Aug. 29, 1967 C. E. WARD ET AL 3,339,149

REFLECTOR AUGMENTED MONOTRON OSCILLATOR
FOR MICROWAVE GENERATION
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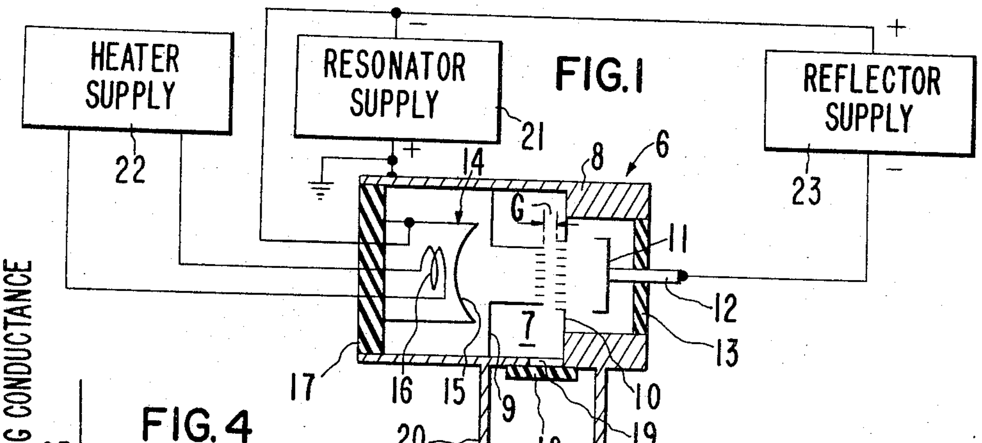

