Oct. 10, 1967 C. K. BIRDSALL 3,346,819

TWO-STREAM CYCLOTRON WAVE AMPLIFIER

Filed June 8, 1964 2 Sheets-Sheet 1

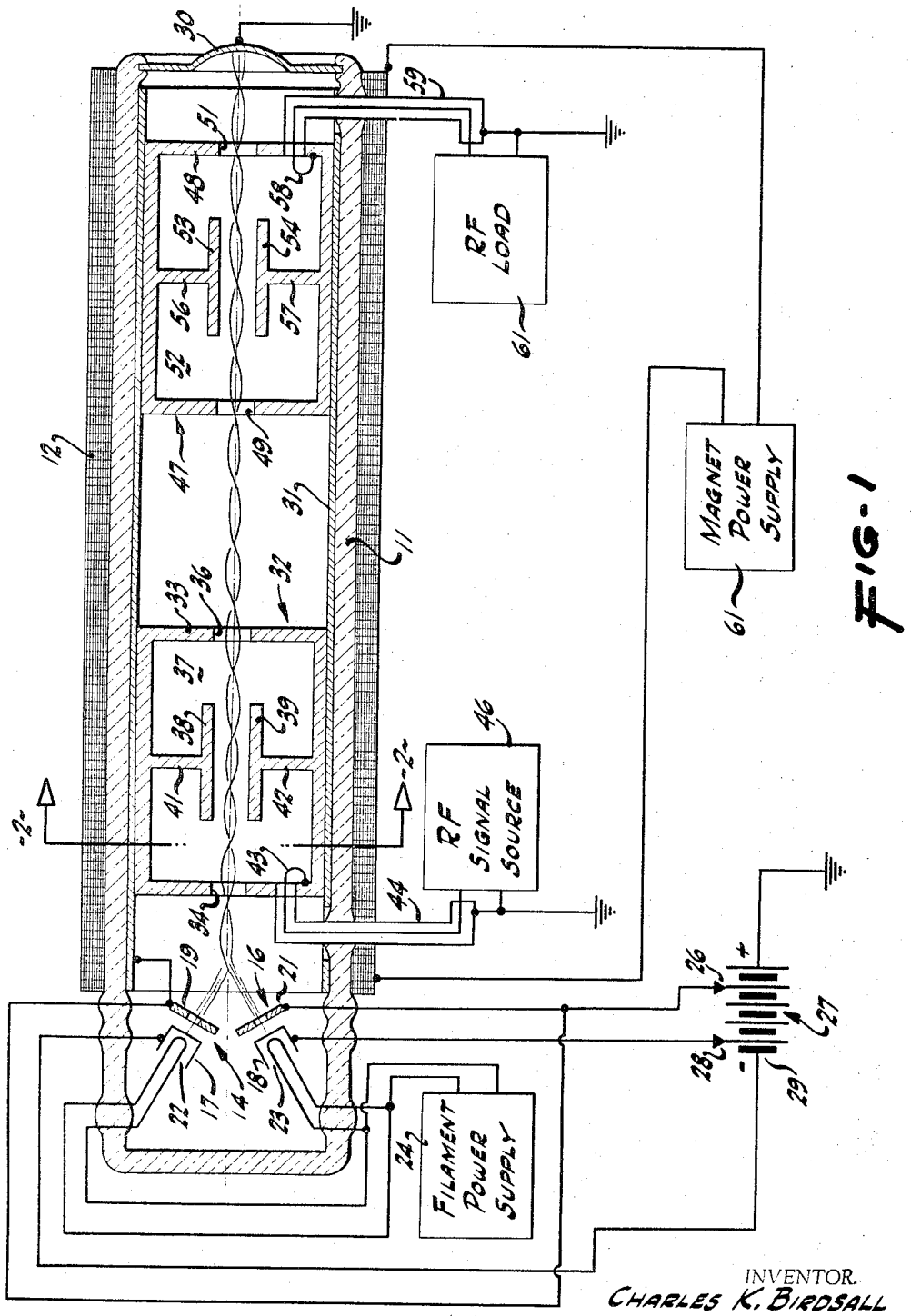


FIG. 1

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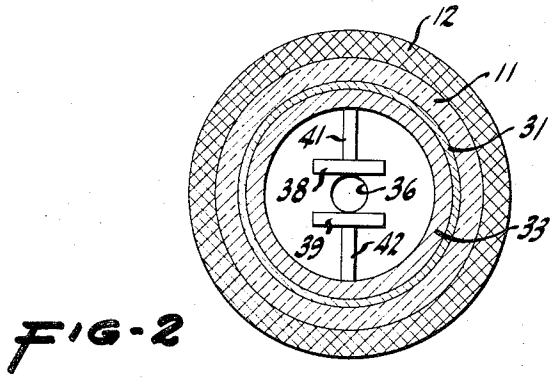


FIG-2

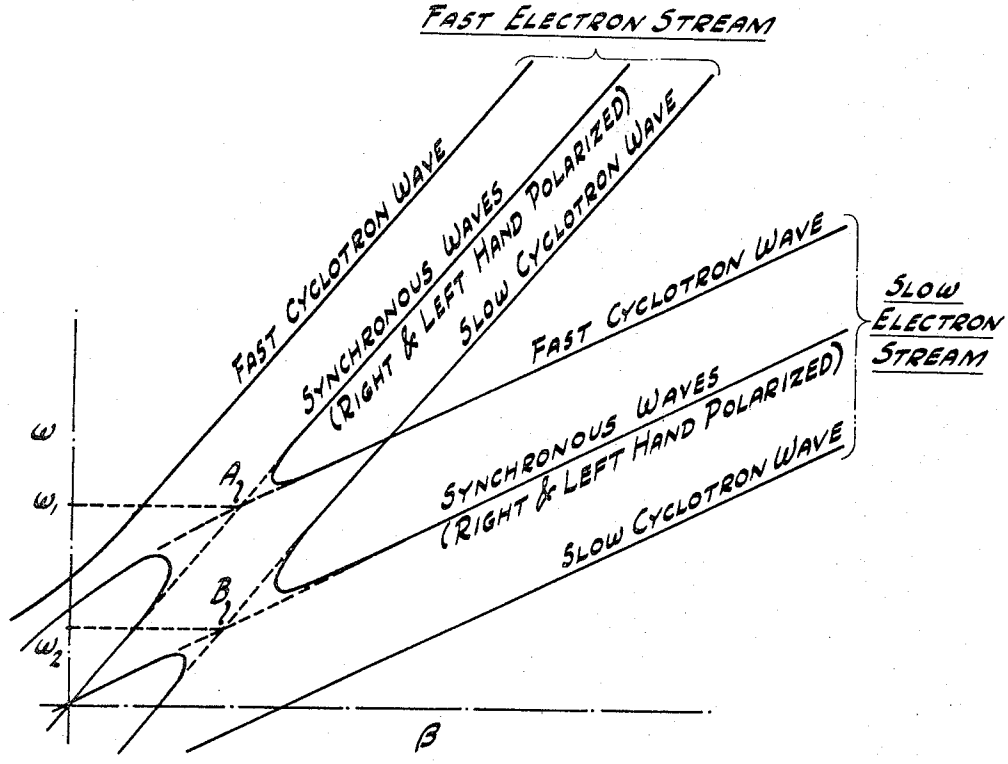


FIG-3

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TWO-STREAM CYCLOTRON WAVE AMPLIFIER

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4 Claims. (Cl. 330—44)

ABSTRACT OF THE DISCLOSURE

The invention disclosed and claimed herein relates to apparatus for interacting cyclotron waves of one electron beam with synchronous waves of another electron beam travelling together at different velocities along a magnetic field. Interaction for the purpose of extremely high-frequency amplification is accomplished by establishing an exciting electric field in the path of the beams, with the excitation frequency being particularly related to mean and relative electron-drift velocity, as well as cyclotron frequency.

