

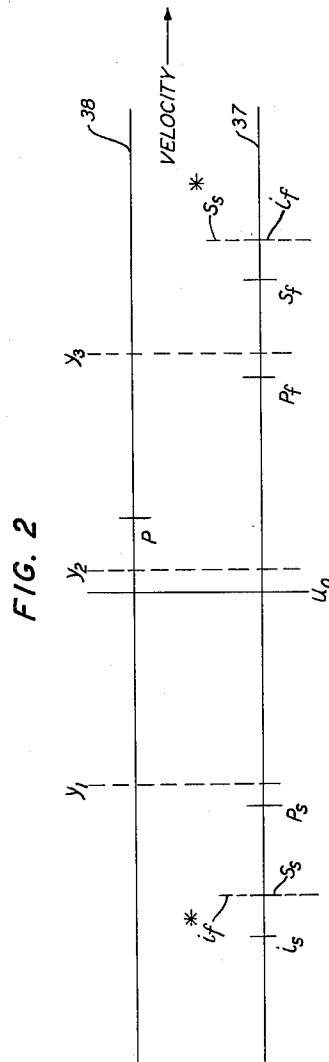
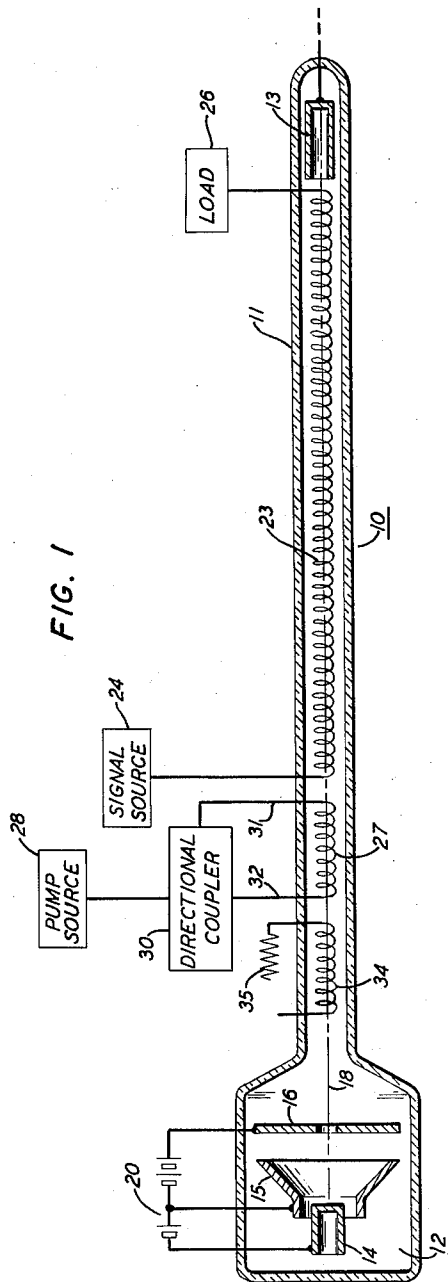
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TRAVELING WAVE TUBE

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TRAVELING WAVE TUBE

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This invention relates to traveling wave tubes and more particularly to means for producing low noise amplification in traveling wave tubes.

Velocity modulation devices such as the traveling wave tube have proven capable of amplification with reasonably high efficiency and stability over a very wide band of frequencies. Detracting from the significant advantages realized by such devices, however, is the noise resulting from the utilization of the electron beam. In the conventional traveling wave tube, 6 decibels is the theoretical minimum noise figure as is established in an article entitled "The Minimum Noise Figure of Microwave Beam Amplifiers," by H. A. Haus and F. N. H. Robinson, Proceedings of the Institute of Radio Engineers, volume 43, pages 981-991, August 1955. Further discussion as to how this minimum noise figure may be reduced, and indeed, be made to approach zero, requires a brief discussion of the nature of an electron beam.

The conventional traveling wave tube achieves electromagnetic signal wave amplification through space charge wave modulation of an electron beam. Any space charge wave which inherently exists on an electron beam, or is introduced onto the beam from some outside source, may propagate along the beam at either of at least two phase velocities. It can be shown that the faster of these two phase velocities at any given frequency is higher than the mean, or D.-C., velocity of the unmodulated beam, whereas the slower phase velocity is lower than the beam's D.-C. velocity. The phase velocities which represent space charge wave propagation at a velocity higher than D.-C. velocity will be referred to as the fast space charge mode, while those phase velocities which represent wave propagation at a velocity lower than the D.-C. velocity will be referred to as the slow space charge mode. Another characteristic of the beam is its dispersion. It can be shown that in the slow space charge mode the phase velocities of space charge waves vary directly with frequency. In the fast mode, however, space charge wave velocities vary inversely with frequency.

