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J. W. KLÜVER

3,176,234

SYNCHRONOUS MODE AMPLIFIER WITHOUT SLOW WAVE CIRCUITS

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FIG. 1

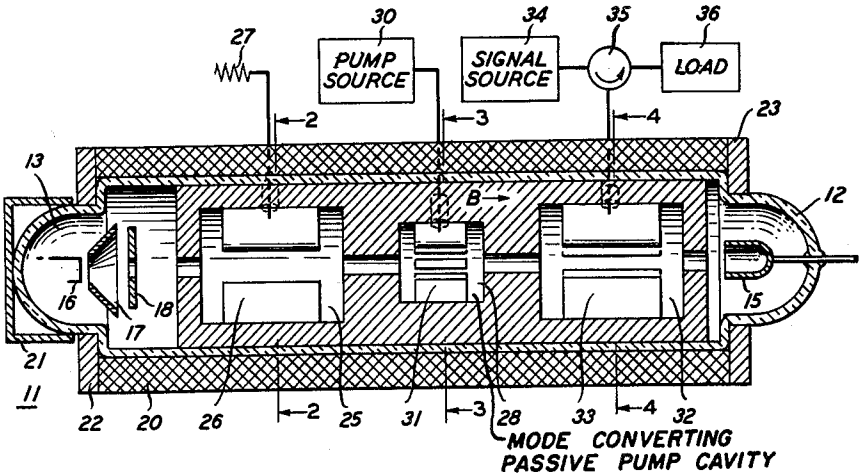


FIG. 4

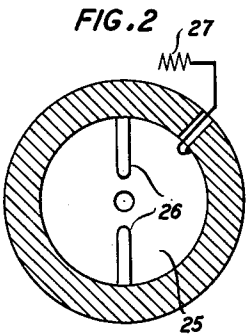
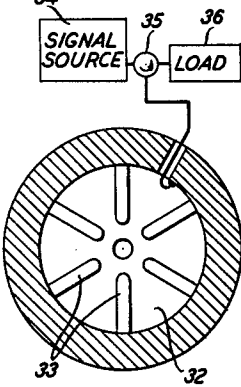
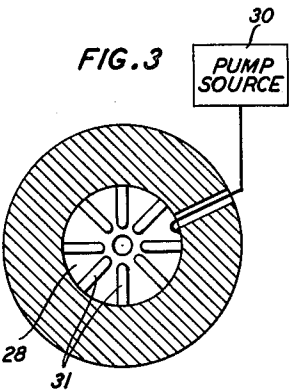


FIG. 3



INVENTOR
J. W. KLÜVER

BY
David P. Kelley
ATTORNEY

1

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Johan W. Klüver, Murray Hill, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York
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This invention relates to electron beam devices and, more particularly, to high-frequency electromagnetic wave amplifiers.

Electron beam velocity modulation devices such as the conventional traveling wave tube have proven capable of amplifying high-frequency electromagnetic waves with reasonably high efficiency and stability over a relatively wide band of frequencies. Detracting from these advantages, however, is the noise which results from signal wave interaction with an electron beam.

The conventional traveling wave tube achieves electromagnetic signal wave amplification through space-charge-wave modulation of the electron beam. Any space-charge-wave which inherently exists on an electron beam, or is introduced onto the beam through modulation by some outside source, may propagate along the beam at either of two phase velocities, the faster velocity being higher than the D.-C. (or mean) velocity of the beam and the slower velocity being lower than the beam's D.-C. velocity. The two ranges of phase velocity are referred to, respectively, as the fast mode and the slow mode. The conventional traveling wave tube effects amplification through electromagnetic signal wave interaction with the slow mode of the electron beam, as is well known. The unique characteristics of the slow mode which result in wave amplification are disadvantageous in that spurious noise power, which inherently exists in both the slow and fast modes of the beam, cannot be extracted from the slow mode by ordinary methods. This is due to the equally well known fact that power transmitted in the slow mode is negative with respect to the D.-C. power of the beam; that is, the presence of a slow mode wave results in a decrease of total beam power.

