traveling wave tube of the parametric amplifier

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type comprising electron gun means for projecting an electron beam along a path, means for applying a signal wave to said electron beam, means for applying a pump wave to said electron beam, means defining a drift region wherein said pump and signal waves are mixed to attain parametric amplification, means for extracting amplified signals from said beam after said parametric amplification in said drift region, and a slow wave structure adjacent said drift region and coupled to said electron beam, said slow wave structure having sufficient attenuation to prevent propagation of an electromagnetic wave therealong and including means providing stopbands at the frequencies of said pump and signal waves.

14. A traveling wave tube of the parametric amplifier type comprising electron gun means for projecting an electron beam along a path, means for applying a signal wave to said electron beam, means for applying a pump wave to said electron beam, means defining a drift region wherein said pump and signal waves are mixed to attain parametric amplification, means for extracting amplified signal waves from said beam after said para-

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metric amplification in said drift region, and means for preventing noise coupling to said signal wave in said drift region, said last-mentioned means comprising a slow wave structure including means defining stopbands at the frequencies of said pump and signal waves.

15. A traveling wave tube in accordance with claim 14 wherein said slow wave structure comprises a wire helix encompassing said beam path in said drift region.

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