The present invention relates generally to dual stream interaction microwave amplificaion devices, and is more particularly directed to a device of this type wherein amplification is obtained through interaction between cyclotron and synchronous waves of two electron streams traveling in the same direction with different drift velocities.

Traveling wave tubes, double stream plasma amplifiers, and the like, have long been employed in the amplification of microwave signals. However, these devices have not been particularly well suited to the amplification of signals of 100 or more gigacycles (one gigacyle=10° c.p.s.) having wavelengths of the order of a millimeter, or fraction thereof. Previously, extremely tiny circuits having an extreme criticality of dimensions, or devices employing extremely intense electron streams, were required to accomplish amplification at the foregoing frequencies. For example, conventional double stream space-charge-wave amplifiers have depended upon longitudinal interaction between fast and slow space charge waves of the respective electron streams, and the operating frequency has been a function of the plasma frequency of the electron streams. More particularly, the operating frequency of double stream space-charge-wave amplifiers is generally limited by the expression:

$$\frac{\omega}{\omega_p} \simeq \frac{v_{mean}}{v_{relative}}$$

where ω is the operating frequency of the device, ω_p is the plasma frequency, v_{mean} is the mean velocity of the two electron streams, and $v_{relative}$ is the relative velocity of the two electron streams. Inasmuch as plasma frequency is given by:

$$\omega_p = \sqrt{\frac{e^2 n}{m\epsilon}}$$

where e is electronic charge, n is density of the electron stream, m is electronic mass and ϵ is the permittivity of vacuum, it will be appreciated that extremely high density electron streams are required to facilitate operation of double stream space-charge-wave amplification devices with microwaves in the millimeter or fractional millimeter range.

The present invention overcomes the foregoing difficulties and limitations by providing an amplification device which depends upon transverse interaction between cyclotron and synchronous waves excited in two electron streams traveling in the same direction with different

velocities. In this case the operating frequency is limited by the expression:

$$\frac{\omega}{\omega_c} \simeq \frac{v_{mean}}{v_{relative}}$$

ω_c being the cyclotron frequency which is given by:

$$\omega_c = \frac{eB_0}{m}$$

B_0 being the flux density of a magnetic focusing field through which the electron streams are traveling. It will, thus, be noted from this expression that the operating frequency of the cyclotron wave interaction device of the present invention is primarily limited by the flux density of the magnetic focusing field. For flux densities of practicable magnitudes, for example, of the order of 10^5 gauss, it will be seen that operating frequencies of the order of 100 gigacycles are easily attained. In accordance with the general aspects of the invention, a magnetic field is generated in an evacuated interaction region into which two well coupled electron streams are directed with different velocities substantially along the field lines. Within the interaction region means are provided to generate an oscillating electric field transverse to the magnetic field at a signal frequency of the order of, or much larger than, the cyclotron angular frequency of electrons for the particular flux density of the magnetic field generated in the interaction region. The oscillating electric field can excite four waves in each of the electron streams, namely, fast and slow cyclotron waves and right- and left-hand polarized synchronous waves. As these waves can have angular or azimuthal variations, they are referred to by azimuthal mode number, m. In the invention hereof $|m|=1$ is implied although $|m|\geqslant 1$ is allowed. As the electron streams continue through the interaction region, cyclotron and synchronous waves of the respective streams interact to produce a wave of increasing intensity. Output means are disposed in the interaction region at a position longitudinally displaced from the input means in the direction of stream motion and are coupled in energy transfer relation to the streams to thereby extract an amplified signal from the wave of increasing intensity resulting from the interaction between the cyclotron and synchronous waves of the respective streams. It will, thus, be appreciated that the amplifier of the present invention is effective to amplify microwave signals, and the frequency of these signals may be of the order of 100 or more gigacycles with the employment of electron streams of relatively low density and magnetic focusing fields of practicable magnitudes.

