July 24, 1962 J. M. HOUSTON 3,046,439

FIELD EMISSION REFLEX KLYSTRON

Filed April 29, 1960

Fig. 1.

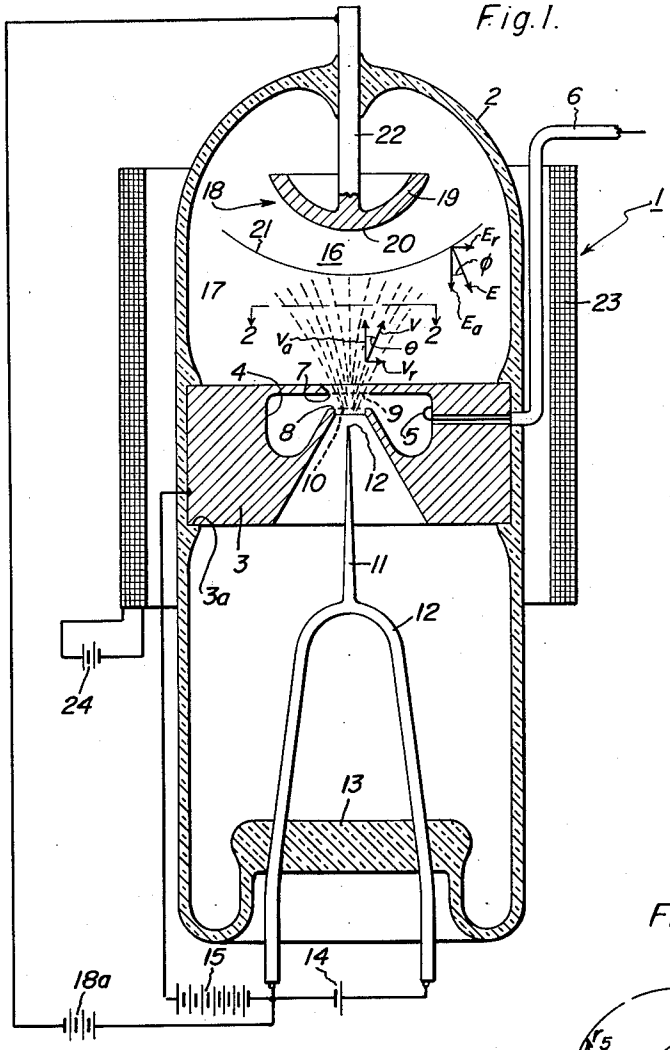


Fig. 2.

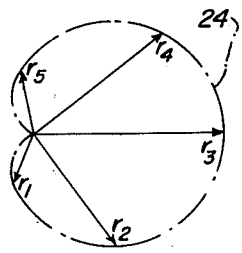


Fig. 3.

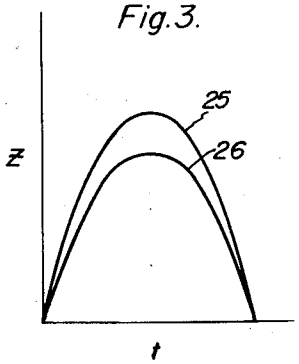
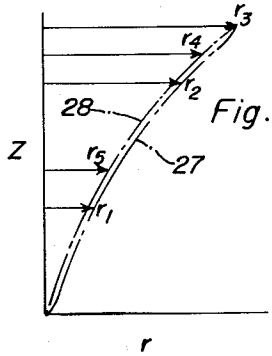


Fig. 4



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FIELD EMISSSION REFLEX KLYSTRON

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My invention relates to a device of the type commonly called a reflex klystron which is useful for producing high frequency electromagnetic oscillations.

