Oct. 7, 1947. B. CASSEN 2,428,554

ULTRA HIGH FREQUENCY OSCILLATION GENERATOR

Filed Dec. 3, 1942 2 Sheets-Sheet 1

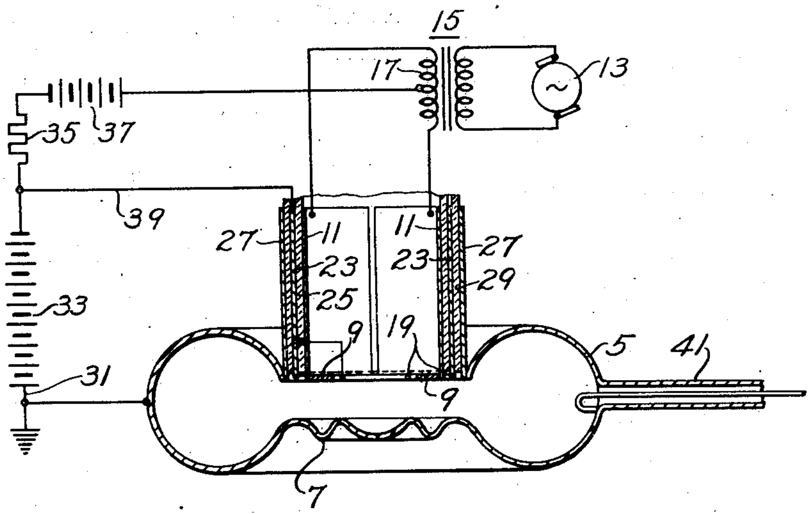

Fig. 1.

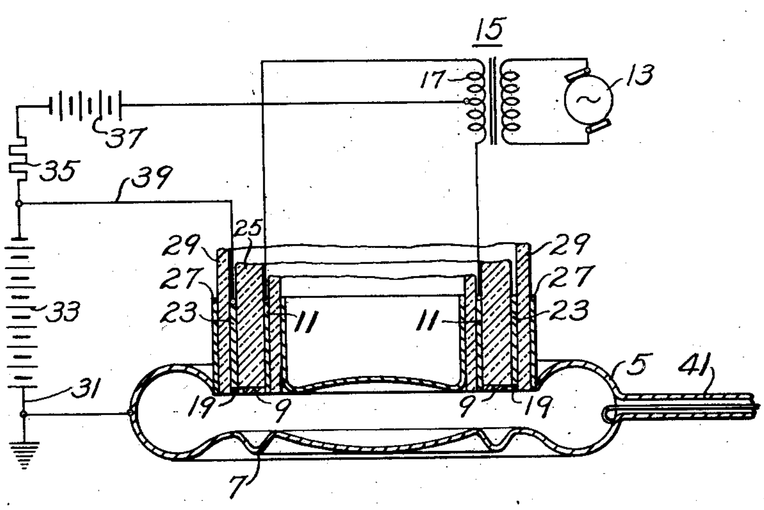

Fig. 2.

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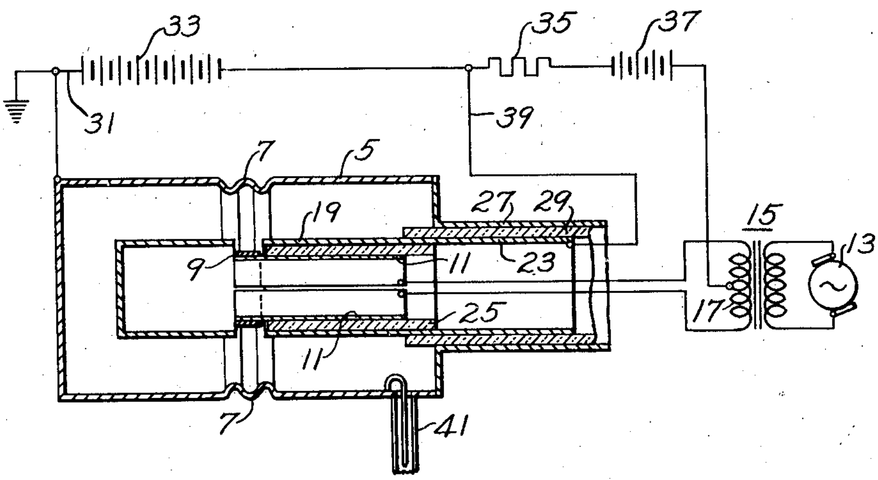
Fig. 3.



