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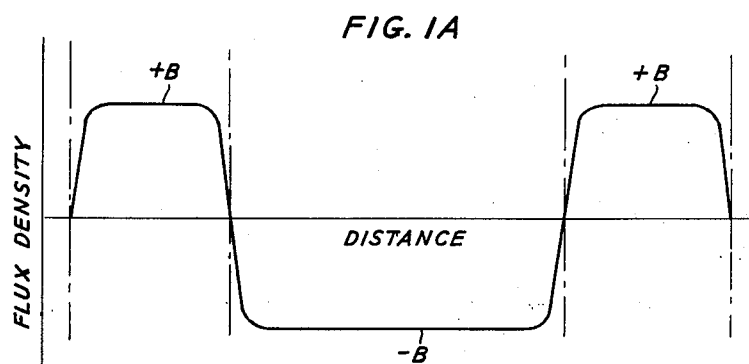
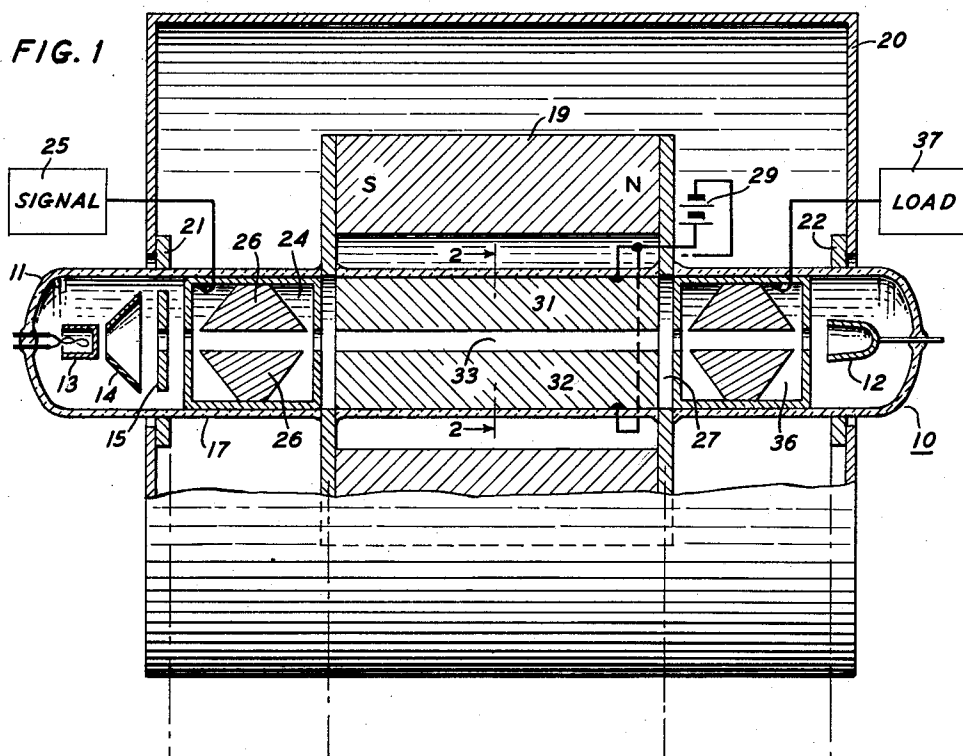
R. C. MILLER