Briefly, a reflex klystron is a type of electron tube device which, in general, includes an enclosure with a resonant cavity, and which is centrally apertured for accommodating the passage of an electron beam. A cathode disposed on one side of the aperture serves as a source of electrons and a high positive potential applied to the enclosure with respect to the cathode accelerates the electrons from the cathode to produce a beam. The vast majority of the electrons so produced in the beam, pass through the aperture. A repeller electrode is spaced from the aperture and is on the side thereof remote from the cathode. A high potential is applied to the repeller and is negative with respect to the cathode in order to decelerate the electrons and repel the same back through the aperture after which they are collected. This action gives rise to electromagnetic oscillations within the cavity in a known manner to produce an alternating potential across the gap of the aperture. Such an alternating potential serves to impart increments or decrements of velocity to the electrons in the beam, depending on the phase of the alternating potential at the particular instant the electron is traversing the gap. By proper acceleration and repeller potentials and cavity resonator size, the time period for deceleration of the electrons by the repeller and the return of the electrons through the aperture may be made so that the electrons are density modulated or bunched as they traverse the gap on their return passage. Such bunches are in such phase with respect to the alternating potential across the gap so as to enhance the same. Thus, the newly emitted electrons are more strongly velocity modulated and produce higher potentials across the gap and a regenerative action occurs to produce oscillations.

In various electrical circuits, a need frequently exists for a source of high frequency electromagnetic oscillations. An example of such a need is a local oscillator in a receiver such as is used in a radar system. The reflex klystron oscillator which possesses attributes of high stability and easy tuning is well adapted for service as such a local oscillator. The powder requirements for this use are relatively low and the conventional reflex klystron with characteristically low power capabilities is adequate for such purposes.

However, other uses exist for sources of high frequency oscillations wherein the power requirements and/or the required operating frequency are somewhat greater than are obtainable with conventional reflex klystron structures. Since the frequency requirements of a klystron control the cavity size and therefore, to a considerable extent, also the gap dimensions, higher power capabilities in conventional klystrons of a predetermined frequency were obtainable primarily by higher electron beam densities. Considerable improvement has been recently realized in providing conventional cathodes of larger surface areas and/or capable of higher emission densities by reason of use of improved emission enhancing materials, to provide such higher beam densities. However, the extent to which these two factors may be utilized to increase power capabilities is also limited. In addition to the foregoing, as a rule, the size of a resonant cavity varies inversely with its resonant frequency and the requirement for higher frequencies requiring smaller resonant cavities imposes further restrictions on the gap dimensions of the cavity.

It is accordingly a principal object of my invention to provide a reflex klystron type of electron tube device which is capable of higher power and higher frequency operation and which is not limited by the factors applicable to conventional reflex klystrons.

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, together with further objects and advantages thereof, may best be understood with reference to the drawing in which:

FIGURE 1 is a cross-sectional view of a reflex klystron incorporating features of my invention.

FIGURE 2 is a view taken along section 2—2 of FIGURE 1, and illustrating the movement of an electron in a plane perpendicular to the tube axis, and

FIGURES 3 and 4 are graphs useful in illustrating the coordination of an electron in respective axial and radial directions in the tube.

Pursuant to the aforementioned object and in accordance with my invention, a reflex klystron device capable of relatively high power operation is provided with a field emitter as an electron source, disposed adjacent to one side of an enclosure containing a resonant cavity and in alignment with a pair of apertures forming a gap in the resonant cavity. The field emitter comprises a sharp, needle type of electrode and is capable of very high electron densities. A direct potential, which may be continuous or pulsed, applied between the emitter and the enclosure of the cavity, produces electron emission from the emitter which is characteristically in a beam divergent from the emitter. The emitter is disposed near enough to the apertures in the cavity so that the beam is narrow enough to pass through the apertures. In accordance with a feature of my invention, provision is made to cause essentially all of the electrons in the beam, irrespective of initial angle of divergence, to pass through the apertures into a region on the side of the enclosure remote from the emitter and to return back to the cavity in bunches. The region between the enclosure and repeller electrode is herein referred to as the "drift" region, it being understood that it is different, however, from the usual field free drift regions of some multi-cavity klystrons in that this region is not electric field free. The structure providing for the return of electrons in such bunches includes a repeller electrode spaced from the enclosure on the side remote from the emitter and shaped to produce equipotential electric fields convex to the enclosure and a cooperative axial magnetic field, uniform in time and space, immersing the space between the emitter and repeller. Electrons of different angles of divergence from the tube axis have different components of axial velocity. By proper proportioning of potentials, magnetic field strength and sizes of components, the electrons of the beam pass into the drift region and are repelled by an opposing electric field which decreases somewhat in intensity away from the tube axis. The magnetic field causes the electrons to travel in curved, generally circular paths, and is proportioned to cause the electron to make a complete loop in the plane perpendicular to the tube axis in the same period of time that the repeller electric field returns the electron axially to the tube cavity. Thus, each electron initially passing through the cavity gap at the same instant of time is returned to the cavity gap after the same time interval. In other respects, the klystron operates conventionally to impart increments and decrements of velocity to electrons passing through the cavity to produce bunching.