FIG.1

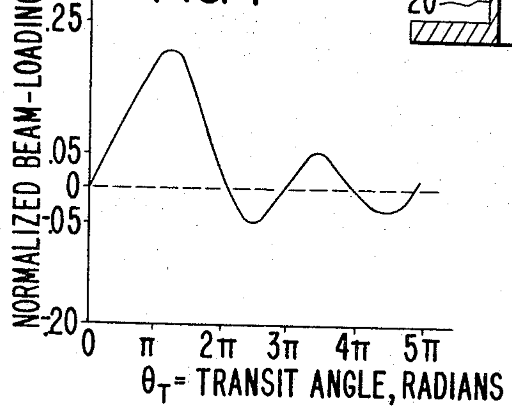

FIG. 4

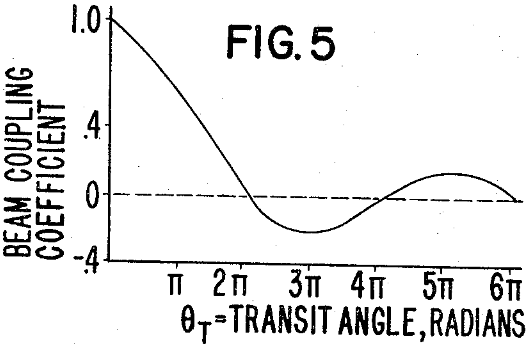

FIG. 5

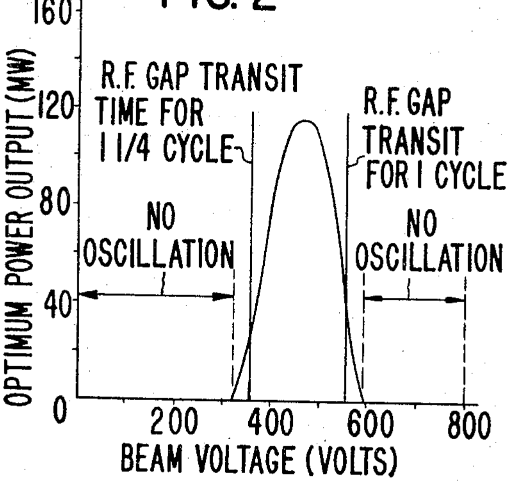

FIG. 2

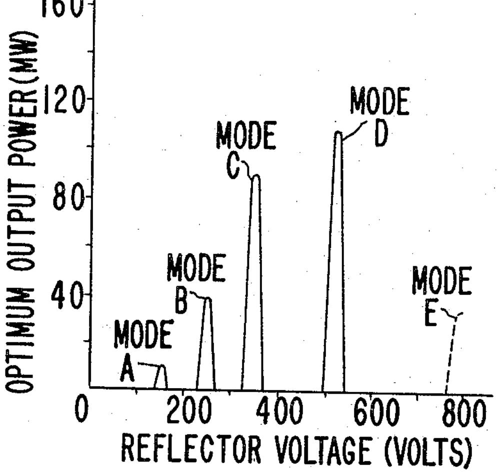

FIG. 3

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REFLECTOR AUGMENTED MONOTRON OSCILLATOR FOR MICROWAVE GENERATION

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ABSTRACT OF THE DISCLOSURE

The start oscillation current for a monotron oscillator is reduced considerably by the introduction of reflex klystron bunching in conjunction therewith to produce a reflex augmented monotron oscillator. The oscillator will preferably have a gap size transit angle expressed in radians centered about $2\pi(n+\frac{1}{4})$ where $n=1, 2, 3, 4$, etc. with the reflector means producing electron bunching in a manner to coherently aid the monotron energy exchange.

This invention relates in general to high frequently electron discharge devices operable in the microwave spectrum and more particularly to a novel high frequency electron discharge device which can be characterized as a reflector augmented monotron oscillator (R.A.M.O.).

Some of the more pertinent design constraints imposed on manufacturers of microwave oscillators operable in the millimeter wave region such as for example the klystron are first and foremost, cost considerations which involve fabrication problems, ease of manufacture, etc., and for any oscillator, of course, stability is always a problem which must be considered by the tube designer. Stability of a klystron type of microwave oscillator is generally very critically dependent upon environment and operational temperature changes as well as environmental conditions wherein vibration presents a problem. Both temperature changes and vibration conditions introduce pronounced changes with regard to stability by virtue of the generally small gap size and thus critical nature of the gap spacing in conventional klystron oscillators. As the frequency spectrum within which commercial microwave oscillators, such as e.g. the klystron, is extended into the X-, K-, Q- and V-bands which cover such frequencies as 5 to 50 gcs. fabrication problems due to the extremely small dimensional parameters involved in the cavity, interaction gaps and grids become rather pronounced.

The present invention, through the utilization of a novel concept involving what can be characterized as a reflector augumented monotron oscillator, (R.A.M.O.) provides the tube designer with the advantage of being able to construct, by way of example, X-band oscillators utilizing typical C-band dimensional parameters. If the tube designer can construct an X-band tube utilizing, by way of example, C-band dimensional parameters, the fabrication costs are considerably reduced since as the tube dimensions such as cavity, gap, grid, mesh size, etc., are decreased, the cost of manufacture increases in what might be termed a proportional relationship. Therefore, as microwave oscillators are extended up into the K-, Q- and V-bands, the manufacturing problems inherent in the extremely small dimensions required for the cavity and grid parameters result in a considerable increase in cost, if conventional klystron oscillator techniques are utilized.

With the above considerations in mind with regard to millimeter wave design limitations the present invention evolved. Theoretical considerations had previously shown the possibility of constructing what can be termed a monotron oscillator which involved the utilization of a single critical gap size in conjunction with a resonant

cavity and electron beam to produce coherent oscillations in a single transit of the beam through the cavity. The critical gap size can be shown to have a transit angle θ_T expressed in radians which falls within the following limits: $2\pi\rightarrow3\pi$, $4\pi\rightarrow5\pi$, $6\pi\rightarrow7\pi$ etc. and which is preferably $2\pi(n+\frac{1}{4})$ where $n=1, 2, 3, 4$, etc. With the aforementioned interaction gap size both electron bunching and extraction will occur within a single transit of the beam through the cavity.

