

Oct. 15, 1946.

W. SHOCKLEY

2,409,227

ULTRA HIGH FREQUENCY ELECTRONIC DEVICE

Filed July 11, 1941

3 Sheets-Sheet 1

FIG. 1

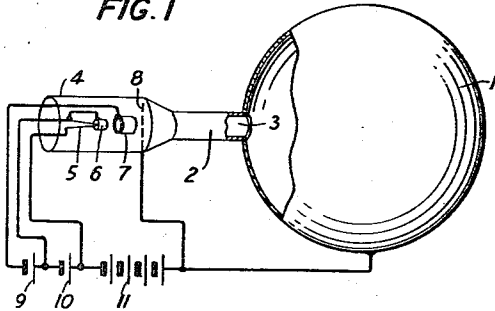


FIG. 2

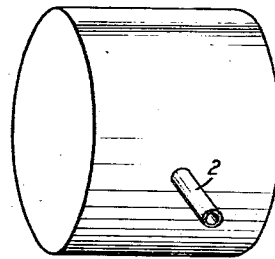


FIG. 3

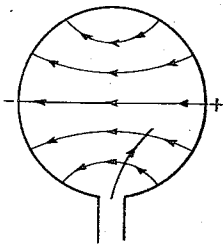


FIG. 4

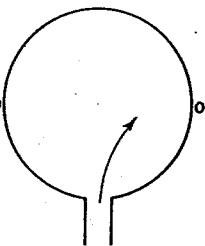


FIG. 5

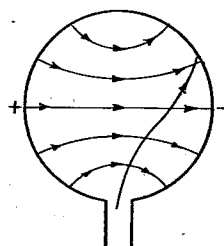


FIG. 6

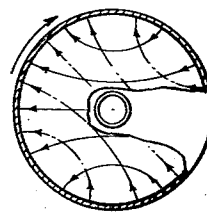


FIG. 7

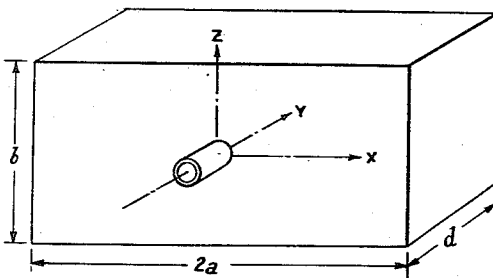


FIG. 8

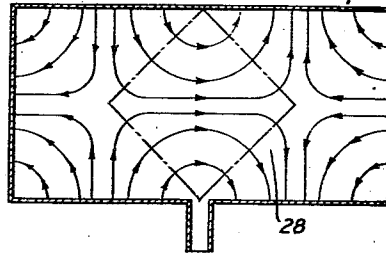


FIG. 9

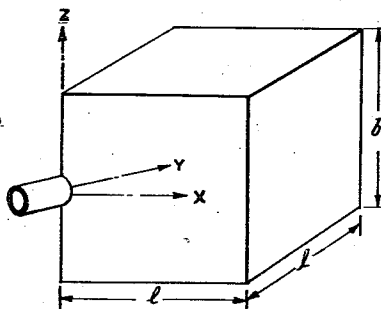
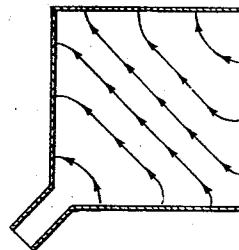


