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J. R. PIERCE

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GENERATION OF MICROWAVES

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FIG. 1

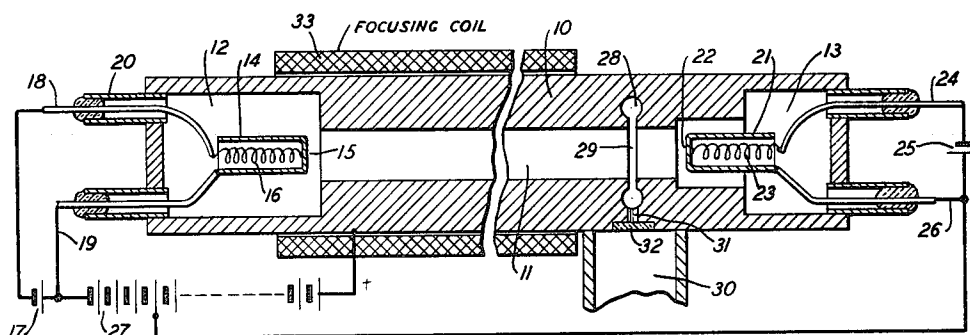


FIG. 2

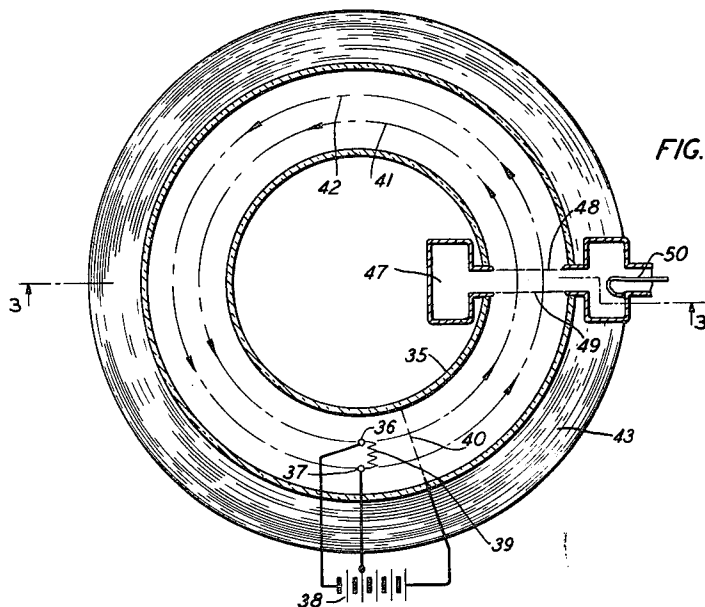
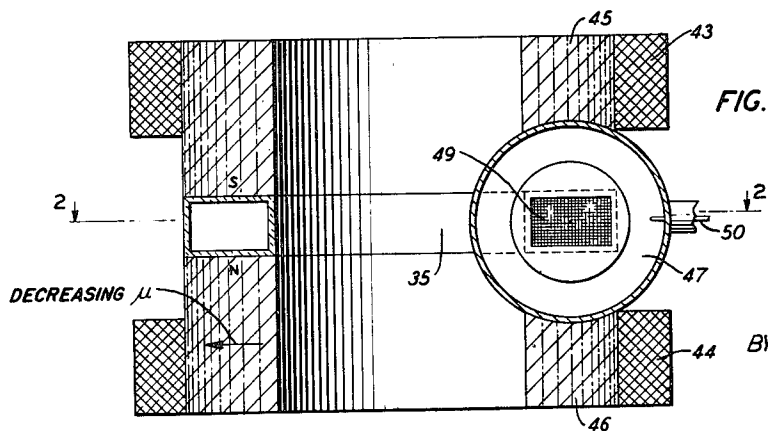


FIG. 3



INVENTOR
J. R. PIERCE
BY
M. D. Gering
ATTORNEY

UNITED STATES PATENT OFFICE

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GENERATION OF MICROWAVES

John R. Pierce, Millburn, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

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14 Claims. (Cl. 315-5)

1

This invention relates to the production of ultra-high-frequency oscillations through the use of interacting electron streams in an evacuated enclosure.

