

April 6, 1948.

C. H. TOWNES

2,438,954

ELECTRONIC OSCILLATOR OF THE CAVITY RESONATOR TYPE

Filed Nov. 12, 1941

3 Sheets-Sheet 1

FIG. 1

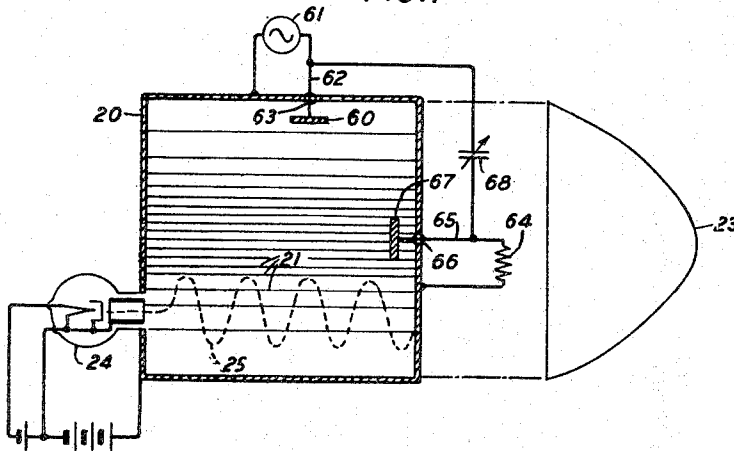


FIG. 2

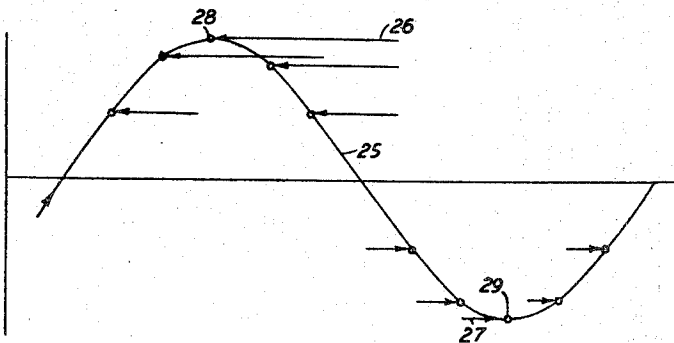
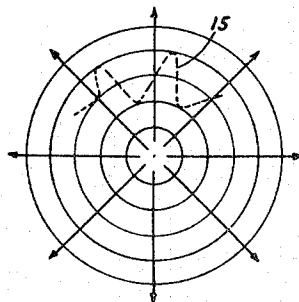


FIG. 3



INVENTOR
BY C. H. TOWNES
Franklin Mohr
ATTORNEY

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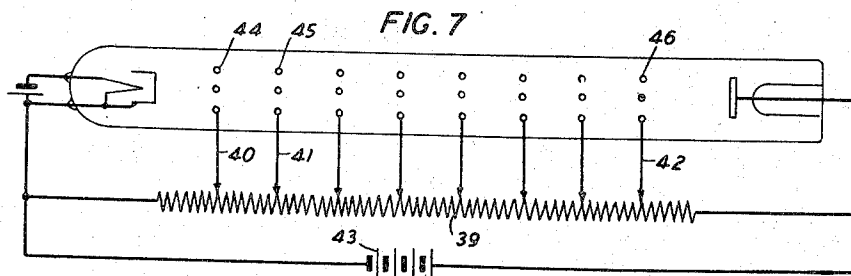
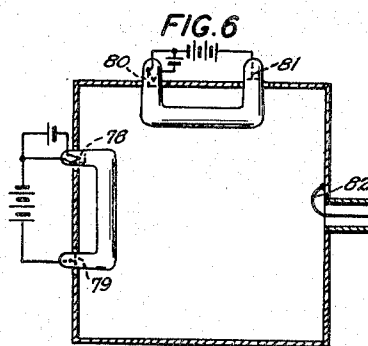
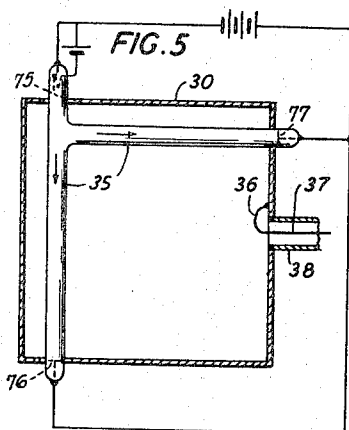
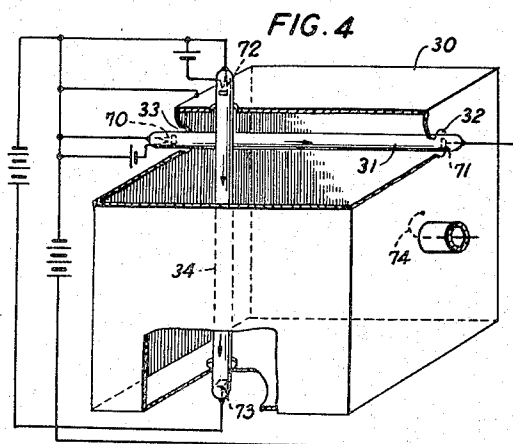
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3 Sheets-Sheet 2