FIG. 10



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FIG. 11

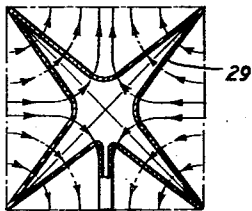


FIG. 12

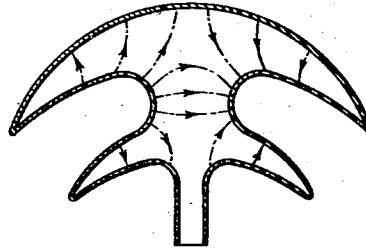


FIG. 13

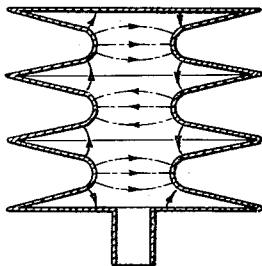


FIG. 14

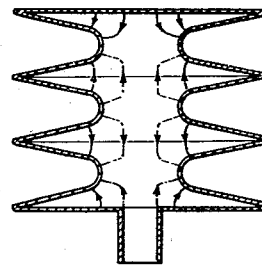


FIG. 15

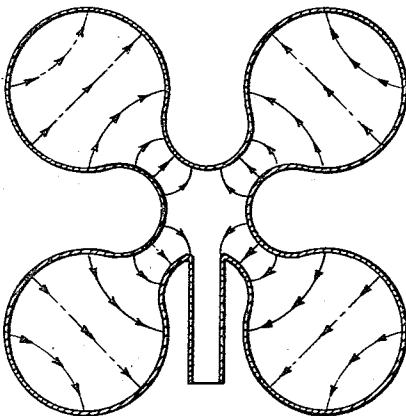
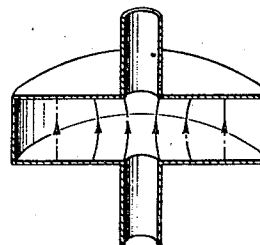


FIG. 16



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FIG. 1A

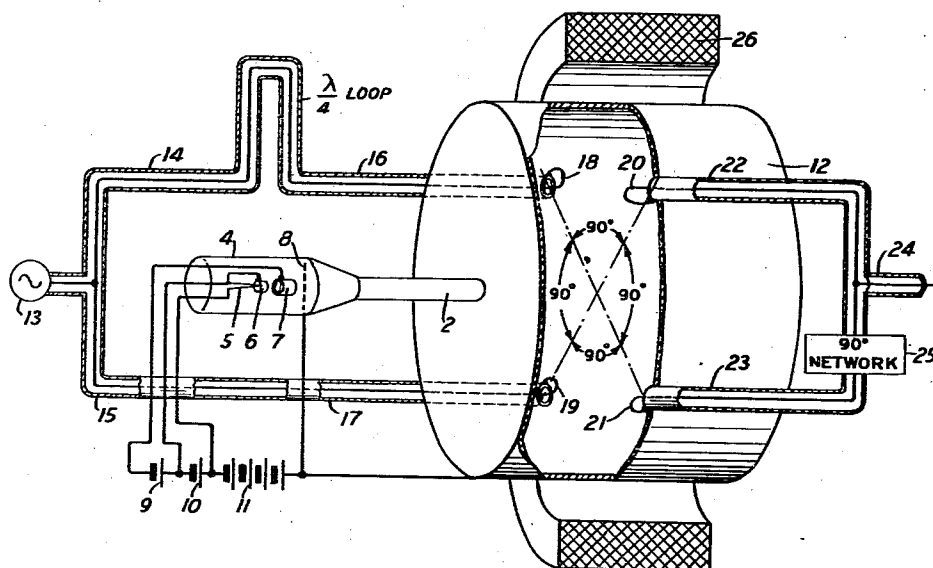
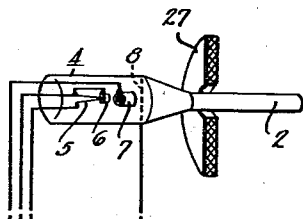


FIG. 1B.



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ULTRA HIGH FREQUENCY ELECTRONIC
DEVICE

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Application July 11, 1941, Serial No. 401,913

10 Claims. (Cl. 250—36)

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This invention relates to systems involving interaction of electron beams and electromagnetic waves.

An object of the invention is to transfer energy from an electron beam to an electromagnetic wave.

Another object of the invention is to utilize an electron beam to impart additional energy to the electromagnetic field within a resonant cavity.

A further object is to introduce energy from an electron beam into an enclosed electromagnetic field without permitting loss of the energy of the field through the apertures of the enclosure through which the beam is introduced.

An additional object of the invention is to provide a resonant cavity into which an electron beam may be projected of such geometrical configuration that an entering electron which tends to impart the energy to the electromagnetic field within the cavity may continue to do so throughout its transit across the space within the cavity.

In accordance with the invention, an electron beam is introduced into the space within a resonant cavity in order to impart energy to the electromagnetic field therewithin. Under ordinary conditions, the speed of electrons is very much lower than that of the change in the electromagnetic field. The cavity is therefore preferably given such a configuration and such a contour in the direction of its electrical resonance paths as will make these paths physically long so that the rate of change of electromagnetic field conditions at a point in the enclosed space relative to the rate of movement of the electrons of the beam is reduced. Moreover, the beam may be introduced into the cavity and in some instances led out therefrom by a section of wave guide having such a small diameter that its transmission band lies wholly above the frequency of the oscillations to which the cavity is resonant thus preventing loss of the energy of such oscillations through the apertures of the cavity at which the wave guide sections are connected.