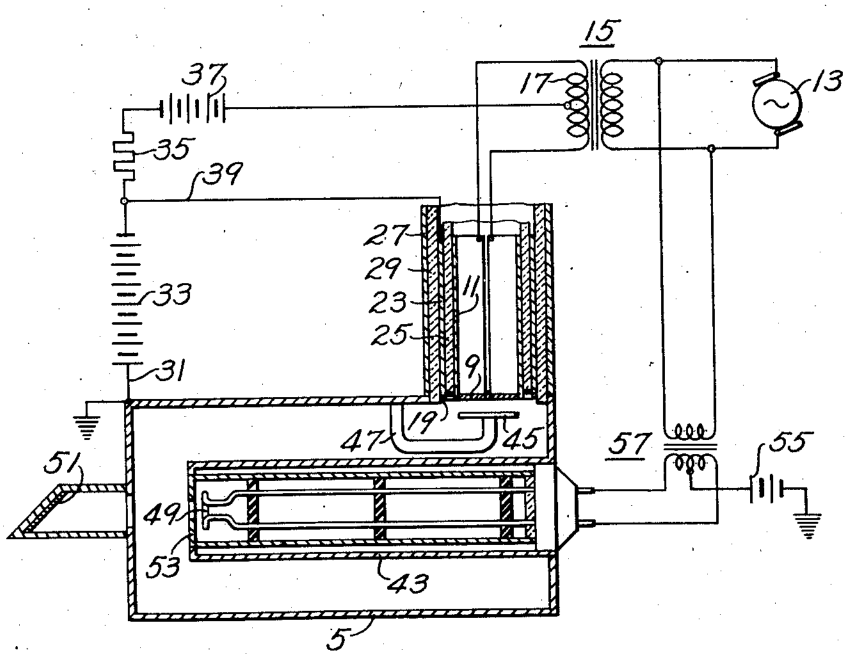


Fig. 4.

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Patented Oct. 7, 1947 2,428,554

UNITED STATES PATENT OFFICE

2,428,554

ULTRA HIGH FREQUENCY OSCILLATION GENERATOR

Benedict Cassen, Pittsburgh, Pa., assignor to Westinghouse Electric Corporation, East Pittsburgh, Pa., a corporation of Pennsylvania

Application December 3, 1942, Serial No. 467,773

7 Claims. (Cl. 315—5)

This invention relates to an oscillation generator, and more particularly to apparatus for generating ultra high-frequency oscillations.

In the past, attempts have been made to generate high-frequency oscillations by use of a triode vacuum tube arranged for class C operation. In such an arrangement a constant potential field is maintained between the anode and cathode and if an alternating potential is impressed on the grid of the triode, plate current flows during the peak portion only of the half period in which the grid is positive. In other words, electrons are liberated from the cathode in pulses with each pulse occurring at the peak portion of the positive half period of grid potential. To generate oscillations, the alternating potential impressed upon the grid is made 180° out of phase with the alternating plate potential. Pulses of electrons are then liberated from the cathode 180° out of phase with the alternating field between the plate or anode and cathode in the anode-grid space, so that they do work upon or contribute energy to that field while abstracting energy from the constant potential field maintained between the anode and cathode. An oscillator of this type is generally known as a density modulated oscillator for the grid controls the density distribution of electrons having the same velocity.

When an oscillator as described is to be used for generating ultra high-frequency oscillations, the time required for the electrons to pass from the cathode to the grid becomes appreciable in terms of a period of the alternating field. Because of this relatively high travel time, the electron pulse is no longer 180° out of phase with the alternating field between the anode and cathode when it reaches the grid-anode space and efficient generation of oscillations is not effected. The travel time may, of course, be reduced by decreasing the space between the elements of the triode. However, the necessary smaller spacing is impractical and requires too high a direct-current voltage on the plate to obtain sufficient power for satisfactory operation.