The invention, together with further advantages and possible objects thereof, will be better understood upon consideration of the following detailed description of a preferred embodiment thereof with reference to the accompanying drawings, wherein:

FIGURE 1 is a transverse sectional view of a preferred embodiment of the two-stream cyclotron wave amplifier of the present invention, electrical components being illustrated in schematic;

FIGURE 2 is a transverse sectional view taken at line 2—2 of FIGURE 1; and

FIGURE 3 is a plot of angular frequency versus phase constant of the two electron streams of the amplifier graphically depicting regions of interaction between the synchronous and cyclotron waves of the respective streams.

As noted hereinbefore, the present invention utilizes to good advantage the interaction between cyclotron and synchronous waves of two electron streams traveling at different velocities in the same direction as opposed to conventional dual stream amplification devices which heretofore have generally utilized the interaction between

the space-charge-waves of the respective streams to produce amplification. More particularly, two well intermixed electron streams are directed into a magnetic field with different drift velocities v_1 and v_2 parallel to the field and an oscillating electric field is applied to the streams transverse to the magnetic field with an angular signal frequency ω. The drift velocities v_1 and v_2 of the respective electron streams are selected such that their mean velocity, v_{mean},

$$\left(v_{mean}=\frac{v_1+v_2}{2}\right)$$

and relative velocity, v_{rel}, ($v_{rel}=v_2-v_1$) are related to the signal angular frequency ω and the cyclotron angular frequency ω_c for electrons in the magnetic field of the particular magnitude employed, by the following expression:

$$\frac{v_{mean}}{v_{rel}}\cong\frac{\omega}{\omega_c}$$

The transverse electric field excites cyclotron and synchronous waves in the respective electron streams in a well known manner. For the slower stream of drift velocity v_1 there are excited fast and slow cyclotron waves and right- and left-hand polarized synchronous waves. As is well known and described, for example, in "Coupled Mode and Parametric Electronics," by William H. Louisell, John Wiley & Sons, Inc., 1960, the cyclotron waves are transverse velocity waves in contrast to the synchronous waves which are transverse displacement waves. More particularly, the cyclotron waves arise from electrons rotating about the magnetic field lines with the cyclotron frequency ω_c and simultaneously translating in the longitudinal direction with the drift velocity of the particular electron stream, v_1 in the case of the slow stream and v_2 in the case of the fast stream. The cyclotron waves may, accordingly, be visualized by imagining a string of electrons glued to a cylinder in the form of a helix and the cylinder to be rotating at the cyclotron frequency ω_c and translating in the longitudinal direction with hte drift velocity of the particular electron stream. However, as viewed by a fixed observer facing the longitudinal direction, different electrons that appear to be a single electron are seen to rotate with the apparent frequency ω. However, for a slow cyclotron wave, the pitch of the spiral of electrons is positive whereas for the fast cyclotron wave, the pitch is negative. Accordingly, a fixed observer facing in the longitudinal direction from which the electron streams arrive, sees the fast and slow cyclotron waves rotate respectively in opposite directions with the apparent frequency ω. In fact, it can be shown that the sense of rotation of the slow cyclotron wave is such that same is right-hand polarized, while the sense of rotation of the fast cyclotron wave is such that same is left-hand polarized. With regard to the individual electron streams, it should be noted that for the slow stream of drift velocity v_1 the phase constant of the fast cyclotron wave is given by $\beta_{e_1}-\beta_{c_1}$, while the phase constant of the slow cyclotron wave excited therein is given by: $\beta_{e_1}+\beta_{c_1}$, where

$$\beta_{e_1}=\frac{\omega}{v_1}\text{ and }\beta_{c_1}=\frac{\omega_c}{v_1}$$

Similarly, for the fast stream at drift velocity v_2, the fast cyclotron wave excited therein has a phase constant which is given by $\beta_{e_2}-\beta_{c_2}$ and the slow cyclotron wave excited therein has a phase constant given by $\beta_{e_2}+\beta_{c_2}$, where

