

April 6, 1965

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3,177,440

MULTIPLE GRID AMPLIFIER USING BREMSSTRAHLUNG

Filed Jan. 31, 1963

2 Sheets-Sheet 1

FIG. 1

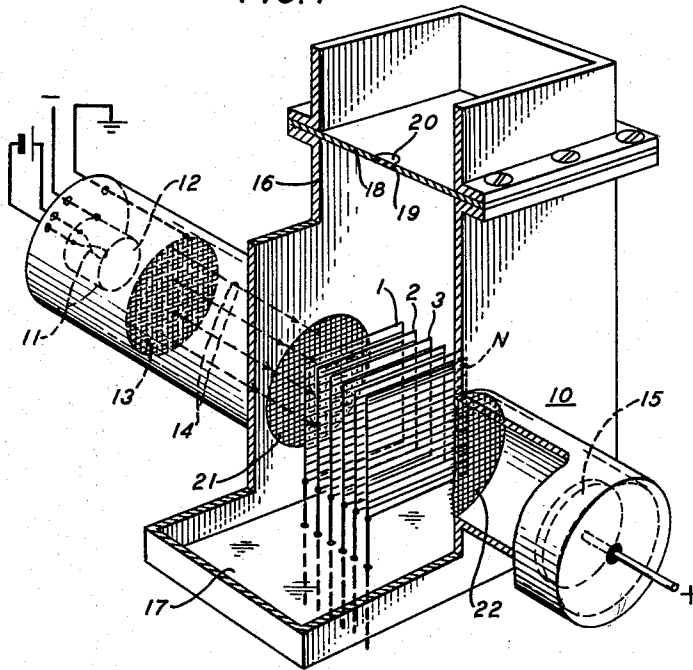


FIG. 2

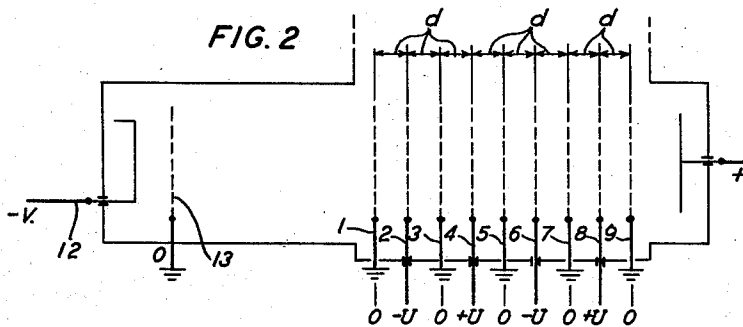
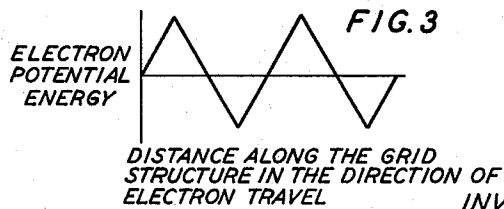