In accordance with another feature of the invention, the electrons are introduced into the resonant cavity with a velocity which is substantially at right angles to the direction of the electric field. During a portion of the transit the electron is deflected by the field and incidentally accelerated to some extent. The field then reverses in direction and thereafter the electron travels in a direction which has a component in opposition to the field. During this portion of its transit the electron imparts energy to the field preferably until it strikes the wall of the cavity. In order

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that successive electrons entering the cavity may find conditions substantially the same in spite of the varying phase of the field at the time of entry, the electric field may be arranged to rotate about an axis coincident with the original velocity of the electrons.

In the drawing,

Fig. 1 is a view, partly broken away and partly diagrammatic, of an embodiment of the invention in a spherical resonator;

Fig. 1A is a similar view of an embodiment in a cylindrical resonator with means for initiating and maintaining a rotating electromagnetic field;

Fig. 1B is a fragmentary view showing a modified field coil suitable for substitution in the arrangement of Fig. 1A;

Fig. 2 is a perspective view of a cylindrical resonator with an access tube attached to the cylindrical wall;

Figs. 3, 4, 5 and 6 are diagrams useful in explaining the reaction between an electron and a transverse electric field;

Fig. 7 is a perspective view of a resonator in the form of a parallelepiped with an access tube in the middle of one side;

Fig. 8 is a diagram suggesting the configuration of a suitable electric field in the resonator of Fig. 7 for practicing the invention;

Fig. 9 is a perspective view of a resonator in the form of a square prism with an access tube entering diagonally from one of the edges;

Fig. 10 is a diagram suggesting the configuration of a suitable electromagnetic field inside the resonator of Fig. 9;

Fig. 11 is a diagram useful in explaining how the shape of a resonant cavity may be altered to enable an electron with a moderate velocity to traverse the cavity within a single cycle of alternation of the electromagnetic field; and

Figs. 12 to 16, inclusive, show various shapes of cavities adapted for the same purpose as the cavity illustrated in Fig. 11.

Referring to Fig. 1, a hollow spherical resonator 1 is shown having conductive walls, for example of copper, and with a small conductive access tube 2 conductively joined to the wall of the resonator and communicating with the interior through an aperture 3. Sealed in suitable manner to the tube 2, is an insulating envelope 4, which may be of glass, containing the usual elements of an electron gun including a heater 5, a cathode 6, a focussing electrode 7 and an accelerating electrode 8. The interior of the resonator 1, the tube 2, and the insulating envelope 4 forms a continuous chamber which is evacuated

and hermetically sealed. Batteries 9, 10 and 11, or other suitable sources, are provided to energize respectively the focussing electrode 7, the heater 5, and the accelerating electrode 8. The resonator 1 is preferably connected to the battery 11 along with the accelerating electrode 8.

The operation of the system of Fig. 1 will be described with reference to Figs. 3, 4 and 5. Presupposing that in some manner a transverse electric field has been set up inside the resonator 1 and is alternating at an ultra-high frequency rate to which the resonator is tuned, Fig. 3 suggests the conditions when an electron has entered the resonator from the tube 2 at an instant when the field has a given direction as indicated by the arrows. Coming in at right angles to the field, the electron will be deflected towards the positively charged portion of the wall of the resonator. Assuming a sufficiently high speed of the entering electron, the electron will have penetrated about halfway to the wall in a curved path by the time the field reverses. During this portion of its travel, the electron will not have extracted much energy from the field because its velocity has been substantially at right angles to the field with at most only a relatively small component in the direction of the field. After the field reverses and is building up in the opposite direction the electron has a considerable component of velocity in the direction of the field and in the proper sense to impart some of its energy to the field before striking the wall of the chamber. Individual electrons will, of course, enter the chamber in various phases of the electromagnetic wave. Depending upon the direction of the field at the time of entry, a given electron will be deflected either to the left or to the right as the case may be. In general, each electron will contribute a certain net amount of energy to the field although the contributions of the individual electrons may be somewhat different. The resonating chamber has a natural decrement of its own due to the finite conductivity of its walls or to other causes; however, if the energy furnished by the electron beam exceeds this amount, the amplitude of the wave will increase until limited by various restraining effects which arise at large amplitudes, and thus a condition of sustained oscillation is reached.