The focusing action of the magnetic field in returning

the electrons to the cavity gap is not perfect because of the velocity modulation of the electron stream. Electrons which gain a velocity increment will take a slightly longer time to return to the cavity gap compared with electrons gaining no velocity and will, therefore, complete slightly more than a complete loop (when viewed in projection on a plane perpendicular to the tube axis). This is so because the axial distance of travel of such an electron into the drift region is further, requiring a longer period of time for its return to the cavity gap, and during such increased period, the angular travel of the electron is greater even though its velocity remains substantially constant. Similarly, electrons which lose a velocity increment will complete slightly less than one loop. However, theoretical analysis indicates that these transit time differences due to velocity modulation are at most plus-or-minus one-quarter of the cavity period, whereas the total transit time in the drift space is typically 5 or 10 periods. Thus, a degree of focusing can be achieved which is adequate for reflex klystron operation.

Referring now more particularly to FIGURE 1 of the drawings for a more detailed description of my invention, **1** designates generally the entire reflex klystron tube structure embodying my invention and which includes an envelope **2** of glass or other suitable material for containing certain components of the klystron device. The envelope is evacuated and hermetically sealed to enable the provision of an electron beam therein.

Within the envelope **2** and at a location intermediate to its ends, a conductive block **3** is securely mounted between opposed flanges **3***a* and **3***b* in the wall of the envelope. An annular resonant cavity **4** is formed in the block **3** for sustaining electromagnetic oscillations. For abstracting high frequency energy from the cavity, a conductive loop **5** forming the end of a coxial output line **6**, is connected to a wall of the cavity and forms an inductive coupling to the cavity. Central opposed portions of block **3** are apertured at **7** and **8** to provide a gap. For establishing a more uniform radio-frequency electric field across the gap, a pair of grids **9** and **10** may be provided at the respective aperatures **7** and **8** as shown, although the use of grids is not essential in this invention.

In accordance with a feature of my invention a field emitter **11** is provided as an electron source for the tube. The emitter **11** comprises an elongated conductive member extending substantially along the tube axis into a recess **11***a* in block **3** and terminating in a very sharp point **12**, which is disposed in proximity to the aperture **8** in the block **3**. In the presence of an electric field, the emitter **9** is effective to emit electrons copiously in a divergent beam.

For supporting the emitter **11**, it is mounted on one end of a hairpin shaped, conductive member **12** which in turn has its legs embedded in a reentrant stub **13** of the envelope **2**. The legs of hairpin **12** extend externally of envelope **2** for connection to respective terminals of a suitable source of electrical energy, such as a battery **14** which is effective to pass a heating current through the hairpin. The heat thus produced in the hairpin is conducted to the emitter in order to heat it.

The electric field required for providing field emission from emitter **11** is provided by a high potential source represented by a battery **15** having its negative terminal connected to hairpin **12** and its positive terminal connected to block **3**. It is to be understood that the potential source represented by battery **15** can be either an intermittent (pulsed) source or else a continuous source. This potential source establishes a high electric field at the tip of emitter **11** which causes the field emitter to profusely emit electrons.