A conventional traveling wave tube effects amplification through electromagnetic signal wave interaction with the slow space charge mode of an electron beam. As is well known, the unique characteristics of the slow space charge mode which permits wave amplification is disadvantageous in that spurious noise power which is inherent on the slow mode of the beam cannot be extracted by ordinary methods. This is due to the equally well-known fact that power transmitted in the slow space charge mode is negative with respect to the unmodulated D.-C. power of the beam. In the conventional traveling wave tube one is therefore generally limited to methods of reducing noise power in the electron gun region. Although sophisticated electron guns have been built which produce beams having a noise figure of less than 6 decibels, these methods of reducing noise are limited.

In the patent of C. F. Quate, 2,974,252, granted March 7, 1961, there is disclosed a completely different approach to the problem of reducing noise in a beam device. By making use of the principles of parametric amplification, the Quate device effects interaction between a signal wave and the beam's fast space charge mode, thereby achieving desired amplification of the signal. Because fast mode noise power adds to the D.-C. beam power, thus produc-

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ing an increase in the absolute beam energy, it can be extracted from the beam through any of a number of well-known devices.

In the Quate device, energy for signal wave amplification is derived from a source of "pump" energy which is at a higher frequency than the signal energy. This mechanism for amplification is disadvantageous by comparison to the conventional traveling wave tube which effects amplification through the conversion of D.-C. beam energy to signal wave energy. In the Quate device the electron beam merely serves as a non-linear transmission medium rather than as an energy source. Further, the high frequency energy power required for the pump wave is often very difficult to produce, particularly when power requirements are high. Since high gain in the Quate device requires high pump power, one can see that high-frequency high-power operation of the Quate device may impose serious difficulties.

It is an object of this invention to eliminate the effects of noise power existing on an electron beam of a traveling wave tube.

It is a specific object of this invention to eliminate the effects of noise power originating on the slow mode of an electron beam of a traveling wave tube.

It is another object of this invention to reduce "pump" power requirements for very low noise electromagnetic wave amplification in a traveling wave tube.

These and other objects of the present invention are obtained in one illustrative embodiment thereof which comprises an electron discharge device having an evacuated envelope with an electron gun therein for forming and projecting an electron beam along an extended path. A slow wave circuit such as a helix is positioned along the path of flow for propagating signal energy in coupling relationship with the slow space charge mode of the beam. As the signal wave propagates along the slow wave circuit, longitudinal electric fields that are associated therewith interact with the beam in a conventional well-known manner to produce amplification of the signal energy. Since interaction takes place entirely in the slow mode, energy for amplification is derived entirely from the D.-C. kinetic energy of the beam.

It is a feature of this invention that pump energy be coupled to the beam along a certain predetermined distance by means of a slow wave coupler that is positioned between the electron gun and the slow wave interaction circuit. It is a corollary feature of this invention that the coupled pump wave propagates at a velocity substantially equal to that of the slow signal mode velocity plus one-half the difference in velocities of the slow signal mode and the fast idler mode. The term slow signal mode velocity is intended to denote the velocity of an uncoupled space-charge wave of the signal frequency propagating in the slow mode of the beam; likewise, fast idler mode velocity refers to the velocity of an uncoupled space-charge wave of the idler frequency propagating in the fast mode of the beam. The idler frequency is equal to the difference of the pump and signal frequencies. Under these conditions, a beating phenomenon occurs which causes signal frequency slow mode noise to be transferred to the fast mode, and idler frequency fast mode noise to be transferred to the slow mode.

It is another feature of this invention that the slow wave circuit pump coupler have a length substantially equal to the square root of the product of the reduced plasma wavelength at the pump frequency and the reduced plasma wavelength at the idler frequency, that quantity divided by the fraction of beam current modulation of the pump wave. The aforementioned transfer between the fast and slow modes takes place over a specific predetermined distance. When this transfer is complete, a re-transfer will take place if pump energy is still

coupled to the beam. The pump coupler is therefore of a predetermined length so that pump energy is advantageously removed from the beam at a particular distance that represents one complete cycle of energy transfer between the fast and slow modes. At this point, fast mode idler frequency noise exists substantially completely in the slow mode while slow mode signal frequency noise travels in the fast mode.

