

April 13, 1965

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3,178,653

CAVITY RESONATOR WITH BEAM-CONCENTRIC RING ELECTRODE

Filed April 4, 1960

2 Sheets-Sheet 1

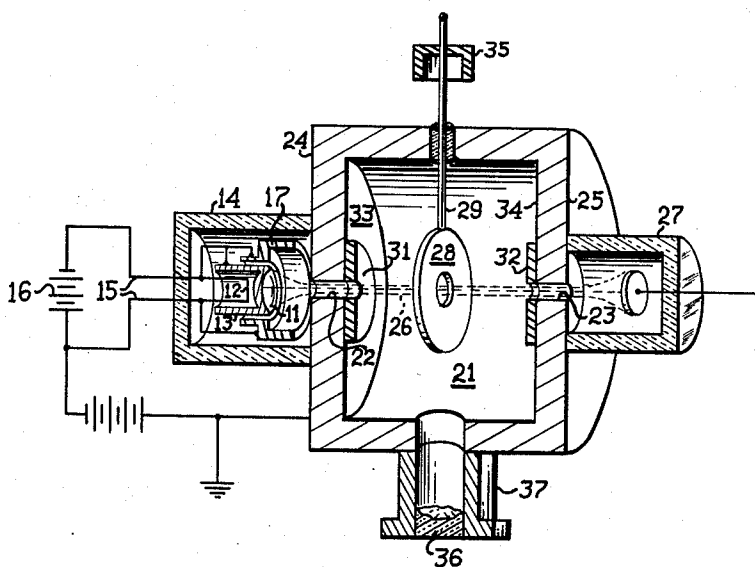


FIG. 1

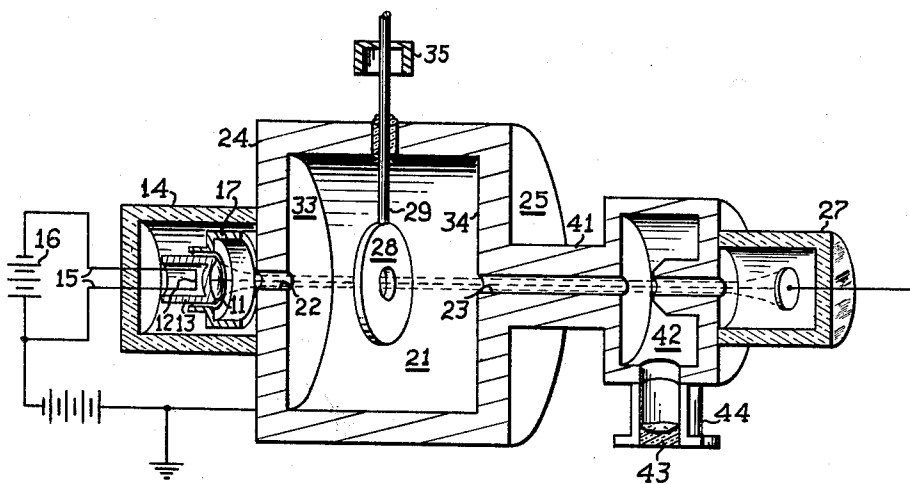


FIG. 2

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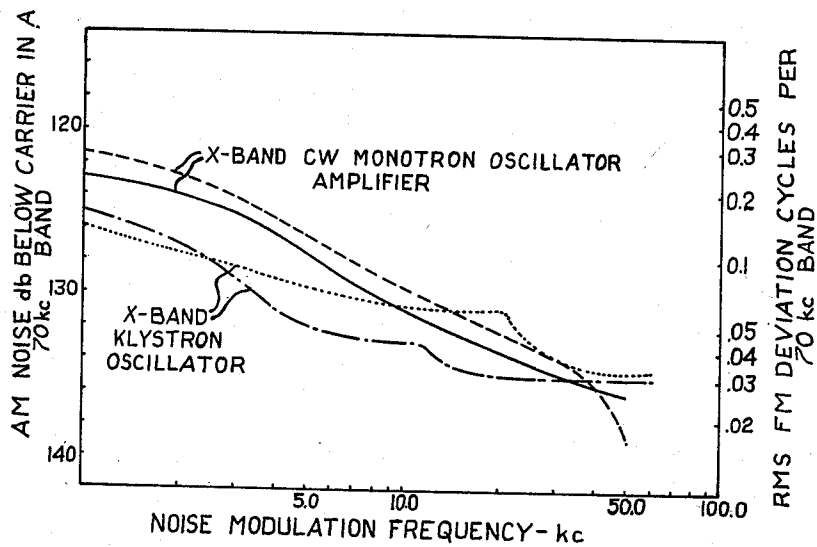


