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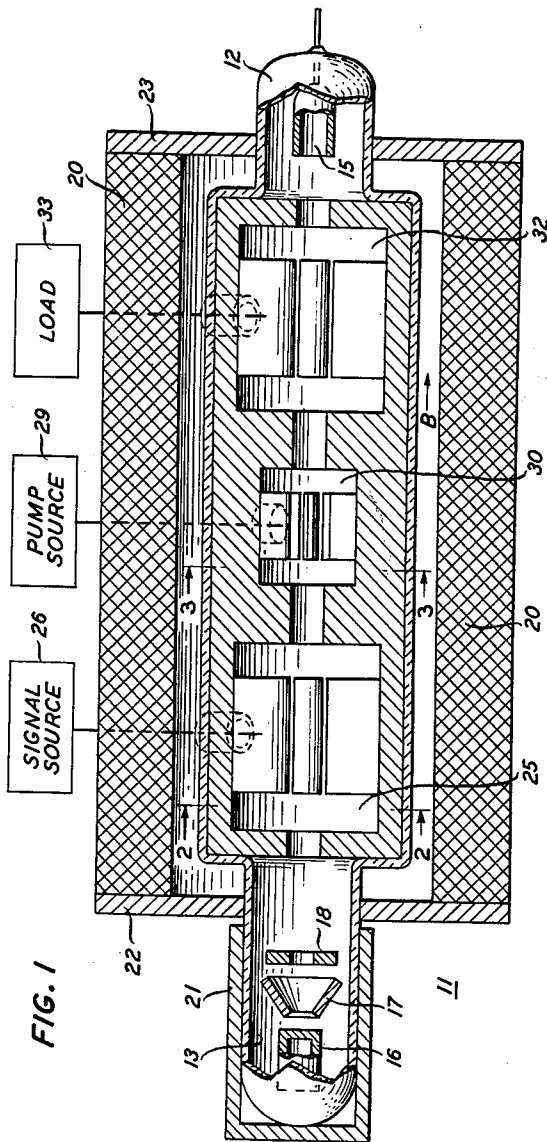


FIG. 1

FIG. 3

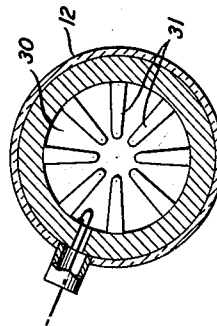
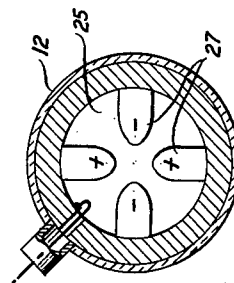


FIG. 2



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CYCLOTRON WAVE PARAMETRIC AMPLIFIER WITH DECREASED MAGNETIC BIAS

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6 Claims. (Cl. 330-43)

This invention relates to electron beam devices and, more particularly, to cyclotron wave amplifiers.

A recent important advance in the art is the cyclotron wave amplifier, known also as the quadrupole amplifier. By employing the principles of fast cyclotron wave amplification, this device permits the direct removal of beam noise energy. Beam noise energy has heretofore been a serious drawback of electron beam amplifiers such as the klystron and traveling wave tube.

The electron gun of the aforementioned device produces a beam which flows successively through an input coupler, a quadrupole amplifier, and an output coupler. The beam is immersed in a uniform magnetic field that is parallel to the path of the beam, and which establishes a cyclotron frequency at which the electrons will rotate if acted upon by forces transverse to the field.

The input coupler is a resonant circuit that is tuned to the cyclotron frequency. It serves to introduce signal frequency energy to the fast cyclotron mode of the beam and extract fast cyclotron wave signal frequency noise energy from the beam. The pump coupler is also a resonant circuit and is excited by a pump wave of twice the cyclotron frequency. The pump interacts with the beam and amplifies the fast signal cyclotron wave on the beam. A necessary condition for amplification is the production of quadrupole electric fields throughout the beam within the pump coupler; hence, the term "quadrupole amplifier." The output coupler is identical with the input coupler and it extracts the amplified low noise signal wave from the beam.