FIG. 3



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2 Sheets-Sheet 2

FIG. 4

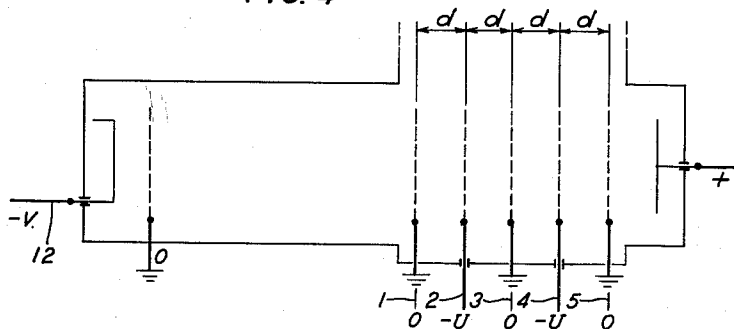


FIG. 5

ELECTRON
POTENTIAL
ENERGY

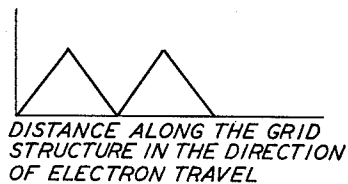
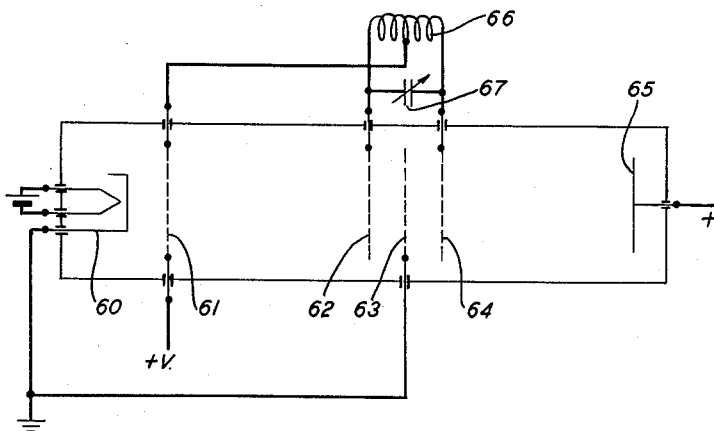


FIG. 6



1

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**MULTIPLE GRID AMPLIFIER USING
BREMSSTRAHLUNG**

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9 Claims. (Cl. 330-44)

This invention relates to electromagnetic wave devices, and, more particularly, to amplifiers and oscillators whose mode of operation is based upon the stimulated emission of radiation from free electrons.

It is known that radiation can be emitted from a free electron in the presence of a static electric field. This process, known as bremsstrahlung or deceleration radiation, is described at page 364 in "The Theory of Protons and Electrons," by J. M. Jauch and F. Rohrlich, published by the Addison-Wesley Publishing Company, Inc., 1955.

It is a characteristic of bremsstrahlung that it is incoherent and that the energy emitted is radiated over a continuous spectrum in contrast to the radiative transitions between bound energy states utilized in the maser.

In my copending application, Serial No. 225,318, filed September 21, 1962, several methods of inducing coherent radiations from free electrons in the presence of a coulomb field (that is, point charges) are described. This stimulated emission of bremsstrahlung was accomplished by causing electrons to pass in the vicinity of a nucleus (or other point charge) in the presence of a superimposed high frequency electromagnetic field. This can be done by causing the electron-nucleus interaction to occur in a resonant cavity. It was shown that the superimposed high frequency field causes the radiation associated with bremsstrahlung to be coherent and to fall within a frequency band defined by the resonant cavity.

It has now been discovered, however, that stimulated emission can be induced employed other types of static fields.

It is, accordingly, an object of this invention to provide additional means for inducing stimulated emission of bremsstrahlung.

It is a more specific object of this invention to induce stimulated emission of bremsstrahlung in homogeneous static electric fields.

In accordance with the invention, stimulated emission of bremsstrahlung is induced in a homogeneous, constant electric field between parallel grids. In the illustrative embodiments of the invention to be described in greater detail hereinbelow, a stream of electrons is passed through an array of particularly spaced, parallel, planar grids in the presence of a signal radiation field. Each grid in the array is charged to a steady potential such that each is positively or negatively biased with respect to the immediately adjacent grids.

Two distinct classes of devices or modes of operation will be described. A first of these classes of devices, wherein some of the grids are alternately biased positively and negatively with respect to the electron accelerating electrode, is characterized by a relatively large power handling capacity when used as an amplifier and a relatively high power output capability when used as an oscillator. In a second class of devices, the grids are alternately biased at the same potential as the electron accelerating electrode and negatively with respect to the accelerating electrode. In particular, when the voltage between adjacent grids is equal to the electron accelerating voltage, this latter class of devices is characterized by a relatively high power gain but a relatively low power handling capability.

In one of the specific illustrative embodiments of the

2

invention, the grid structure is enclosed within a resonant cavity. In a second embodiment, the grid structure comprises a portion of the capacitance of a lumped parameter L-C oscillatory circuit.