INVENTOR
BY C. H. TOWNES

Franklin Mohr
ATTORNEY

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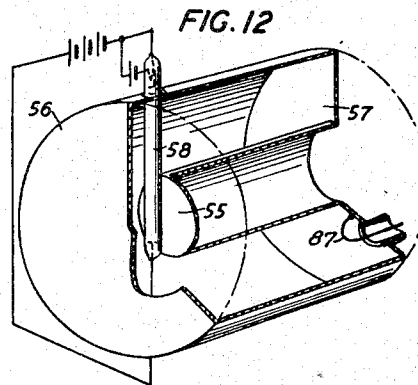
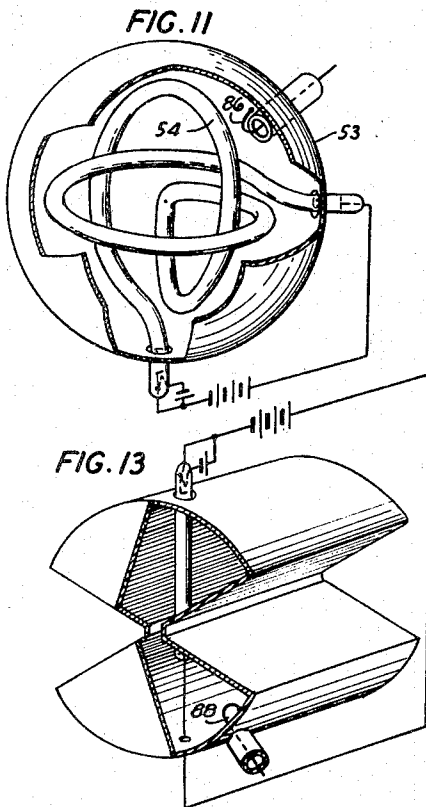
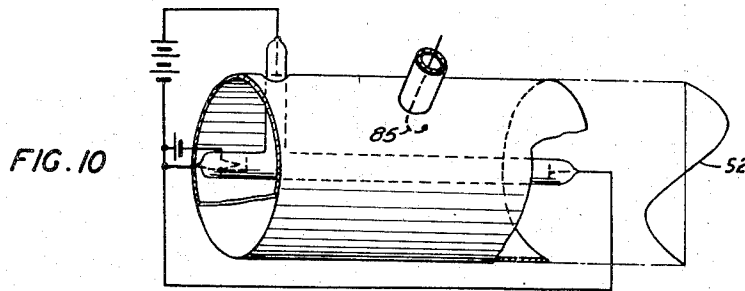
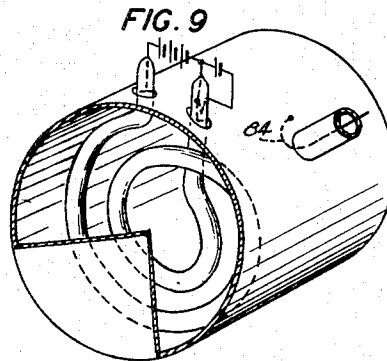
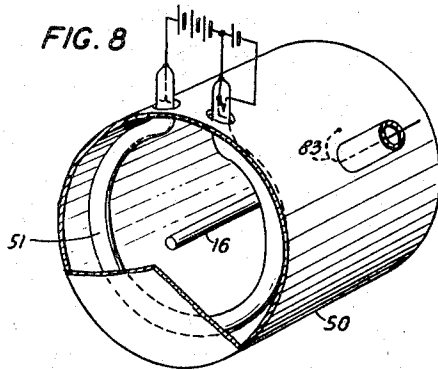
C. H. TOWNES

