Aug. 20, 1968 J. L. HIRSHFIELD 3,398,376

RELATIVISTIC ELECTRON CYCLOTRON MASER

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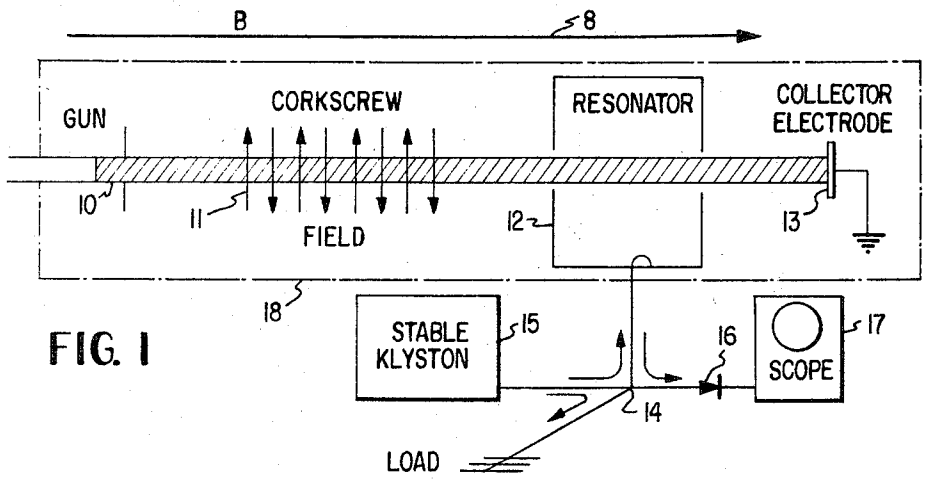


FIG. 1

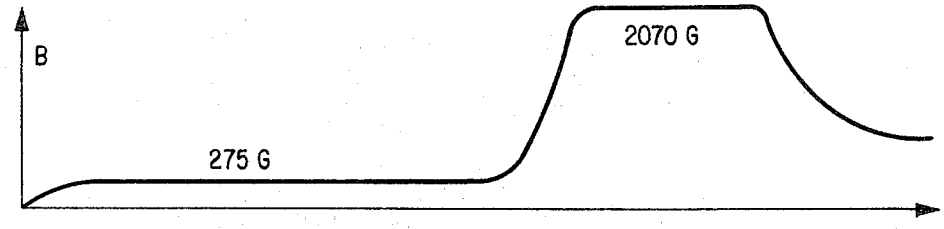


FIG. 2

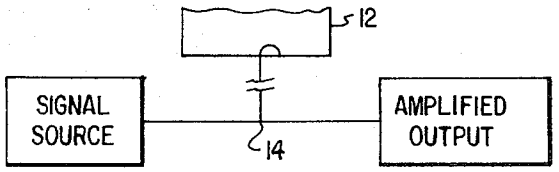


FIG. 1a

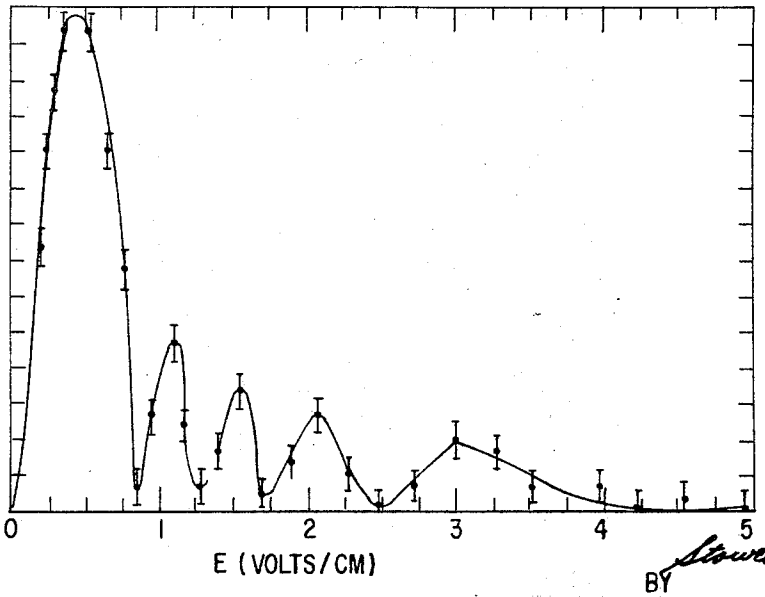


FIG. 6

INVENTOR.
JAY L. HIRSHFIELD

BY Stowell & Stowell ATTORNEYS.