$$\beta_{e_2}=\frac{\omega}{v_2}\text{ and }\beta_{c_2}=\frac{\omega_c}{v_2}$$

Considering now the synchronous waves of the respective electron streams in greater detail, as noted above a synchronous wave is essentially a transverse displacement wave and the electrons associated with such a synchronous

wave therefore do not have transverse velocity, although successive electrons are transversely displaced relative to each other. More particularly, a synchronous wave may be likened to the motion of water sent out from a garden hose nozzle that is rotated, provided gravity is neglected. Thus, each electron follows a straight line trajectory in the longitudinal direction, but successive electrons lie on a spiral. There are two synchronous waves of this variety for each electron stream, the difference between the two synchronous waves being that successive electrons of one wave lie on a left-hand wound spiral, while electrons of the other wave lie on a right-hand wound spiral. The phase velocity of each synchronous wave of the respective streams is equal to the drift velocities of the streams, i.e., the velocity v_1 for the slow stream and the velocity v_2 for the fast stream. Thus, a fixed observer facing in the longitudinal direction for each stream sees two synchronous waves wherein different electrons as time progresses for the respective waves appear as single electrons rotating respectively in clockwise and counterclockwise directions with the angular frequency ω. Each stream thus has a right-hand polarized synchronous wave and a left-hand polarized synchronous wave. The phase constant of the synchronous waves of the slow electron stream is equal to β_{e_1}, whereas the phase constant of the synchronous waves of the fast stream is equal to β_{e_2}.

With fast and slow cyclotron waves and left- and right-hand polarized synchronous waves of the foregoing type excited in the respective electron streams of drift velocities v_1 and v_2, and these velocities related to the signal frequency ω and cyclotron frequency ω_c, as described above, various interactions can occur between the waves of the respective streams as the streams progress through the interaction region. More particularly, the fast cyclotron wave of the slow electron stream, which is left-hand polarized, can be made to have a phase constant and angular frequency which are comparable to the left-hand polarized synchronous wave of the fast electron stream. Similarly, the slow cyclotron wave of the fast stream, which is right-hand polarized, can be made to have a phase constant and angular frequency which are equal to those of the right-hand polarized synchronous wave of the slow electron stream. When two waves have the same polarization, phase constant, and angular frequency, the waves interact with each other to produce growing and decaying waves. Thus, under one set of conditions, the fast cyclotron wave of the slow electron stream interacts with the left-hand polarized synchronous wave of the fast electron stream, and under another set of conditions, the slow cyclotron wave of the fast electron stream interacts with the right-hand polarized synchronous wave of the slow electron stream, to thereby produce growing and decaying waves. These sets of conditions or regions for interaction are graphically illustrated in the diagram of FIGURE 3 of signal frequency, ω, versus phase constant, β, for a relatively fast and a relatively slow electron stream. The slopes of the straight lines depicting the cyclotron and synchronous waves of the fast and slow streams represent the phase velocities of the waves

$$v_p=\frac{\omega}{\beta}$$

which, as noted previously, are the drift velocities of the respective streams. By virtue of the difference between the velocities of the respective streams, and the difference in the phase constants of the waves induced in each stream for any given value of signal frequency, various of the wave representing lines of one stream intersect various of the wave representing lines of the other stream. In this regard, the line denoting the synchronous waves of the fast stream intersects the line denoting the fast cyclotron wave of the slow stream at point A. Similarly, the line denoting the synchronous waves of the slow stream intersects the line denoting the slow cyclotron wave of the fast stream at point B. These intersection points A and B are,