Other oscillators, such as the Klystron and magnetron oscillators, have been employed to generate ultra high-frequency oscillations. The Klystron oscillator is a velocity-modulated oscillator requiring apparatus for focusing an electron stream, the modulation being in the velocity distribution of the electrons as distinguished from the density modulation, and has a maximum theoretical efficiency of only fifty eight percent. The magnetron also has certain disadvantages,

one of the principal disadvantages being the necessity for producing a magnetic field over a considerable volume of space especially for the delivery of high average power.

It is, accordingly, an object of my invention to provide a new and improved apparatus for generating ultra high-frequency oscillations.

Another object of my invention is to provide a generator of ultra high-frequency oscillations in which the spacing of elements may be such as to afford a readily manufactured device.

A further object of my invention is to provide a generator of ultra high-frequency oscillations having a relatively high efficiency.

Still a further object of my invention is to provide a generator of ultra high-frequency oscillations in which the anode potential may be comparatively low while the generator delivers relatively high steady power.

In accordance with my invention, I provide a density modulated cavity resonator oscillator. The oscillator comprises a cavity resonator adapted to have an ultra high-frequency electromagnetic field therein and means responsive to the postive peaks of the high-frequency field for initiating passage of a group or pulse of electrons along a predetermined path through the high-frequency field, the length of the predetermined path relative to the frequency of the field being such that the kinetic energy of the group of electrons is substantially zero at the end of the path. The electron pulse enters the high-frequency field during the positive peaks of that field. While in the high-frequency field, energy is supplied to the electrons by a substantially constant direct current potential field. The electrons continue in the field through most, if not all, of the succeeding negative half period of the high-frequency field in which they deliver to the high-frequency field substantially all of the energy derived from the direct current potential field.

The electron pulse may be provided by positioning an anode and a cathode so that they are subject to the high-frequency field within the cavity resonator. The anode and cathode may form a portion of the walls of the resonator or they may be independent thereof. A control element is positioned adjacent to the cathode and, because the practical spacings are small, the control member is preferably co-planar with the cathode. A direct-current potential is applied between the anode and cathode and a small direct-current biasing potential is applied between the grid and cathode.

The performance of the oscillator is somewhat analogous to the class C vacuum tube oscillator. The cathode is exposed to the direct current potential field between the anode and cathode and to the high-frequency field of the cavity resonator. During the positive half period of the high-frequency field, both of these fields tend to liberate electrons from the cathode. However, the biasing potential on the control member is such that electrons are liberated from the cathode during the positive peak portion only of the high-frequency field. Consequently, pulses of electrons leave the cathode in phase with the high-frequency field and start out with that field doing work on them. Because of the slow speed of the electrons relative to the frequency of the field, the electron pulse does not get very far before the field reverses and the energy which the electrons derive from the direct current potential field enables them to do work on or contribute energy to the high-frequency field. The anode is spaced from the cathode a distance such that the electron pulse is collected by the anode before the high-frequency field reverses again. Part of the energy thus delivered to the high-frequency field by the electrons is employed in maintaining that field while the remainder of the energy may be extracted in any well-known manner and supplied to a load.

From the foregoing it is apparent that the spacing of the anode and cathode is definitely related to the frequency of the high-frequency field and the value of the direct current anode-cathode potential. To derive this relationship an electron may be considered as starting from the cathode at a distance from the cathode $x=0$ at the time $t=0$. At this instant of liberation of an electron, the high-frequency field E is at its peak value and is superimposed upon a constant potential field F. The equation of motion of the electron is

$$\frac{m}{e}\frac{d^2x}{dt^2}=E\cos\omega t+F \qquad (1)$$

where m is the mass of the electron and e its charge and ω is angular frequency of the field E.

Integrating Equation 1 once gives

$$\frac{\omega m}{eE}\frac{dx}{dt}=\sin\omega t+\frac{F}{E}\omega t \qquad (2)$$

as

$$\frac{dx}{dt}=0 \text{ when } t=0$$

If

$$\frac{dx}{dt}$$

is to be equal to zero at some subsequent time, when

$$t=T+0, \text{ then } \sin\omega T=-\frac{F}{E}\omega T \text{ or } \frac{F}{E}=-\frac{\sin\omega T}{\omega T} \qquad (3)$$

This is only possible if π radians $<\omega T<2\pi$ radians for otherwise

$$\frac{F}{E}$$

would be negative.