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FIG. 3

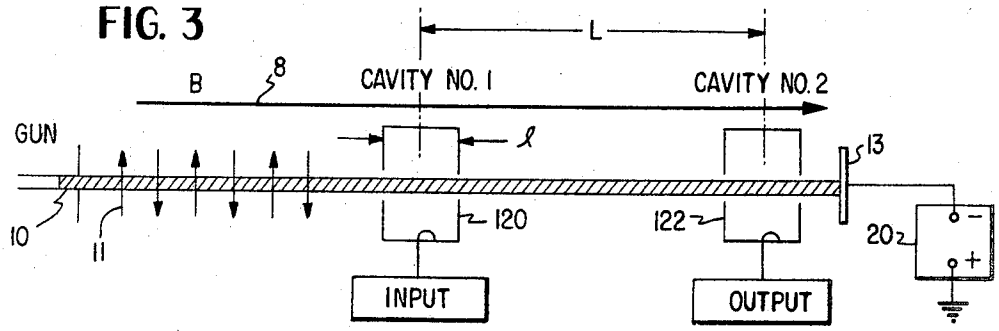
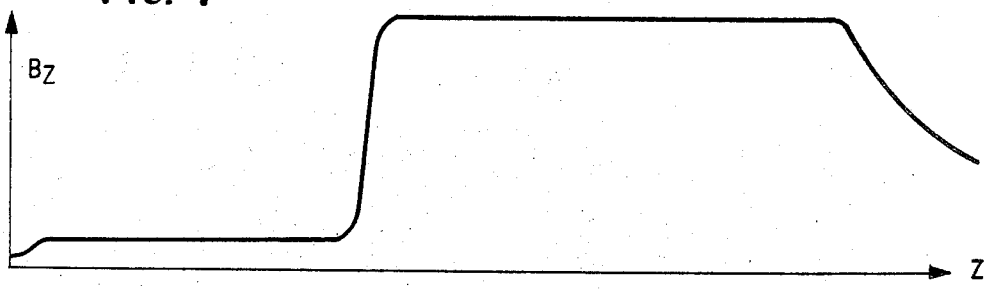