FIG. 3

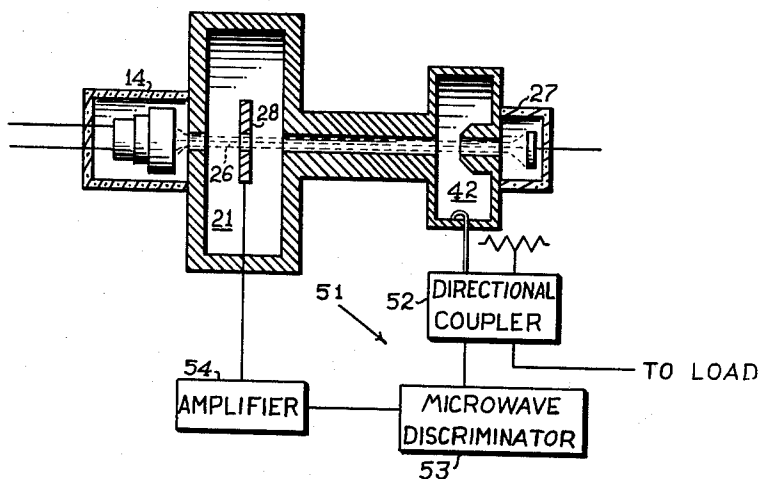


FIG. 4

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CAVITY RESONATOR WITH BEAM-CONCENTRIC RING ELECTRODE

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Filed Apr. 4, 1960, Ser. No. 19,717
6 Claims. (Cl. 331-6)

This invention relates generally to an electronic discharge device and the invention has reference, more particularly, to ultra-high frequency devices as of the klystron or traveling wave type of the kind in which the electron beam is modulated in velocity and which employs a single oscillator resonant cavity.

Heretofore, electron tubes of the klystron type have been classified into three general types; firstly, the most usual type is a klystron having a resonator or resonators having relatively large re-entrant hollow cones, the ends of which are closed by grids. This type has a number of good and bad features. The good features are that the cross section through which the beam is projected is relatively large. This allows for wide tolerances in the electron optical system which projects electrons through the resonator, no magnetic focusing is required, and it is possible to design electron guns which operate at relatively low voltage and high current, thus making possible the design of klystrons operating at relatively low voltages.

The objectionable features of this type of klystron are firstly, a multiplicity of grids result in the loss of a considerable fraction of the electrons by impact thereon before they can become useful in generating power, secondly, the grids being relatively large in diameter and closely spaced produce a large amount of capacity loading, thus reducing the shunt impedance and the gain bandwidth product, and thirdly, what is usually more serious is that the grids being subject to bombardment by the electron beam give off secondary electrons which absorb a large amount of the power delivered to the resonator or resonators by the bunches in the beam, or by the input signal. This effect may in typical cases reduce the efficiency of tubes by a very large factor. The three factors combined may reduce the efficiency by a factor of ten or more. In spite of the very low efficiency of this type of tube, it is nevertheless used in large numbers because of the good features mentioned above.