These and other objects, the nature of the present invention, and its various features and advantages, will appear more fully upon consideration of the various specific illustrative embodiments of the invention now to be described in connection with the accompanying drawings, in which:

FIG. 1 shows, in perspective, a first embodiment of the invention;

FIG. 2 shows the grid biasing arrangement for a first mode of operation;

FIG. 3, given for purposes of explanation, shows the potential energy of an electron within the grid structure for the biasing arrangement shown in FIG. 2;

FIG. 4 shows the grid biasing arrangement for a second mode of operation;

FIG. 5, given for purposes of explanation, shows the potential energy of an electron within the grid structure for the biasing arrangement shown in FIG. 4; and

FIG. 6 shows schematically an alternate embodiment of the invention.

Referring to FIG. 1, there is shown a multigrid amplifier in accordance with the invention. The amplifier is enclosed in an evacuated envelope 10 and includes a source of electrons comprising a heater element 11 and a cathode 12. Means in the form of an electrode 13, are provided for accelerating and focusing the electrons emitted from cathode 12 into a beam 14.

The beam 14 passes through an array of uniformly spaced, parallel, planar grids 1, 2, 3 . . . N and on to an electron collector 15.

The grids 1, 2, 3 . . . N are interconnected such that the odd numbered grids 1, 3, 5 . . . are at a first steady potential that is approximately equal to that of the accelerating electrode 13. The even numbered grids 2, 4, 6 . . . are at a second steady potential that is typically different than that of the odd numbered grids thereby establishing a homogeneous, constant electric field between each pair of adjacent grids. The preferred potentials and the distance between adjacent grids will be considered in greater detail hereinafter.

In accordance with the invention, the grids 1, 2, 3 . . . N are located in a region of the device that is simultaneously supportive of a high frequency signal field. In the illustrative embodiment, the signal supporting structure is a section of rectangular waveguide 16 conductively terminated at both ends by means of transverse terminating members 17 and 18 to form a resonant cavity. Termination 18 is supplied with means, such as an aperture 19, for coupling electromagnetic energy into and out of the cavity. A seal 20 is inserted into the aperture in order to maintain the air-tight integrity of the envelope 10.

The grid structure is disposed within this cavity such that the electrons traverse the cavity in a direction that is substantially parallel to the direction of the high frequency electric field. While the instantaneous intensity of the high frequency field may vary over the surface area of each of the grids, the instantaneous intensity of the field along the direction of electron travel through the grid structure is advantageously constant. In the embodiment of FIG. 1, the preferred field conditions are established by projecting the electrons in a direction perpendicular to the wide walls of waveguide 16. The high frequency field is confined within the cavity in the vicinity of the grids by means of screens 21 and 22.

It is to be understood that the unitary structure described above is merely intended to be illustrative. For example, as an alternative arrangement, the high fre-

quency wave supporting structure can be separate from the electron source and grid structure with provisions for receiving and mounting the latter in the former. In addition, other types of wave supporting structures having the requisite field configuration can be used.

An analysis of the problem and a derivation of the relationships among the parameters of the structure of FIG. 1 can be made using the techniques of quantum electrodynamics or using classical methods. Both methods have in fact been employed and have been shown to yield the same results. However, it has been found that if the grid voltages are small compared to the electron accelerating voltage, the results are more readily arrived at by the use of quantum electrodynamics. On the other hand, the problem yields more readily to the classical methods when the voltage between adjacent grids is equal to the accelerating potential.

When using the techniques of quantum electrodynamics, the treatment of the periodically arranged grids follows closely the treatment given in my above-mentioned copending application.

For the first mode of operation to be considered, the grid voltages vary both positively and negatively with respect to the electron accelerating electrode. This arrangement is illustrated in FIG. 2, wherein the voltage applied to the cathode 12 is $-V$ with respect to the accelerating electrode 13, which is shown to be at ground potential. Grid 1, the first grid adjacent to electrode 13, is at the same potential as the accelerating electrode ($U=0$). Thereafter the potentials on alternate grids are $+U$ or $-U$ with respect to the accelerating electrode potential. In the illustrative embodiment shown in FIG. 2, which has a total of nine grids, grids 2 and 6 are at a potential $-U$ and grids 4 and 8 are at a potential $+U$. The remaining grids 3, 5, 7 and 9 are at zero potential.