A recent important advance in the art is the discovery that the principles of parametric amplification can be applied to electron beam devices to permit interaction in the fast mode of the beam. This achievement is significant because noise power that propagates as a fast wave can conveniently be extracted from the beam.

It has been found that parametric amplification is usually more successful when used in connection with cyclotron wave interaction than with space-charge wave interaction. In cyclotron wave devices, the circuit that couples wave energy to the beam is designed to produce electric fields that are transverse to the direction of beam flow. In the presence of a longitudinal magnetic focusing field the resultant transverse forces produce transverse or rotational velocity components on the electrons of the beam, causing them to follow substantially helical trajectories. The phase positions of successive rotating electrons as they pass through a fixed plane transverse to the beam define a cyclotron wave. The interaction principles that apply to cyclotron wave devices are analogous to those that apply to space-charge wave devices.

Generally speaking, amplification through electron beam interaction can be said to result from "active" coupling between two waves, one of which may propagate on an external slow wave circuit. In the conventional traveling wave tube, signal wave energy on an external circuit couples with the slow space-charge mode of the beam to excite a slow signal frequency wave on the beam. The excitation of this slow signal wave results in a loss of

2

D.-C. beam power which is ultimately converted into electromagnetic signal wave energy, thereby giving amplification. In the parametric amplifier an idler frequency is defined which is equal to the difference of the pump and signal frequencies. Strong active coupling is induced between the fast mode signal and idler frequency waves, with the energy for amplification of the exponentially growing wave being ultimately derived from the pump source.

A third category of electron beam waves, which is analogous to cyclotron and space-charge waves, is the synchronous waves. These waves are defined by the relative displacements of successive electrons as the beam flows through a given transverse plane. It has heretofore been thought that all synchronous waves travel at the D.-C. beam velocity, but in order to preserve the analogy with cyclotron and space-charge waves, positive and negative energy synchronous waves have been known, respectively, as fast and slow synchronous waves. As is explained in the patent of A. Ashkin-E. I. Gordon, No. 3,054,964, granted September 18, 1962, and the publication of Klüver, "Parametric Coupling Between Transverse Waves on O- and M-Type Beams," Journal of Applied Physics, June, 1961, energy may be transferred between the cyclotron mode and the synchronous mode by a process known as "passive" coupling. (Space-charge, cyclotron, and synchronous modes, and active and passive coupling are also defined and explained in the book "Coupled Mode and Parametric Electronics," by W. H. Louisell, John Wiley & Sons, Inc., 1960). More particularly, it is possible to transfer energy between the fast cyclotron mode and the slow synchronous mode so that the advantages of fast wave parametric amplification can be combined with the advantages of slow wave amplification. For example, noise energy can be stripped from the fast cyclotron mode in an input coupler; the noiselessness of the fast cyclotron mode can be transferred to the slow synchronous mode; a signal wave can be propagated in interacting relationship with the slow noiseless synchronous mode to give substantially noiseless amplification.

One advantage of this device is that energy for amplification comes from the beam, so that low noise amplification is achieved without thereby depending upon high frequency pump energy as a power source. However, slow wave structures are necessary and may be disadvantageous because, by comparison to cavity resonators, they are complicated and difficult to build. Further, devices that use only cavity resonators are physically shorter than devices with slow wave structures.

It is an object of this invention to achieve low noise amplification through interaction with the slow mode of an electron beam in a device that does not require any slow wave structures.

This and other objects of my invention are realized in an illustrative embodiment thereof which comprises an electron gun for forming an electron beam and projecting it through three successive cavity resonators. The first resonator strips noise from the fast cyclotron mode of the beam; the second resonator transfers this noiselessness to the slow synchronous mode through passive coupling; signal energy is amplified in the third cavity through signal wave interaction with the noiseless slow synchronous mode of the beam.