The electron stream may be brought up to a suitable initial velocity at the aperture 3 by the effect of the accelerating voltage impressed upon the electrode 8 and the resonator wall by the battery 11, which battery also affords a return path for current to the cathode.

Fig. 1A shows a modification of the arrangement of Fig. 1 to make use of a rotating electric field in order that the electrons regardless of the phase at which they enter the resonating chamber, will all enter under substantially similar conditions and give equal contributions of energy to the field. A cylindrical resonator 12 is shown although a spherical one may be used instead as in Fig. 1. The entrance tube 2 is placed at the center of one of the end plates of the cylindrical resonator. The electron gun 4 and the batteries 9, 10 and 11 are employed in the same manner as in Fig. 1. A number of arrangements are shown in this figure for initiating and maintaining a rotating electromagnetic field within the resonator 12, any one or more of which arrangements may be employed as desired. One such arrangement comprises an auxiliary oscillator 13 coupled to the resonator 12 through branch lines 14 and 15 differing in electrical lengths by a quarter

wave-length and terminating in small coupling loops 18 and 19, respectively, projecting inwardly into the resonating chamber at points separated by 90 degrees along the circumference of the cylindrical wall of the resonator. Another arrangement comprises an output and feedback system in which coupling loops 20 and 21, also separated circumferentially by 90 degrees, are set into the walls of the resonating chamber and connected by transmission lines 22 and 23 which join in a common transmission line 24 which may be connected to any desired load circuit or utilization system, one of the lines 23, including a 90-degree phase shifting network 25 of any suitable sort. Phase differences of any odd number of quarter wave-lengths may, of course, be used for the present purposes although a single quarter wave-length or 90-degree phase shift will usually be preferred. Other arrangements for initiating or maintaining a rotating electromagnetic field include a long solenoidal electromagnet 26 and a relatively flat coil electromagnet 27, the latter as shown in Fig. 1B. Permanent magnets may also be employed if desired.

Except for the rotating field feature, the arrangement of Fig. 1A operates in substantially the same manner as the system of Fig. 1. The effect of the rotating field may be explained by reference to Fig. 6 which shows a diagrammatic representation of a section of the field in the resonator 12, showing two positions of the electric field lines, one in full line and another in broken line, representing the position of the field at different instants of time. The field is represented as rotating in a clockwise direction as viewed from the access tube 2. Assuming that the rotating field is properly initiated and maintained, any electron entering the resonating chamber 12 approaches the field at right angles as shown in Fig. 3, the only difference confronting individual electrons being the particular direction of the field in the plane of the paper at the time of entry. Each electron will follow a path which is curved but which cannot be represented in a plane as in the case of the system of Fig. 1. The general reaction of the electron to the field, however, is similar to that of the system of Fig. 1, the electron delivering energy to the field after the field has swung about to such an extent that the electron is traveling with a relatively large component of its velocity contrary to the direction of the field.

To initiate the rotating field, the auxiliary generator 13 may be employed in conjunction with the lines 14 and 15 differing by a quarter wave-length to impress waves in time and space quadrature upon the coupling coils 18 and 19. When the rotating field has been established and the electron stream has been adjusted to a proper initial velocity, the electron stream will continue to supply energy to the rotating field. A swirling motion of the electrons will thus be obtained which will support a rotating field and the auxiliary generator may be disconnected.

The field may be maintained in another way by means of a feedback, using the output lines 22 and 23. In this case, energy initially intercepted by the coupling coil 20 will be fed back to the resonator through the lines 22 and 23 in time and space quadrature, thus, when properly adjusted, building up and maintaining the rotating field. A single phase output may be obtained in the transmission line 24 in the arrangement as illustrated, or two-phase output may be secured by

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coupling a two-phase load circuit to the lines 22 and 23 in any suitable manner.

If magnetic instead of electric means are to be employed to obtain the rotary motion of the electrons, the solenoid 26 may be used to set up a substantially uniform magnetic field in the interior of the resonator 12 and any electron in the stream whose velocity varies even slightly from the direction of the field will be constrained to move in a curved somewhat helical path. Alternatively, a relatively flat coil 27 may be used as shown in Fig. 1B to produce a divergent magnetic field especially conducive to developing curved electron trajectories. When the coil 27 is used the solenoid 26 may be omitted.