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ELECTRONIC OSCILLATOR OF THE CAVITY RESONATOR TYPE

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3 Sheets-Sheet 3



INVENTOR
BY C. H. TOWNES

Franklin Mohr

ATTORNEY

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ELECTRONIC OSCILLATOR OF THE CAVITY
RESONATOR TYPECharles H. Townes, Mendham, N. J., assignor to
Bell Telephone Laboratories, Incorporated,
New York, N. Y., a corporation of New York

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6 Claims. (Cl. 250—36)

1

This invention relates to oscillators, amplifiers and the like and more particularly to systems in which an alternating electromagnetic field is energized by a stream of charged particles such as electrons.

If an electron or other charged particle moves in an alternating electromagnetic field, it may give energy to the field during one half cycle of the alternation by moving against the electric force exerted on it, but usually during the next half cycle it will receive an almost equal amount of energy from the field because the electric vector is reversed. In order that the electron stream may maintain the electromagnetic field in continuous oscillation and supply sufficient energy to offset the radiation and ohmic losses associated with the oscillating field, conditions must be such as to permit a net unidirectional flow of energy from the stream to the field. For present purposes the energy flow during a half cycle of the field oscillations may be represented by eES , where e is the electronic charge, E is an average of the magnitude of the electric field and S is the distance the electron moves in the direction of the field. The desired net unidirectional flow of energy over a complete cycle or a number of cycles, can be obtained by arranging a system whereby with every half cycle the magnitude of either E or S is changed or else the direction of motion of the electron is reversed. In various known arrangements for maintaining oscillations the desired effect is obtained by means of suitable static fields. In the Barkhausen type of oscillator, for example, static fields force the electron to reverse its direction of motion on every half cycle. In the split-plate magnetron, electrons move in a strong electric field during one half cycle, and in a weak field during the next half cycle. These devices in general require relatively strong static fields to produce the proper electronic motion, and in addition require some method of removing electrons which enter the field in incorrect phase.

In accordance with the present invention electrons or other charged particles are controlled by means of an auxiliary alternating electromagnetic field to move during successive half cycles in portions of the main field having different magnitudes or directions, in other words, portions of the field having different values of the vector force associated therewith. The stream is projected initially in a direction parallel to the lines of force of the principal oscillating electromagnetic field. By means of the auxiliary alternating field the stream is constrained to follow an

2

undulating or sinusoidal path. By locating the path of the stream in a non-uniform portion of the principal field, the energy of the stream may be utilized to sustain the principal field in continuous oscillation, the device serving as a repeater or an amplifier. By proper arrangements, the auxiliary field may also be made self-sustaining, the device serving as an oscillator.

The operation of the invention does not depend upon any critical value of the transit time of the electrons traversing the field, nor does it depend upon the transit time being comparable with or shorter than a cycle or half cycle of the alternating field. The electrons may, in fact, advantageously be allowed to execute a plurality of successive oscillations before leaving the field, delivering a net increment of energy to the field during each oscillation.

The invention is more fully described hereinafter in connection with the accompanying drawings and its scope is indicated in the appended claims.

In the drawings,

Fig. 1 represents one embodiment of the invention;

Figs. 2 and 3 are diagrams useful in explaining the principle of the invention;

Fig. 4 is a perspective view, partially broken away, illustrating another embodiment of the invention;

Figs. 5 and 6 are fragmentary views of arrangements alternative to the one shown in Fig. 4;

Fig. 7 is a diagrammatic representation of a special form of vacuum tube which may be employed in practicing the invention;

Figs. 8 to 13, inclusive, are perspective views, partially broken away, illustrating additional alternative embodiments of the invention.

Referring to Fig. 1, a resonator 20 of the cavity type is shown in section and represented as containing an oscillating electromagnetic field, the electric lines of force of which are represented by lines 21 in the horizontal direction. The electric field intensity varies sinusoidally in space in the vertical direction as represented diagrammatically by the curve 23 as well as by the non-uniform spacing of the lines 21. A vacuum tube 24 containing any suitable apparatus such as an electron gun for projecting an electron stream is mounted over an aperture in the wall of the resonator 20 and the assembly hermetically sealed so that the interior of the tube and resonator may be evacuated or may be provided with any desired gaseous atmosphere. By suitable means such as are described in detail hereinafter