3,122,710

SYNCHRONOUS WAVE PARAMETRIC AMPLIFIER AND CONVERSION MEANS

Filed Dec. 5, 1961

2 Sheets-Sheet 1



INVENTOR
R. C. MILLER
BY
Arthur J. Tossiglian
ATTORNEY

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R. C. MILLER

3,122,710

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FIG. 2

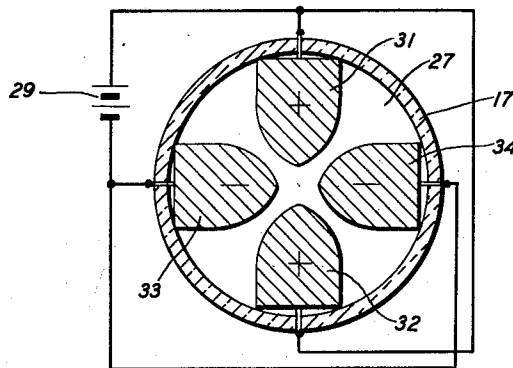
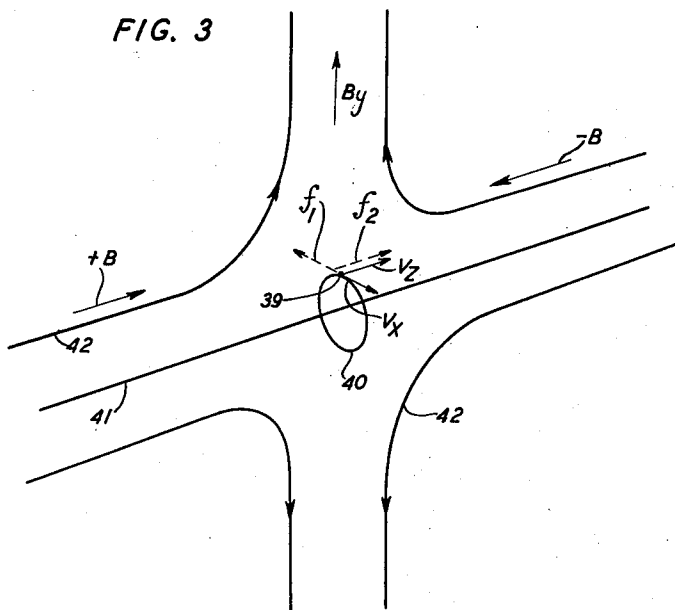


FIG. 3



INVENTOR
R.C. MILLER
BY
Arthur J. Torciglieri
ATTORNEY

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SYNCHRONOUS WAVE PARAMETRIC AMPLIFIER AND CONVERSION MEANS

Richard C. Miller, Summit, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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4 Claims. (Cl. 330-4.7)

This invention relates to electron beam devices and, more particularly, to high frequency electromagnetic wave amplifiers.

A recent development in the microwave amplification art is described in the application of E. I. Gordon, Serial No. 854,737, filed November 23, 1959. This development is embodied in a device which comprises an input resonator for coupling microwave energy to an electron beam in such a manner that the energy propagates as a cyclotron wave. An array of electrostatically charged quadrupoles deflects the electrons of the beam to amplify the microwave energy and an output resonator extracts the amplified energy from the beam.

Although the Gordon device is a high frequency amplifier, two factors place an upper frequency limit on its use. First, as will be explained later, a magnetic electron beam focusing field is required that must be increased with increasing frequency so that at extremely high frequencies the weight requirements of the focusing magnet may be unreasonably high. Secondly, the electrostatic quadrupoles must be spaced closer together axially at higher frequencies, thus giving rise to serious fabrication problems.

Accordingly, it is an object of this invention to simplify the manufacture of high frequency electron beam devices.

It is another object of this invention to reduce the magnetic weight requirements of high frequency electron beam devices.

These and other objects of the invention are attained in an illustrative embodiment comprising an electron gun for forming an electron beam and projecting it along a path toward a collector. The beam is prevented from diverging by a magnetic focusing field which is substantially parallel with its path of flow. As it flows through an input resonator the beam is modulated by signal wave energy having electric field components that are transverse to the beam path. The combined action of the transverse signal field forces and constraining force of the magnetic field causes the electrons of the beam to rotate in orbits of varying radius. Wave energy that propagates as electron rotational energy in this manner is referred to as cyclotron wave energy.

According to one aspect of this invention the cyclotron waves are converted to synchronous waves as the beam leaves the input resonator. Synchronous wave modulation is a particular type of electron beam modulation characterized by a displacement of electrons from the beam axis in proportion to the modulation energy which is imparted thereto. As will be explained hereafter, it is advantageous to amplify high frequency synchronous waves because synchronous wave amplification requires only a single electrostatic quadrupole, rather than an array of electrostatic quadrupoles as is necessary for cyclotron wave amplification.