An object of the invention is to generate electromagnetic waves efficiently at wavelengths as short as a centimeter or less.

The invention makes use of the discovery which was disclosed in the application of W. B. Hebenstreit and J. R. Pierce, Serial No. 38,928, filed July 15, 1948. In accordance with that discovery, a space charge wave can be propagated along an electron stream, with an amplitude that increases with distance of travel, when a second electron stream of a different velocity is made to interact with the first stream, provided certain quantities involved are properly proportioned. In particular, a sufficiently high electron current density should be used and the difference between the velocities of the two streams should be sufficiently great.

In accordance with the present invention, oscillations are generated by methods and means utilizing the property of amplification which is possessed by devices of the type disclosed in the above-noted Hebenstreit-Pierce application. In devices which embody the present invention, two interacting electron streams of different velocities serve to amplify, along a path of travel, a disturbance which appears in either or both of them and at least a portion of the amplified disturbance is conveyed back in electron stream form to the beginning of the path to reinforce the initial disturbance for the purpose of creating sustained oscillations.

Although the actual mechanism of energy interchange between electron streams appears to be highly complex and involved, embodiments of the present invention which are to be described may be considered, for purposes of explanation, to operate in the following manner. Two streams of electrons are projected along a predetermined path of travel at different velocities in a coupled relationship. If a disturbance of any kind appears in one of the streams, interaction of electrons will produce a corresponding disturbance in the other stream. When the disturbance appears on the second stream, electron interaction will reinforce the disturbance on the first stream, causing it to increase in amplitude. When the increased disturbance appears on the first stream, electron interaction will then reinforce the disturbance on the second stream, and so on. As a result, the disturbances on both streams increase in amplitude as the streams progress along

2

the path of travel. If initial disturbances appear in both streams, a similar phenomenon occurs. When the initial disturbance appearing in one or both of the streams amounts to a velocity modulation, a recurrent bunching of electrons or density modulation takes place, with the bunching becoming more pronounced as the streams progress along the path. This phenomenon may be referred to as a space charge wave of negative attenuation, or, in other words, a space charge wave with an amplitude that increases with distance of travel.

The increased disturbances on the electron streams at the end of their path of travel amount to an amplification of the initial disturbance. When the amplified disturbances, or disturbances corresponding to the amplified disturbances, are conveyed back in electron stream form to the beginning of the amplification path, further amplification results. The amplified disturbances then appear in the original two streams at that point and are amplified still further as the two streams progress along the path once more in interacting relationship. The amplitude of the disturbances involved increases with each passage along the path until limiting conditions are finally reached. At that point, due generally to non-linearities of the system, amplification resulting from energy interchanges between electrons of the two streams falls off and sustained oscillations result. Amplification, at that amplitude level, is just sufficient to counteract losses and to replace any power drained from the system to supply an external load. Unless controlled by a resonator or some similar device coupled to at least one of the electron streams, the oscillations will tend to occur at the frequency where the amplification over the path is greatest.

Initial disturbances which appear in the electron streams may be caused by spontaneous fluctuations in electron current density as the electrons leave an emitter surface, that is, shot noise. Disturbances from various other causes may also serve to initiate oscillations. Systematic disturbances such as, for example, velocity or density modulation may be produced by a resonator coupled to at least one of the streams after oscillations have begun to build up and serve to add a great degree of stability to the system. In such an event, the oscillation frequency will generally be governed by the frequency to which the resonator or other such device is tuned.

Although specific mention has thus far been made only of streams of electrons, it is contemplated that, in general, streams of charged par-

ticles traveling in coupled relationship at different average velocities will serve to support the previously-mentioned space charge wave of negative attenuation. Thus, amplification and oscillation may be obtained even if, for example, one of the above-noted electron streams is replaced by a stream of slowly moving positive ions.