FIG. 4



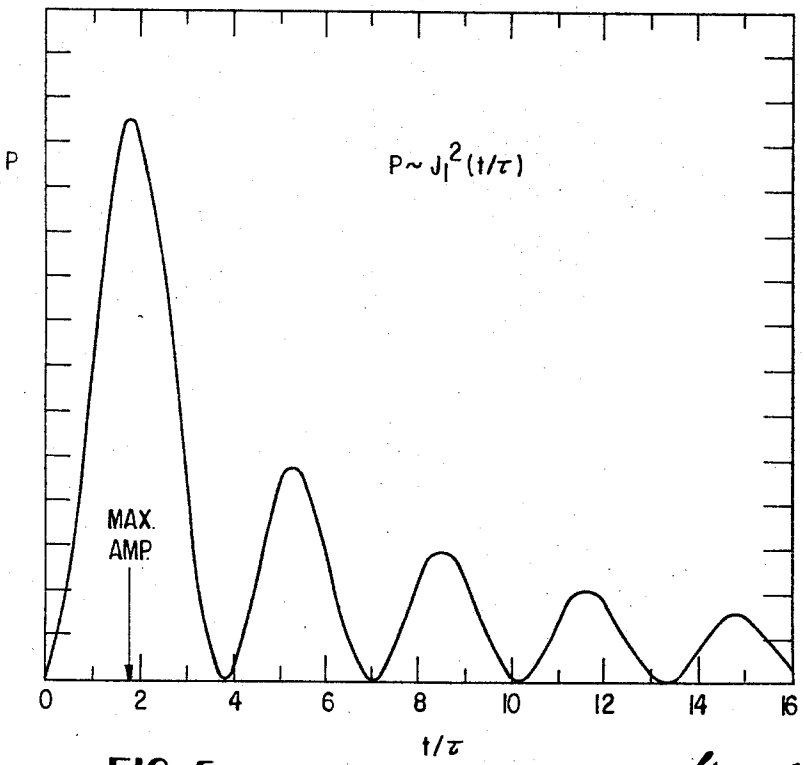


FIG. 5

INVENTOR.
JAY L. HIRSHFIELD

BY Stowell & Stowell
ATTORNEYS.

United States Patent Office

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RELATIVISTIC ELECTRON CYCLOTRON MASER

Jay L. Hirshfield, 85 Blake Road,
Hamden, Conn. 06514

Continuation-in-part of application Ser. No. 569,713, Aug. 2, 1966. This application Dec. 11, 1967, Ser. No. 693,045

7 Claims. (Cl. 330—4.3)

ABSTRACT OF THE DISCLOSURE

An electron cyclotron maser high frequency generator/amplifier utilizing stimulated emission of cyclotron radiation comprising an electron gun whose electron beam passes through a resonator. A magnetic field coaxial with the electron beam, and a twisted D.C. electric or magnetic field, upstream of the resonator, acts on the beam to give a spiral motion to the individual electrons. The strength of the magnetic field may be greatest at the resonator. As an amplifier, a second resonant cavity may be added downstream of the first resonator and is subject to the same axial magnetic field strength as the first.

This application is a continuation-in-part of application Ser. No. 569,713, filed Aug. 2, 1966, now abandoned. This was in turn a continuation-in-part of Ser. No. 451,219, filed Apr. 27, 1965, now abandoned, this in turn being a continuation-in-part of Ser. No. 365,468, filed May 6, 1964, now abandoned.

This invention relates to a method and apparatus for generating electromagnetic radiation in the microwave and millimeter wave bands from about 1 gc. (10^9 cycles per second) to above 100 gc. in frequency by stimulating the coherent emission of cyclotron radiation from a beam of free electrons.

The objects of the invention are attained by subjecting a beam of electrons immersed in a longitudinal magnetic field to the action of a corkscrew magnetic or electric field to impart to the electron a spiral trajectory and thereafter passing the spiralling electron beam into a resonator element of an electromagnetic circuit having an operating frequency including the cyclotron frequency of the electrons in the spiralling beam.

Theoretical discussions indicating the possibility of enhanced stimulated emission of electric dipole (and higher multipole) radiation at electron cyclotron frequencies are contained in references cited in an article by applicant and J. M. Wachtel in "Physical Review Letters," 12, 533–536 (1964).

In the method and apparatus of the invention the operating frequency f is determined by the strength of the applied DC magnetic field at the position of the resonator element in accordance with the relation

$$f=2.8nB$$

wherein f is the frequency in gigacycles per second, B is the magnetic field strength in kilogauss, and n is 1, 2, 3 . . . , depending on whether the transitions are dipole, quadrupole, octupole, and so on.

The longitudinal magnetic field may conveniently be provided by a solenoidal winding surrounding the electron beam, the magnetic field strength being increased in the direction of travel of the beam by known methods such as the interposition of iron circuits or by varying the number of solenoid windings per unit axial length.

The corkscrew field can be provided by distorting the main longitudinal field with a helical iron (ferromagnetic) strap or with a bifilar winding carrying its own DC current. Alternatively, a corkscrew electric field can be provided by an intertwisted pair of helical wires maintained at different electrostatic potentials.

It is advantageous to provide a weaker longitudinal magnetic field at the locus of the corkscrew field. This has the advantage of facilitating the production of the corkscrew field, the pitch of which must match the electron trajectory pitch and also of reducing the size of the region in which the high field is maintained.