I have found that cyclotron waves are fully converted to synchronous waves by an abrupt spatial reversal of the direction of the magnetic focusing field, providing that the magnitude of the field is the same before and after the reversal. Conversely, synchronous waves are converted to cyclotron waves by such an abrupt field reversal. Accordingly, a magnetic focusing field reversal occurs between the input coupler and the electrostatic quadrupole for converting cyclotron waves to synchronous

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waves. Another field reversal occurs immediately downstream from the quadrupole for converting the amplified synchronous waves back to cyclotron waves. The amplified cyclotron wave energy is then extracted from the beam by an output coupler that is substantially identical to the input coupler.

One advantage of my device is the magnet weight reduction that is possible through the two magnetic field reversals; such reversals cannot be incorporated into conventional cyclotron wave devices. Another advantage is the fact that a synchronous wave amplifying section comprising only a single electrostatic quadrupole (which is much simpler to construct than any corresponding cyclotron wave amplifying section) can be used in conjunction with well-known conventional cyclotron wave input and output couplers. These and other advantages and definitive features will be more readily appreciated from a consideration of the following detailed description, taken in conjunction with the accompanying drawing in which:

FIG. 1 is a sectional view of an illustrative embodiment of this invention;

FIG. 1A is a graph of flux density versus distance in the device of FIG. 1;

FIG. 2 is a view taken along lines 2-2 of FIG. 1; and

FIG. 3 is a representation of the trajectory of an electron of the device of FIG. 1.

Referring now to FIG. 1 there is shown an electron beam device 10 comprising an electron gun 11 for forming an electron beam and projecting it along a path toward a collector 12. For illustrative purposes, electron gun 11 is shown as comprising a cathode 13, a beam forming electrode 14, and an accelerating anode 15. An evacuated envelope 17 of suitable non-magnetic material maintains the electron beam within a substantial vacuum. The various electrodes are biased in a conventional manner by a battery which, for purposes of simplicity, has not been shown.

The solid beam of circular cross section is focused by the combined action of a cylindrical permanent magnet 19 and a ferromagnetic encasement 20, in accordance with the principles set forth in the application of M. S. Glass, Serial No. 142,850, filed October 4, 1961. Encasement 20 surrounds magnet 19 and has on opposite ends a pair of pole pieces 21 and 22. With the polarity shown a magnetic flux density $-B$ is produced along a direct flux path between the two poles of magnet 19. The directing fields of the magnet follow a low reluctance flux path through pole piece 22 adjacent the collector 12, encasement 20, and pole piece 21 adjacent the gun 11; a flux density $+B$ is therefore produced in the air gap between the magnet and pole piece 22 and between the magnet and pole piece 21. The magnitude and directions of these flux densities are shown in FIG. 1A. As disclosed in the Glass application, the magnitudes of $+B$ and $-B$ are substantially equal if the distance between magnet 19 and each of the pole pieces 21 and 22 is equal to half the length of magnet 19. Hence, the encasement 20 doubles the effective length of magnet 19 and thereby reduces the weight requirements of the focusing apparatus.

Surrounding a portion of the beam between gun 11 and magnet 19 is an input resonator 24 for modulating the beam with signal frequency energy from source 25. Input resonator 24 is of the well-known type that modulates the beam in the cyclotron mode and is described in detail in the aforementioned Gordon application. Briefly, resonator 24 operates on the principle that an electron in a magnetic field will rotate at a predetermined frequency (called the cyclotron frequency) if acted upon by a force that is transverse to the magnetic field. In

resonator 24, signal energy oscillates between parallel poles 26 at or near the cyclotron frequency to give successive electrons rotational velocity components that are representative of the applied signal energy. Energy propagating on an electron beam in this manner constitutes a cyclotron wave.

The direction of electron rotation depends upon the direction of the magnetic field. The magnetic field distribution shown in FIG. 1A cannot therefore be used in conventional cyclotron wave devices because the field reversal would completely disrupt the propagating cyclotron wave. I have found, however, that the abrupt magnetic field transition from $+B$ to $-B$ converts the signal cyclotron wave to a synchronous wave. The signal synchronous wave displacement is then amplified in a quadrupole section 27, a cross-sectional view of which is shown in FIG. 2. A quadrupole electrostatic field is produced along the beam by battery 29 which biases two of the poles 31 and 32 at positive potentials, and the other two, 33 and 34, at negative potentials. After amplification has taken place, the synchronous wave is converted back to a cyclotron wave by the field transition from $-B$ to $+B$. The amplified signal cyclotron wave is then extracted by a conventional output resonator 36 and transmitted to an appropriate load 37.

