Nov. 30, 1965 I. KAUFMAN ETAL 3,221,207

MICROWAVE POWER GENERATING BY PERIODIC SWEEP OF ELECTRON BEAM ALONG LENGTH OF RESONANT WAVEGUIDE

Filed June 5, 1963 2 Sheets-Sheet 1

Fig. 1(a)

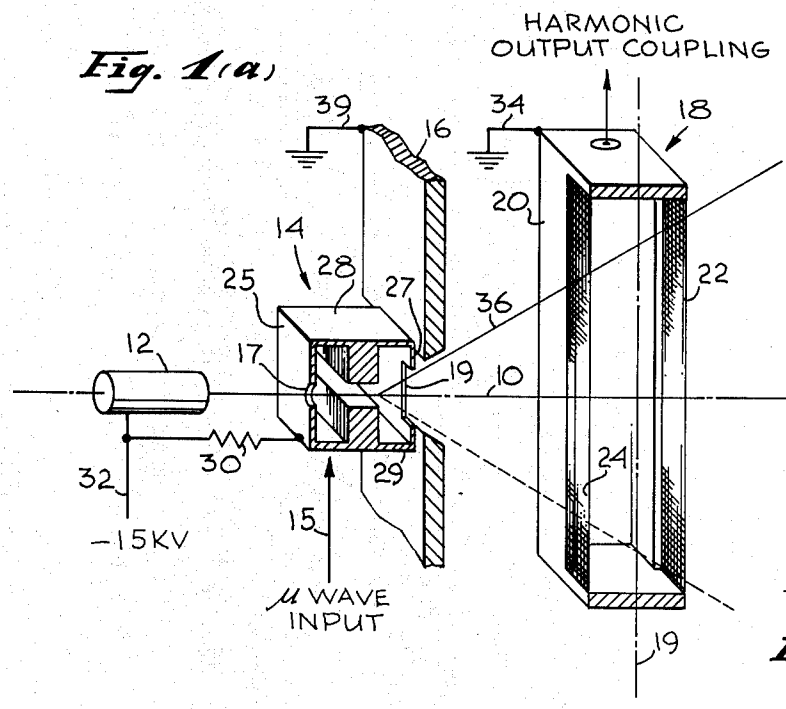


Fig. 1(b)