At frequencies up to about 30 gc. the resonator element may conveniently be a TE_{011} cylindrical mode cavity of length L and radius R determined by the relation

$$f=\frac{c\sqrt{1+(2L/1.64R)^2}}{2L}$$

wherein c is the speed of light. For higher frequencies an open-ended cylindrical or plane-parallel "Fabry-Perot" resonator may be used. At 140 gc., for example, where the radiation wave-length is about 2 mm., such a resonator in the cylindrical form could have a length of 50 mm. and a radius of 15 mm., but the dimensions are not critical, as with the single-mode resonator.

The electron beam may be supplied by a standard electron gun, such as a Pierce type gun immersed in the magnetic field.

The invention further exhibits utility as an amplifier by coupling in a manner analogous to a klystron, i.e., the provision of a first or input resonant cavity and a second or output resonant cavity, although the beam in the subject apparatus is not returned as in a klystron. The invention may also be employed as an amplifier by the use of the same resonant cavity in a manner analogous to a reflux klystron.

In the drawings:

FIGURE 1 is an illustrative diagrammatic view of a first embodiment of the invention susceptible of use as a generator of high frequencies.

FIGURE 1*a* is a partial view indicating the use of the apparatus of FIGURE 1 as an amplifier.

FIGURE 2 is a plot of typical variation in strength of a magnetic field B longitudinal with respect to the apparatus of FIGURE 1.

FIGURE 3 is an illustrative diagrammatic view of a second embodiment of the invention, here displaying particular utility as an amplifier.

FIGURE 4 is a plot similar to FIGURE 2 but for the embodiment of FIGURE 3.

FIGURES 5 and 6 are theoretical and experimental plots, respectively, of the power radiated from the beam of electrons at its cyclotron frequency after its passage through the first cavity in the embodiment of FIGURE 3.

In FIGURE 1 of the drawings **10** is an electron gun, **11** is the locus of a corkscrew field, **12** is the cavity resonator, and **13** is the collector electrode, all of which are positioned in an evacuated tube **18**. The plot of FIGURE 2 of the drawing shows the axial variation of an axial magnetic field, B of FIGURE 1, along tube **18** provided by solenoid windings (not shown).

In a typical operation, electrons are accelerated in vacuo from a thermionic cathode of electron gun **10** through potentials of for example up to 5000 volts. The cathode is immersed in a longitudinal magnetic field **3** of about 275 gausss and the electrons drift through a four-turn periodic corkscrew **11** of 5.7 cm. pitch (R. Wingerson, Physical Review Letters 6, p. 466 (1961)). This corkscrew, a bifilar winding arranged so as to superpose an adjustable transverse twisted magnetic field of up to 50 gauss on the 275 gauss longitudinal field, serves to transform any desired fraction of the kinetic energy of the electrons into spiralling motion about the field lines. Variation of the corkscrew field therefore adjusts the electron distribution on a shell in velocity-space.

Following the corkscrew, the now spiralling electrons

pass through a gradually increasing magnetic field into a uniform region of 2070 gauss. This mirror ratio of 2070/275=7.5 increases the transverse kinetic energy of the electrons by the same factor, assuming the motion to be adiabatic, so that the corkscrew is required to transfer only 13% of the electron kinetic energy into transverse motion in order to achieve a full transfer in the 2070 gauss region. In this latter region, the electrons drift through a TE_{011} mode cylindrical microwave cavity **12** which is resonant at 5800 mc. s. The cavity, with a loaded Q of about 10^4, may contain four off-axis longitudinal rods to suppress other modes but this is not an essential feature. The D-C magnetic field is axially homogeneous over the cavity **12** to ±0.2 gauss. Following the cavity, the electrons are collected at a water-cooled electrode **13**. The entire apparatus is stainless steel and copper, assembled with copper gaskets; following bake-out at 400° C. for 18 hours the system achieved pressures of 1×10^{-9} torr under continuous pumping.

Evidence of the effectiveness with which the corkscrew functions is provided by the fact that current to the collector can be completely cut off as one increases the corkscrew field beyond the usual operating range, indicating that the electrons are able to receive greater than 13% transverse energy and thus do not penetrate the magnetic mirror.