FIG. 3 is a curve showing the variations in the potential energy of the electrons as they traverse the grid structure. For the particular embodiment shown, there are nine grids, resulting in a two cycle variation in the electron potential energy. More generally, the relationship between the number of periods M and the number of grids N is given by

$$N=(4M+1) \quad (1)$$

For the purposes of analysis, the grid voltage U is assumed to be small compared to V , of the order of one-tenth or less. For this range of values, the device exhibits its highest power handling capabilities but its lowest power gain. As the ratio

$$\frac{|U|}{|V|}$$

increases, the power capability decreases but the power gain goes up.

For the particular case where U is small compared to V , the power P delivered by the electron stream to the high frequency electromagnetic field supported by the high frequency cavity is given by

$$P = \frac{8e^3 U^2 w I}{\pi m^3 v^4 f^2 \beta} \frac{1}{\cos 2\beta} \cos M\beta \sin^2 \frac{1}{2}\beta$$

$$\left\{ 2 \sin^2 \frac{1}{2}\beta (\tan \beta \cos M\beta - M \sin M\beta) + \sin \beta \cos M\beta \right\} \quad (2)$$

where

e is the electron charge,

U is the grid potential (relative to the accelerating electrode),

w is the energy density in the radiation field,

I is the electron current in electrostatic units,

m is the electron mass,

v is the electron velocity equal to

$$\sqrt{\frac{2ev}{m}}$$

f is the radiation field frequency, and

$$\beta = 2\pi \frac{fd}{v} \quad (3)$$

is the transit time angle (that is, the phase angle of the field as the electron proceeds along the grid structure).

The expression for the power, given by Equation 2, peaks for the particular values of β given by

$$\beta = (2u+1) \frac{\pi}{2} \quad (4)$$

where u is any integer 0, 1, 2, . . . Since β also appears in the denominator of Equation 2, a maximum peak occurs when $u=0$, which would suggest that the amplifier be designed to operate at this value. However, by substituting the value of β from Equation 4 into Equation 3, we see that the spacing between grids is also a function of u (that is,

$$d = \left(\frac{2u+1}{4} \right) \frac{v}{f}$$

and is smallest when $u=0$. Since, at high frequencies the grid spacing can become extremely small, practical considerations associated with the fabrication of the grids may dictate a value of u greater than zero.

Assuming the multiple grid structure to be enclosed in a cavity of volume G and $Q=Q_L$, oscillations occur when the current I is greater than the threshold level as defined by

$$I > \frac{\pi^3 m^3 v^4 f^3 G}{2e^3 U^2 (N-1)^2 Q_L} \left(\frac{(-1)^u (2u+1)}{\sin (2u+1) \frac{\pi}{4}} \right)^2 \quad (5)$$

Below the threshold level, the device is capable of amplifying signal wave energy coupled into the cavity.

It will be noted that the grid spacings in the embodiment of FIG. 2 are equal. For this particular mode of operation, however, a nonuniformly spaced grid structure can be used by removing grids 3, 5 and 7. These grids, which are at potential $U=0$, contribute essentially nothing to the operation of the embodiment of FIG. 2 and hence can be omitted. When omitted, however, Equation 1 changes to $N=(2M+2)$ and the term $(N-1)^2$ in Equation 5 changes to $4(N-2)^2$.

For the second mode of operation to be considered, the grids are alternately biased at the same potential as the accelerating electrode and negatively with respect to the accelerating electrode. This biasing arrangement is illustrated in FIG. 4 wherein the cathode 12 is at a potential $-V$ with respect to the accelerating electrode 13, which is shown to be at ground potential. The grids 1, 3 and 5 are at the potential of electrode 13 ($U=0$) whereas grids 2 and 4 are at a potential $-U$.

FIG. 5 shows the potential energy of the electrons with respect to the electrode potential as they traverse the grid structure.