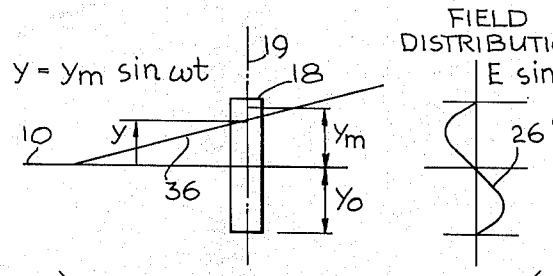


Fig. 3

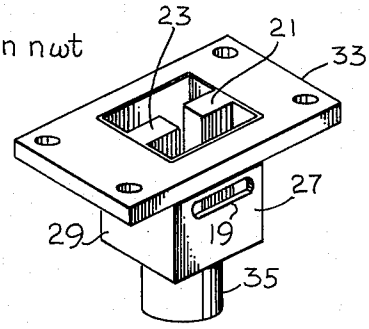


Fig. 2

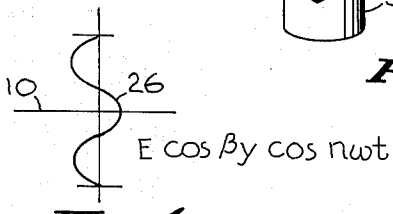


Fig. 4

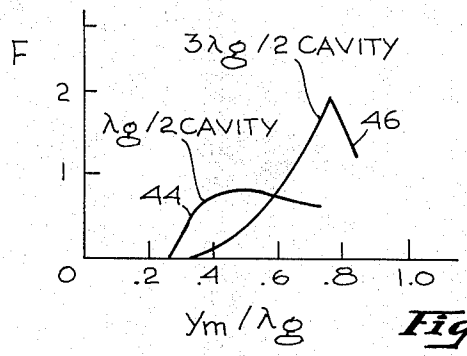


Fig. 5

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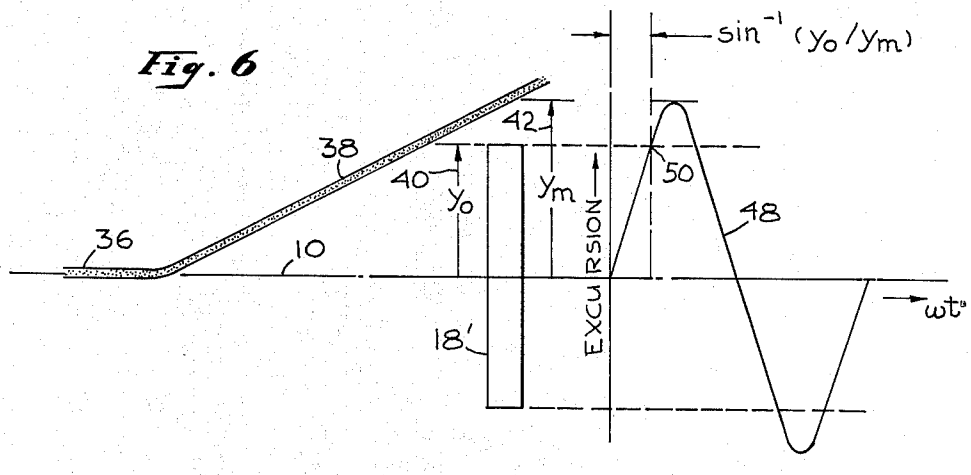
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Filed June 5, 1963 2 Sheets-Sheet 2

Fig. 6



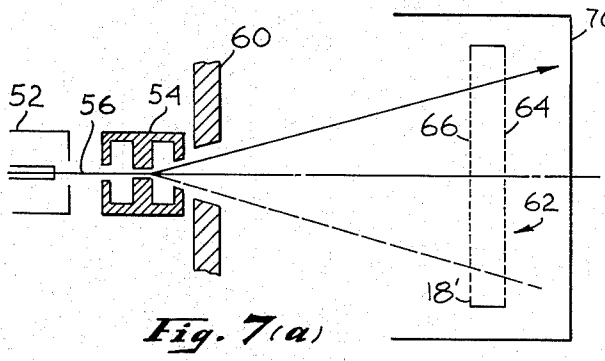


Fig. 7(a)

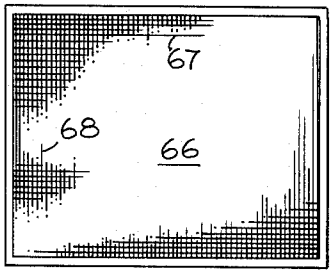


Fig. 7(b)