It has become apparent that for some applications, the quadrupole amplifier has certain drawbacks which may prove to be quite serious. One of these is the requirement that the signal frequency be approximately equal to the cyclotron frequency. The cyclotron frequency is directly proportional to the magnetic field and therefore, high frequency operation requires a very high magnetic field. The heavy and bulky magnet necessary to meet these requirements may seriously limit the device's usefulness.

One solution of this problem is the substitution of distributed circuits for the resonant circuit couplers as described in the application of Kompfner, Serial No. 77,323 filed December 21, 1960. When distributed circuits are used, the signal and pump waves are propagated as traveling waves in coupling relationship with the beam so that synchronism between the couplers and the beam is determined not only by the time alternating frequency of the waves, but also by the spatial periodicity, or phase constant, of the circuit. As a consequence, the cyclotron frequency is lower than the signal frequency under conditions of synchronism and the magnetic field requirements are reduced.

The use of distributed circuits poses certain inherent problems, the major one being the mechanical fabrication problems involved in constructing a distributed pump circuit that produces the required quadrupolar electric fields. Accordingly, it is an object of this invention to reduce the magnetic field requirements of cyclotron wave parametric amplifiers without resorting to the use of distributed circuits.

According to one feature of this invention the electron

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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 are imparted to the various electrons in the input coupler during the 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 accordance with the principles of Brillouin flow. As is known, under this condition, the electron beam rotates at a uniform angular frequency of approximately one-half the cyclotron frequency after being injected into the magnetic field.

The rotational velocity component of the electron beam gives the unmodulated electrons an inherent periodicity that is not present in a non-rotating beam. If the azimuthal periodicity of the signal wave that couples with the cyclotron mode of the beam is increased, synchronism between the wave and the beam can be attained even if the cyclotron frequency is lower than the signal frequency, and hence, the magnetic field requirements can be reduced. For example, it can be shown that a quadrupole input resonator can be used in conjunction with a Brillouin flow beam to modulate cyclotron mode of the beam with signal frequency energy that is one and one-half times the cyclotron frequency. Since the cyclotron frequency is directly proportional to the magnetic field this feature lowers magnetic field requirements so that a field that is only two-thirds as large as that normally required, is used.

To simplify tube structure, it can be shown that the azimuthal periodicity of the pump wave, which interacts with the beam in the pump resonator, shall be twice that of the signal wave. Accordingly, in the illustrative embodiment comprising a quadrupole input resonator, an octopole pump resonator is used. After the signal energy has been amplified in the pump resonator, it is extracted from the beam by a quadrupole output resonator which is substantially identical with the input resonator.

Other embodiments may be used, such as six-pole input and output resonators in conjunction with a 12-pole pump resonator, which will reduce the magnetic field requirements even further than the foregoing embodiment. Further magnetic field reductions can be made by imparting a larger initial uniform rotational velocity component onto 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; and

FIG. 3 is a section taken along lines 3-3 of FIG. 1.

Referring now to FIG. 1 there is shown a schematic illustration of 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.

Besides focusing the beam, the magnetic field B estab-

lishes fast and slow cyclotron modes of wave propagation within the beam. Waves traveling in these modes are referred to as cyclotron waves and are generally excited by applying high frequency electric fields to the beam that are transverse to the magnet field. The transverse forces exerted by the electric fields on the electrons combine with the focusing forces of the magnetic field and the longitudinal kinetic energy in the beam to cause the electrons to follow helical paths to the collector. The resulting cyclotron wave is defined by the relative phase position of successive gyrating electrons as they pass a transverse frame of reference.

As is known, the phase constant of a cyclotron wave is a function of its frequency, the mean (or D.-C.) velocity of the beam, and the magnetic focusing field. Waves at any given frequency can, however, travel at either of two phase constants depending upon whether they are excited by the addition of energy. If they are excited by adding energy to the beam they travel faster than the mean beam velocity, and are known as fast cyclotron waves; if not, they travel slower than the beam and are called slow cyclotron waves.