According to one feature of this invention the electron beam is given an initial "twist" or uniform rotational velocity component before it is modulated. This initial twist should not be confused with the rotational velocity components that characterize cyclotron wave modulation. One satisfactory device for imparting an initial twist is a magnetically shielded electron gun which injects the beam into the longitudinal magnetic field in

3

accordance with the principles of Brillouin flow. As is known, under this condition, the electron beam rotates at a uniform frequency of approximately one-half the cyclotron frequency after being injected into the magnetic field. The rotational component of the electron beam gives the beam an inherent periodicity and, under certain conditions, permits synchronous wave interaction without requiring any distributed circuits. In one embodiment, those conditions are met if the first cavity is excited in the $n=1$ mode, the second cavity is excited with pump energy in the $n=4$ mode, and the third cavity is excited in the $n=3$ mode with signal wave energy. The mode numbers refer to the azimuthal periodicity of the wave around the circumference of the beam.

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

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

FIG. 2 is a section taken along lines 2—2 of FIG. 1;

FIG. 3 is a section taken along lines 3—3 of FIG. 1; and

FIG. 4 is a section taken along lines 4—4 of FIG. 1.

Referring now to FIG. 1, there is shown an electron discharge device 11 utilizing the principles of my invention. Located at opposite ends of an evacuated envelope 12, which may be of glass or other suitable material, are an electron gun 13 for forming and projecting an electron beam and a collector 15 for collecting the beam. For illustrative purposes electron gun 13 is shown as comprising a cathode 16, a focusing electrode 17 and an accelerating electrode 18. Surrounding a major portion of the envelope is a magnet 20 which focuses the electron beam through the production of a longitudinal magnetic field B as indicated by the arrow. Magnet 20 is shown as being an electromagnet although it could also be a permanent magnet.

As was pointed out above, three types of waves can be excited on an electron beam through three types of modulation: space-charge waves are produced through longitudinal velocity modulation of the electrons of the beam; cyclotron waves are produced through transverse velocity modulation; synchronous waves are produced through transverse displacement modulation. Space-charge waves produce no effects on the device of FIG. 1 because, among others, all modulation is in the transverse direction.

This invention is based in part upon my discovery that the phase velocities of synchronous waves are not necessarily equal to the D.-C. velocity of the beam but are in fact also a function of any uniform rotational velocity component of the unmodulated beam and the azimuthal periodicity of the electromagnetic wave that excites the synchronous wave. In the device of FIG. 1, a uniform rotational velocity component is imparted to the beam by magnetic shielding of the electron gun in accordance with the known principles of Brillouin flow. A magnetic shield 21 of soft iron, or other suitable ferromagnetic material, surrounds electron gun 13 and is of sufficient thickness to remain magnetically unsaturated. A pair of pole pieces 22 and 23 are located at opposite ends of magnet 20 for concentrating the magnetic field in the volume enclosed by the magnet. Under this condition, upon being injected into the magnetic field, the unmodulated electron beam will rotate at one-half the cyclotron frequency, where the angular cyclotron frequency ω_c is given by:

$$\omega_c = B\eta \quad (1)$$

where

B is the flux density of the magnetic field, and η is the charge-to-mass ratio of an electron.

Fast cyclotron wave noise is extracted from the beam by a noise extraction cavity resonator 25. Cavity reso-

4

nator 25 is resonant at the cyclotron frequency and, as is seen in FIG. 2, it comprises two parallel poles 26 on opposite sides of the beam. Resonator 25 is known in the art as a Cuccia coupler, and its function is to extract fast cyclotron wave noise from the beam which is then transmitted to, and dissipated by, an impedance 27.

It can be shown that the phase constant β_{fc} of a fast cyclotron wave of frequency ω_1 on a rotating electron beam is given by:

$$\beta_{fc} = \frac{\omega_1 - \omega_c - (n_1 - 1)\omega_r}{v_0} \quad (2)$$

where ω_c is the angular cyclotron frequency, n_1 is the azimuthal mode of the cyclotron wave, ω_r is the angular frequency of beam rotation, and v_0 is D.-C. beam velocity. The azimuthal mode n_1 is numerically equal to the azimuthal periodicity around the circumference of the beam. In cavity resonator 25, there are only two poles 26 which, at any given instant of time, are at opposite electrical polarities. Hence, at any given instant, there is one cycle of change of electrical polarity around the beam circumference, and the azimuthal mode n_1 is equal to 1. Applying Equation 2, β_{fc} is equal to zero because resonator 25 is a lumped, rather than distributed, circuit. With n_1 equal to 1, ω_1 is equal to ω_c , which indicates that fast cyclotron wave noise centered about the cyclotron frequency is removed through the coupling action of resonator 25. Although this is known in the art, it demonstrates the applicability of Equation 2.