While in the case of a rotating field, resonators having rotational symmetry are preferable for obvious reasons, various different shapes of resonators may be employed either in a system similar to that shown in Fig. 1 or in a system similar to that shown in Fig. 1A. Fig. 2 shows a cylindrical resonator having the access tube connected to the cylindrical surface instead of to one of the end plates. Fig. 7 shows a resonator in the form of a parallelepiped with the access tube located at the center of one of the larger faces. Fig. 8 shows a diagrammatic representation of a suitable configuration for the electromagnetic field in the resonator of Fig. 7. The section shown in Fig. 8 is taken at the horizontal plane through the access tube and is representative of other planes parallel thereto.

Fig. 9 shows a resonator in the form of a rectangular prism with the access tubes located in one of the edges. The corresponding appropriate field configuration is shown in Fig. 10 and corresponds to the portion of the field configuration in Fig. 8 enclosed within the dot-dash square 28.

In resonators of the simple types so far illustrated, it is found that the length of the path to be traversed by the electrons is of the order of magnitude of a free-space wave-length at the operating frequency and, more particularly, approximately one-half wave-length. As the speed of propagation of the electromagnetic wave in the resonator is very high, approximately the speed of light, a very high speed electron stream is required in order that the electrons may keep pace with the electromagnetic wave. It is found that voltages in the neighborhood of 80,000 volts or more are required to produce suitable electron speeds for the purpose. In many cases, such high voltages are disadvantageous. Various special shapes of resonators having the property of presenting a relatively short path for the electrons may be employed some of which are disclosed in Figs. 11 to 16, inclusive. The resonators of Figs. 12 and 13 are adapted to deflect electrons projected across the field at some point of their path, whereas the resonators of Figs. 11, 14, 15 and 16 are adapted mainly to accelerate or decelerate electrons entering parallel to the field.

In Fig. 11, 29 represents the cross section of a resonator derived by consideration of a well known field configuration related to a square. The distance traversed by the electrons in going from the access tube to the opposite reentrant portion of the wall is readily seen to be short relative to the wave-length involved.

Each of the resonators represented in Figs. 11 to 15, inclusive, may be constructed either to have rotational symmetry like the spherical resonator shown in Fig. 3 or bilateral symmetry like the parallelepiped shown in Figs. 7 and 8. In the case of a resonator having rotational symmetry

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the section shown in any of the Figures 11 to 15, inclusive, is a typical section on any plane perpendicular to the axis of symmetry. It will be noted that the field configurations indicated in Figs. 12 and 13 are not of a kind which can possess rotational symmetry, the configuration shown being true for the diametral plane parallel to the principal direction of the field intensity. The field configurations indicated in Figs. 11, 14 and 15 are of a type such as to be consistent with rotational symmetry and the configurations shown are true for any diametral plane. In the case of prismatic or cylindrical forms having bilateral symmetry the section shown in any of the Figures 11 to 15, inclusive, is a section through the access tube and perpendicular to the plane of symmetry. The field configuration indicated is true for any plane section parallel to the section shown.

In Fig. 16 the resonator is shaped somewhat like a pillbox and has access tubes at the centers of the faces. The wave-length is determined primarily by the diameter of the resonator and the electron path primarily by the distance between the parallel faces and it is evident that the two dimensions are independent of each other within wide limits.

In all the figures, the access tubes are shown with diameters relatively much smaller than the operating wave-length. It is well known that the transmission of electromagnetic waves through a wave guide, for example, a cylindrical pipe, is accompanied by very great attenuation unless the wave-length to be transmitted is sufficiently small to be comparable with the diameter of the guide. It is a feature of the present invention that the access tubes are made of such small diameter relatively to the operating wave-length that the cut-off frequency of the access tube, considered as a section of wave guide, is well above the operating frequency, preferably two or more times higher. Consequently, the waves at the operating frequency encounter great attenuation in traveling along the access tube. By using a sufficiently long access tube, as for example, of the order of one to four or more diameters, the attenuation may be made so great that leakage through the access tube is reduced to any desired minimum. Thus, the cut-off property of the access tube prevents the field from escaping from the resonator but does not prevent the entrance or exit of the electron beam. If desired, the electrons may be collected at a low potential after passing through the resonator—thus high speed electrons may be used and some part of their energy not given to the field regained. Useful energy may be extracted from the resonator in any known manner as, for example, through an aperture and associated transmission line as in the system of Fig. 1A.