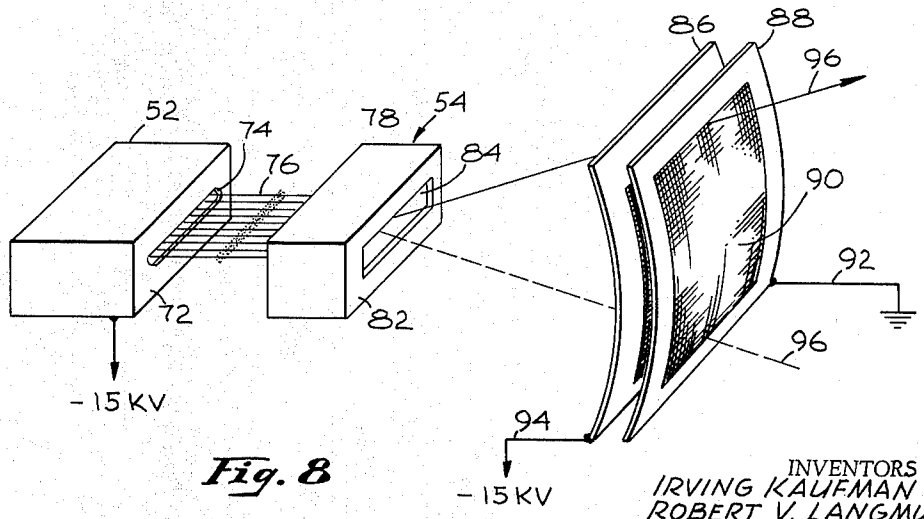


Fig. 8

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3,221,207

MICROWAVE POWER GENERATING BY PERIODIC SWEEP OF ELECTRON BEAM ALONG LENGTH OF RESONANT WAVEGUIDE

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Filed June 5, 1963, Ser. No. 285,781
4 Claims. (Cl. 315—5.25)

The present invention relates generally to the art of generating, amplifying and frequency multiplying microwave signals and is especially useful for converting direct current energy to radio frequency energy in the millimeter and submillimeter wavelength regions.

More particularly, this invention has reference to frequency multipliers, oscillators, and amplifiers employing microwave or ultramicrowave cavity resonators in which the propagation of electromagnetic fields is excited and sustained by the use of controlled electron beams which traverse portions of the cavity resonator. One apparatus of the general class to which the present invention belongs is disclosed in copending patent application Ser. No. 135,640, filed September 1, 1961, by Irving Kaufman, which application is assigned to the same assignee as that of the present invention. In that application, there is disclosed a microwave generating system in which an electron beam is circularly deflected and is directed to pass through a toroidol waveguide resonator which is circularly slotted at its front and back surfaces to permit ingress and egress of the high velocity beam electrons. We have found that such apparatus suffers from the disadvantages that it is difficult to manufacture the components required for perfectly circular deflection of an electron beam at microwave frequencies and it is difficult to maintain the tolerances required for causing the circularly deflected electron beam to efficiently traverse a narrow slot in the toroidal output resonator. Additionally, such apparatus requires very considerable high frequency input power in order to deflect the electron beam both vertically and horizontally to describe a circular Lissajous pattern. Further, such apparatus has the disadvantages that it requires precise control of the input deflection signal voltage amplitude and, as an oscillatory system, it is not self-starting.

Accordingly, it is a general object of the present invention to provide improved apparatus for generating electromagnetic waves in the millimeter and submillimeter wavelength ranges.

It is another object of the present invention to provide an apparatus for generating alternating current power in the frequency range from about 3.0 to about 3000 kilomegacycles in which such power is derived from a direct current energy input rather than solely from high frequency energy sources.

It is a further object of our invention to provide for generation of ultramicrowave power at frequencies above the operative limits of practical prior art generating devices.

It is a different object of our invention to provide for generation of ultramicrowave or submillimeter wavelength signals at power levels substantially exceeding the output capacity of previously available ultramicrowave oscillators and amplifiers.

It is a still further object of our invention to provide improved apparatus for generation of electromagnetic oscillations within a resonating chamber having dimensions of the order of millimeters by means of a controlled cathode ray which is deflected at relatively low frequencies compared to that of the oscillations within the resonating chamber.

It is still another object of our invention to provide apparatus of the type described for frequency multiplication and/or power amplification of ultramicrowave signals.

It is another general object of our invention of our invention to provide improved apparatus for generating electromagnetic waves having wavelengths in the 100–10,000 micron range of the electromagnetic spectrum.