The second type of klystron tube is currently increasing in use because it is capable of much greater efficiency, although it is deficient in most of the good features of the first type of tube. This type of tube is generally a relatively high voltage tube which is entirely devoid of grids. The apertures through which the electrons pass must be small enough so that reasonably good electron coupling to the field in the cavity exists throughout the beam. Since the tube is without grids, the positive ions are fairly completely drained out of the beam, and so the beam would rapidly expand as a result of its own space charge were it not prevented from doing so by the use of a strong magnetic field along the axis of the beam. These tubes usually operate at high voltage and high power, and actually approach the efficiency that theory would predict.

A third type of tube is useful only as reflex tubes, and consists of a beam focused through a gridless aperture in a resonator after which it expands rapidly in diameter because there is no magnetic field, but is refocused through the hole of the resonator by a concave negative reflecting electrode.

A fourth type less well known than the aforementioned types is the so-called monotron which is one of the simplest of microwave oscillators. Basically, the monotron consists of a single microwave cavity with an electron beam passing through at an appropriate place. The conditions are adjusted so that a portion of the kinetic energy of the

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electron beam is transferred to the fields of the cavity to sustain oscillation. It is, in general, similar to the klystron oscillator except the buncher and catcher functions are performed by the single cavity.

The principle of operation of the monotron was first suggested shortly after the invention of the klystron in 1939. However, so far as is known, heretofore a practical and dependable monotron with a reasonable efficiency was never developed and hence the monotron, while theoretically possessing substantial advantages over the klystron, never came into general use. In attempting to perfect a practical monotron considerable attention in the past has been paid to achieving an R.F. field distribution in the cavity that would result in efficient operation. Nevertheless, only weak oscillations were observed at the proper beam velocity. Difficulties caused operation which was not in agreement with theory and no significant power was generated. Other and later attempts aimed at correcting faults in beam focusing, oscillation build-up time, and starting current, including an extensive theoretical analysis, were made and an S-band monotron constructed. These attempts were also unsuccessful in that only feeble oscillations or no oscillations at all were observed.

Briefly, one embodiment of the present invention comprises a monotron oscillator which is driven as a self-excited oscillator by an electron beam. Located inside the monotron cavity and insulated therefrom so that a signal or potential may be applied to it is an electrode. A device constructed in accordance with the present invention operates as a conventional monotron oscillator with the negative conductance of the beam cancelling the positive conductance of the beam and load. This produces R.F. oscillations at the cavity resonant frequency when the velocity of the beam traversing the cavity is properly adjusted. Power is coupled from the cavity by suitable means such as, for example, an inductive loop and thereafter transmitted to a useful load by a suitable transmission line such as, for example, a waveguide, coaxial line or the like.

A unique feature of the present invention is the inclusion of an electrode such as, for example, a ring in the center of the monotron cavity concentric with the beam. Another unique feature is the addition of graphite to at least the cavity faces opposite the ring. These features function to minimize the effect of multipactor in the monotron cavity, change the R.F. field seen by the beam in such a manner that improved performance may be achieved, and to permit amplitude modulation and/or frequency modulation of the oscillator with little modulating power by a varying potential or variation of a D.C. potential applied to the ring. These effects have all been observed in experimental models that have been constructed. Further, variation in the D.C. ring potential changes the amount of time spent by the beam in the various portions of the cavity R.F. field. Also, the ring changes the shape of the R.F. cavity field in the beam region. The change in the field shape by the ring increases the efficiency of the device and also increases the obtainable normalized beam conductance. This latter effect simplifies practical design since it permits the use of a lower perveance gun and/or a higher degree of cavity loading. Changes in the ring voltage vary the efficiency and the R.F. voltage of the monotron thereby permitting amplitude modulation. A focusing magnetic field, for example, may be used to prevent appreciable current flow to the ring, hence little power is required. Such a device is fundamentally different from the floating drift tube type of klystron oscillator since in that device the beam drifts in a field free region, whereas in the present invention the beam is continuously under the influence of the R.F. field as it moves across the monotron cavity.