It is a feature of one embodiment of this invention that fast mode noise stripping apparatus be included between the electron gun and the slow wave pump coupler. The stripping apparatus is constructed such that it will extract beam noise from the fast idler mode so that the noise energy transferred to the slow mode is negligible and substantially noiseless interaction can be effected.

It is a feature of another embodiment of this invention that the pump frequency be much higher than the signal frequency. As will be shown hereinafter, the noise power transferred from the fast idler mode to the signal slow mode is directly proportional to the ratio of the signal frequency to the idler frequency. By making the pump frequency much higher than the signal frequency, this ratio becomes very small so that fast idler mode noise power transferred to the slow mode is likewise very small.

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

FIG. 1 is a schematic illustration of one embodiment of this invention; and

FIG. 2 illustrates the phase velocities of certain waves which may exist respectively on the slow wave pump coupler and the electron beam of the device of FIG. 1.

Referring now to the drawing, the embodiment shown in FIG. 1 comprises a traveling wave tube 10 having an electron gun 12 and a collector 13 at opposite ends of an evacuated envelope 11. For purposes of illustration, electron gun 12 is shown as comprising a cathode 14, a beam forming electrode 15, and an accelerating anode 16 which coact to form and project an electron beam, schematically shown as 18, toward the collector 13. Battery 20 maintains the various electrodes at proper potentials as is well known in the art. Suitable means for focusing the electron beam are used which, because they are well known in the art, have not been shown.

Extending along a major length of the tube is a slow wave interaction circuit 23. A signal source 24 is coupled to the input of circuit 23 while a suitable load 26 is coupled to the output. Circuit 23 is of the general type used in conventional traveling wave tubes; it delays the axial phase velocity of the signal wave to approximately the velocity of the electron beam 18. More specifically, it delays the signal wave velocity to a value slightly below that of the D.-C. beam velocity so that longitudinal field components of the signal wave will be in approximate synchronism with slow mode space-charge waves of corresponding frequency in beam 18. Interaction between the signal wave and the slow mode of the beam takes place in a well-known manner to produce amplification of the signal wave.

Between the electron gun and the interaction circuit is a slow wave coupler 27 for propagating pump wave energy from a pump source 28 in coupling relationship with beam 18. Directional coupler 30 channels pump energy from source 28 and transmission line 31 to transmission line 32.

Interposed between electron gun 12 and slow wave coupler 27 is a noise extraction helix 34 for removing fast mode idler frequency noise energy from the beam. The term idler frequency is used herein to denote the difference in frequency of the pump and signal waves. Although the terms idler frequency and pump frequency are usually used in connection with parametric amplification devices, the present device is not to be regarded as a parametric amplifier; amplification is attained by

conventional traveling wave tube techniques as pointed out hereinabove. After extraction, fast mode idler noise energy is transmitted to, and dissipated by, an impedance 35. It should be pointed out that elements 23, 27 and 34 have been shown as helices only for purposes of illustration; various other structures could also be used for coupling wave energy to and from the beam as is well known in the art.

The usefulness of noise extraction helix 34 and pump wave coupler 27 in conjunction with a conventional traveling wave tube can be appreciated by a consideration of FIG. 2. Graph 37 illustrates the spectrum of phase velocities of space-charge waves which may propagate along beam 18 while graph 38 illustrates a similar spectrum with reference to pump wave coupler 27. Both graphs are one-dimensional, of the same scale, and show increases in phase velocity from left to right as indicated by the arrow labeled "velocity." The D.-C. velocity u_0 of beam 18 is used as a reference for both graphs because all fast mode space-charge waves travel faster than u_0 , while all slow mode space-charge waves travel slower than u_0 .

The uncoupled velocity of a slow mode space-charge wave of the signal frequency is shown on graph 37 by the position of s_s , while the fast signal mode velocity is shown by s_f . Likewise, i_s is the slow idler mode velocity, while i_f is the fast idler mode velocity. The phase velocity of an uncoupled pump wave on coupler 27 is shown on graph 38 by the position of p .

As is pointed out in chapter VIII of the book "Traveling Wave Tubes," by J. R. Pierce, Van Nostrand Company, Inc., 1950, a wave of a given frequency that results from coupling between a slow wave circuit and an electron beam may travel at either or a combination of three different velocities, which Pierce designated y_1 , y_2 and y_3 . The relative velocities of these three "normal modes" are shown on FIG. 2 as extending through both graphs 37 and 38 because they represent propagation of a coupled wave which travels on both beam 18 and coupler 27.