For test purposes the microwave cavity **12** was connected to one arm of a magic tee **14** and decoupled with a coupling coefficient of 0.15. Thus small changes in microwave power from a stabilized klystron **15** reflected from the cavity, as registered at a crystal detector **16** in another of the magic tee arms were, in the standard approximation, sensibly proportional to the real part of the electron's plasma conductivity $Re\sigma$, or to the absorption coefficient $Im k$, since $1\sigma/we.1<<1$.

The 2070 gauss magnetic field was swept over a narrow range at 35 c.p.s. and the crystal detector current was displayed on oscilloscope **17**. When the corkscrew field was optimized, sharp absorption was indicated in the region of 2091 gauss. The 21 gauss upward shift corresponds to the 1% relativistic mass increase of 5000 volt electrons. In the apparatus illustrated oscillation powers at 5800 mc./sec. in excess of 10 milliwatts have been measured with a half-width at half-power of less than 25 kc./sec. It will be understood that the elements **15**, **16** and **17** exhibit utility as testing adjuncts to the main apparatus.

The principle of operation of the invention is based on the stimulated emission of cyclotron radiation from free electrons in a magnetic field. Such stimulated emission is possible for relativistic electrons, but not for low energy ones. It involves a fast wave interaction, since the phase velocity of the radiation is equal to, or greater than, the speed of light. No synchronism is required between a beam and a guided wave as in a traveling wave tube or a cyclotron wave amplifier; thus no slow wave circuits are required.

An electron is said to be relativistic in the sense that its kinetic energy E is comparable to its rest energy m_oc^2, about 500,000 electron-volts. In order for the device to operate on the above principle, it is generally a requirement that NE/m_oc^2 be at least of the order of magnitude of one, where N is the number of cycles spent by the electron, having a kinetic energy E, in the resonator. Thus, even though an electron may have a kinetic energy E lower than that considered to be relativistic, if it spends enough cycles N in the resonator **12**, it will act to stimulate coherent emission of cyclotron radiation. Further, the above requirement may be met even though the motion is not adiabatic.

It is to be observed that the transition of the electrons from the lower magnetic field of 275 gauss to the higher field of 2070 gauss represents a convenience. Otherwise, the imparting of the corkscrew motion to the electrons while within the higher strength magnetic field would impose difficulties of a practical nature with presently available techniques. Thus the different axial (longitudinal) magnetic fields illustrated follow from the relative ease of imparting the corkscrew motion to the electrons in the smaller field as compared to the larger field. The specific means described for imparting the spiral motion to the individual electrons is intended to be by way of example. It will be further observed that the cyclotron frequency, i.e., the frequency of rotation of the individually spiralling electrons in the beam, coincides with the frequency of a mode of the resonator **12**.

At the lower frequency (1 gc.$<f<$20 gc.) the device can be constructed to operate at fixed frequency, while at the higher frequencies (10 gc.$<f<$300 gc.) the device can be easily made electrically or magnetically tunable. (Lower frequency operation can be mechanically tunable.)

The electron gun and corkscrew field act together to produce a beam of electrons most of whose momentum is directed perpendicular to the DC magnetic field; only a small component of momentum is from left-to-right. The individual electron trajectories are helical with a very small pitch to allow the electrons to spend sufficient time in the resonator so that they have time to give up their radiation to the resonator. Typically, the axial component of velocity within the resonator may be of the order of 10^7–10^8 cm./sec., while the transverse (circular) velocity is of the order of 10^9–10^{10} cm./sec.

The apparatus of the invention has the advantages of simple construction and a high Q. It exhibits a high mode density when a Fabry-Perot configuration, is employed. Further, by the use of a Fabry-Perot resonator, the apparatus may be tuned to different modes (frequencies) by merely changing the magnetic field B.

The apparatus illustrated in FIGURE 1 may also be employed as an amplifier. For this purpose, the element **15** is replaced by a signal source which is to be amplified, the "load" of the magic tee **14** is omitted, the other T leg now carrying the amplified signals. Element **14** is commonly referred to as a "circulator." FIGURE 1*a* illustrates this modification.