If a continuous potential source (represented by battery **15**) is used, then the field emitter must be kept relatively cool (i.e. below approximately 500° C.) and is usually operated at room temperature. Hairpin heating is then applied only occasionally, with battery **15** disconnected,

in order to smooth and clean the field emitter tip. If an intermittent or pulsed potential source (represented by battery **15**) is used, then it is permissible to apply hairpin heating continuously in order to achieve a type of electron field emission (usually called T-F emission) which is more stable in the presence of gas atoms. These modes of field emitter operation are well-known to those familiar with the field emission of electrons.

The electrons emitted from cathode tip **12** are attracted toward the aperture **8** in block **3** and the majority of them pass through the grids **9** and **10**, into the drift region **16**. The beam pattern produced by such an emitter is divergent as represented by the dotted lines **17**.

In accordance with another important aspect of my invention, provision is made to repel substantially all of the electrons projected into drift region **16**, notwithstanding their divergent paths, and to return these electrons back through the grids **9** and **10** of the central aperture of the enclosure. To this end, a repeller electrode **18** is supported in spaced relation to the block **3** on the side thereof remote from emitter **11** and has applied thereto a direct potential, negative with respect to the emitter **11**, from a potential source represented by battery **18***a*. Also, the region between the emitter **11** and repeller **18** is immersed in a direct magnetic field having flux lines substantially parallel to the tube axis.

In accordance with another feature of my invention, the repeller electrode includes a member **19** having a spherical, convex surface portion **20** exposed to the block **3** for providing substantially spherical equipotential surface portions in the drift region in response to a potential difference between the repeller and the enclosure. A representative equipotential surface portion is represented by the line **21** at which the potential is the same as that of emitter **11**. The member **19** is supported by a conductive stem **22** embedded in envelope **2** and extending externally thereof for conductive connections to the repeller. The axial magnetic field is provided by a solenoid **23** surrounding a portion of envelope **2** and energized by a direct potential source represented by a battery **24**. It is to be understood that a permanent magnet could also be used to obtain the require magnetic field.

The combination of spherical equipotential surfaces of electric field in drift region **16** and the axial magnetic field produces forces on each of the electrons in the beam to cause the same to be repelled and to return through the aperture **7**, and in addition, in accordance with this arrangement, the period of time required for electrons to make their flight into drift region **16** and return through the aperture is essentially independent of the projection angle of the electron.

For a further understanding the manner in which this result is achieved according to my invention, it can be assumed with good accuracy that each of the electrons from emitter **11** are emitted with negligible initial velocity and are accelerated to substantially the same absolute velocity by the electric field between the block **3** and emitter **11**. The angle of initial movement of the electrons however, varies over a predetermined range of the order of thirty degrees divergent from the tube axis whereby the total beam is initially formed in substantially a conical shape. The radial component of movement of any electron entering the drift space **16** causes it to travel transversely to the magnetic field lines produced by solenoid **23** whereby Lorentz forces on these electrons impart an orbital component of movement of the electron. As a result of this Lorentz force the orbit of any one electron appears as shown at **24** in FIGURE 2 when projected onto a plane such as section **2—2** of FIGURE 1. The composite motion of an electron therefore consists of an approximately circular loop (when projected onto a plane such as section **2—2**) accompanied by a simultaneous axial motion in which the electron rises toward the repeller, slows down due to repelling fields, and falls back toward the aperture **7**. The axial displacement versus time would form a curve that is nearly parabolic

as shown in the curves of FIGURE 3 of the drawings wherein the ordinate Z represents the axial displacement of the electron from the aperture **7** and the abscissa represents elapsed time.

It is to be noted that with substantially the same absolute velocity of each electron, the axial component of velocity varies as the cosine of the angle of deviation of its flight from the tube axis. This is made clear by the vector diagram shown in the drift region **16** in FIGURE 1 wherein v represents the absolute velocity of the electron, θ represents its angle of deviation from the tube axis and v_a represents the axial component of velocity equal to v cosine θ. Thus, a constant repelling force on the different electrons would overcome the axial motion of different angled electrons in different periods of time since electrons of larger angle of deviation have lesser axial components of velocity. Accordingly, the different electrons would return through the aperture **7** in different periods of time.