This invention is based upon the fact that the phase constants of cyclotron waves are also a function of any uniform rotational velocity component of the unmodulated beam and the azimuthal periodicity of the electromagnetic wave that excites the cyclotron 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 the 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. The inclusion of these elements effectively shields cathode 16 from the magnetic field. Under this condition, upon being injected into the magnetic field, the unmodulated electron beam will rotate at one-half the cyclotron frequency, the cyclotron frequency being given by:

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

where η is the charge-to-mass ratio of an electron.

The rotating electron beam is modulated in the cyclotron mode as it flows through a quadrupole input resonator 25 which is excited by signal energy from a source 26. I have found that signal energy will be transferred to the fast cyclotron mode of the electron beam if the phase constant of the signal wave, β_s , substantially fulfills the condition:

$$\beta_s = \frac{\omega_s - \omega_c - (n-1)\omega_r}{v_0} \quad (2)$$

where ω_s is the angular signal frequency, ω_r is the angular frequency of beam rotation, v_0 is the D.-C. beam velocity, and n is the azimuthal mode of beam excitation which is numerically equal to the azimuthal periodicity of the signal wave. Fast cyclotron wave electron beam noise of the signal frequency is removed from the beam by resonator 25 by the reverse operation. The beam noise energy is converted to wave energy and dissipated in the signal source 26.

As can be best seen in FIG. 2, input resonator 25 comprises four poles 27 in quadrature. When the resonator 25 is excited by source 26 adjacent poles 27 have opposite instantaneous polarities as shown by the plus and minus signs. Signal cyclotron waves are therefore excited in the $n=2$ mode because the azimuthal periodicity within the quadrupole resonator is equal to two. With reference to Equation 2, n is equal to two, ω_r is equal to $\frac{1}{2}\omega_c$ because of the Brillouin flow condition, and β_s is equal to zero because input resonator 25 is a lumped

circuit rather than a distributed circuit. Equation 2 therefore reduces to:

$$X_s = \frac{1}{2}\omega_c \quad (3)$$

This represents a distinct improvement over the conventional cyclotron wave parametric amplifier, in that the latter device requires a sufficiently high magnetic field to make the cyclotron frequency equal to the signal frequency. It should be pointed out that the operation of the conventional cyclotron wave parametric amplifier is consistent with Equation 2. In the conventional device ω_r is usually equal to zero and, because the input resonator comprises only a single pair of poles, n is equal to one.

The modulation process causes signal wave energy to propagate within the beam as a fast cyclotron wave. Because the original excitation was in the $n=2$ mode the signal cyclotron wave propagation in the beam is in the $n=2$ mode. This is to be distinguished from the beam of the conventional cyclotron wave device wherein the signal cyclotron wave propagates in the $n=1$ mode. Because of this difference, pump energy from pump source 29 is applied to the beam through an octopole pump resonator 30 rather than a quadrupole pump resonator as in the conventional cyclotron wave device. As is best seen in FIG. 3, pump resonator 30 comprises eight equally spaced poles 31 which surround the beam.

Pump resonator 30 is excited in a known manner to produce opposite instantaneous polarities on adjacent poles 31. In the magnetron art this type of excitation is known as π mode excitation but will be known herein as the $n=4$ mode because it produces an azimuthal periodicity of 4.

During the parametric amplification processes an idler frequency ω_i is defined which is given by:

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

where ω_p is the pump frequency. A well-known condition for parametric amplification is:

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

where $\beta_{(p, s, i)}$ are the phase constants in the pump, signal and idler frequencies, respectively. In addition to the known relationships of Equations 4 and 5, I have found that the following relationship is also a condition for parametric amplification:

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

where $n_{(p, s, i)}$ is equal to the azimuthal mode of the pump, signal, and idler waves, respectively.