The monotron oscillator has advantages over the conventional two-cavity klystron oscillator, floating drift tube oscillator, and reflex oscillator in that separate bunching and feedback means are not required. However, the conventional monotron oscillator requires a very high start oscillation beam current density which results in very low efficiencies and high cathode loading.

The present invention provides an improvement in both of the aforementioned parameters by introducing a reflector electrode in a monotron oscillator with the resultant beneficial advantages of increased operating efficiency and reduction in start oscillation current and thus reduced cathode loading in comparison to a conventional monotron oscillator. The addition of the reflector electrode results in what can be termed a reflector augmented monotron oscillator. The reflector electrode which when suitably biased to provide a high negative potential relative to a resonator voltage or beam voltage results in a reflex bunching mechanism occurring which when added to the initial monotron bunching results in enhanced monotron efficiency with accompay reduced start oscillation beam current density requirements. The time spent in the reflector region of the R.A.M.O. must fall within the limits for optimum phase correlation between the reflex bunching mechanism and the interaction gap R.F. field in order to optimize the power output for any given reflector mode. This is only another way of saying that the center of each bunch of electrons formed in the reflector region should re-enter the interaction gap when the R.F. voltage is at its proper phase for optimum interaction or transfer of beam energy to the R.F. field in the cavity.

In essence then the present invention involves the provision of a microwave oscillator having a gap transit angle θ_T expressed in radians for optimum power transfer which is centered about $2\pi(n+\frac{1}{4})$ radians whene $n=1, 2, 3, 4, 5$, etc., and which has an appropriate reflector mode phase angle θ_n expressed in radians for optimum transfer of energy from the returning electron bunches so as to coherently aid the monotron energy exchange. This inter-relationship permits operation of a monotron oscillator at a beam current density which is below the start oscillation beam current level for a conventional monotron oscillator which results in increased efficiency.

Therefore, the present invention, besides introducing a novel concept which as mentioned previously involved a reflector augmented monotron oscillator, also enables the tube designer to construct millimeter wave microwave oscillators utilizing resonant cavity, gap, and mesh sizes of greater physical dimensions at higher frequencies than is possible with conventional klystron oscillators. Inherent in the increased cavity dimensions and increased gap dimensions is the increase in frequency stability under vibration and temperature variations encountered in certain environmental usages. Expressed another way, since the optimum beam coupling coefficient will occur for a gap to mesh size ratio which is equal to a constant then the R.A.M.O. can operate at larger mesh sizes since the gap size is increased. Therefore, the possibility of constructing millimeter wave oscillators with very coarse grids, or no grids at all, or vane grids which are much easier and simpler to manufacture than the conventional mesh grids, is inherent in the teachings of the present invention. Furthermore, since the resonant frequency of a re-entrant resonant cavity is critically dependent upon the changes in gap spacing in operation and since the gap spacing is greatly increased in the R.A.M.O. of the present invention, perhaps by a factor of 5 in comparison to a conventional reflex klystron oscillator, it is obvious that the sensitivity of the R.A.M.O. of the present invention to temperature and vibration variations and conditions is greatly decreased on a percentage basis in comparison to a reflex klystron.

It is therefore an object of the present invention to provide a novel reflector augmented monotron oscillator operable in the microwave spectrum.

A feature of the present invention is the provision of a microwave oscillator which is characterized by having a gap transit angle θ_T expressed in radians and falling within the following ranges: $2\pi \rightarrow 3\pi$, $4\pi \rightarrow 5\pi$ and which is preferably centered about $2\pi(n+\frac{1}{4})$ where $n=1$ and 2 with said oscillator being provided with a reflector electrode and having a reflector mode phase angle θ_n adjusted to deliver energy to the cavity so as to aid the monotron phenomena.