Various devices are known for generating radio frequency power at wavelengths of a few millimeters. Such devices which have utilized linear electron beams are divisible operationally into two general classes: (1) devices employing longitudinal compression or "bunching" of the electron beam, and (2) devices using radio frequency deflection of an electron beam in conjunction with a slotted or apertured target for chopping the beam. In systems of the first above-mentioned type, such as klystrons and traveling wave tubes employing beam density modulation or beam velocity modulation, the electron bunches created must be considerably shorter than the wavelength which is to be generated. It has been extremely difficult to attain that requirement, at millimeter wavelengths and with appreciable electron densities. Generally, extremely low efficiencies result and even if sufficiently short electron bunches are created in such devices, the bunches are quickly stretched by longitudinal space charge forces within the beam. Thus devices of the electron bunching type have not been particularly satisfactory for generation of submillimeter wavelength electromagnetic energy.

Referring to the second class of device mentioned above, it is a relatively simple matter to create electron bunches by the beam chopping technique. However, such systems have the extreme disadvantage that as the frequency is increased, the electron bunch is shortened without being increased in density and therefore contains proportionately fewer electrons. Accordingly, the amount of high frequency power which can be generated becomes prohibitively small as the frequency is increased toward the submillimeter wavelength regions.

One example of a prior art "beam-chopping" system is disclosed in United States Patent No. 2,408,437, issued October 1, 1946, wherein an electron beam is deflected in a sinusoidal manner at a high frequency and periodically enters a single small aperture in the wall of a microwave cavity resonator. That prior art apparatus periodically shoots a pulse or short duration group of electrons through the cavity resonator to shock excite electromagnetic oscillation therewithin. When properly timed, such pulses would be effective to regenerate or sustain microwave oscillations within the cavity. The difficulty with such apparatus is that for proper timing the electron beam can be permitted to enter the cavity aperture only for a very small fraction of each beam deflection cycle. Thus only a very small percentage of the beam electrons pass through the cavity and most of the kinetic energy of the beam is wasted by heat dissipation at the exterior walls of the cavity. That

is, only those electrons which pass through the cavity aperture can contribute energy to the microwave oscillations therein. All the kinetic energy represented by other beam electrons is dissipated without doing any useful work. The consequent low efficiency has prohibited practical utilization of such systems.

The present invention overcomes the foregoing handicaps of previous systems by utilizing a major portion of the beam current produced by the electron gun and by recovering most of the kinetic energy of the beam electrons to reduce by an order of magnitude the load imposed on the high voltage direct current source used for accelerating the beam. In addition, the present invention deflects the electron beam in a single direction or single plane only, thereby reducing by a factor of two the input microwave power required for deflection of the electron beam. Further, the present invention, by the provision of means for post-deflection acceleration, very substantially reduces the deleterious effects of aberration in the longitudinal velocity of the cathode ray beam electrons.

In accordance with a preferred embodiment of the present invention, the foregoing results are accomplished by an arrangement in which the electron beam is deflected in a single plane under the control of and in synchronism with an input microwave signal. The successive electrons of the beam traverse successive portions of an elongated microwave resonator device which is adapted to derive energy from the beam by deceleration of the beam electrons. Preferably, the microwave resonator comprises an elongated waveguide member having its longitudinal axis positioned in a plane substantially perpendicular to the normal axis of the electron beam and arranged to internally receive the electrons of the beam through a longitudinally extending slot or aperture which coincides with the plane of deflection of the electron beam.

The microwave resonator is constructed and arranged to provide a decelerating field in the region where each electron is internally traversing the structure at the time of such traversal. By decelerating the beam electrons, the electromagnetic fields within the microwave resonator absorb kinetic energy from the moving electrons and thereby regenerate the oscillations within the resonator. Further, in accordance with preferred embodiments of the invention, the electron beam is deflected by the input microwave signal at a point in the system where the beam electrons have a relatively low velocity. The beam is thereafter increased in energy by a direct current energized accelerating system so that the total ultramicrowave energy may be derived from the resonator can be greater than the microwave input power required for deflecting the beam.