After leaving noise extraction resonator 25, the beam passes through a pump resonator 28, the purpose of which is to interchange energy between the fast cyclotron mode and the slow synchronous mode. In effect, pump resonator 28 transfers slow synchronous wave noise to the fast cyclotron mode and transfers the noiselessness of the fast cyclotron mode to the slow synchronous mode. This energy interchange is a result of parametric passive coupling between fast cyclotron and slow synchronous modes which is induced by electromagnetic pump energy of approximately twice the cyclotron frequency from pump source 30. As seen in FIG. 3, resonator 28 contains eight radially extending poles 31 which are excited in a known manner by pump source 30 such that adjacent poles have opposite instantaneous electrical polarity. In the magnetron art this type of excitation is known as π mode excitation but it will be referred to herein as the $n=4$ mode because it produces an azimuthal periodicity of 4.

Upon emergence from pump resonator 28 the beam enters an interaction resonator 32 with a substantially noiseless slow synchronous mode. Interaction resonator 32 contains six radially extending poles 33 which are excited in the $n=3$ mode by electromagnetic signal frequency energy from a signal source 34. The signal frequency is approximately equal to the cyclotron frequency and is channeled to resonator 32 by a ferrite circulator 35. The signal energy interacts with the noiseless slow synchronous mode of the beam and thereby becomes amplified, whereafter it is channeled by circulator 35 to an appropriate load 36.

It has heretofore been thought that interaction with the slow synchronous mode of a beam could be achieved only by propagating the signal wave on a slow wave structure at approximately the D.-C. beam velocity. I have found that phase constant β_{ss} of a slow synchronous wave of frequency ω_s is in fact variable, and is given by:

$$\beta_{ss} = \frac{\omega_s - (n_s - 1)\omega_r}{v_0} \quad (3)$$

Since interaction resonator 32 is a lumped circuit, β_{ss} is equal to zero. The azimuthal mode n_s is equal to 3, and with ω_r equal to $\omega_c/2$, ω_s is equal to ω_c . This means that a signal frequency of approximately the cyclotron frequency will be in proper synchronism in resonator 32 to interact with the slow synchronous mode of the beam.

Consider next the requirements for the pump frequency

5

and number of poles 31 in pump resonator 28 necessary to interchange energy between the fast cyclotron and slow synchronous modes. Such interchange can be considered to result from passive coupling between a slow synchronous signal frequency and a fast cyclotron idler frequency, where the idler frequency ω_i is defined by:

$$\omega_i = \omega_p - \omega_s \quad (4)$$

where ω_p is the pump frequency and ω_s is the signal frequency. Two conditions for passive coupling can be shown to be:

$$\beta_p = \beta_s + \beta_i \quad (5)$$

$$n_p = n_s + n_i \quad (6)$$

where $\beta_{(p,s,i)}$ is a phase constant of the pump, signal, and idler frequency waves, respectively, and $n_{(p,s,i)}$ is the azimuthal mode of the pump, signal, and idler frequency waves. If β_i is set equal to β_{ic} of Equation 2, and β_s is set equal to β_{ss} of Equation 3, then the noiselessness of the fast cyclotron wave at frequency ω_i will be transferred to the slow synchronous mode at frequency ω_s . This is desirable because interaction with the slow synchronous mode takes place in resonator 32 at frequency ω_s of equation 3. Therefore, Equation 5 can be expressed as:

$$\beta_p = \beta_{ic} + \beta_{ss} \quad (7)$$

Setting β_p equal to zero and substituting Equations 2 and 3 into Equation 7:

$$\omega_i - \frac{\omega_c - (n_i - 1)\omega_r}{v_o} + \frac{\omega_s - (n_s - 1)\omega_r}{v_o} = 0 \quad (8)$$

$$(\omega_s + \omega_i) = [(n_s + n_i) - 2]\omega_r + \omega_c \quad (9)$$

and from Equations 4 and 6:

$$\omega_p = (n_p - 2)\omega_r + \omega_c \quad (10)$$

From Equation 6, it can be seen that n_p must be equal to 4. With ω_r equal to $\omega_{c/2}$ Equation 1 reduces to:

$$\omega_p = 2\omega_c \quad (11)$$

which verifies that pumping must, in this case, be at twice the cyclotron frequency, and the pump resonator must have eight poles to produce an $n=4$ mode.

The foregoing explanation shows that many other combinations of frequencies and azimuthal modes can be used to achieve the objectives of the invention. Each of the three resonators must be designed so that noise is originally stripped from an appropriate fast cyclotron wave idler channel; that idler channel is passively coupled to an appropriate slow synchronous signal channel; and interaction is produced with the slow synchronous signal channel. For example, if interaction resonator 32 contained four poles instead of six, interaction would take place in the $n=2$ mode. From Equation 3, ω_s would equal $\omega_{c/2}$. From Equation 6 n_p would equal 3 so that cavity 28 would necessarily contain six poles. Equation 10 would take the form:

$$\omega_p = (3 - 2)\omega_{c/2} + \omega_c = 3\omega_{c/2} \quad (12)$$

Equation 4 is used to determine the resonant frequency at which noise extraction resonator 25 should be tuned:

$$\omega_i = \omega_p - \omega_s = 3\omega_{c/2} - \omega_{c/2} = \omega_c \quad (13)$$

Hence, under the modified condition, the pump frequency would be $3\omega_{c/2}$, pump resonator 28 would contain six poles, interaction resonator 32 would contain four poles, and the signal frequency would be centered about $\omega_{c/2}$. Noise extraction resonator 25 would be tuned to the idler frequency which is equal to ω_c , and the pump and interaction resonators would be tuned, respectively, to the pump and signal frequencies.

As another example, assume that it is desired to use a signal frequency that is three times the cyclotron frequency. This may be advantageous because a low cyclotron frequency permits a proportionally low magnetic field to be used. Assume further that the beam is made to rotate at the cyclotron frequency, rather than half the

6

cyclotron frequency. As is known, this can be done by producing a magnetic field in electron gun 13 that is equal in magnitude but opposite in direction to the magnetic field in the rest of the device. Under these conditions, the number of poles to be used in interaction resonator 32 is determined by setting Equation 3 equal to zero:

$$\beta_{ss} = \frac{3\omega_c - (n_s - 1)\omega_c}{v_o} = 0 \quad (14)$$

$$n_s = 4 \quad (15)$$

Equation 15 indicates that eight poles must be used in the interaction resonator. Assume next that it is desirable to use four poles in the noise extraction resonator 25. The frequency ω_i , to which resonator 25 must be tuned to strip the appropriate idler frequency ω_i , is determined by setting Equation 2 equal to zero:

$$\omega_i - \omega_c - (2 - 1)\omega_c = 0 \quad (16)$$

$$\omega_i = 2\omega_c \quad (17)$$

The pump frequency is determined from Equation 4:

$$\omega_p = \omega_s + \omega_i = 5\omega_c \quad (18)$$

The azimuthal mode of the pump wave is determined from Equation 6:

$$n_p = 4 + 2 = 6 \quad (19)$$

which indicates that twelve poles must be used in pump resonator 28. Present techniques now used in the magnetron art can be used to make a twelve-pole resonator.

From the foregoing it can be appreciated that there are many possible embodiments of the invention, due to the number of variables involved. This makes the invention inherently very flexible because it can be adapted to meet a wide range of requirements. Its most obvious advantages are its low noise capabilities, its short length, the absence of slow wave structures, and the fact that energy for amplification is taken from the beam according to slow mode interaction principles. Further, the device can be modified such that higher frequency operation does not necessitate a higher magnetic field as in the conventional parametric amplifier.