charged particles emitted within the tube 24 are constrained to follow undulating or sinusoidal paths, such as one represented diagrammatically by the dotted line 25. The vertical deviation of the path is shown in greatly exaggerated form in order to bring out more clearly the principle of the invention. The upward excursions of the particles bring them into a relatively strong portion of the principal field 21 whereas the downward excursions carry them into a relatively weak field. The forces acting upon a given particle during its typical excursion are shown more clearly in Fig. 2 in which a portion of the path 25 is shown on a larger scale. Each dot represents the particle in one of its successive positions during its travel along the path 25. The horizontal arrows, such as 26 and 27 represent the vector force exerted upon the electron when the latter is at the position of the head of the arrow, the lengths of the arrows indicating the relative magnitudes of the forces. For example, when the electron is in the position 28 it is moving in opposition to a relatively strong force represented by the arrow 26. At a slightly later time the electron, having arrived at the position 29, is being accelerated by a relatively small force represented by the arrow 27. The electron when at position 28 will be slowed down thereby yielding some of its energy to the electromagnetic field. When at position 29 it will be speeded up, receiving energy from the field. In general, in the arrangement of the invention, in yielding energy to the field the electrons will contribute greater amounts than are received by them in abstracting energy from the field, because of the fact that the electrons are in a stronger field when traveling against the force of the field and in a weaker field when traveling in the same direction as the force. To satisfy the conditions of the described mode of operation it is evident that the auxiliary means preferably acts in synchronism with the principal field and either in the same time phase or in exactly opposite time phase. The auxiliary field is preferably directed at right angles to the principal field. In the case of the arrangement of Fig. 1, the lines of force of the auxiliary field are preferably vertical. It will be evident that it is advantageous to locate the path of the electron stream in a region of most rapid variation of the principal field. In the arrangement of Fig. 1 the space rate of change, or gradient, of the field is greatest near the top and bottom surfaces of the resonator.

Arrangements for providing and controlling a suitable auxiliary field to effect amplification in the system of Fig. 1 may be provided as shown, comprising a plate antenna 60 substantially parallel to the lines of force of the main field and energized by a source 61 of waves to be amplified. The source 61 has one of its terminals connected to the wall of the resonator 20 and the other terminal connected to the plate antenna 60 by a lead 62 passing through an insulating bead 63 sealed into an aperture in the wall. An output circuit for amplified waves may be provided, comprising for example a utilization device represented by a resistor 64 with one terminal connected to the wall of the resonator 20 and the other terminal connected through a lead 65 and an insulating bead 66 to a plate antenna 67 substantially perpendicular to the lines of force of the main field. A feedback coupling device such as a variable condenser 68 may be connected, if desired, between the leads 62 and 65. The resonator 20 is preferably of square cross section or

otherwise designed to insure resonance of the main and auxiliary fields at a common frequency.

In the operation of the system of Fig. 1 as an amplifier, the wave from the source 61 sets up initially a pair of crossed electromagnetic fields, propagated from the antennae 60 and 67 within the cavity of the resonator 20. If the source 61 is adjusted to the resonant frequency of the resonator, standing wave patterns will be set up, the antenna 67 setting up a pattern of horizontal lines of electric force like that indicated at 21, but representing usually a relatively weak field, at least until the amplifying action establishes itself. The pattern set up by the antenna 60 comprises lines of force substantially perpendicular to the lines indicated at 21, that is, vertical. For simplicity, the vertical lines are omitted in the showing of Fig. 1. Both field patterns will, of course, be modified in the immediate vicinity of the antennae but the modifications may be so limited as to be of no consequence with respect to the operation of the system. With the tube 24 properly adjusted, the beam of charged particles is influenced by the vertical field to follow an undulating path as explained hereinabove. Any other suitable arrangement for setting up the crossed fields may be employed in place of the antennae 60 and 67 and it will be understood that in any case the details of the connections between the antennae and the source and load are to be arranged in accordance with a technique which is proper at the operating frequency used.