More specifically, the apparatus of the present invention differs from that of the above-mentioned Patent No. 2,408,437 in that our ultramicrowave resonator is not a simple resonant cavity but rather is a length of waveguide adapted to support one or more standing waves and having at least one wall which is slotted or longitudinally apertured over a length such that the beam electrons are internally received by the resonator during a major portion of each beam deflection cycle. Because of such increased utilization of the beam electrons, it is possible to convert a much larger fraction of the kinetic energy of the beam to sustenance of the electromagnetic fields within the resonator. Accordingly, the present invention provides a practical apparatus for generation of several watts of power at any selected frequency in the millimeter and submillimeter wavelength ranges of the spectrum.

The present invention, together with further objects and advantages thereof may be best understood by reference to the following description taken in accordance with the accompanying drawings in which like reference characters indicate like parts and in which:

FIGURE 1 diagrammatically illustrates a microwave power generating system of the type to which the present invention relates;

FIGURE 2 is a perspective view of a ridged waveguide cavity structure which is used for deflection of the electron beam in a preferred embodiment of the invention;

FIGURES 3 and 4 are diagrammatic representations useful in considering the operation and certain inherent characteristics of the apparatus of FIGURE 1;

FIGURE 5 is a graphical representation showing the optimum dimensional parameters of one embodiment in accordance with the present invention for generation of maximum ultramicrowave power;

FIGURE 6 is a diagrammatic illustration of the beam deflection geometry of the apparatus of FIGURE 1 which is useful for analysis of the power output characteristics of such apparatus;

FIGURES 7*a* and 7*b* schematically illustrate a further embodiment of apparatus in accordance with the present invention; and

FIGURE 8 is a fragmentary perspective view representing a structural modification of the post-deflection acceleration means which forms a part of the apparatus of FIGURE 7*a*.

In FIGURE 1 of the accompanying drawings, there is shown, diagrammatically, a system in accordance with the present invention which utilizes linear or planar deflection of an electron beam **36**. The electron beam is derived from a conventional electron gun **12** which is positioned to normally direct a pencil beam of electrons along a central axis **10**. The electron gun **12** may take any one of various forms known in the art. Along the electron beam axis **10** immediately subsequent to the beam forming gun **12** is positioned a beam deflection system **14** preferably comprising a generally rectangular resonant chamber or microwave cavity having top and bottom walls **28** and **29** and front and rear walls **25** and **27**. In describing the various components of the present invention, the term "front" is used as meaning that wall or surface of the component which faces toward the source of the electron beam. Thus the front wall **25** is that wall of the deflection cavity **14** which is first traversed by the beam electrons. The rear wall **27** is that wall through which the beam electrons exit from the deflection cavity. As more clearly shown in FIGURE 2, the top wall **28** of the deflection cavity is provided with an inwardly projecting rectangular member **21** and the bottom wall **29** is provided with a similar inwardly projecting ridge member **23** with the spacing between the inner surfaces of the ridges **21** and **23** being slightly larger than twice the electron beam diameter. This structural arrangement provides for high intensity electric fields in the small space or gap between the ridges **21** and **23** so that a high velocity electron passing through the deflection cavity is subjected to maximum deflection during the relatively small time interval required for the electron to pass between the ridges **21** and **23**. To permit ingress of the electron beam to the deflection cavity, the front wall **25** is provided with a circular aperture **17** having a diameter slightly larger than that of the electron beam. After deflection by the electric field between ridges **21** and **23** the beam electrons pass out of the deflection cavity through a substantially rectangular aperture **19** which has a width slightly larger than the maximum beam width and which has a height dependent on the beam deflection angle which is to be used.