Although signal energy source 34 is shown as being connected directly to the interaction resonator 32, it could also be connected to the noise extraction resonator 25. In this case the signal energy would modulate the beam in the fast cyclotron mode, the modulation energy would be transferred by pump resonator 28 to the slow synchronous mode, and it would be amplified and extracted in interaction resonator 32. Various other modifications may be made by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electron discharge device comprising:
 - means for forming and projecting a beam of electrons along a path;
 - means for establishing a synchronous mode of wave propagation within said beam comprising means for producing an axial magnetic field along the path;
 - means for imparting a substantially uniform rotational velocity component to said beam;
 - a source of electromagnetic signal frequency energy;
 - means for amplifying said signal energy by inducing interaction between the electromagnetic signal wave energy and said synchronous mode of the beam comprising an interaction resonator surrounding part of said path which is directly connected to the signal frequency source;
 - said interaction resonator having an even number of conductive poles extending radially toward said beam, the number p of said poles being substantially determined by the relationship

$$\omega_s - \left(\frac{p}{2} - 1\right)\omega_r = 0$$

where ω_s is the angular frequency of said signal fre-

quency and ω_r is the angular frequency of said beam rotation.

2. The electron discharge device of claim 1 further comprising:

a circulator;

said signal frequency source being connected to a first port of said circulator;

said interaction resonator being connected to a second port of said circulator; and

a load being connected to a third port of said circulator.

3. An electron discharge device for amplifying electromagnetic signal wave energy comprising:

means for forming and projecting an electron beam along a path;

means for focusing said beam comprising means for producing an axial magnetic field throughout the beam;

the magnetic field inherently producing fast and slow cyclotron and synchronous modes of propagation within the beam;

means adjacent the beam forming means for imparting a substantially uniform rotational velocity component to the beam;

means comprising a first cavity resonator, resonant within a predetermined frequency band, for extracting from the beam fast cyclotron wave noise energy within said predetermined frequency band, thereby establishing noiseless cyclotron mode energy in the beam;

passive coupler pump means comprising a second cavity resonator, downstream from the first resonator, for converting said noiseless cyclotron mode energy to noiseless slow synchronous mode energy;

and means comprising a third cavity resonator, resonant at said signal frequency and downstream from said second resonator, for amplifying said electromagnetic signal wave energy by inducing interaction between the electromagnetic signal wave energy and said noiseless slow synchronous mode of the beam;

said third cavity resonator having a plurality of conductive poles extending radially toward the beam, the number p of the poles being determined by the relationship

$$\omega_s - \left(\frac{p}{2} - 1\right)\omega_r = 0$$

where ω_s is the angular signal frequency and ω_r is the angular frequency of beam rotation.

4. The electron discharge device of claim 3 wherein the first and second cavity resonators each contain a

plurality of conductive poles extending radially toward the beam;

the number of poles in the second resonator being equal to the total number of poles in the first and third resonators;

and a source of pump frequency energy being connected to the second resonator;

the pump frequency ω_p being given by

$$\omega_p = \left(\frac{p_p}{2} - 2\right)\omega_r + \omega_0$$

where p_p is the number of poles in the pump resonator and ω_0 is equal to the flux density of the axial magnetic field multiplied by the charge-to-mass ratio of an electron;

the predetermined frequency band to which the first resonator is tuned being substantially equal to the difference of the pump and signal frequencies.

5. The electron discharge device of claim 3 wherein: the axial magnetic field establishes an inherent cyclotron frequency in the electron beam;

the first resonator has two poles on opposite sides of the beam and is tuned to approximately the cyclotron frequency;

the second resonator has eight poles extending radially toward the beam and is tuned to approximately twice the cyclotron frequency;

a source of pump frequency energy of approximately twice the cyclotron frequency is connected to the second resonator;

and the third resonator has six poles extending radially toward said beam and is tuned to approximately the cyclotron frequency.

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GEORGE N. WESTBY, *Primary Examiner*.

ARTHUR GAUSS, ROY LAKE, *Examiners*.