Equation 2 can be integrated a second time, giving

$$\frac{\omega 2/m}{eE}x=1-\cos\omega t+\tfrac{1}{2}\frac{F}{E}\omega^2t^2 \qquad (4)$$

To obtain maximum power from the oscillator, the electron should be collected at the anode at the instant that its kinetic energy becomes zero. If X is the separation of the anode from the cathode, by using Equations 3 and 4

$$\frac{\omega^2m}{eE}X=1-\cos\omega T-\tfrac{1}{2}\omega T\sin\omega T \qquad (5)$$

If V is the direct-current anode voltage, then $V=FX$. Substituting this in (3) gives

$$E=-\frac{\omega T}{\sin\omega T}\frac{V}{X}$$

Substituting in (5) and letting $\alpha=\omega T=$transit time of an electron for a distance X in terms of frequency of the field E,

$$\frac{\omega^2m}{eV}X^2=-\frac{\alpha}{\sin\alpha}\left(1-\cos\alpha-\frac{\alpha}{2}\sin\alpha\right) \qquad (6)$$

From Equation 6, it is apparent that a positive and, therefore, an allowable value of

$$\frac{X^2}{V}$$

is obtainable when α is greater than π radians and less than 2π radians. From a practical standpoint, it is desirable to have the anode-cathode voltage V as small as possible and the anode-cathode spacing X as large as possible. However, analysis of Equation 6 indicates that X^2 cannot be increased a great deal for a given V without greatly increasing

$$\frac{E}{F}$$

As will be explained later, an increase of

$$\frac{E}{F}$$

makes the starting of oscillations more difficult and increases the capacity current much faster than the increase in X decreases it. I prefer to make $\alpha=3/2\pi$ radians at which value a desirable performance is obtained with a practical apparatus.

For this value of α,

$$\frac{E}{F}=4.71$$

and from Equation 6

$$X^2=\frac{15.8eV}{m\omega^2}=\frac{15.8e\lambda^2V}{4\pi^2mc^2}$$

where λ is wave length in centimeters and c is the velocity of light in centimeters per second. Then,

$$X=\sqrt{\frac{15.8e}{m}}\times\frac{1}{2\pi c}\lambda V^{1/2}=.015\lambda V^{1/2} \text{ centimeters}$$

with V in e. s. u. Using this relationship the following table gives values of

$$\frac{X}{\lambda}$$

and peak high frequency voltages for various anode-cathode voltages V.

V	X/λ	Peak H. F. volts
500	.016	2,350
1,000	.022	4,700
2,000	.032	9,400
5,000	.050	23,500
10,000	.07	47,000
20,000	.10	94,000
50,000	.16	235,000
100,000	.22	470,000

The foregoing analysis shows that electrons liberated from a cathode by the positive peaks of the high-frequency field can be collected with negligible kinetic energy on a suitably placed anode. During the time of emission there is only a thin layer of space charge near the cathode so that for the same instantaneous current density, the space charge field at the cathode surface is small compared to that present in the steady state. If electrons leave the cathode during only .1 cycle of the high-frequency field and the instantaneous emission is I amperes from the entire cathode, which is considered approximately constant over .1 cycle, the average direct-current anode current will then be .1 I. Thus in the theoretical limit of high bias, neglecting filament power, the oscillator is 100% efficient. This efficiency may be compared to that of the Klystron oscillator which is only 58%.