The purpose of this invention is to produce parametric amplification through the use of a device of single structure. It is necessary for low noise amplification that cyclotron wave noise be stripped from the beam at both the signal and idler frequencies. Signal and idler noise can both be stripped by input resonator 25 only if the idler and signal frequencies are approximately equal and if the azimuthal modes of the signal and idler wave are equal. This will be true if:

$$\omega_p \approx 2\omega_s \quad (7)$$

$$n_p = 2n_s \quad (8)$$

In the device of FIG. 1, the frequency of the pump wave is therefore approximately twice the frequency of the signal waves, and the number of poles in pump resonator 30 is twice the number of poles in input resonator 25.

The energy from source 29 that is applied through octopole pump resonator 30 serves to amplify the helical rotations of the signal wave beam modulations and thereby amplify the signal cyclotron wave of the beam. The specific mechanism of energy transfer is similar to that of the conventional cyclotron wave devices, although it is complicated by the fact that the individual electrons are located in a rotating frame of reference because of the uniform rotational velocity component of the beam.

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After amplification, the amplified signal energy is removed from the beam by an output resonator 32 which is substantially identical to input resonator 25. The amplified signal energy is removed in the same manner that noise energy is removed by the input resonator and is thereafter transmitted to an appropriate load 33.

It should be emphasized that the embodiment of FIG. 1 merely is illustrative of the principles of my invention. Although resonators were used for coupling energy on and off the beam, distributed circuits could also be used for these purposes provided they comply with the conditions outlined above. Such distributed circuits have not been shown because it is a purpose of this invention to reduce magnetic field requirements without resorting to the use of distributed circuits. As pointed out above, this objective is obtained by using an electron beam with a uniform rotational velocity component in conjunction with an input resonator having an even number of poles greater than 2, and a pump resonator with twice the number of poles as the input resonator.

Other various possible embodiments are best appreciated if Equation 2 is set equal to zero and is re-written as follows:

$$\omega_s = \omega_c + \left(\frac{p}{2} - 1\right)\omega_r \quad (9)$$

where p is the number of poles in the input resonator.

$$\frac{p}{2}$$

is, of course, numerically equal to the azimuthal mode n only if resonators are used. Equation 9 demonstrates that the signal frequency can be increased by increasing either the frequency ω_r of beam rotation or the number of poles p in the input resonator. If only three resonators are to be used in the device, the pump frequency must be approximately twice the signal frequency, and the number of poles in the pump resonator must be twice the number of poles in the input resonator as given in Equations 7 and 8. If the conditions of these equations are not met, a fourth resonator must be used to strip idler frequency noise. This type of embodiment might be desirable to permit the use of a low frequency pump wave.

Various other methods can be devised for imparting a rotational velocity component to the beam; for example, a reversal in the direction of magnetic field through the beam will produce a rotational component which is equal to the cyclotron frequency. Various other embodiments may be devised by those skilled in the art without departing from the spirit and scope of this invention.

What is claimed is:

1. A parametric amplifier comprising:

means for forming and projecting an electron beam having an inherent periodicity;

means for focusing said beam comprising a magnetic field which is parallel with said beam;

means for modulating said beam with signal frequency energy comprising a resonator having p number of poles extending radially toward said beam, where p is any even number greater than two, said signal wave having a periodicity in synchronism with the periodicities of said beam;

a source of pump energy having a frequency substantially equal to twice said signal frequency;

means coupled to said source for parametrically amplifying electron beam modulations comprising a cavity resonator having $2p$ number of poles extending radially toward said beam;

and means for demodulating said beam, comprising an output resonator having p number of poles extending radially toward said beam.

2. A parametric amplifier comprising:

means for forming and projecting an electron beam;

means for producing an inherent cyclotron frequency

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within said beam comprising a magnetic field which is parallel with said beam;

means for imparting a uniform rotational velocity component to said beam;

means for modulating said beam comprising a resonator having p number of poles extending radially toward said beam where p is an even number greater than two;

means for transmitting signal energy to said input resonator, the signal energy having a frequency ω_s which is substantially given by:

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

where ω_c is the angular cyclotron frequency and ω_r is the angular frequency of said uniform beam rotation;

means for parametrically amplifying electron beam modulations comprising a pump resonator having $2p$ number of poles extending radially toward said beam; and means for demodulating said beam comprising an output resonator having p number of poles extending radially toward said beam.