Other features and advantages of the present invention will become more apparent upon a perusal of the following specification taken in conjunction with the accompanying drawings wherein,

FIG. 1 is a schematic view of a reflector augmented monotron oscillator incorporating the teachings of the present invention,

FIG. 2 is an illustrative graphical portrayal depicting optimum power output versus beam voltage for reflector mode D operation of a reflector augmented monotron oscillator such as depicted in the embodiment of FIG. 1,

FIG. 3 is an illustrative graphical portrayal depicting optimum output power versus reflector voltage for a reflector augmented monotron oscillator such as embodied in FIG. 1,

FIG. 4 is an illustrative theoretical graphical portrayal of Normalized-Beam Loading Conductive versus θ_T used for explanatory purposes.

FIG. 5 is an illustrative theoretical graphical portrayal of Beam Coupling Coefficient versus θ_T used for explanatory purposes.

Referring now to the drawings, there is shown in FIG. 1 a microwave oscillator **6** which is characterized as a R.A.M.O. or a reflector augmented monotron oscillator.

The R.A.M.O. **6** includes a resonant cavity **7** having a re-entrant gap denoted by G formed by conventional manufacturing techniques such as the utilization of metal body block **8** having a resonant cavity integrally formed therein or by utilization of spaced header members **9**, **10**, etc. A reflector electrode **11** is supported by a conductive rod **12** extending through a suitable insulation disc **13** so as to remain in D.C. voltage isolation with respect to the body **8**. An electron beam can be generated from a conventional electron gun **14** such as the Pierce type of which the literature is replete and which will include a conventional cathode schematically represented by **15** disposed at the up stream end portion of the oscillator. Therminonic emission can be provided by means of a heater schematically represented by **16** in a conventional manner which is supported on a suitable insulation disc **17** which completes the vacuum envelope of the device.

Any conventional electrostatic focusing techniques of which the literature is replete can be utilized for proper beam generation and focusing and will not be gone into in detail herein since they do not form part of the present invention. R.F. energy is extracted through a conventional dielectric window **18** forming a vacuum seal across R.F. coupling aperture **19**, in a manner well known in the art. A suitable flanged waveguide **20** can be utilized for purposes of coupling the R.A.M.O. to other system components. A resonator voltage supply **21** is utilized to provide a suitable fixed or variable beam voltage such as for example around 1000 volts D.C. A suitable heater voltage supply **22** is utilized to supply the heater **16** voltage requirements. A suitable reflector voltage supply of any conventional type **23** is utilized to provide reflector voltage. For example, supplies capable of variations between 0 and 1000 volts would be typical. The main body block **8** is generally operated at ground as shown for purposes of safety.

The prior art is replete with various means for tuning klystron oscillators which means involve variations in axial gap spacing or capacitive tuning, variations in cavity volume or inductive tuning and external cavity tuning means and the present invention can advantageously incorporate such techniques if desired. For examples of such tuning techniques, see for example, U.S. Patent No. 2,789,248 by J. A. Brown, issued Apr. 16, 1957; U.S. Patent No. 2,789,250 by S. F. Varian et al., issued Apr. 16, 1957; U.S. Patent No. 2,798,184, by B. C. Gardner et al., issued July 2, 1957, all of which are assigned to the same assignee as the present invention. The aforementioned list of patents also discloses typical constructional details which may advantageously be employed in the fabrication of the R.A.M.O. of the present invention.

In order to better understand the nature of the R.A.M.O. as taught by the present invention, reference to the illustrative graphical portrayals of FIGS. 2–5 will now be made.

In FIG. 2 a graphical portrayal depicting optimum power output in milliwatts versus beam or resonator voltage in volts for a R.A.M.O. such as shown in FIG. 1 over an operating beam voltage which ranges from 0 to 800 volts is shown. The R.A.M.O. was designed to operate at X-band and had an operating frequency centered at 9.8 gigacycles and with an R.F. gap axial dimension of .056 inch and oscillations were observed to occur only over a region of approximately 300 to 600 volts with no oscillation at upper voltages within the limits of beam power operation and lower beam voltages. If one observes the accompanying R.F. gap transit times it is self-evident that monotron oscillations occur since a conventional reflex would show oscillations occuring over the entire beam voltage range of one sort or another. The optimum power output versus beam voltage characteristics depicted in FIG. 2 were run for mode D operation as illustrated in the optimum output power versus reflector voltage characteristics of FIG. 3. The reflector modes A, B, C, etc., are similar to conventional reflector modes as found in reflex klystrons and correspond to an optimum phase angle to deliver energy to the cavity. The optimum phase angle is determined for each reflector mode A, B, C, etc. by simple adjustment of the reflector voltage to peak power for each mode in a conventional manner. The gap transit time θ_T for the R.A.M.O. was varied between approximately 1¼ to 1 cycle over the operating beam voltage range as indicated in FIG. 2.