To prove that the oscillator is self-starting, a situation should be considered in which the oscillations within the cavity resonator, such as may be produced by thermal fluctuations or other conditions, are very feeble so that electrons strike the anode with high energy. Then

$$\frac{E}{F}=r$$

is very small. From Equation 4 the time t_r at which electrons strike the anode is given by

$$\frac{\omega^2 m}{eF}X=r(1-\cos\omega t_r)+\tfrac{1}{2}\omega^2 t_r^2 \qquad (7)$$

Considering X and F as fixed and t_r as a function of r, differentiating with respect to r gives

$$\frac{d(\omega t_r)}{dr}=\frac{\cos\omega t_r-1}{\omega t_r+r\sin\omega t_r} \qquad (8)$$

The numerator is always negative but the denominator is positive if

$$r>\left(-\frac{\omega t_r}{\sin\omega t_r}\right)$$

when

$$\left(-\frac{\omega t_r}{\sin\omega t_r}\right)$$

is positive. Therefore, if when r equals zero,

$$\left(-\frac{\omega t_r}{\sin\omega t_r}\right)$$

is positive, the time t_r will continuously decrease from t_0 to its running value T as r goes from zero to its running value. It is thus apparent that when r is small, the electrons strike the anode with less kinetic energy than when r equals zero. The difference must be given up to the high-frequency field. From Equation 2, if

$$v_r=\frac{dx}{dt}$$

at X,

$$\frac{\omega^2 m^2}{e^2F^2}v_r^2=r^2\sin^2\omega t_r+2r\omega t_r\sin\omega t_r+\omega^2 t_r^2 \qquad (9)$$

which for small r is $2r\,\omega t_r+\omega^2 t_r^2$. Then the sign of $v_r^2-v_0^2$ will be given by that of $2r\omega t_r \sin\ t_r$, which will be the same as that of $2r\omega t_0$, which in turn is negative. This proves that for low losses in the cavity resonator circuit, the oscillations are self-starting as long as the direct current bias varies in proportion to the amplitude of the high-frequency field. To obtain a biasing potential which varies in the desired manner, a small fixed biasing potential and a resistor are connected between the grid and cathode in the anode-cathode circuit. The small fixed biasing potential is provided to prevent an excessive plate current before the oscillations are started.

As previously pointed out, the distance between the anode and cathode is preferably such that the electron transit time is equal to $^3/_2\ \pi$ radians in terms of the angular frequency of the high-frequency field which is entirely practical in most cases. At extremely low wave lengths even this distance may become too small for practical purposes but satisfactory operation is obtainable if the distance is such that the electron transit time is $^3/_2\pi+2\pi n$ radians, where n is a whole number. Under such circumstances, the electron pulse is still collected at the anode when its kinetic energy is substantially zero.

The novel features that I consider characteristic of my invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and its method of operation together with additional objects and advantages thereof will best be understood from the following description of specific embodiments when read in connection with the accompanying drawings, in which:

Figures 1, 2, 3 and 4 illustrate various embodiments of my invention.

As shown in Figure 1, a hollow body or cavity resonator **5** having a shape similar to a doughnut and adapted to have an ultra high-frequency electromagnetic field therein has an anode **7** forming a portion of the wall thereof. A cathode **9** formed of a flat ring preferably of tantalum, forms a portion of the wall of the resonator **5** opposite the anode **7**. The cathode **9** is mounted on a split tubular member **11** and filament power is supplied from an alternating source **13** through an auxiliary transformer **15** whose secondary **17** is connected to different portions of the tubular member **11**.

A control member **19** is mounted adjacent to the cathode and is made up of a wire ring within the cathode **9** and a second wire ring encircling the cathode. The control rings **19** are preferably substantially co-planar with the cathode **9** because of the small spacings and may be formed of tantalum or molybdenum wire. The control rings **19** are connected to and mounted upon a second tubular member **23** separated from the first tubular member **11** by an insulating material **25** such as glass. A third tubular member **27** is connected to the main wall of the resonator **5** and is insulated from the second tubular member **23** by insulating material **29** which may also be glass. The three tubular members **11**, **23** and **27** are of such length as to form a quarter wave length resonant bypass for the high-frequency field so that a high-frequency potential does not appear between the control rings and cathode. The glass insulation may also be extended to form a vacuum tight enclosure.