Two well-known kinds of self-excited klystron power oscillators are the "two-cavity" and the "floating drift tube" types. Another embodiment of the invention which may also be classified as a self-excited klystron power oscillator comprises an oscillator as described hereinbefore with the addition of an electron beam drift space followed by a conventional klystron amplifier cavity. Such a device is fundamentally different from the two-cavity and floating drift tube types of oscillators because the load is not coupled to the oscillator circuit. This results in an operating frequency independent of the applied load. Since there is no feedback from the load circuitry to other parts of the oscillators, greater efficiency is obtainable than that of the two types of oscillators referred to immediately hereinabove.

Although the device operates at a very low power level, it produces beam velocity modulation which is converted into current velocity in the drift space which in turn drives the amplifier cavity and its associated load. The feedback mechanism required to sustain oscillation is associated entirely within fields in the monotron or oscillator cavity. The operating frequency, which is extremely stable as compared with that of other oscillators, is governed primarily by the resonant frequency of the monotron cavity. There are two major reasons why the operating frequency is extremely stable. In the first place, the unloaded Q's of the cavities embodied in a monotron range from about 3,500 up to 6,000, which is higher than can be achieved in any other microwave oscillator. Thus, the operating frequency is less influenced by changes in beam current than in other microwave beam oscillators. Secondly, the operating frequency is independent of load as has been already pointed out.

A self-excited power oscillator built in accordance with this invention has many other advantages. For example, noise has been observed to be at least the same as that of the best low-noise two cavity klystron oscillators; the operating frequency may be varied about 0.3 percent electronically, which unique feature can be used to degenerate noise even further; size and weight are considerably less than the same parameters of a two-cavity klystron chain; and a reduction in power supply, size and weight as well as in R.F. plumbing may be effected. Further, only two cavities are required instead of the three or four used in prior art amplifiers to achieve comparable results. Still further, since efficient operation occurs with a very short drift space, a shorter over-all beam with a correspondingly smaller magnet and smaller tube volume is realized.

Thus, it may now be readily apparent that the high efficiency, good frequency stability, low noise and reduced weight and volume of the invention are results never before achieved and that the achievement of these results is much more than would be expected by one skilled in the art.

Another embodiment of the present invention contemplates the reduction of noise, for example, by employing a feedback circuit between the amplifier cavity and the oscillator cavity of the self-excited power amplifier. In this arrangement a sample of the R.F. output power is fed into an R.F. discriminator and the output of the discriminator is fed through an amplifier. The amplifier output is connected to the ring electrode with the polarity adjusted to reduce the change in operating frequency. It may be expected that noise degeneration of this type will reduce noise by a factor of about 10.

These and other objects and features of the invention, together with their incident advantages, will be more readily understood and appreciated from the following detailed description of the embodiments thereof selected for purposes of illustration and shown in the accompanying drawings in which:

FIG. 1 is a pictorial cross sectional view of a novel tube embodying the present invention;

FIGS. 2 and 4 are similar views of modified structures; and

FIG. 3 is a graphic illustration of the AM and FM noise characteristics of an uncompensated X-band, C.W.-type tube having a power output of 200 watts as compared to the AM and FM noise characteristics of a low-noise X-band C.W. klystron type oscillator having a power output of 20 watts which theory indicates may be expected for a tube constructed in accordance with the present invention.

Referring now to FIG. 1, the reference numeral 11 designates a focusing type cathode surface, 12 is a heater for heating the surface 11, 13 is the heater sleeve which is mounted on a base 14 and provided with electrical connections 15 for connecting the heater 12 to a power source 16. A focusing electrode 17 is shown electrically connected to cathode 11.