The power of the pump wave which is propagated along coupler 27 is quite small. It can therefore be shown that, for purposes of this discussion, possible pump wave propagation at velocities y_1 and y_3 can be neglected. This is primarily due to the fact that the uncoupled circuit pump mode velocity p is fairly widely separated, in terms of velocity, from y_1 and y_3 , and therefore a fairly high power pump wave is required to excite these normal modes to any substantial extent. Coupler 27 is constructed such that the difference in velocities of y_2 and s_s is substantially equal to the difference in velocities of y_2 and i_f ; the purpose of this particular condition will be explained hereinafter.

As is well known in the parametric amplifier art, the presence of a pump wave on an electron beam tends to cause coupling between signal frequency space-charge wave energy and idler frequency space-charge wave energy. When any two waves couple, the strength of coupling varies inversely with the difference in velocity of the waves. It can be shown, however, that the signal wave s_s "sees" the idler wave i_f as if it was traveling at its "image" velocity i_f^* , while the idler wave "sees" the signal wave s_s as if it was traveling at its "image" velocity s_s^* . Hence, strong coupling between the fast idler wave and the slow signal wave occurs at velocity s_s , i_f^* , and i_f , s_s^* , and the coupled wave may travel at either of these two velocities. From this standpoint, the slow and fast mode of the beam can be considered as being analogous to two coupled transmission lines. The wave energy on the fast and slow modes will beat together such that the coupled slow mode energy will be gradually transferred to the fast mode while the coupled fast mode energy is gradually being transferred to the slow mode. When this transfer is complete the process repeats itself; transfers and re-transfers take place

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as long as coupled pump energy at velocity y_2 exists on the beam. It should be noted in passing that the uncoupled slow mode and fast mode velocities are imaged about the beam velocity u_0 that is, i_s is the same distance from u_0 as i_t ; s_s is the same distance from u_0 as s_t . Further, if the pump frequency is twice the signal frequency, the signal and idler frequencies are equal. Therefore, if the pump frequency is twice the signal frequency, y_2 should be at the same velocity as u_0 .

The purpose of coupler 27 is to transfer slow mode noise to the fast mode. Coupler 27 is therefore terminated a predetermined distance at which this transfer is complete. It can be shown that the distance required for one complete cycle of energy transfer between the fast and slow modes, and therefore, the desired length L of coupler 27 is given by:

$$L = \frac{\sqrt{\lambda_{q1}\lambda_{q2}}}{M} \quad (1)$$

where λ_{q1} is the reduced plasma wavelength of beam 18 at the signal frequency, λ_{q2} is the reduced plasma wavelength of the beam at the idler frequency, and M is the fraction of beam current modulation by the pump frequency ($M=1$ being 100% beam current modulation). The reduced plasma wavelength of a beam at various frequencies is readily calculable by methods well known in the art.

It can be appreciated that upon leaving coupler 27, beam noise originating in the slow signal mode has been transferred to the fast mode; the only noise existing at velocity s_s is that which formerly traveled at a fast idler mode velocity i_t . Since the fast idler mode noise has been stripped by extraction helix 34, the slow signal mode contains substantially no noise energy as it enters the interaction region defined by slow wave helix 23. Conventional slow wave amplification can thereby be attained with substantially no noise appearing with the signal wave at the output end of helix 23.

It is known that the effect of fast idler mode noise in a parametric amplifier can be reduced through the use of a high frequency pump wave. It can be shown that the effective reduction of idler noise is determined by:

$$P_1' = P_1 \frac{\omega_s}{\omega_1} = P_1 \frac{\omega_s}{\omega_p - \omega_s} \quad (2)$$

where P_1 is the noise power originating in the fast idler mode, ω_s is the signal frequency, ω_1 is the idler frequency, ω_p is the pump frequency and P_1' is the noise power appearing at the signal frequency subsequent to parametric mixing, as a result of the fast idler noise input.

This relationship can be used in the present device to obviate the necessity of fast idler mode noise extraction apparatus such as helix 34. If, for example, the pump frequency is five times the signal frequency, from Equation 2, the fast idler noise power transferred to the slow signal mode will be equal to only one-fourth the noise power originating in the fast idler mode. Of course, any other desired ratio of pump frequency to signal frequency could be used depending upon the desired degree of noise suppression. This method of noise reduction, however, has the obvious disadvantage of requiring a high pump frequency. Consequently, for very high frequency operation it will usually be desirable to use fast idler mode noise stripping apparatus.

It is to be understood that the above-described embodiments are intended only for purposes of illustration. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of my invention.