Any detailed mathematical description of the conversion and amplification mechanisms would be very complex and so will not be given. The conversion process can be appreciated from a consideration of FIG. 3 which shows an electron 39 having a longitudinal drift velocity v_z and rotating clockwise in an orbit 40 with a tangential velocity of rotation v_x . Electron 39 is intended to represent an electron which has been modulated in input resonator 24 of FIG. 1 and which therefore rotates clockwise around a central axis 41 at the cyclotron frequency ω_c given by:

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

where B is the magnetic flux density and η is the charge-to-mass ratio of the electron. Electron 39 can also be considered as being representative of the center of mass of the electron beam of FIG. 1 at a given time. The position of electron 39 is between input resonator 24 and quadrupole section 27, and so the flux density changes direction in a manner shown by magnetic field line 42.

As electron 39 enters the region of magnetic field reversal it is acted upon by a diverging or vertical flux density component B_y . By the "lefthand rule" flux density B_y combines with velocity v_z to exert a force f_1 on the electron that induces counterclockwise rotation. This force is given by:

$$f_1 = v_z B_y \quad (2)$$

By the same token, B_y acts with the velocity v_x to exert a force f_2 given by:

$$f_2 = v_x B_y \quad (3)$$

The result of these two forces is to increase v_z at the expense of v_x or in other words to convert rotational kinetic energy to longitudinal kinetic energy.

Consider next the degree to which the frequency of rotation is changed. It is known from Brillouin flow theory that an electron that enters a uniform magnetic field parallel with the field will thereafter rotate at one-half the cyclotron frequency (see, for example, "Theory and Design of Electron Beams," by J. R. Pierce, D. Van Nostrand Company, Inc., 1954, p. 152). Conversely, when a rotating electron leaves a magnetic field, its rotation will be diminished by one-half the cyclotron frequency. The frequency of rotation of electron 39 can therefore be thought of as diminishing from ω_c to $\omega_{c/2}$ as the flux density changes from $+B$ to zero and then diminishing from $\omega_{c/2}$ to zero as the field changes from zero to $-B$. Hence, the complete reversal from $+B$ to $-B$ completely converts all rotational energy of electron 39 to longitudinal energy.

If the transition from $+B$ to $-B$ is abrupt, electron 39 will remain displaced from central axis 41 a distance equal to its original radius of rotation. Successive electrons having this type of displacement characteristic form a synchronous wave, and in the device of FIG. 1 intelligence from the signal source 25 is propagated along quadrupole section 27 as a synchronous wave. In the case of a substantially linear change of magnetic field as shown, a substantially complete mode conversion will occur if the field reverses within one-third of a cyclotron wavelength, that is, the longitudinal distance an electron travels during one-third of a cyclotron rotation. However, the interchange between synchronous and cyclotron waves can also be made to occur for magnetic field reversals which are not abrupt, or linear, or even taken between equal and opposite initial and final values of magnetic field. In any of the latter circumstances, however, the transition from 0 to $-B$ must compensate for any spurious displacements which may result from the transition from $+B$ to 0.

As the electrons travel through quadrupole section 27, most of them are attracted toward the two positive poles 31 and 32 while others are repelled by the two negative poles 33 and 34 toward the central axis of the device. The net displacement of the electrons is increased, however, with a resulting net amplification of the synchronous wave. It should be pointed out that poles 31-34 of quadrupole section 27 do not impart any net energy to the beam, but merely act as electrostatic deflecting plates.

It is intended that quadrupole section 27 be only exemplary of a number of synchronous wave amplifying sections that could be used. It is, in fact, a special form of pumping mechanism for parametric amplification of the synchronous wave. It can be shown that a pump wave that produces quadrupole electric fields throughout an electron beam will parametrically amplify a synchronous beam wave if its angular frequency ω_p is determined by:

$$\omega_p = \beta_p v \quad (4)$$

where ω_p is the frequency of the pump wave, β_p is the phase constant of the pump wave and v is the longitudinal drift velocity of the electron beam. In the device of FIG. 1, both the frequency ω_p and the phase constant β_p are equal to zero and Equation 4 is satisfied.