The apparatus so far described constitutes a cathode gun structure of known design. The character of the gun employed to produce the electron beam is an important factor insofar as achieving low noise is concerned. It must be designed in any suitable way such that it produces the proper electron trajectories for electrostatic beam focusing. A reliable design will result if a gun that has already proved successful in a low noise klystron oscillator is employed, since there are many factors in the gun geometry and the character of the cathode emitter that influence noise, and these factors are not well understood. The balance of the monotron oscillator structure comprises a single cavity resonator 21 of the pill-box provided with passages 22, 23 in opposite walls 24, 25 in axial alignment with the path of the electron beam 26 derived at the cathode 11 and focused by electrode 17. A collector 27 of conventional construction is provided at the side of the cavity resonator remote from the electron gun and in axial alignment with the electron beam 26. Disposed within the resonator 21 at about the center thereof and concentric with the electron beam 26 is a generally ring-shaped electrode 28. The electrode 28 may be supported as by a rod 29 which is insulated from the resonator 28 to allow a signal or potential such as, for example, a D.C. potential to be applied to it. The inside diameter of the ring 28 should be at least as large as the diameter of the passages 22, 23. The electrode 28 has a dimension parallel to the electron beam 26 that small with respect to the same inside dimension of the resonator 21. The dimension of the ring 28 transverse to the beam is considerably greater than the dimension of the ring parallel to the beam. There is also provided a layer 31, 32 of material having a low secondary emission characteristic such as, for example, graphite or the like on the resonator wall faces 33, 34 opposite the electrode 28, i.e., the walls 24, 25 transversely disposed to the longitudinal axis of the electron beam 26. The entire inner surface of the resonator 21 may be coated with graphite, for example, but coating of the wall faces 33, 34 concentric with and at the passages 22, 23 for at least a distance about equal to the diameter of the ring 28 has been found satisfactory. An R.F. choke 35 is included in the ring support external to the resonator to prevent disruption of the Q of the resonator by the presence of the ring support circuit. The output signal is coupled out of the resonator 21 through a window 36 in coupling flange 37. It is to be understood that suitable means other than that shown and described may be used to support the ring or to couple the output signal to a waveguide, coaxial line and the like and thence to a load.

The unique features of the embodiment shown in FIG. 1 are the inclusion of an electrode such as, for example, a ring formed of molybdenum in the center of the resonator concentric with the electron beam and/or the addition of graphite to the resonator faces opposite the electrode. These features minimize the effect of multipactor in the resonator, change the R.F. field as seen

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by the beam in such a manner that improved performance may be achieved, and permit amplitude modulation of the oscillator with little modulating power by variation of the D.C. potential applied to the electrode. Multipactor, as used herein, describes a particular phenomenon that degrades the operation of klystron-type tubes. This disturbance results in a loading of the cavity or resonator by electrons which in general, are not in the electron beam although the initial build-up of the phenomenon may be aided by the presence of beam electrons. The multipactoring electrons emanate from the cavity walls by secondary emission as well as from gas molecules that exist in the cavity. Multipactor has a wide range of severity. The electrons producing the cavity loading may be just those resulting from secondary emission and a much greater degree of cavity loading may occur if these secondary electrons produce an R.F. gaseous discharge across the cavity. In general, the less violent form of multipactor involving just secondary electrons may occur under the two following conditions which are required for multipactor in a resonator. For purposes of explanation, assume an electron leaves one wall of a cavity and strikes the opposite wall. If more than one secondary electron is produced, and if their phase (relative to the A.C. gap voltage) and their initial velocities are the same as those of the initial electron when it left the first wall, multipactor will occur. It has been found that the conditions under which this occurs is a function of the secondary emission ratio of the cavity walls, the R.F. electric field, the R.F. frequency in the cavity, and the cavity dimensions. The exact method by which multipactor is minimized is not completely known. However, the secondary emission condition is disrupted by a graphite coating, for example, as described hereinabove and application of a potential to the electrode changes the multipactoring electron transit time conditions and thereby upsets the transit time requirements for the occurrence of multipactor.

Variation of a D.C. potential on the electrode 28 changes the amount of time spent by the electron beam in the various portions of the resonator R.F. field. Also, the electrode 28 changes the shape of the R.F. resonator field in the beam region. The change in the field shape by the electrode 28 increases the efficiency of the device and also increases the obtainable normalized beam conductance. As pointed out hereinabove this latter effect simplifies practical design since it permits the use of a low perveance gun and/or a higher degree of resonator loading. Changes in voltage on the electrode 28 vary the efficiency of the device thereby permitting amplitude modulation and the use of a focusing magnetic field (not shown) will prevent appreciable current flow to the electrode, hence little power is required.