The anode **7** is grounded and is connected through conductor **31**, to a source of direct-current potential **33**, a resistor **35**, a second source of direct-current potential **37**, secondary **17** and member **11** to the cathode **9**. In this manner, a direct current potential field is created between the anode **7** and the cathode **9**. The control rings **19** are connected through conductor **39** to the junction point of the first potential source **33** and the resistor **35** so that a direct-current biasing potential consisting of the small constant potential of the second source **37** and the variable potential across the resistor **35** appears between the control member and the cathode. This biasing potential then varies in accordance with the amplitude of the high-frequency field within the resonator and is of such magnitude that electrons are liberated from the cathode during the peak portions only of the positive half periods of the high-frequency field. A pulse of electrons enters the high-frequency field during a positive peak. The high-frequency field soon reverses and the electrons contribute energy to the high-frequency field which they are deriving from the direct current potential field between the anode and cathode. Some of this energy is used to maintain the high-frequency field and a coaxial output line **41** is magnetically coupled to the resonator to convey the remaining energy to a load. The anode and cathode are, of course, spaced so that the electrons are collected when their kinetic energy is substantially zero.

The resonator disclosed in Fig. 1 is designed for operation in the first radial mode but Fig. 2 discloses a resonator designed for operation in the second radial mode. In other words, the electromagnetic wave has a nodal point along the large diameter edge of the resonator and a maximum point in the middle thereof in Fig. 1, but in Fig. 2 the wave his nodal points at the large diameter edge of the resonator and another at the center thereof. Consequently, the cathode ring in Fig. 2 must be of a sufficient diameter to be subject to the maximum point on the electromagnetic wave. Otherwise, the operation of Fig. 2 is identical with Fig. 1 and the same reference numerals are employed for similar elements.

Another resonator design is shown in Fig. 3. This modification operates in the same manner as Fig. 1 and includes similar elements. However, the resonator is shaped differently to enable a generation of oscillations having larger wave lengths with a compact apparatus.

Fig. 4 illustrates another embodiment of my invention in which the oscillations generated are employed to increase the speed of an electron stream for the production of X-rays. The resonator **5** takes the form of a cylinder having a reentrant portion **43**. The cathode **9** forms a part of the wall of the cylinder, but the anode **45** is mounted on a support **47** within the cylinder and spaced the proper distance from the cathode. A filament **49** is positioned at the inner end of the reentrant portion **43** of the resonator to project electrons upon a target **51** positioned opposite thereto. A screen **53** is positioned adjacent to the filament **49** and is biased by an auxiliary source of potential **55**. The electron flow from the filament, which is energized from source **13** through an auxiliary transformer **57**, is blocked by the biasing potential until the electromagnetic potential exceeds a predetermined magnitude. In passing through the high-frequency field in the resonator the electrons from the filament **49** are accelerated and impinge upon the target **51** producing X-rays. The generation of the high-frequency oscillations is, of course, accomplished in the manner described hereinbefore.

Although I have shown and described certain specific embodiments of my invention, I am fully aware that many modifications thereof are present. I do not intend, therefore, to restrict my invention to the specific embodiments illustrated.

I claim as my invention:

1. An oscillation generator comprising a cavity resonator adapted to have an ultra high-frequency electromagnetic field therein and means defining an electron path through said resonator comprising electron liberating means including a cathode mounted at one end of said path with a surface subject to said field and electron collecting means positioned at the other end of said path, said liberating means being responsive only to each positive peak of said field to initiate passage of a group of electrons from said cathode surface along said path, the length of said path within said resonator being equal to the distance over which substantially all of said group of electrons travel after initiation of the passage thereof in a predetermined time interval greater than $\frac{1}{2}\pi+2\pi n$ radians but no more than $\frac{3}{2}\pi+2\pi n$ radians in terms of angular frequency of said field, where n is zero or any whole number.

2. An oscillation generator comprising a cavity resonator adapted to have an ultra-high-frequency electromagnetic field therein and means defining an electron path through said resonator comprising electron liberating means including a cathode mounted at one end of said path with a surface subject to said field and electron collecting means positioned at the other end of said path, said liberating means being responsive only to each positive peak of said field to initiate passage of a group of electrons from said cathode surface along said path, the length of said path within said resonator being equal to the distance over which substantially all of said group of electrons travel after initiation of the passage thereof in a predetermined time interval of the order of $\frac{3}{2}\pi+2\pi n$ radians in terms of angular frequency of said field, where n is any whole number or zero.