Referring now to FIGURE 3 of the drawings, the illustration is of an amplifying apparatus and the correspondence between the elements of this two-resonator embodiment and the elements of the single resonator embodiment of FIGURE 1 will be readily apparent. Here the input resonator is denoted as **120** and the output resonator, usually identical in construction, is denoted as **122**, with input and output coupling conventionally indicated. The collector electrode **13** is shown as coupled to a retarding field power supply **20** to yield well known depressed collector operation which increases the efficiency of the device.

The general principle of operation is the same as that for the oscillator embodiment of FIGURE 1. For very high frequency operations, as with the oscillator, the TM_{010} mode cavities are replaced with Fabry-Perot resonators.

FIGURE 4 is analogous to FIGURE 2 and shows the variation of axial magnetic field supplied by solenoid windings (not shown) along the amplifier of FIGURE 3. As previously, the magnetic field at the region where corkscrew motion is imparted is of lesser strength than that at the resonators.

FIGURES 5 and 6 show, respectively, theoretical and experimental plots of the expression

$$P=\frac{e^2N^2}{\sigma\pi\epsilon_oc^3}w^2J_1^2\left(\frac{e^2EB_zw^1}{m^2c^2u^2}L\right) \text{ watts}$$

wherein P is the power radiated at the cyclotron frequency from the electron beam subsequent to its passage through the first or input cavity **122** at a distance L downstream thereof; e, m are the electron charge and mass; ϵ_o is the permittivity of free space; N is the instantaneous number of electrons in the second or output

cavity **122** ($N=I1/eu$); w and u are the components of electron velocity perpendicular and parallel to the magnetic field H; I is the DC beam current; E is the RF electric field in the first cavity **120**, c is the speed of light; and $J_1(x)$ is the first order Bessel function of the first kind of argument x. It will be observed from the plots, as well as from the theory presently embraced, that maximum amplification obtains when the quantity within the brackets in the above expression for P is equal to 1.84. It is to be noted that for values of this quantity less than 1.84, the amplification is linear, since $J_1(x)\sim x/2$ for $x<<1$, so that $P_{out}\sim P_{in}\sim E^2$.

I claim:

1. An electron cyclotron maser apparatus for generating or amplifying high frequency oscillations comprising:

(a) an electron source for imparting motion to electrons in a first axial direction to thereby define an electron beam traveling in said first direction,

(b) a cavity resonator positioned along said first axial direction to receive therethrough the beam of electrons,

(c) means for producing a magnetic field parallel to said first axial direction, said magnetic field extending axially through said cavity resonator,

(d) means for imparting a second motion to the electrons in said beam having a component perpendicular to said first direction to thereby cause said electrons in said beam to execute a spiralling motion,

(e) said cavity resonator having a mode frequency equal to the cyclotron frequency of the spiralling electrons in said beam.

(f) the product of the number of cycles spent by a spiralling electron while traversing the resonator, multiplied by the entire kinetic energy of the spiralling electron, all divided by the rest energy m_oc^2 of the electron, being at least of the order of magnitude of unity.

2. The apparatus of claim **1** including a collector electrode positioned downstream of said cavity resonator.

3. The apparatus of claim **1** wherein said cavity resonator is a Fabry-Perot resonator, whereby transition between the densely spaced modes thereof may be effected by changing the strength of the said axial magnetic field.

4. The apparatus of claim **1** wherein said means for producing a magnetic field produces a magnetic field between said electron source and said resonator which is stronger within the resonator than between said electron source and said resonator.

5. The apparatus of claim **1** including a second cavity resonator downstream of said first mentioned cavity resonator, the magnetic field produced by the means c extending from the first mentioned cavity resonator through said second cavity resonator.

6. The apparatus of claim **5** wherein both cavity resonators are Fabry-Perot resonators.

7. The apparatus of claim **5** including signal input and signal output means coupled, respectively, to said first and second cavity resonators.

No references cited.

ROY LAKE, *Primary Examiner.*

DARWIN R. HOSTETTER, *Assistant Examiner.*