Either positive or negative feedback may be provided according to the phase relationship between the antennae 60 and 67. As illustrated in Fig. 1 the two antennae are excited in like time phase, which means for example that when antenna 60 is positively charged with respect to the wall of the resonator the antenna 67 is likewise positively charged. Since the inertia of the electron makes it lag behind the vertical field, then when the antenna 60 is positively charged the electrons are in one of the lower loops of their respective paths of the type depicted in curve 25 and so are in the weaker portion of the main field. Since the antenna 67 is also positively charged at the same instant, the electrons with reference to their horizontal motion from left to right, imparted to them by the electron gun, are being accelerated by the main field. Conversely, when both antennae are negatively charged the electrons are being decelerated in the stronger portion of the field. Hence the phase conditions are suitable to facilitate transfer of energy from the electrons to the field, and the feedback is what is generally designated as positive feedback. As the main field builds up it induces currents in the antenna 67 which are fed to the load resistor 64. Through the feedback connection, a portion of the output current is fed back to the input circuit where it supplements the current delivered to the antenna 60 by the source 61, producing regenerative amplification.

Negative feedback may be secured by reversing the direction of the field produced by either antenna, as may be done, for example, by inserting the antenna 67 into the resonator from the left instead of from the right as shown. With a negative feedback arrangement, the current fed back to the input circuit reduces the current delivered to the antenna 60 by the source 61, with important incidental effects such as distortion correction, etc., well-known in conventional amplifier practice.

The system of Fig. 1 is capable of functioning as an amplifier even without the feedback element 68 or in the absence of any feedback whatsoever, provided there is some initial excitation of the horizontal field. Such excitation will be set up spontaneously by any slight electromagnetic oscillation such as is known to arise in any resonator due to thermal agitation of electrons in the walls of the resonator or other natural cause. In a practical embodiment, furthermore, there will generally be sufficient deviation of the cross section of the resonator from a perfect square or other lack of symmetry or regularity to provide a coupling between the vertical oscillating system and the horizontal oscillating system.

The system of Fig. 1 may be operated as an oscillator by providing a strong positive feedback, in which case the source 61 may be open-circuited or omitted. In that case the vertical field will be energized by currents fed back to the antenna 60 from the antenna 67.

Other combinations of fields mutually at right angles may be employed, such as, for example, the combination of circular lines and radial lines of Fig. 3. By use of appropriate boundary conductors, either or both of the fields in Fig. 3 may be modified to render them non-uniform in space so as to permit operation in the manner described in connection with Fig. 1. Embodiments employing non-uniform fields derivable from the configuration of Fig. 3 are described hereinafter and illustrated in Figs. 8 and 9.

Another mode of operation may be employed, using uniform circular and radial fields as shown in Fig. 3 unmodified. The stream of charged particles is constrained to move initially in a circular path, as for example by applying a radial static electric field superposed upon the oscillating field represented by Fig. 3 and directing the stream initially tangentially to the circular lines. The particle will be pulled inwardly and outwardly along the radial direction by the radial component of the alternating field, following a path such as is indicated by dotted curve 15. Conservation of the angular momentum of the particle requires that when the particle is drawn closer to the axis its speed along one of the concentric circles must increase, and when it is pushed away from the axis, its speed must decrease. To promote sustained oscillations it is then necessary to arrange the time phases of the alternating fields so that the particles oppose the force of the circular field when travelling at increased speed and go along with the force of the circular field when at decreased speed.

Fig. 4 shows an oscillator in accordance with the invention in which the resonator is a hollow cubical box 30. Near the middle of the top surface of the box a vacuum tube 31 is shown passing through a pair of apertures 32 and 33. The tube 31 may be a high vacuum electron tube having an electron gun 70 of any suitable design at one end and an anode 71 at the other. When suitably provided with a cross field the tube 31 is capable of maintaining in oscillation the principal field as explained in connection with the arrangement of Fig. 1. The cross field may be maintained by means of a similar tube 34 mounted at right angles to the tube 31 and near the middle of one of the side faces of the resonator 30. Tube 34 may have an electron gun 72 at one end and an anode 73 at the other. Due to the square cross section of the resonator 30, the fundamental resonant frequency of the auxiliary field will be the same as that of the principal

field. When both tubes 31 and 34 are properly energized, as by means of batteries as shown, both the principal field and the auxiliary field will be set up spontaneously by building up any slight fortuitous electromagnetic oscillations, as explained in reference to the system of Fig. 1. A component of electric field parallel to the axis of tube 31 provides a cross field for the electron stream in the tube 34 and correspondingly a component of field parallel to the axis of tube 34 provides a cross field for tube 31. Either field may be regarded as the principal field and the other as the auxiliary field. The resonator walls may be of metal and the inner surfaces should be smooth and of high electrical conductivity. A coupling loop 74 may be provided for taking energy out of the device.