After the synchronous wave has been amplified it is converted to a cyclotron wave by the magnetic field transition from $-B$ to $+B$. The reverse process from that shown in FIG. 3 takes place; displaced electrons are caused to rotate around central axis 41 by a conversion of longitudinal drift energy to transverse kinetic energy. The transverse or rotational energy of the electrons is then extracted by output resonator 36 and transferred to an appropriate load 37.

It is intended that the above-described embodiment be only illustrative of the principles of my invention. For example, the patent of Ashkin et al., No. 3,054,964, granted September 18, 1962, discloses several other uses for synchronous wave-cyclotron wave conversion. In the terminology of the Ashkin et al. patent, the magnetic field reversal constitutes a "passive coupler" which transfers energy between the "fast" cyclotron and the synchronous waves or "slow" cyclotron and synchronous waves, but not between "fast" and "slow" waves. The above-described magnetic field reversal can therefore be substituted for the electrostatic passive coupler of the Ashkin et al. patent. 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. In combination: means for forming and projecting a beam of electrons along a path; means for causing electromagnetic wave energy to propagate along said beam as cyclotron wave energy; and means for converting said cyclotron wave energy to synchronous wave energy comprising means for producing throughout said

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beam a longitudinal magnetic field which is of substantially uniform magnitude but which spatially reverses direction within a distance equal to one-third of a cyclotron wave length.

2. In combination: means for forming and projecting an electron beam, means for causing electromagnetic wave energy to propagate along said beam as a synchronous wave; and means for converting said synchronous wave to a cyclotron wave comprising means for producing throughout said beam a magnetic field that is of substantially uniform magnitude and substantially parallel with said beam but which spatially reverses direction within a distance equal to one-third of a cyclotron wave length.

3. An electron beam device comprising: means for forming and projecting a beam of electrons; means for producing a longitudinal magnetic focusing field through the beam; means for causing electromagnetic wave energy to propagate along said beam as cyclotron wave modulations; means for converting said cyclotron wave modulations to synchronous wave modulations comprising means for reversing the direction of the magnetic field within a distance equal to one-third of a cyclotron wave length; means for amplifying said synchronous wave modulations; means for converting said synchronous wave modulations back to cyclotron wave modulations comprising second means for reversing the direction of the magnetic field within one-third of a cyclotron wavelength; the magnitude of the magnetic field immediately upstream and downstream from each of the field reversals being substantially equal; and means for extracting cyclotron wave modulation from said beam.

4. An electron beam device comprising: means for forming and projecting a beam of electrons; a magnetic focusing field extending longitudinally through said beam;

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a source of signal frequency energy; an input resonator coupled to said source and surrounding a first part of said beam; said input resonator having a resonant frequency that is substantially equal to the product of the flux density of the magnetic focusing field and the charge-to-mass ratio of an electron; a pair of poles within said resonator for concentrating signal frequency energy along a portion of said beam; four conductive poles arranged in quadrature around a second part of said beam, two of which are biased at a positive electrostatic polarity and the other two at a negative electrostatic polarity; means for reversing the direction of the magnetic field between the input resonator and the four conductive poles; an output resonator surrounding a third part of the beam for extracting energy from said electron beam; said output resonator having substantially the same resonant characteristics as said input resonator; and means for reversing the direction of the magnetic field between the four conductive poles and the output resonator; the magnitude of the magnetic field through said first, second, and third parts of the electron beam being substantially equal.

References Cited in the file of this patent

UNITED STATES PATENTS

3,051,910	Rigrod	Aug. 28, 1962
3,051,911	Kompfner	Aug. 28, 1962
3,072,817	Gordon	Jan. 8, 1963

OTHER REFERENCES

Journal of Applied Physics (Coupled Mode Theory of Electron-Beam Parametric Amplification), by Gould et al., vol. 32, No. 2, February 1961.

Kluver: "Journal of Applied Physics," June 1961, pages 1111-1114.