An advantage common to the structures herein disclosed is that no constant or direct current electric fields are required inside the resonating chamber. Such fields entail the necessity of introducing insulated leads through the walls of the resonating chamber. In the arrangements herein illustrated, the only exit for electromagnetic energy other than to the load device is through the access tubes for accommodating the electron stream. By the use of restricted and elongated access tubes, as above described, radiation losses through the access openings may be substantially prevented and the total radiation losses held to a very small value.

What is claimed is:

1. In combination, a resonant chamber having a conductive wall with a relatively small aperture therethrough, means for projecting a beam of electrons into the interior of the chamber through said aperture, means for initiating an electromagnetic field in rotation about an axis lying in the line of projection of said electron beam, and means for bringing the speed of the electrons at the point of entry into said chamber to a value at which said electromagnetic field is sustained by energy contributed to the field by the motion of electrons in said beam.

2. In an ultra-high frequency electronic oscillator, a resonant chamber, means for initiating a rotating electromagnetic field within said chamber, and means for injecting electrons into said chamber in a direction substantially perpendicular to the direction of the field and at a speed such that a substantial proportion of said electrons are so deflected as to travel in a direction opposed to the field over a sufficient part of their path to contribute a net increment of energy to the field.

3. In an oscillation generating system, a hollow cylindrical resonator having an aperture in the wall thereof at a point on the axis of the cylinder, means for projecting a beam of electrons through said aperture in the axial direction, means for initiating an electromagnetic field in rotation about said axis, a pair of receiving loops located in space quadrature along the circumference of the cylinder, a load circuit, and a pair of transmission lines connecting said respective receiving loops with said load circuit, said lines differing in length by an odd number of quarter wave-lengths at the resonant frequency.

4. In combination, a resonant chamber having an aperture in the wall thereof, means for projecting a beam of electrons through said aperture, a section of wave guide surrounding said aperture and connected to the wall of said chamber, said section being of such small diameter as to transmit a band of frequencies lying substantially above the resonant frequency of said chamber and to highly attenuate and substantially suppress waves of frequencies lower than said band and including the natural resonant frequency of the chamber which might tend to escape through said aperture.

5. In an ultra-high frequency electronic device, a substantially closed resonant chamber having a relatively small aperture in its wall, means for projecting a beam of electrons through said aperture, and means to substantially prevent the leakage of electromagnetic radiations through said aperture while not interfering with the passage of said electron beam, said means comprising an open-ended section of wave guide projecting outward from the wall, surrounding said aperture and accommodating the passage there-

through of said electron beam, and said wave guide being of sufficiently restricted cross-sectional dimensions that the lower limiting freely-transmitted frequency of said wave guide lies materially above the resonant frequency of said resonant chamber.

6. In an ultra-high frequency electronic device, means for producing an electron beam, a substantially closed resonant chamber having a relatively small aperture in its wall for the passage of said electron beam therethrough, and means to substantially prevent the leakage of electromagnetic radiation through said aperture while not interfering with the passage of the electron beam, said means comprising an open-ended section of wave guide surrounding said aperture, and said wave guide being of sufficiently restricted cross-sectional dimensions that the lower limiting freely-transmitted frequency of said wave guide lies above the resonant frequency of said resonant chamber.

7. In an oscillation generating system, means for setting up an electromagnetic field having lines of electric force substantially parallel to each other in a given region, means for causing said field to rotate about an axis substantially perpendicular to said parallel lines of force, means for projecting a stream of electrons into the said given region in the direction of said axis of rotation, and means to correlate the velocity of projection of the electrons of said stream with the angular velocity of rotation of said field to cause the field to be sustained by energy contributed to the field by the moving electrons.

8. In an oscillation generating system, a resonant chamber, means for setting up within said chamber an oscillatory electromagnetic field having substantially parallel lines of electric force in at least a portion of the chamber, means for causing said field to rotate about an axis substantially perpendicular to said parallel lines of force, means for injecting electrons into said chamber in a direction substantially perpendicular to said parallel lines of force, and means to adjust the speed of injection of electrons to cause the field to be sustained by energy contributed to the field by the moving electrons.

9. In combination, a resonant chamber, and a conductive access tube projecting outwardly from the wall of said chamber, said tube having a diameter relatively small compared with the wave-length to which said chamber is resonant.

10. In combination, a resonant chamber and a conductive access tube projecting outwardly from the wall of said chamber, said tube having a diameter relatively small compared with the wave-length to which said chamber is resonant and having a length at least of the order of a diameter of the tube.

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