For the biasing arrangement of FIG. 4 wherein $|V|=|U|$ the power transferred from the electrons to the radiant signal field is given by

$$P = \frac{\sqrt{2\pi} ew I (N-1)^2}{\pi^2 m f^2 (2u+1)} \sqrt{\frac{eU}{kT}} \quad (6)$$

where k is Boltzmann's constant, and T is the absolute temperature of the cathode.

The optimum spacing of the grids d is given by

$$d = \frac{(2u+1)}{8} \frac{v}{f} \quad (7)$$

and oscillations occur when the current I exceeds the threshold level as defined by

$$I > \frac{\pi^2 \sqrt{2\pi m f^3 (2u+1) G}}{2e(N-)^2 Q_L} \sqrt{\frac{kT}{eU}} \quad (8)$$

The following tabulation shows the threshold current I required for self sustained oscillations and the estimated minimum power output available from a cavity having a volume $G=10 \text{ cm}^3$ and a $Q=10^4$ at different frequencies and for different grid structures.

Gr./f, sec.	u	d , cm.	I , amp.	N	Estimated minimum power output in watts
10-----	0	1.66×10^{-2}	1.63×10^{-4}	25	10^{-5}
	1	4.98×10^{-2}	4.40×10^{-3}	9	4×10^{-4}
	2	8.30×10^{-2}	2.04×10^{-2}	5	2×10^{-3}
50-----	0	3.32×10^{-2}	2.04×10^{-2}	25	2×10^{-3}
	1	9.96×10^{-2}	5.50×10^{-1}	9	5×10^{-2}
	2	1.66×10^{-2}	2.55	5	2×10^{-1}
100-----	0	1.66×10^{-2}	1.63×10^{-4}	25	10^{-5}
	1	4.98×10^{-2}	4.40	9	4×10^{-1}
	2	8.30×10^{-2}	20.4	5	2

The power transferred to the radiant signal field, as given by Equation 6, was calculated for the case of $|V|=|U|$ since analysis has shown that the effect is greatly enhanced when the potential between grids is equal to the electron accelerating potential. As the grid voltage deviates from this optimum value, the transferred power decreases. The grid potential at which the transferred power is reduced to one-half its maximum value is given by

$$|U| = \left[1 - .9 \left(\frac{kT}{eV} \right) \right] V \quad (9)$$

For a typical case where $T=1000^\circ \text{ K.}$, and $V=500$ volts, the half power point is reached when U is reduced by only one-tenth of a volt. In practice, however, the power roll-off would not be as sharp as Equation 9 appears to indicate due to space charge effects which were neglected in the derivation of Equation 6.

The principles of the invention can also be applied at lower frequencies by using an L-C circuit in which the grids comprise a part or all of the capacitor. This type of arrangement, illustrated in FIG. 6, comprises a cathode 60, an accelerating electrode 61, grids 62, 63 and 64 and an electron collector 65. The cathode 60 is connected to the center grid 63. The two end grids 62 and 64 and a trimmer capacitor 67 are connected to the ends, respectively, of an inductor 66. The electrode 61, biased positively with respect to cathode 60, is connected to the center tap on inductor 66.

The oscillation condition for a device of this type is satisfied when

$$I > \frac{\pi^2 m f^3 G}{2e Q_L} \frac{1}{2\sqrt{\frac{2eV}{\pi kT}} - 1} \quad (10)$$

For a 70 mc./sec. oscillator with $Q_L=10$, $G=10 \text{ cm}^3$, $V=200$ volts, $T=10^3 \text{ }^\circ \text{K.}$, and $d=1.5 \text{ cm.}$, I is computed from Equation 10 to be 1.4×10^{-2} milliamperes.

An oscillator, constructed in accordance with the embodiment shown in FIG. 6, was constructed and oscillated at 70 mc./sec. when the current exceeded 30 milliamperes. The increase of the threshold current over the theoretical value of 1.4×10^{-2} milliamperes can be attributed to an increased spread in the velocity distribution of the beam electrons due to space charge effects. The theory is based on the assumption that the spread of the velocity distribution of the electrons is strictly of thermal origin.