of course, indicative of the waves represented by the intersecting lines having the same phase constant and angular frequency. The conditions for interaction are fulfilled at points A and B, the further requirement of like polarizations of the waves being satisfied at point A between the left-hand polarized synchronous wave of the fast stream and fast cyclotron wave of the slow stream, and at point B between the right-hand polarized synchronous wave of the slow stream and slow cyclotron wave of the fast stream. Thus, for an angular signal frequency ω_1 corresponding to point A the left-hand polarized synchronous wave of the fast stream interacts with the fast cyclotron wave of the slow stream to produce growing and decaying waves. Similarly, for an angular signal frequency ω_2 corresponding to point B, the right-hand polarized synchronous wave of the slow stream interacts with the slow cyclotron wave of the fast stream to produce growing and decaying waves. More particularly, in both of the foregoing cases, the bunched electrons of one of the waves periodically slip by those of the other wave, and in so doing generate a decaying wave, which damps out, and a growing wave which is, thus, periodically re-enforced. The electrons helically slip one wavelength of the signal frequency each cycle of the cyclotron frequency such that the frequency of the re-enforced growing wave is equal to the signal frequency. By virtue of the growing wave, an amplified signal may be derived from the electron streams by suitable output means coupled in energy transfer relation to the electron streams at a position longitudinally displaced from the electric field generating means in the direction of stream motion.

Considering now the two-stream cyclotron wave amplifier, generally outlined hereinbefore in greater detail with respect to the preferred embodiment illustrated in FIGURE 1, it is to be noted that the interaction region is preferably defined by means of an evacuated envelope **11** having a solenoid **12** disposed concentrically thereabout and energized by a direct current magnet power supply **13** to thereby generate the magnetic focusing field longitudinally through the envelope. At one end of the envelope there are provided a pair of electron guns **14** and **16** which respectively include cathodes **17** and **18** and accelerating electrodes **19** and **21**. The cathodes may be, for example, of the indirectly heated variety as shown, with filaments **22** and **23** respectively disposed within the cathodes **17** and **18** to heat same and effect the thermionic emission of electrons therefrom. Heating current is supplied to the filaments by means of a filament power supply **24**, or equivalent means, commonly connected thereto. The accelerating electrodes **19** and **21** are preferably in the form of centrally apertured metallic discs in spaced alignment with the cathodes **17** and **18**. The axes of the guns **14** and **16** are slightly inclined with respect to the axis of the envelope **11** such that upon the establishment of potential gradients between the accelerating electrodes and cathodes of the respective guns, electrons are directed through the apertures of the accelerating electrodes with radial and longitudinal components of velocity. The elevtron streams of the respective guns are thereby intermixed adjacent the axis of the envelope and focused axially therethrough by the longitudinal magnetic field. The streams from the respective guns have longitudinal drift velocities which are determined by the potential difference between the accelerating electrodes and cathodes thereof. In this regard, different drift velocities are established for the respective streams in accordance with the considerations discussed hereinbefore by providing different potential difference between the accelerating electrodes and cathodes of the respective guns. This may be accomplished by commonly connecting the accelerating electrodes **19** and **21** to a negative terminal **26** of a D-C power supply **27**, the positive terminal of which is connected to ground. The cathode **18** of gun **16** is connected to a negative terminal **28** of the supply which is more negative than terminal **26** and the cathode **17** of gun **14** is connected to a negative terminal **29** which is more negative than the terminal **28**. Thus, since the accelerating electrodes **19** and **21** are at the same potential, while the cathode **17** is at a more negative potential than the cathode **18**, the electron accelerating potential difference between cathode **17** and accelerating electrode **19** is greater than that between cathode **18** and accelerating electrode **21**. As a result, the electrons from gun **14** have greater velocity than the electrons from gun **16**. Consequently, electron gun **14** produces the fast electron stream, while electron gun **16** produces the slow electron stream previously considered. Preferably a field-free region for the drifting electron streams is extended longitudinally through the envelope to a metallic collector **30** at the opposite end thereof from the electron guns and which is preferably connected to ground. Preferably a conducting cylinder **31** is provided at the inside of the envelope **11** and held at constant potential, such as that of anodes **19** and **21**, to provide the field-free drift region.