It should also be noted that, due to space charge effects, the two electron streams employed in many embodiments of the present invention do not have discretely different velocities, but rather, each stream generally includes a range of velocities. Those velocity ranges may be contiguous if sufficient electrons of each stream tend to concentrate at velocities intermediate in their respective velocity ranges, thus producing an over-all multiple-peaked rather than single-peaked velocity distribution curve. It is contemplated that the electron velocities of one stream, or a velocity at which electrons of that stream tend to concentrate, may, in some instances, approach zero.

In general, the two interacting streams of electrons or charged particles will be either intermingled or in close proximity with one another. It has been found that, as a general rule, in the absence of other coupling mechanism the amplification or gain that takes place as the two streams progress along their path of travel decreases rapidly as the separation distance between the two streams increases.

The nature and objects of the present invention will appear more fully from the following detailed description of two specific embodiments. In the drawings:

Fig. 1 is a longitudinal cross-section view of an embodiment of the invention in which two initially oppositely directed electron streams are employed;

Fig. 2 is a plan sectional view, taken on line 2-2 of Fig. 3, of an embodiment of the invention in which the electron path is curved and closed back upon itself; and

Fig. 3 is a cross-section view of the structure shown in Fig. 2, taken on the line 3-3.

Referring to Fig. 1, the tube envelope 10 is made of metal, such as copper, and is provided with a relatively narrow central bore 11 and with larger diameter end spaces 12 and 13. Located in the end space 12 is a metal 14 having an activated face 15, facing toward central bore 11, which serves as a cathode when it is heated. A heating coil 16 is provided within cylinder 14 and is supplied with heating current from battery 17 by way of leads 18 and 19. Lead 18 is brought out from one terminal of the coil 16 through and concentric with a short metal tube 20 which is provided at its extremity with a glass vacuum seal. The opposite terminal of the coil 16 is joined to the cathode cylinder 14, from which lead 19 is brought out through a short length of tubing and glass seal in the same manner as lead 18.

In the opposite end space 13, a second metal cylinder 21 having an activated face 22, facing central bore 11, which serves as a second cathode is provided. A heating coil 23 is located within cylinder 21. A lead 24 from the heating coil 23 is brought out through a glass bead in the end of a short tube joined to the envelope 10 and is connected to one pole of a battery 25. The other end of coil 23 is connected to cathode cylinder 21, which is connected through a lead 26 to the other pole of battery 25 and to an intermediate point on a divided battery 27; battery 27 being connected between lead 19 and the metal envelope 10. The most positive terminal of battery 27 is

connected to envelope 10. Cathode 22 is heated partly by power from battery 25 and partly by bombardment by electrons from cathode 15.

An annular resonant cavity 28 is provided in the envelope 10 along the path defined by central bore 11, preferably nearer the more positive cathode 22, and opens into the space 11 through a narrow circumferential slot 29. This resonant cavity communicates with the interior of a wave guide 30 through an orifice 31 which may be provided with a cover glass 32 suitably sealed to the tube 10 to enable the interior of the tube 10 to be evacuated. The end of wave guide 30 is so shaped as to provide a snug fit against envelope 10 and an air-tight seal is provided. A magnetic focusing coil 33 is applied around the exterior of the tube 10 and is supplied with direct current from any suitable source, not shown, for producing a longitudinal magnetic field directed along the axis of the tube 10 for focusing the electrons into a well defined cylindrical beam. A jacket may be provided around the tube 10 for circulating cooling fluid.