The device shown in FIG. 2 is a self-excited oscillator-amplifier combined in one tube. It comprises the oscillator shown and described in connection with FIG. 1 with the addition of an electron beam drift tube 41 followed by an amplifier cavity resonator 42 interposed in sealing relationship between the single oscillator cavity 21 and the collector 27 all of which, of course, are evacuated. In this embodiment shown by way of example, the electron gun, electrode, oscillator cavity resonator, and collector may be the same as illustrated in FIG. 1 and bear the same reference numbers. The graphite coatings shown in FIG. 1 have been omitted. The output signal is taken from the amplifier cavity resonator through, for example, a window 43 in a coupling flange 44 and may be supplied in conventional manner to a suitable load (not shown) such as an antenna in a C.W. radar.

The device of FIG. 2 operates in the following manner. The electron beam 26 enters the oscillator cavity resonator 21 from the left and passes therethrough in a region where the R.F. electric field is intense and parallel to the direction of electron flow. The velocity of the beam is

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adjusted so that it appears as a negative resistance across the resonator terminals. Upon proper adjustment of the oscillator cavity resonator conductance oscillations occur and these oscillations cause the beam leaving the oscillator cavity resonator 21 to have a velocity modulation. This velocity modulation is converted into current modulation in the drift tube or space 41. The beam current modulation in turn drives the amplifier resonator 42 in conventional manner. The electrode 28 in the oscillator cavity resonator 21 provides among other things a means for controlling multipactor in the oscillator cavity resonator 21. Also, when a D.C. potential is applied to the electrode 28 the operating characteristic of the oscillator will change significantly as will the current and velocity modulation emanating from the oscillator cavity resonator 28.

The operating frequency of the device is governed primarily by the resonator frequency of the oscillator cavity resonator and the feedback mechanisms required to sustain oscillation is associated entirely with the fields in the oscillator cavity resonator 21. Further, the operating frequency is extremely stable as compared with that of other prior art oscillators because the load is not coupled to the single cavity oscillator circuit. This in itself provides greater efficiency than prior art oscillators which require three or four cavity resonators instead of two as required by the present invention. Further, the reduction in the number of cavity resonators required results in a shorter over-all electron beam with a correspondingly smaller magnet and tube volume. Obviously, this results in a lighter weight tube that is smaller in addition to its high efficiency and low noise characteristics. By way of example the general and operating characteristics of an experimental model is given below.

Frequency	2800 mc.
Beam voltage	15 kv. (nominal).
Beam perveance	0.8 micro pervs.
Normalized beam radius	0.79 radian.
Normalized funnel radius	0.632 radian.
Beam focusing field	Twice Brillouin.
Beam voltage	15.6 kv.
Beam current	1.290 amp.
Ring voltage	-7.8 kv.
Power output	6,415 watts.
Total Efficiency	31.9%.
Amplifier gap conversion efficiency	38.55%.
Frequency	2780 mc.
Oscillator power	68 watts.
Oscillator conversion efficiency	0.34%.

It has been indicated theoretically that under optimum conditions a total conversion efficiency, defined as the ratio of the total power delivered to the amplifier cavity resonator and the total beam power, of 65 percent is possible.

A comparison of the noise characteristics of an X-band C.W.-type tube having a power output of 200 watts and a 20 watt X-band C.W. low noise klystron type oscillator representative of that which may be expected for a tube in accordance with the present invention may be seen by reference to FIG. 3. It may be seen that both tubes have approximately the same noise characteristics. Also, as was pointed out with respect to the oscillator shown in FIG. 1 the operating frequency of the device is influenced by the potential or signal applied to the electrode 28. In an experimental model a frequency sensitivity of at least 0.3 kc. per volt was measured with a power dissipation in the electrode of only 0.5 percent of the beam power.