Modulation of the two electron streams traveling with different drift velocities longitudinally through the envelope **11** with a transverse electric field at a predetermined signal frequency may be variously effected. For example, a pair of transversely spaced-apart plates may be disposed within the envelope on opposite sides of the axis thereof and a radio frequency signal source coupled between the plates. More preferably, however, the oscillating transverse electric field is established by means of a Cuccia coupler **32** coaxially disposed within the envelope adjacent the electron guns **14** and **16**. As is conventional, the coupler **32** includes a hollow metallic cylinder **33** having axially aligned stream inlet and outlet apertures **34** and **36** at its opposite ends. The cylinder **33** defines a cavity **37** within which a pair of transversely spaced-apart plates **38** and **39** are disposed on opposite sides of the cylinder axis and are in integral connection therewith as by means of stems **41** and **42**. An oscillating transverse electric field is established between the plates **38** and **39** upon excitation of the cavity **37** as by means of a radio frequency coupling loop **43** disposed therein and connected by means of a coaxial cable **44** to a radio frequency signal source **46**. The signal source has an angular operating frequency ω selected in the manner hereinbefore described and the oscillating transverse electric field oscillates at this frequency to excite the cyclotron and synchronous waves in the electron streams as they pass through the coupler **32**.

The output means for extracting energy from the re-enforced growing wave of the electron streams and providing an amplified signal is similar to the input means and may, accordingly, be provided as a pair of parallel transversely spaced plates disposed on opposite sides of the envelope axis. Preferably, however, the output means comprises a second Cuccia coupler **47** which includes a closed hollow cylinder **48** coaxially disposed within the envelope **11** at a position longitudinally displaced downstream from the coupler **32**. The cylinder **48** is provided with axially aligned stream inlet and outlet apertures **49** and **51** at its opposite ends and defines a cavity **52** within which a pair of transversely spaced parallel plates **53** and **54** are disposed on opposite sides of the cylinder axis and integrally connected therewith as by means of stems **56** and **57**. A radio frequency coupling loop **58**, or equivalent means, and coaxial cable **59** are employed to couple the cavity **52** to a radio frequency load **61**. The re-enforced wave in the electron streams in traversing the coupler cavity **52** between the plates **53** and **54** establishes an oscillating transverse electric field by condenser action and such field induces the flow of amplified signal current through the load **61**.

While the present invention has been described hereinbefore with respect to a single preferred embodiment, it will be appreciated that numerous modifications and changes may be made therein without departing from the true spirit and scope of the invention, and thus it is

not intended to limit the invention except by the terms of the following claims.

What is claimed is:

1. A two-stream cyclotron wave amplifier comprising means generating a magnetic field in an evacuated interaction region, means directing two well coupled electron streams respectively having different velocities into said interaction region substantially parallel to said magnetic field, input means generating an electric field in said interaction region transverse to said magnetic field and having a frequency of ω defined by the relation

$$\omega=\frac{v_M}{v_R}\omega_c$$

wherein v_M is the mean drift velocity of electrons in the two streams, v_R is the relative drift velocity of electrons in the two streams and ω_c is the cyclotron frequency of electrons in the streams, to thereby excite synchronous and cyclotron waves in each of said electron streams with a cyclotron wave of one stream interacting with a synchronous wave of the other stream during transit of the streams through the interaction region to produce a wave of increasing intensity, and output means coupled in energy transfer relation to said streams at a position of said interaction region displaced from said input means in the direction of stream motion for extracting an amplified signal from said wave of increasing intensity.

2. A two-stream cyclotron wave amplifier comprising an evacuated envelope, means generating a magnetic field longitudinally through said envelope, electron gun means disposed at one end of said envelope directing two intermixed electron streams through said envelope respectively with different longitudinal drift velocities v_1 and v_2, said streams thereby having a mean velocity

$$\frac{v_1+v_2}{2}$$

and relative velocity v_2-v_1, said drift velocities v_1 and v_2 being selected such that