In the operation of the device of Fig. 1 electrons emitted from the cathode 15 are accelerated lengthwise of the tube due to the high voltage impressed upon the tube from battery 27 and the number of these which strike the inner walls of the tube in the channel 11 is minimized due to the focusing action of the magnetic coil 33. These electrons strike the second cathode 22. Cathode 22, due to heating caused by the impact of electrons from cathode 15, to heating from coil 23, and to secondary emission, is caused to emit electrons at a rate which varies appreciably in conformity with the incoming stream. The emitted electrons are projected toward the left in the figure along the channel 11, that is, toward the first cathode 15, due to the difference in direct-current potential of the elements 22 and 10. It will be noted that the beam from cathode 15 which travels toward the right is accelerated by the voltage of the full battery 27 while the beam from cathode 22 traveling toward the left is accelerated by a fractional part of the potential of the full battery 27. Since the potential between element 22 and envelope 10 is less than that between element 15 and envelope 10, the electrons traveling toward the left will not reach the cathode 15 after traversing central bore 11, wherein the potential gradient is essentially zero, but will be turned back by the relatively steep potential gradient existing between the end of central bore 11 and cathode 15 and will travel toward the right along with but at a somewhat lower velocity than the electrons originating from cathode 15.

The electrons of the beam emanating from cathode 15 interact with those of the beam emanating from cathode 22, after the latter electrons have reversed direction just before reaching cathode 15. Small disturbances such as, for example, variations in electron current density caused by cathode emission irregularities and transient effects introduced by closing a switch connecting main battery 27 into the circuit tend to appear in both beams and increase in magnitude as the electrons comprising the beams progress to the right in the direction of cathode 22. As the disturbance bearing electron beams strike cathode 22, the beam being emitted by that element toward the left is caused, by secondary emission and by the varying space charge of the beams, approaching cathode 22, to vary in accordance with the amplified disturbances. The amplified disturbances are then conveyed back by the beam,

5

virtually unaltered, to the other end of the path defined by central bore 11. By interaction of electrons, similar increased disturbances are caused to appear in the stream being emitted by cathode 15 after the stream emanating from cathode 22 reverses direction and starts back toward cathode 22. Further amplification then takes place due to interaction between the electrons of the respective streams as they travel once more toward cathode 22.

As the disturbance-bearing electron streams pass slot 29, they yield energy to resonator 28, tending to set up an alternating field therein. Once an alternating field is established in resonator 28, density modulations large in comparison with the initial disturbances appearing in the beams are impressed upon the beams as they pass slot 29. The frequency of operation is thus stabilized at the tuned frequency of resonator 28 by the time limiting conditions are reached and sustained oscillations occur. The generated oscillations may be extracted through wave guide 30 for application to a desired load circuit.

It should be noted that if the resonator 28 has a low Q, that is, the ratio of energy stored to energy lost per oscillation cycle is low, or is so coupled to wave guide 30 as to give band-pass or aperiodic characteristics, it will not control the frequency of oscillation. The oscillation mechanism will then be chiefly electromechanical and the frequency will be controlled by the beam diameter, beam current and voltage, and the velocity separation between the two beams, that is, the voltage between cathodes 15 and 22. Under these circumstances the frequency of oscillation can be changed by varying the beam current or voltage.

Calculations indicate that for wavelengths of the order of from five to ten centimeters, the channel 11 might typically be ten inches long and one-tenth of an inch in diameter and might supply currents of from one to ten milliamperes. If the diameter is unduly large, the potential of the electron stream will be lower than that of the wall because of space charge. More important, if $\omega a/v$ is too large (ω =radian frequency, a =radius of hole in resonator, v =mean electron velocity), there will be too little coupling between electron streams and resonator. Battery 27 might have a voltage of about two hundred volts and cathode 22 could be about ten volts positive with respect to cathode 15.

Referring to Figs. 2 and 3, a doughnut-shaped or toroidal glass envelope 35 defines a closed circular path and is provided with cathodes 36 and 37, which are situated adjacent to one another at a point in the path defined by envelope 35. Cathodes 36 and 37 may be either indirectly heated or filamentary cathodes, the latter type being shown, which are supplied with heating current from a portion of the cells of battery 38. For this purpose the two filamentary cathodes 36 and 37 may be connected in series with a resistance 39 between them which is considerably higher than the resistance of either filament. When this is done the average voltage of the cathode 36 will be negative with respect to the average voltage of cathode 37 by substantially the voltage of the heating current source. Electrons from the two cathodes 36 and 37 are accelerated counter-clockwise in Fig. 2 by a grid member 40 which is displaced somewhat from cathodes 36 and 37 along the path of travel. Grid 40 is at positive potential with respect to both cathodes due to its connection to the positive pole

6

of battery 38. The electron stream starting from cathode 36 will be the high velocity stream and that from cathode 37 will be the low velocity stream because of the lesser difference in potential available for driving the latter with respect to the former.