A primary consideration in the design of a tube constructed in accordance with the present invention is that random amplitude and frequency modulations of the output signal (AM and FM noise) shall not exceed a limit that would impair proper operation of, for example, a C.W. radar system in which the device of FIG. 2 may

serve as the transmitter tube. The type of noise as related to tube construction that is of interest in a tube for this type of application will now be described.

The FM noise which is of importance here is defined as random deviations of the oscillator from its true frequency of oscillation at modulation rates that may range from several kilocycles to about 100 kilocycles. The FM noise is described by the RMS value of this deviation integrated over the video range of interest as well as by the R.M.S. deviation in a narrow band located in the video range of interest. This latter type of noise is referred to as coherent FM noise.

Of interest are both the integrated value of the AM noise power in the video range and the coherent AM noise as may be determined by measuring the R.F. power in the side bands of the carrier in the range from several kilocycles to 100 kilocycles away from the unperturbed carrier frequency. In a radar system, for example, the range of video frequencies of interest is determined by the expected Doppler shifts produced by the targets to be observed by the radar system.

The noise considerations here assume that no noise degeneration described hereinafter in connection with FIG. 4 is applied to the tube. A factor which will effect the noise properties of the tube is the power supply. This factor may be neglected if the ripple on the voltages applied to the tube are kept in conventional manner below a level suitable to prevent introduction of noise. There are numerous other factors which influence the noise characteristics. Some of the major ones are the electron gun, the beam and its focusing scheme, the gas pressure in the tube, the amount of dirt and loose particles in the tube, and the degree to which mechanical resonance can be eliminated.

It has been found that a klystron oscillator with an electrostatically focused beam is considerably quieter than one using a magnetically focused beam. The reasons for this are not completely understood. However, since the presence of a magnetic field may tend to promote multipactor, which could certainly generate noise, it may be preferred to use electrostatic focusing. In this case, part of the focusing may be accomplished by the electrostatic lens action of the electrode 28 in the oscillator cavity resonator 21. It is to be understood, however, that the invention is not limited to electrostatic focusing and other suitable means may be used.

In general, a low beam perveance is to be preferred because it favors low-noise operation. A low perveance provides better electrostatic beam focusing with a reduction in interception noise. Also, it reduces the absolute value of the beam susceptance appearing across the oscillator cavity resonator 21. Random variations in beam voltage will cause changes in this susceptance with constant frequency modulation of the output signal. As has been pointed out hereinabove, a reliable design will result if an electron gun that has already proved successful in a low-noise klystron oscillator is employed.

One major source of coherent noise is the existence of microphonics which may be produced by small mechanical perturbations of the cavity walls, as well as by mechanical perturbations of the gun electrodes. These perturbations may be produced, for example, by external forces applied to the tube or by forces produced by the flow of a coolant through the tube. Since microphonics are most pronounced when a tube component, which influences the power output or operating frequency, has a mechanical resonance in the video band of interest, it is desirable that such components have a mechanical resonance outside the video band of interest.

Since the element most sensitive to microphonics is the oscillator cavity resonator, the use of a pill-box shaped cavity is preferred since this type is much less frequency-sensitive to dimensional changes than the usual re-entrant type of klystron cavity. The cavity should be of rugged construction to minimize any perturbation. Also, since

the electrode in this cavity may also produce microphonics it must, of course, be so mounted as to minimize any vibration thereof.

Another feature which can change the resonant frequency of the oscillator cavity resonator 21 is a radial movement of the beam. This problem is unique with a single cavity or monotron oscillator, since the longer gap causes the beam to occupy a greater portion of the cavity volume than in conventional klystron oscillators, hence, radial movement of the beam causes a greater change in the cavity dielectric constant. If this problem exists, it may be overcome by employing an extremely rugged electron gun construction wherein, for example, the gun elements are supported by cones, which, in turn, may be soldered into ceramic elements that will provide both mechanical support and electrical insulation.