What is claimed is:

1. A traveling wave tube comprising an electron gun for forming and projecting an electron beam, said beam being characterized by fast and slow modes of propagation, spurious noise energy, and a mean velocity, means

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for propagating signal frequency energy in an interacting relationship with the slow mode of said beam, means included between said electron gun and said propagating means for extracting noise energy from the fast mode of said beam, means included between said extracting means and said propagating means for transmitting a wave of approximately twice said signal frequency in coupling relationship with said beam, said transmitting means being so constructed that the coupled phase velocity of said wave is substantially equal to said mean beam velocity, and means for collecting said beam.

2. 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, a source of signal frequency energy, a signal input line, a signal output line, means for amplifying said signal energy comprising slow wave circuit means extending between said input and output lines for propagating said signal frequency energy in coupling relationship with the slow mode of said beam, and means for minimizing the noise content of the amplified signal energy comprising means for transferring noise energy at said signal frequency from said slow mode to said fast mode.

3. The traveling wave tube of claim 2 wherein said transferring means comprises a source of pump energy and transmitting means interposed between said electron gun and said signal input line for propagating said pump energy in coupling relationship with the beam.

4. The traveling wave tube of claim 3 wherein said transferring means further comprises means for transferring fast mode noise energy at said signal frequency to said slow mode, and means included between said electron gun and said transferring means for extracting fast mode signal energy from said beam whereby the fast mode energy that is transferred to the slow mode is substantially negligible.

5. An electron discharge device comprising a source of signal frequency energy, a source of pump frequency energy, means for forming and projecting an electron beam, said beam being characterized by a slow signal mode velocity and a fast signal mode velocity at which uncoupled signal frequency energy may propagate and a slow idler mode velocity and a fast idler mode velocity at which uncoupled wave energy at a frequency equal to the difference of said pump and signal frequencies may propagate, means connected to said signal source for transmitting signal energy in coupling relationship with the slow signal mode of said beam, and means for propagating pump energy in coupling relationship with said beam at a velocity intermediate said slow signal mode velocity and said fast idler mode velocity comprising a slow wave circuit interposed between said electron gun and said transmitting means which is connected to said pump source.

6. The electron discharge device of claim 5 wherein said slow wave circuit is so constructed that the difference of said coupled pump wave velocity and said slow signal mode velocity is substantially equal to the difference of said fast idler mode velocity and said coupled pump wave velocity.

7. The electron discharge device of claim 5 wherein said electron beam is characterized by a first reduced plasma wavelength at said signal frequency and a second reduced plasma wavelength at a frequency equal to the difference of said pump and signal frequencies, and wherein said slow wave circuit is of a length L substantially determined by:

$$L = \frac{\sqrt{\lambda_1 \lambda_2}}{M}$$

where λ_1 is said first reduced plasma wavelength, λ_2 is said second reduced plasma wavelength, and M is the fraction of beam current modulation of said pump wave.

8. The electron discharge device of claim 5 wherein

said pump frequency is at least four times said signal frequency.

9. The electron discharge device of claim 5 further comprising means included between said electron gun and said slow wave circuit for extracting wave energy from said beam which travels at said fast idler mode velocity.

10. A traveling wave tube comprising an electron gun for forming and projecting a beam of electrons having fast and slow modes of propagation and noise waves thereon, means for propagating signal frequency energy in an interacting relationship with the slow mode of said beam, means for transferring slow mode noise energy to the fast mode of said beam comprising means for transmitting pump frequency energy in coupling relationship with said beam, the coupling of said pump energy with said beam giving rise to a coupled pump wave that travels at a velocity substantially equal to one-half the sum of the velocities of an uncoupled slow mode beam wave of the signal frequency and an uncoupled fast mode beam wave of a frequency equal to the difference of said pump and signal frequencies.

11. The traveling wave tube of claim 10 wherein said beam is characterized by a first reduced plasma wavelength at said signal frequency and a second reduced plasma wavelength at a frequency equal to the difference of said pump frequency and said signal frequency, said pump energy being propagated in coupling relationship

with the beam along a distance L which is substantially defined by:

$$L = \frac{\sqrt{\lambda_1 \lambda_2}}{M}$$

where λ_1 is said first reduced plasma wavelength, λ_2 is said second reduced plasma wavelength and M is the fraction of beam current modulation by said pump energy.

12. The traveling wave tube of claim 11 further comprising fast mode noise stripping apparatus interposed between said electron gun and said pump energy propagating means.

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