In accordance with another important feature of my invention, this variation in the period of electron flight in drift space **16** is overcome by the spherical equipotential repelling fields produced by repeller electrode **18**. It is noted that the axial component of repelling electric field diminishes with radial distance from the tube axis for points at the same longitudinal displacement. This is made clear by another vector diagram in drift region **16** representing the electric field components. In this region, the absolute field at a point is represented by vector E and the axial component of field is represented by E_a which is equal to E cosine ϕ wherein ϕ represents the angle of deviation of the absolute field from the tube axis. Accordingly, electrons having a lesser axial velocity component in drift region **16** by reason of their larger angles of divergence are repelled by lesser electric fields. By proper interrelationship of magnetic field, potentials and electrode contours, the decrease of E_a may be coordinated with the decrease of v_a, whereby the period of flight of the different electrons which initially pass through the cavity aperture **7** at the same moment of time, can be made substantially the same. This is represented clearly in FIGURE 3 of the drawings wherein **25** represents the axial displacement versus time plot of an electron having a certain initial angle of divergence of flight and wherein **26** represents the axial displacement versus time plot of an electron having a larger initial angle of divergence of flight.

The relative angular and axial positions of an electron during its flight is shown in FIGURE 4 of the drawings wherein the ordinate Z represents axial displacement of the electron from the emitter and r represents the radial displacement of the electron from the tube axis. It is to be understood that this figure is not a plot of a projection of the movement of an electron on a plane but rather may be considered as a plot of the projection of an electron on a plane rotating about an edge thereof along the tube axis and with an angular velocity equal to the angular velocity of the electron. An electron with an initial radial component of movement travels with increasing radial and axial displacement as represented by line **27** and reaches the axial extremity of its flight and returns with progressively decreasing radial and axial displacement as represented by line **28**. The axial and radial displacements of the electron on upward and return movement of the electron are substantially the same and realistically lines **27** and **28** would be superimposed or very close together. Thus, to represent this condition, the lines are so shown.

The correlation between FIGURES 2 and 4 may be understood by the vectors r, r_2, r_3 and r_4 representing the radial position of an electron at different periods of time and shown in each of these figures.

It is therefore noted that each electron having a radial component of velocity as well as an axial component of velocity, passes into drift region **16** by reasons of the accelerating field described and in its excursion into the drift region, it makes a complete revolution in the plane perpendicular to the tube axis while in the same period of time it is decelerated by the repeller electrode and returned to the plane of the cavity. Thus, with such coordination of movements, each electron is utilized in the operation of the klystron.

It is to be understood that the movement of the electron in the plane perpendicular to the tube axis need not be a single revolution but may be any number of discrete revolutions, it being necessary only to return the electron to the region of the cavity aperture in this plane at the same time that the electron is returned in the axial direction from the repeller.

It is to be noted that in accordance with my invention, the high emission characteristics of a field emitter are exploited to produce an unusually high power and high frequency reflex klystron electron tube by the novel cooperation of the axial magnetic field and repeller electrode producing sperical equipotential surfaces repelling electrons emitted from the field emitter back to the gap in the tube cavity.

While the present invention has been described by reference to particular embodiments thereof, it will be understood that numerous modifications may be made by those skilled in the art without actually departing from the invention. I, therefore, aim in the appended claims to cover all such equivalent variations as come within the true spirit and scope of the foregoing disclosure.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. An apparatus comprising an enclosure having a resonant cavity for sustaining electromagnetic oscillations, portions of said enclosure being spaced to provide a gap in communication with said cavity, means for establishing a magnetic field across said gap, a conductive member having a sharp point on one side of said gap for emitting electrons and a repeller electrode on the other side of said gap, said repeller electrode presenting a convex surface to said gap, whereby application of high positive potential to said enclosure with respect to said member, negative potential to said repeller with respect to said member and an axial magnetic field between said member and said repeller is effective to cause electrons emitted from said member to pass from said member through said gap and be repelled to return through said gap in bunches.