Fig. 5 shows by means of a cross section of resonator 30 an alternative arrangement to that of Fig. 4 in which a branched tube 35 takes the place of the tubes 31 and 34. A single electron gun 75 is provided in the unbranched end and anodes 76 and 77, respectively, are included in the branches. To provide greater currents of electrons and at the same time to facilitate the deflection of the electrons into the horizontal branch of the tube 35 the tube may have a suitable gas content which provides a supply of positive ions. The presence of the positive ions tends to offset the deleterious effects of electron space charge, thereby increasing the available electron current. It is also well-known that with gas tubes, due to ionic collisions, the discharges readily follow curves and even sharp bends in the direction of the envelope. Collisions should, however, not be numerous enough to deleteriously affect the transfer of energy between the stream and the field.

In this embodiment, as well as in any of the others illustrated herein, energy may be taken out of the resonator for utilization or transmission by any suitable output means such as, for example, an inductive loop 36 connected to the inner conductor 37 of a coaxial transmission line having outer conductor 38, or a plate antenna as shown at 67 in Fig. 1. Likewise, input arrangements and feedback circuits may be supplied and the system operated as an amplifier.

Fig. 6 shows another alternative arrangement, in which the efficiency of operation may be increased by confining the paths of the electrons to the regions where the cross fields are strongest, that is, near the center of the respective faces of the resonator. The vertical tube may contain an electron gun 78 and an anode 79 while the horizontal tube may contain an electron gun 80 and an anode 81. An output coupling loop 82 may also be provided.

Fig. 7 represents a type of tube which may be used in any of the embodiments illustrated herein and which has a plurality of grids to which positive biasing potentials may be applied for the purpose of neutralizing space charge. A potentiometer 39 is connected across a battery 43 or other source of electromotive force. The respective space charge grids, for example the grids designated 44, 45, 46 are connected to taps 40, 41, 42 and others, respectively, providing graded potentials along the potentiometer. The tube shown in Fig. 7 may be highly evacuated so as to provide a substantially pure electron discharge. The effect of the space charge grids is to increase the electron current available with a given electromotive force applied to the anode.

Fig. 8 shows an embodiment of the invention employing a cavity resonator 50 in the form of a right circular cylinder. The ends of the cylindrical section are preferably closed by flat plates. A vacuum tube 51 in the form of a nearly closed ring is mounted near one end of the resonator. In this arrangement the electron current can give energy to a circular field if there is a radial field present, that is, an H_0 wave may be sustained if an E_0 wave is present. The radial field may be energized by an external source, amplifier energy being made available in the circular field, or, if a self-oscillating system is desired, there may be introduced some type of coupling between the two types of waves. Such coupling will generally be present in a given system due to lack of perfect symmetry in the construction. If desired, a second tube may be provided to deliver energy to the radial field or a small concentric cylinder 16 may be introduced to facilitate the generation of a radial field without involving much loss due to currents induced in the concentric cylinder by the circular field.

Fig. 9 represents a system similar to that shown in Fig. 8 except that the vacuum tube is longer and is formed into two loops. Since in a gas tube there are large potential drops adjacent to the anode and cathode, there is a gain in efficiency to be had by using a longer loop, thereby reducing the importance of the anode and cathode potential drops.

Fig. 10 shows another embodiment of the invention in a cylindrical resonator. In this case one of the fields has its lines of force parallel to the axis of the cylinder and the field is directed in opposite directions in the upper and lower portions of the cylinder as indicated diagrammatically by the sinusoidal curve 52. The second field is preferably radial. The portion of the vacuum tube which is employed to sustain the longitudinal field is located on the axis of the cylinder as the gradient of the field is greatest at that place. The radius and length of the circular cylindrical section are preferably correlated to give the same resonant frequency for the axial and radial fields.

Fig. 11 shows an embodiment of the invention employing a spherical resonator 53 and a long curved vacuum tube 54 which is coiled so as to excite two mutually perpendicular fields inside the sphere.

Fig. 12 shows a resonator formed of coaxial cylindrical sections, the inner cylindrical conductor being closed at one end by a circular plate 55 and the outer cylindrical conductor being closed by a large circular plate 56 separated by a small space from the plate 55. The remaining end of the inner conductor may be open while the edge of the inner conductor at the open end is connected with the outer conductor by an annular plate 57.