$$\frac{v_1+v_2}{2}/v_2-v_1\cong\omega/\omega_c$$

where ω is a predetermined angular signal frequency and ω_c is the cyclotron angular frequency for electrons in said magnetic field, means generating an electric field in said envelope transverse to said magnetic field and at said predetermined angular signal frequency ω, said electric field exciting in said first stream a fast cyclotron wave of left-hand polarization having a phase constant $\beta_{e_1}-\beta_{c_1}$, a slow cyclotron wave of right-hand polarization having a phase constant $\beta_{e_1}+\beta_{c_1}$, and synchronous waves of right- and left-hand polarizations having phase constants β_{e_1}, where

$$\beta_{e_1}=\frac{\omega}{v_1}$$

and

$$\beta_{c_1}=\frac{\omega_c}{v_1}$$

said electric field exciting in said second stream a fast cyclotron wave of left-hand polarization having a phase constant $\beta_{e_2}-\beta_{c_2}$, a slow cyclotron wave of right-hand polarization having a phase constant $\beta_{e_2}+\beta_{c_2}$, and synchronous waves of right- and left-hand polarizations having phase constants β_{e_2}, where
and

$$\beta_{e_2}=\frac{\omega}{v_2}$$

and

$$\beta_{c_2}=\frac{\omega_c}{v_2}$$

said fast cyclotron wave having said phase constant $\beta_{e_1}-\beta_{c_1}$ interacting with said synchronous wave of left-hand polarization having said phase constant β_{e_2} to produce a re-enforced wave having said frequency ω, or said slow cyclotron wave having said phase constant $\beta_{e_2}+\beta_{c_2}$ interacting with said synchronous wave of right-hand polarization having said phase constant β_{e_1} to produce a re-enforced wave having said frequency ω, and transverse coupling means disposed in said envelope in energy transfer relation to said electron streams at a position downstream from said electric field for extracting an amplified signal from said reinforced wave.

3. A two-stream cyclotron wave amplifier according to claim 2, further defined by said means generating an electric field comprising a hollow cylindrical coupler defining a cavity coaxially disposed in said envelope and having axial stream inlet and outlet apertures at its opposite ends, said coupler having integral parallel transversely spaced plates disposed in said cavity on opposite sides of the axis thereof, and a radio frequency signal source coupled to said cavity to induce a transverse electric field therein, and by said transverse coupling means comprising a second hollow cylindrical coupler defining a cavity coaxially disposed in said envelope and having axial stream inlet and outlet apertures in its opposite ends, said second coupler having integral parallel transversely spaced plates disposed in said cavity on opposite sides of the axis thereof, and a load coupled to the cavity defined by said second coupler.

4. A two-stream cyclotron wave amplifier comprising a cylindrical vacuum envelope, a pair of electron guns disposed in said envelope adjacent one end thereof at off axis positions, said electron guns each including a cathode and an accelerating electrode positioned to direct electrons towards the axis of said envelope and longitudinally thereof when a potential is applied between the cathode and accelerating electrode, means for establishing positively increasing potentials of different magnitudes between the cathodes and accelerating electrodes of the respective guns whereby the electron streams therefrom have different drift velocities, a collector disposed at the opposite end of said envelope from said guns to receive the electron streams therefrom, a direct current energized solenoid concentrically disposed about said envelope to establish a magnetic field longitudinally therethrough, a first hollow cylindrical coupler defining a cavity coaxially disposed in said envelope adjacent said guns and having inlet and outlet apertures in its opposite ends for traversal by said electron streams, said coupler having integral parallel plates disposed within said cavity transversely spaced on opposite sides of the axis thereof, a source of radio frequency energy coupled to said cavity to excite an electric field therein between said plates, said source having an angular frequency which is approximately equal to the ratio of the mean to relative velocities of said electron streams times the angular cyclotron frequency of electrons in said magnetic field, a second hollow cylindrical coupler defining a second cavity coaxially disposed in said envelope adjacent said collector and having inlet and outlet apertures in its opposite ends for traversal by said electron streams, said second coupler having integral parallel plates disposed within said second cavity transversely spaced on opposite sides of the axis thereof, and an output load coupled to said second cavity for receiving radio frequency energy therefrom.

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