3. An oscillation generator comprising a cavity resonator adapted to have an ultra high-frequency electromagnetic field therein, means defining an electron path through said resonator including a cathode mounted at one end of said path and subject to said high-frequency field, and an anode positioned at the other end of said path, means connected to said anode and cathode for establishing a direct current potential field therebetween, and means connected to said cathode for establishing a biasing field adjacent to said cathode of a magnitude permitting liberation of electrons from said cathode only during the positive peaks of said high-frequency field whereby said liberated electrons move along said path from said cathode to said anode, the length of said path within said resonator being equal to the distance over which said electrons travel in a time period of the order of $\frac{3}{2}\pi+2\pi n$ radians in terms of the angular frequency of said high-frequency field, where n is a whole number or zero.

4. An oscillation generator comprising a cavity resonator adapted to have an ultra high-frequency electromagnetic field therein, means defining an electron path through said resonator including a cathode mounted at one end of the path and subject to said high-frequency field, and an anode positioned at the other end of said path, means connected to said anode and cathode for impressing a direct-current potential therebetween, a control member positioned adjacent to said cathode, and means connected to said control member and cathode for impressing a direct-current biasing potential therebetween of a magnitude permitting liberation of electrons from said cathode only during the peak portion of the positive half-periods of said high-frequency field, the length of said path within said resonator being equal to the distance over which said electrons travel in a time period of the order of $\frac{3}{2}\pi+2\pi n$ radians in terms of the angular frequency of said high frequency field where n is a whole number or zero.

5. An oscillation generator comprising a cavity resonator adapted to have an ultra high-frequency electromagnetic field therein, means defining an electron path through said resonator

including a cathode mounted at one end of the path and subject to said high-frequency field, and an anode positioned at the other end of said path, means connected to said anode and cathode for impressing a direct-current potential therebetween, and means connected to said cathode for establishing a biasing potential field adjacent to said cathode which varies according to the amplitude of said high-frequency field and is of a magnitude permitting liberation of electrons from said cathode only during the peak portion of the positive half-periods of said high-frequency field, the length of said path within said resonator being equal to the distance over which said electrons travel in a time period of the order of $\frac{3}{2}\pi+2\pi n$ radians in terms of the angular frequency of said high frequency field where n is a whole number or zero.

6. An oscillation generator comprising a hollow body resonator adapted to have an ultra-high frequency electromagnetic field therein, means defining an electron path through said resonator including a cathode mounted at one end of said path and subject to said high-frequency field, and an anode positioned at the other end of said path, means connected to said anode and cathode for impressing a direct-current potential therebetween, a control member positioned adjacent to and substantially co-planar with said cathode, and means connected to said control member and cathode for impressing a biasing potential therebetween which varies according to variations in the amplitude of said field and is of a magnitude permitting liberation of electrons from said cathode only during the peak portion of the positive half-periods of said field whereby said liberated electrons move from said cathode to said anode, the length of said path within said resonator being equal to the distance over which the liberated electrons travel in a predetermined time interval after liberation thereof which is of the order of $\frac{3}{2}\pi+2\pi n$ radians in terms of angular frequency of said high-frequency field where n is zero or any whole number.

7. An oscillation generator comprising a cavity resonator adapted to have an ultra-high-frequency electromagnetic field therein, means defining an electron path within said resonator including a cathode mounted at one end of said path and subject to said high-frequency field, and an anode positioned at the other end of said path, means forming a first source of direct-current potential connected in series with an impedance and means forming a second source of direct-current potential between said anode and cathode, said second source being opposite in polarity and smaller in magnitude than said first source with said first source being of a polarity tending to effect liberation of electrons from said cathode, a control member positioned adjacent to said cathode, circuit means connecting said impedance and second source between said control member and cathode to impress a biasing potential therebetween of a magnitude permitting liberation of electrons from said cathode only during the positive peaks of said high-frequency field, whereby said liberated electrons move along said path from said cathode to said anode, the length of said path within said resonator being equal to the distance over which the liberated electrons travel in a time period of the order of $\frac{3}{2}\pi+2\pi n$ radians in terms of the angular frequency of the high frequency field where n is a whole number or zero.

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