The principal electric field in this type of resonator is between the plates 55 and 56. The field is most intense in the neighborhood of the axis and varies rapidly toward the outer edges of the plate 55. The lines of force in the region of the rapidly varying field intensity have both axial and radial components. A vacuum tube 58 is placed in the region between the plates 55 and 56 as indicated. The electron stream in the tube 58 in passing through the region of the large field gradient is in a position to deliver a net contribution of energy to the complex field.

Fig. 13 shows another arrangement of a vacuum tube in a region of rapidly varying field intensity. The resonator in this case resembles a

circular cylinder with reentrant dihedral portions.

In the arrangements of Figs. 8-13, inclusive, energizing batteries or other sources may be provided as shown and output coupling loops 83-88, inclusive, may be employed.

In any of the embodiments illustrated, where gaseous tubes are used, the tubes may contain mercury vapor or some gas of relatively low ionization potential.

It will be evident that any suitable resonator regardless of its particular shape may be employed in place of the resonators shown, provided in each case that the resonator will support oscillations having electric field components substantially at right angles and having the same resonant frequency for the two modes of oscillation. It will also be evident that any embodiment described as an oscillator may be modified to operate as an amplifier by providing input means for exciting the auxiliary field.

It will be understood that the particular form of vacuum tube employed is not important nor the particular method for increasing the available electron current, if any such method is employed. Any available apparatus may be employed which will provide a stream of electrons or other charged particles which may be directed along a desired path through the field of the resonator. The important thing is that the stream of charged particles be so controlled that the particles encounter on the average a stronger field, or that they travel further in case of a uniform field, when they are being decelerated and encounter a relatively weak field, or travel a shorter distance in the uniform field, when they are being accelerated, so that in either case a net transfer of energy from the stream to the field is effected.

What is claimed is:

1. A resonating chamber containing an alternating electromagnetic field the intensity of the electric component of which is non-uniformly distributed through the space, means to inject a stream of charged particles into said chamber in energy interchanging relation to the field therein and initially in a direction parallel to the electric component of the said field, means to constrain the particles of said stream to follow undulating paths alternating between field regions of higher and lower electric intensities with a periodicity equal to that of the alternation of the field, and means to regulate the phase relationship of said constraining means and said field, thereby determining a material net unidirectional transfer of energy between said stream and said field.

2. A repeating system comprising a source of waves to be repeated, a resonating chamber for waves from said source, said chamber supporting two modes of oscillation characterized by mutually substantially perpendicular electric forces, means energized by waves from said source to excite one of said modes of oscillation, means to inject a stream of charged particles into said resonating chamber in a direction substantially parallel to the direction of the electric force associated with the other mode of oscillation and in a portion of the field of force of said second mentioned mode where the electric force has a material gradient, thereby imparting energy to said second mentioned mode from the kinetic energy of said stream of charged particles, and means to derive a repeated wave from the

oscillations of said resonating chamber in said second mentioned mode.

3. An oscillating system comprising a resonating chamber having two modes of oscillation characterized by mutually substantially perpendicular electric forces, and means to develop a pair of streams of charged particles, each of said streams being directed initially substantially parallel to the lines of force associated with a respective mode of oscillation and each located in a portion of the field where there is a material gradient of field intensity, oscillation of the chamber in either mode causing lateral vibration of particles in one of said streams and in turn transferring energy from the said one of said streams to the oscillations of the other mode, with the result that both modes of oscillation are sustained.

4. An electronic oscillator comprising a resonating chamber, means to inject an electron stream into said chamber initially in a direction parallel to the electric component of an electromagnetic field configuration existent within said chamber and in a non-uniform portion of said field, and means to constrain the electrons of said stream severally to follow undulating paths through said non-uniform portion of the field, the paths deviating laterally from the line of injection of the stream with a periodicity equal to the periodicity of alternation of the field to vary the vector force of the field encountered by the electron stream and thereby facilitate a

net transfer of energy from the stream to the electromagnetic field.

5. The method of producing sustained oscillations in a field of standing electromagnetic waves which comprises projecting a stream of charged particles initially in the direction parallel to the electric lines of force of said field and through a portion of said field with a material gradient of intensity, and periodically deflecting said stream in synchronism with the alternations of said field to cause the charged particles alternately to oppose the force of a relatively strong electric field and to be accelerated by the force of a relatively weak field.

6. An electronic oscillator comprising a hollow resonating chamber and a pair of electron tubes disposed within said resonating chamber with the axes of the tubes mutually perpendicular.

CHARLES H. TOWNES.

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