Since the amplifier cavity resonator 42 is not a primary element in determining the frequency of the device mechanical perturbation of its walls will only introduce microphonics through phase modulation of the generated signal, which will be much less severe than a corresponding deviation in the oscillator cavity resonator. The amplifier cavity resonator 42 as shown in the drawings may be re-entrant to minimize its R.F. power losses and a conventional tuner (not shown) may be provided in the amplifier cavity resonator 42 for alignment of it with the operating frequency. The tuner may, for example, produce motion through the vacuum envelope by means of a rugged diaphragm and the tuner shaft locked in position once the resonator frequency has been set.

With reference now to FIG. 4 which shows another embodiment of the invention for noise degeneration, the device comprises the oscillator-amplifier shown and described in connection with FIG. 2 with the addition of a feedback circuit 51 between the amplifier cavity resonator 42 and the oscillator cavity resonator 21. In this embodiment shown by way of example, the components of the tube may be the same as is illustrated in FIG. 2 and bear the same reference numbers. In the feedback circuit 51 as shown, a sample of the R.F. output power is coupled by way of a directional coupler 52 into an R.F. discriminator 53 and the output of the discriminator 53 is coupled to an amplifier 54. The output signal of the amplifier 54 which is proportional to change in the operating frequency is connected to the electrode 28 with the polarity adjusted to reduce the change in operating frequency. It may be expected that a noise degeneration feedback circuit will reduce the frequency modulation noise of the sort shown in FIG. 3 by a factor of about 10.

While the present invention has been described in its preferred embodiment, it is realized that modifications may be made, and it is desired that it be understood that no limitations on the invention are intended other than may be imposed by the scope of the appended claims.

What is claimed is:

1. An electron discharge device comprising: a cavity resonator; an electron gun for projecting a beam of electrons through said cavity; a ring electrode disposed at about the center of said resonator and concentric with said beam, said electrode having a dimension transverse to said beam that is large with respect to its dimension in the direction of said beam; means for supporting and insulating said electrode from said resonator; means for applying a signal to said electrode; and means having a low secondary emission characteristic on said resonator faces opposite said electrode.

2. In an electron discharge device the combination comprising: metal walls defining a single cavity resonator; means mounted adjacent said resonator for projecting a beam of electrons through said resonator; a generally ring-shaped electrode disposed at about the center of and insulated from said cavity and concentric with said beam, said electrode having a dimension transverse to said beam that is considerably greater than its dimension in the direction of said beam, the portion of said beam in said

resonator being exposed to the fields in said resonator throughout substantially all of its length; and means for applying an electric potential to said electrode.

3. In an electron discharge device the combination comprising: metal walls defining a single cavity resonator; means mounted adjacent said resonator for projecting a beam of electrons through said resonator; a generally ring-shaped electrode disposed at about the center of and insulated from said cavity and concentric with said beam, said electrode having a dimension transverse to said beam that is considerably greater than its dimension in the direction of said beam, the portion of said beam in said resonator being exposed to the fields in said resonator throughout substantially all of its length; means for applying an electric potential to said electrode; and means having low secondary emission characteristics on said resonator wall faces opposite said electrode.

4. An electron modulating device comprising: a single oscillator cavity resonator and an amplifier cavity resonator having axially aligned passages; a metal tube in communication with a passage in each cavity for the projection therethrough of an electron beam, said amplifier cavity resonator thereby being driven to produce energy; a generally ring-shaped electrode disposed at about the center of and insulated from said oscillator resonator and concentric with said beam, said electrode having a dimension parallel to said beam that is small with respect to the same dimension of said oscillator resonator and a dimension transverse to said beam that is considerably greater than its dimension parallel to said beam; and means for applying a signal to said electrode.

5. The combination as defined in claim 4 wherein said

last-mentioned means comprises a feedback circuit connected between said amplifier resonator and said oscillator resonator.

6. The combination defined in claim 4 wherein said last-mentioned means includes discriminator means; means to supply a sample of the energy in said amplifier resonator to said discriminator means; and means to apply the output signal of said discriminator to said electrode with a polarity selected to reduce any change in frequency.

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