3. A parametric amplifier comprising:

means for forming and projecting an electron beam;

means for producing a magnetic field which is parallel with said beam thereby establishing an inherent cyclotron frequency within said beam;

means for imparting a substantially uniform rotational velocity component to said beam;

means for modulating said beam in the fast cyclotron mode comprising an input resonator for concentrating signal frequency electric field components that are transverse to the direction of the electron beam flow along part of said beam, said resonator having means for imparting to the signal frequency wave an azimuthal periodicity;

said signal frequency being substantially given by:

$$\omega_s = \omega_c + (n - 1)\omega_r$$

where ω_c is the angular cyclotron frequency, n is the azimuthal mode of said signal frequency electric fields, and ω_r is the angular frequency of said uniform beam rotation;

means for parametrically amplifying electron beam modulations comprising a pump resonator for concentrating pump wave electric field components that are transverse to said beam along another portion of said beam;

the azimuthal mode of the pump wave being twice the azimuthal mode of the signal wave;

and means for demodulating said beam comprising an output resonator which is substantially identical to said input resonator.

4. A parametric amplifier comprising:

means for producing a substantially uniform magnetic field;

magnetically shielded cathode means for forming a rotating electron beam and projecting it into said magnetic field substantially parallel with said magnetic field;

said magnetic field establishing within said beam an inherent cyclotron frequency;

a source of signal frequency energy of substantially three-halves of said cyclotron frequency;

a quadrupole input resonator for modulating said electron beam with signal frequency energy;

a source of pump frequency energy of substantially twice said signal frequency;

an octopole pump resonator coupled to said pump source for parametrically amplifying signal frequency electron beam modulations;

and a quadrupole output resonator for extracting signal frequency energy from said pole.

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5. An electron beam device comprising:
 means for forming and projecting a beam of electrons
 along a longitudinal path;
 means for producing a focusing field;
 means for imparting a substantially uniform rotational 5
 velocity component to said electron beam;
 means for extracting substantially all fast cyclotron
 mode noise waves from said beam within a pre-
 determined frequency range and for producing a fast
 cyclotron mode signal wave on said beam compris- 10
 ing an input resonator having four poles radially
 extending toward said beam;
 means for parametrically amplifying said cyclotron
 signal wave comprising a pump resonator having
 eight equally spaced poles radially extending toward 15
 said beam;
 and means for extracting said cyclotron signal wave
 from said beam.
6. A parametric amplifier comprising:
 an electron gun for forming and projecting a beam 20
 of electrons along a path;
 means for imparting a substantially uniform rota-
 tional velocity component to said beam;
 means for producing along said path a magnetic field
 having a predetermined flux density, said magnetic 25
 field giving rise to an inherent cyclotron frequency
 of said electrons;

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a source of signal frequency energy;
 an input resonator which is substantially resonant at
 said signal frequency;
 said input resonator comprising means for causing said
 signal energy to propagate along said beam as fast
 cyclotron waves and for extracting fast cyclotron
 wave noise energy from said beam which is within
 the frequency band of said signal frequency;
 said input resonator having p number of poles extend-
 ing radially toward said beam where p is an even
 number greater than two;
 said signal frequency being substantially given by:

$$\omega_s = \omega_0 + \left(\frac{p}{2} - 1\right)\omega_r$$

where ω_c is the angular cyclotron frequency and
 ω_r is the angular frequency of said uniform beam
 rotation;

means for parametrically amplifying said fast cyclotron
 waves comprising a pump resonator having $2p$ num-
 ber of poles extending radially toward said beam;
 and means for extracting fast cyclotron wave energy
 from said beam comprising an output resonator hav-
 ing p number of poles extending radially toward said
 beam.

No references cited.