2. An apparatus comprising an enclosure having a resonant cavity for sustaining electromagnetic oscillations, portions of said enclousre being spaced to provide a gap in communication with said cavity, a field emitter electrode near said gap and on one side thereof for producing an electron beam and a repeller electrode having a convex surface facing said gap on the other side thereof, means immersing the region between said emitter and said repeller in a uniform axial magnetic field whereby application of a positive potential to said enclosure with respect to said emitter and a high negative potential to said repeller with respect to said enclosure is effective to cause electrons to pass from said emitter through said gap toward said repeller and to be repelled by said repeller to pass in bunches through said gap toward said emitter to produce electromagnetic wave oscillations in said cavity.

3. An apparatus comprising an enclosure having a resonant cavity for sustaining electromagnetic oscillations, portions of said enclosure being spaced to provide a gap in communication with said cavity, a field emitter electrode near said gap and on one side thereof and being responsive to an electric field to produce a divergent electron beam, means on the side of said enclosure remote from said emitter for producing an electric field having spherical equal potential surfaces convex to said enclosure, means immersing the region between said emitter and said means producing said electric field in an axial magnetic field whereby the application of a high potential to said enclosure positive with respect to said emitter is effective to

cause the emission of electrons from said emitter which pass through said enclosure in proximity to said gap and are repelled by the electric field having spherical equal potential surface to be returned through said gap in bunches.

4. An apparatus comprising an evacuated enclosure containing a conductive body having a central aperture, an enclosed region in said body and in communication with said aperture to form a resonant cavity, a field emitter on one side of said aperture and in proximity thereto for producing a divergent beam of electrons in response to an electric field, means on the side of said aperture remote from said emitter for producing a negative electric field having spherical equal potential surface portions convex to said aperture, means establishing a direct magnetic field having flux lines extending substantially parallel to the direction between said emitter and said electric field forming means, whereby the application of a potential to said conductive body positive with respect to said emitter is effective to produce a divergent beam of electrons through said aperture and said repelling electric field is effective to return said electrons through said aperture in bunches.

5. An apparatus comprising an evacuated enclosure containing a conductive body having a central aperture, an enclosed region in said body and in communication with said aperture to form a resonant cavity, a field emitter on one side of said aperture and in proximity thereto for producing a divergent beam of electrons in response to an electric field, means on the side of said aperture remote from said emitter for producing a negative electric field having spherical equal potential surface portions convex to said aperture, means establishing a direct magnetic field having flux lines extending substantially parallel to the direction between said emitter and said electric field forming means, the magnitude of said magnetic field being proportioned with respect to the magnitude of the repelling electric field of said repeller electrode to cause the electrons projected into the region between said aperture and said repeller electrode to complete a discrete number of revolutions in the plane perpendicular to the tube axis in the period of time that the electron is in flight toward the repeller and returns to the aperture, whereby the application of a potential to said conductive body positive with respect to said emitter is effective to produce a divergent beam of electrons through said aperture and said repelling electric field is effective to return said electrons through said aperture in bunches.

6. An apparatus comprising an enclosure having a resonant cavity for sustaining electromagnetic oscillations, portions of said enclosure being spaced to provide a gap in communication with said cavity, and the gapped portions of said enclosure being apertured to accommodate the passage of a beam of electrons, the exterior portion of said enclosure adjacent one of the apertured gaps being reentrant, a conductive member having a sharp point being disposed in said reentrant portion adjacent to said gap for providing a source of electrons, a repeller electrode on the other side of said gap presenting a convex surface to said gap, means for immersing the region between said member and said repeller electrode in an axial magnetic field, whereby application of a high positive potential to said enclosure with respect to said member, a high negative potential to said repeller electrode with respect to said member and an axial magnetic field between said member and said repeller is effective to cause said electrons to pass from said emitter through said gap and be repelled to return through said gap in bunches to produce oscillations in said cavity.

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