In FIG. 4 an illustrative graphical portrayal of Normalized Beam Loading Conductance versus θ_T for a conventional resonant cavity having an interaction gap and traversed by an initially unmodulated electron beam is shown. Certain theoretical assumptions have to be made to justify a curve such as depicted in FIG. 4 but such assumptions will not be listed herein since the only purpose of FIG. 4 is to illustrate that conventional monotron oscillation is possible for θ_T which fall within $2\pi \rightarrow 3\pi$, $4\pi \rightarrow 5\pi$, $6\pi \rightarrow 7\pi$, etc. or expressed another way the gap transit angle shall be centered about the following discrete set of values expressed in radians

$$\theta_T = 2\pi(n + \tfrac{1}{4})$$

where

$$\theta_T = 2\pi f \frac{g}{U_0} = 2\pi(n + \tfrac{1}{4})$$

where:

$n=1, 2, 3, 4, 5, 6$, etc.,

f=R.F. frequency of gap voltage or operating frequency of tube

g= gap length

U_0=D.C. electron beam velocity, and

$$\frac{g}{T_0}=T$$

or gap transit time.

In other words where the beam loading conductance is negative the beam will be giving up energy to the R.F. fields in the cavity rather than extracting energy from the cavity. Since the monotron oscillator operates on the principle of bunching and extracting energy from the beam in a single transit it must of necessity operate within the aforementioned limits.

Another way of defining the characteristics of the present invention is in terms of the gap transit time T as follows:

The gap shall have a transit time of:

$$T=\frac{\theta_T}{2\pi f}$$

where:

θ_T=gap transit angle

f=operating frequency of tube or expressed another way the R.F. frequency of gap voltage and θ_T falls within the following limits:

$$\theta_T=2\pi\rightarrow 3\pi,\ 4\pi\rightarrow 5\pi,\ 6\pi\rightarrow 7\pi,\ \text{etc.}$$

and is substantially centered about

$$2\pi(n+\tfrac{1}{4})$$

where $n=1, 2, 3, 4, 5, 6$, etc.

In FIG. 5 another theoretical illustrative graphical portrayal is depicted which illustrates Beam Coupling Coefficient versus θ_T, again with certain assumptions being made which are not pertinent here. The Beam Coupling Coefficient or K is an expression of the ratio of R.F. current induced in a resonant cavity to the alternating component of beam current which produces it by traversal of the electron beam through the resonant cavity along the interaction gap. FIG. 5 thus serves to illustrate the principal defect of the monotron oscillator, namely the reduction in K with increased θ_T. With the addition of the reflector electrode and thus the concept of a R.A.M.O. as taught herein this defect is partially alleviated as discussed previously by supplementing the monotron induced R.F. with reflector mode R.F. Therefore, if conventional reflector mode operation is observed the phase angle between the center of the bunch of electrons re-entering the gap from the reflector region of the R.A.M.O. should be related to the R.F. voltage in the gap in a manner such that the energy from the returning electron bunches coherently aids the monotron energy exchange.

When the aforementioned pair of relationships are observed it is possible to operate a R.A.M.O. at beam current densities which are considerably less than the start oscillation beam currents required for a conventional monotron oscillator. Reduction factors of perhaps 10 to 1 may be achieved with the R.A.M.O.