In the various illustrative embodiments described hereinabove, the condition for oscillation was given. It is understood, however, that by maintaining the electron

current below the threshold level necessary to produce oscillations, the device can be utilized as an amplifier by the application of a signal wave. Energy extracted from the electron stream is converted to radiant energy at the signal frequency, thereby amplifying the signal. Thus, in all cases it is understood that the above-described arrangements are merely illustrative of but a small number of the many specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. Apparatus comprising:

- a source of electrons;
- a grid structure comprising first, second and third parallel planar grids;
- accelerating means disposed between said source and said grids for projecting said electrons through said grids in a direction substantially perpendicular thereto;
- a center-taped inductor;
- means for conductively connecting the end terminals of said inductor to the first and the third of said grids, respectively;
- means for conductively connecting the center-tap of said inductor to said accelerating means;
- means for conductively connecting said electron source to the second of said grids;
- means for positively biasing said accelerating means with respect to said electron source;
- and means for coupling electromagnetic wave energy to and from said inductor.

2. Apparatus comprising:

- a source of electrons;
- electron collector means;
- a plurality of parallel grids disposed within a resonant structure supportive of high frequency electromagnetic wave energy and located between said source and said collector means;
- said high frequency waves having electric field components extending in a direction perpendicular to said grids;
- means for projecting said electrons through said grids in a direction substantially perpendicular thereto;
- biasing means connected to said grids for maintaining a homogeneous constant electric field of successively alternating polarity between pairs of adjacent grids;
- said homogeneous constant field extending in a direction substantially parallel to the direction of electron flow within the region traversed by said electrons;
- and means for extracting high frequency wave energy from said structure.

3. Apparatus comprising in longitudinal succession:

- a source of electrons;
- a plurality of parallel planar grids;
- and an electron collector;
- an accelerating electrode disposed between said source and said grids for projecting said electrons through said grids in a direction substantially perpendicular thereto;
- means for biasing said electrode to a given potential with respect to said source;
- means for establishing a homogenous constant electric field between adjacent grids within the region traversed by said electrons polarized in a direction parallel to said direction of projection comprising;
- first means for biasing the first grid adjacent to said electrode and successive odd numbered grids at the same potential as said electrode;
- second means for biasing the even numbered grids negatively with respect to said electrode;

7

a resonant structure for supporting a high frequency standing wave having electric field components extending along the direction of electron flow over a region coextensive with said grids;
 and means for coupling high frequency wave energy out of said region. 5
 4. A combination according to claim 3 wherein; said resonant structure is a conductively bounded cavity.
 5. A combination according to claim 3 wherein; said accelerating electrode is positively biased with respect to said source by an amount substantially equal to the bias between said even numbered and said odd numbered grids. 10
 6. A combination according to claim 3 wherein; the electron current caused to flow through said grids is above the threshold current required to cause said apparatus to oscillate at the resonant frequency of said structure. 15
 7. A combination according to claim 3 wherein; the electron current caused to flow through said grids is below the threshold current required to cause said apparatus to oscillate; 20
 including means for coupling high frequency signal wave energy into said region. 25
 8. Apparatus comprising:
 a source of electrons;
 an electron collector;
 a plurality of parallel grids disposed within a resonant structure supportive of high frequency electromagnetic wave energy; 30
 said high frequency waves having electric field components extending in a direction perpendicular to said grids;

8

an accelerating electrode located between said source and said grids for projecting said electrons through said grids in a direction substantially perpendicular thereto;
 means for biasing said accelerating electrode to a given potential with respect to said source;
 first means for biasing the odd numbered grids to the same potential as said accelerating means;
 second means for biasing alternate even numbered grids to a positive potential with respect to said accelerating electrode;
 third means for biasing the remaining even numbered grids to a negative potential with respect to said accelerating electrode;
 and means for coupling high frequency wave energy into and out of said structure.
 9. The combination according to claim 8 wherein; the accelerating electrode is positively biased with respect to said electron source;
 and wherein the amplitude of the potential difference between said odd numbered grids and said even numbered grids is equal to or less than one-tenth the bias between said source and said accelerating electrode.

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ROY LAKE, *Primary Examiner*.NATHAN KAUFMAN, *Examiner*.