The two electron beams indicated in Fig. 2 at 41 and 42 are constrained to move in a circular path by the use of a magnetic field perpendicular to the plane of the paper. This field is produced by windings 43 and 44, as shown in Fig. 3, applied respectively to the annular core members 45 and 46. In order to secure more accurate focusing of the beams, the magnetic field may be made weaker toward the outside of the path of travel than toward the inside by use of variable permeability core material having decreasing permeability toward the outer circumference as indicated in Fig. 3. This decrease in permeability may be accomplished in practice by making the core members of finely divided material or laminations and decreasing the ratio of magnetic material to filling as the outer circumference is approached. If the core members are made in the form of clock spring ribbon, greater separation between turns may be allowed at the outer circumference of the core members than further along toward the inner circumference. Since the magnetic field is stronger toward the inside of the path of travel than toward the outside, the inner stream 41 will move in a circle of smaller radius than will the outer stream 42. Coupling between the two streams is thereby better maintained over the whole path of electron travel.

For the purpose of both modulating the streams and taking off power, a resonant cavity 47 in annular form surrounds the tube 35 at a suitable distance beyond the filaments 36 and 37. The inner portion of the cavity is of restricted width and extends through the tube 35, its opposite walls comprising two grids 48 and 49. The generated oscillations are taken off through a coaxial line, the inner conductor 50 of which is shown coupled to the interior of the cavity 47.

In the operation of this device, small irregularities appear in the electron streams originating at cathodes 36 and 37 and gain in amplitude as the streams progress around the tube in interacting relationship. In the device illustrated, the path is continuous and closed, enabling the amplified disturbances to be conveyed by streams 41 and 42 themselves back to the beginning of the path. The amplified disturbances are further amplified in subsequent trips around the path and yield energy to cavity 47 as they cross gap 48—49 until, as with the Fig. 1 device, an alternating field is established in cavity 47 and the velocity modulations which the streams then receive as they cross gap 48—49 are substantially greater than the original disturbances and control the frequency of oscillation. When limiting conditions are reached, gain along the path falls off, and stable sustained oscillations occur at the resonant frequency of cavity 47. Oscillations produced in cavity 47 are led off to a suitable load circuit over conductor 50.

Electrons are prevented from traveling in a reverse direction around the tube by the action of the magnetic field, which is in such direction as to throw the electrons starting to move in a clockwise direction from cathodes 36 and 37 toward the outer wall of the tube 35.

The embodiments that have been disclosed are to be considered as illustrative and by way of example rather than as limiting, inasmuch as

a variety of embodiments are possible within the spirit and scope of the invention.

What is claimed is:

1. A space discharge device comprising an enclosure defining a path of travel for charged particles, means within said enclosure for projecting a pair of streams of charged particles along said path at respective different velocities, one portion of said path being coupled regeneratively to an anterior portion of said path by at least one stream of charged particles, means situated along said path for systematically varying the density of the charged particle flow of at least one of said streams, and means situated along said path for extracting electromagnetic energy from at least one of said streams.
2. An oscillator comprising an evacuated toroidal enclosure defining a continuous closed path of travel for electrons, a pair of electron-emissive elements within said enclosure, and means coupled to said elements for projecting a pair of electron streams from said elements around said path continuously in the same direction at respective different velocities.
3. An oscillator in accordance with claim 2 which includes means situated along said path for systematically varying the density of the electron flow in at least one of said streams and means situated along said path for withdrawing oscillatory electromagnetic energy from at least one of said streams.
4. An oscillator in accordance with claim 2 in which one of said electron emissive elements is at a higher potential than the other and which includes a grid situated in said path of travel for accelerating electrons from both of said elements, said grid being at a higher potential than either of said elements.
5. A high frequency oscillator which comprises first and second electron-emissive electrodes spaced apart to define a path of electron travel between them, means coupled to said first and second electrodes to hold them at different direct-current potentials, a third electrode disposed along and surrounding the path between said first and second electrodes, means coupled to said third electrode to hold it at a direct-current potential positive with respect to those of said first and second electrodes, and means adjacent to the path between said first and second electrodes to withdraw oscillatory electromagnetic energy from at least one of the electron streams which emanate from said first and second electrodes when energized.
6. A high frequency oscillator in accordance with claim 5 in which said last-mentioned means comprises a cavity resonator.
7. A microwave oscillator which comprises a pair of electron-emissive electrodes spaced apart to define a path of electron travel between them, means coupled to said electron-emissive electrodes to hold them at different direct-current potentials, a tubular electrode surrounding and extending for substantially the whole length of the path between said electron-emissive electrodes, means coupled to said tubular electrode to hold it at a direct-current potential positive with respect to said electron-emissive electrodes, and an electromagnetic resonator disposed in coupled relationship with at least one of the electron streams which emanate from said electron-emissive electrodes when energized.
8. An oscillation generator which comprises an evacuated enclosure defining a path of travel for electrons, electrode means within said enclosure

- to project a pair of streams of electrons in the same direction along a common portion of said path at discretely different velocities, one part of said common portion of said path being coupled regeneratively to an anterior part of said portion of said path by at least one of said streams, means situated along said path for systematically varying the density of electron flow of at least one of said streams to stabilize the oscillation frequency, and means situated along said path for abstracting oscillatory electromagnetic energy from at least one of said streams.
9. An oscillation generator in accordance with claim 8 in which said means to stabilize the oscillation frequency comprises a cavity resonator.
10. An oscillation generator in accordance with claim 8 in which said means to stabilize the oscillation frequency and said energy abstraction means comprise the same cavity resonator.
11. An oscillation generator which comprises an evacuated enclosure defining a path of travel for electrons, first and second thermionic cathodes situated at opposite ends of said path, means including a source of direct potential to maintain said second cathode at a higher direct potential than said first cathode, electrode means coupled to said first cathode to direct electrons therefrom in a stream traveling toward and impinging upon said second cathode, electrode means coupled to said second cathode to direct electrons therefrom in a stream traveling initially toward said first cathode but changing direction before reaching said first cathode and traveling back with the electrons emanating from said first cathode toward said second cathode, and a cavity resonator situated along said path coupled electromagnetically to at least one of the electron streams both to stabilize the frequency of oscillation and to abstract oscillatory electromagnetic energy from that stream.
12. An oscillation generator which comprises an evacuated toroidal enclosure defining a continuous closed loop path of travel for electrons, a pair of thermionic cathodes located adjacent one another in said path, means including a source of direct potential to maintain said cathodes at different direct potentials, electrode means coupled to said cathodes to direct electrons therefrom, and a pair of streams traveling around said path in the same direction but at discretely different velocities and a cavity resonator situated along said path coupled electromagnetically to at least one of the electron streams both to stabilize the frequency of oscillation and to abstract oscillatory electromagnetic energy from that stream.
13. An oscillation generator in accordance with claim 12 which includes magnetic focusing means to confine the electrons of both streams to said path.
14. A high frequency space discharge device which comprises first and second thermionic electron-emissive electrodes spaced apart to define a path of electron travel between them, means including a source of direct potential to bias said second electrode positively with respect to said first electrode, means coupled to said first electrode to direct a stream of electrons from said first electrode toward and to impinge upon said second electrode, means coupled to said second electrode to direct a stream of electrons which includes secondary electrons produced by the impingement of the electrons from said first electrode on said second electrode toward said first electrode, and a cavity resonator adjacent

to the electron path to modulate the electron stream emanating from said second electrode under the control of the electron stream emanating from said first electrode and to withdraw oscillatory electromagnetic energy from at least one of said streams.

JOHN R. PIERCE.

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