In a conventional reflex klystron such as for example of the type set forth in the aforementioned list of patents, a gap transit time T where

$$T=\frac{\theta_T}{2\pi f}$$

which defines the time in terms of cycles of the operating or design frequency within which an electron traverses the axial gap distance denoted G in the embodiment of FIG. 1 normally varies between ¼ to ⅓ of a cycle of R.F. or 1 or 2 radians. The optimum beam coupling coefficient can be expressed as some constant which can be equated to the gap axial distance G divided by a mesh size of a grid which defines the respective axial boundaries of the gap. It can also be shown that resonator capacitance is proportional to A/D where A is the metallic area of the grid and D is the axial gap distance and it follows that the operating frequency of the resonant frequency of the cavity can be expressed as

$$f=\frac{1}{2\pi\sqrt{LC}}$$

The operating frequency is critically dependent upon the gap capacitance in reflex klystron oscillators of conventional design since g is so small. Now as higher frequencies in the microwave spectrum are encountered by the oscillator designer, for example, such as at X-band, it will be found that typical cavity diameters D of 0.425 inch and gap axial dimensions G of 0.012 inch together with gap diameters varying from .140 to .20 inch are typical with grids having equivalent mesh sizes of .015 inch diameter. In contradistinction an X-band R.A.M.O. constructed according to the teachings of the present invention and operable in the same X-band region would have e.g. typically a cavity diameter D of .600 inch, a gap axial dimension G of .056 inch and an average gap diameter which will probably vary from .200 to .400 inch with an equivalent increase in mesh size of a mesh grid in a gridded gap oscillator.

If one compares the aforementioned set of dimensions it is apparent that the fabrication problems are greatly reduced since the dimensional parameters have been greatly increased. Inherent in the increased gap dimensions for a R.A.M.O. as taught in the present invention is the reduced gap sensitivity with respect to variations in temperature encountered in usage as well as vibrational factors which would tend to vary the axial gap spacing. Since as mentioned previously the resonant frequency of a re-entrant cavity such as 7 is dependent on axial gap dimensional changes it is obvious that as the gap distance G is increased the critical dependence upon temperature variations decreases accordingly on a percentage basis in comparison to smaller gaps such as encountered in a conventional reflex klystron oscillator. Furthermore, since the resonant frequency is inversely proportional to the square root of capacitance times the inductance for a conventional cavity resonator it is obvious that larger cavity dimensions will accordingly be utilized for a given operating frequency. Thus, the R.A.M.O. permits increased cavity, gap, gap diameter and gap grid, mesh sizes, if a gridded gap is utilized, to be employed while simultaneously reducing the sensitivity of the oscillator with respect to changes in gap spacing due to temperature or vibrational environmental conditions.

Since many changes could be made in the above construction and many apparently widely different embodiments of the invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawing shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

A high frequency electron discharge device operable in the microwave spectrum including an electron beam forming and projecting means disposed at the upstream end portion thereof and reflector electrode means disposed at the downstream end portion thereof along the beam axis, said device having a resonant cavity means disposed about the beam axis between the beam forming and projecting means and the reflector electrode means, said resonant cavity means defining a pair of axially spaced apertures through which an electron beam travels in use, said resonant cavity further defining an interaction gap which provides an energy exchange mechanism for R.F. energy in said resonant cavity and an electron beam traveling through said cavity, said device being characterized by having an interaction gap transit angle θ_T expressed in radians which falls within the following limits: $\theta_T = 2\pi \rightarrow 3\pi$ or $4\pi \rightarrow 5\pi$, and which is substantially centered about $2\pi(n+\frac{1}{4})$ where $n=1$ or 2, said reflector electrode means being adapted and arranged to return electron bunches back to said resonant cavity in a manner such as to coherently aid the monotron energy exchange, said device including means for coupling electromagnetic energy from the device to a load at the operating frequency f at which the device oscillates as a monotron oscillator within the above θ_T limits, said operating frequency f being inter-related with said gap transit angle by

$$T = \theta_T / 2\pi f$$

where

$$T = g/U_0$$

where

g=interaction gap length and
U_0=D.C. electron beam velocity.

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