The "ridged" waveguide or ridged cavity structure of the deflection cavity **14** enables efficient deflection of the electron beam at microwave frequencies without wasteful radiation of microwave energy into the immediate environment. The ridged or reentrant structure may be similar to that of known waveguide structure of the so-called "ridged" type. In accordance with one embodiment of the invention which has been used for harmonic frequency multiplication of microwave signals the deflection cavity **14** has been designed to receive and utilize deflection power of 8.5 kilomegacycles. By deflection of the beam at that frequency, generation of 34 kilomegacycles electromagnetic fields in the output resonator **20**

has been accomplished. In that particular apparatus, the H-shaped cavity provided between the walls **25**, **27** and the ridges **21**, **23** had a maximum height of 0.658", a gap height of 0.90" with the cavity being 0.658" between the front and rear walls **25**, **27** and being 1.50" deep along the length of the ridges **21** and **23**.

The cavity **14** is preferably formed by constructing a mandrel having the above dimensions. The cavity itself is then electro-formed by electrolytic deposition of copper or the like on all of the exterior surfaces of the mandrel, after which the mandrel is dissolved by means of an etching solution which etches the mandrel material without etching away the electro-deposited walls of the cavity. As shown in FIGURE 2, the cavity structure further comprises an exterior flange **33** to which a microwave waveguide fitting may be bolted for feeding the 8.5 kilomegacycles input deflection energy to the deflection cavity **14**. Further, in accordance with a preferred embodiment of the invention, the wall of the cavity opposite the flange **33** is provided with a cylindrical boss **35** for supporting an axially extending turning screw (not shown) which extends into gap between the ridges **21** and **23** for adjustment of the deflection cavity to precise resonance at the frequency of the input 8.5 kilomegacycle deflection power.

After exiting from the deflection cavity through the exit aperture **19**, the deflected electron beam **36** passes through a slotted plate **16** which constitutes a means for post-deflection acceleration of the beam electrons. To that end, the plate **16**, as shown in FIGURE 1, is connected to ground or a point of reference potential as indicated by the numeral **39**, and the electron gun **12** is connected to a −15 kv. direct current source as indicated at **32**. The deflection cavity **14** is likewise connected to the direct current source **32** through a small resistance **30**. By this arrangement, the electron gun **12** forms and projects a relatively low voltage electron beam which may be deflected with a relatively small amount of input radio frequency energy. After deflection, the beam electrons are post-deflection accelerated by the high potential gradient (15 kv.) which exists between the deflection cavity **14** and the acceleration plate **16**. Thus the deflected electrons which comprise the beam **36** have a kinetic energy corresponding to the potential of the direct current source. These deflected electrons travel outwardly from the acceleration plate **16** to traverse an output resonant cavity **18**.

Preferably, the output cavity **18** takes the form of elongated waveguide structure which has its longitudinal axis **19** positioned in a plane substantially perpendicular to the axis **10** of the electron gun **12**. The front wall **20** of the output cavity is provided with a longitudinally extending slot or aperture which extends substantially the entire length of the output cavity and which has a width substantially equal to or slightly larger than the diameter of the electron beam. The longitudinal aperture is electrically closed by a screening **24** which is welded to the wall **20** at the edges of the cavity and which is preferably formed of gold-plated tungsten wire screen having 100 x 100 wires per inch. In a similar manner the rear wall of the output cavity is provided with a longitudinally extending aperture which is electrically closed by a similar tungsten screening **22** and which permits the high velocity electrons to exit from the output cavity to thereby avoid generation of deleterious secondary electrons within the resonator itself. Additionally, it is frequently desirable to provide a Faraday cup collector (not shown) adjacent the rear wall of the output cavity for collection of the beam electrons. If the beam electrons, after traversing the output cavity **18**, were allowed to strike a target or anode having the same direct current potential as the output cavity **18**, a considerable amount of heat loss would occur at the target. Also, and more importantly, that dissipation of the kinetic energy of the beam electrons would impose a substantial load on the high voltage direct current source **32** which supplies the system. By the use of a Faraday collector connected to a point of potential equal to that of the electron gun, the electrons which exit from the output cavity **18** are decelerated before collection thereby conserving the energy represented by the velocity of the electrons and thereby substantially reducing the load which otherwise would be imposed on the direct current source **32**.

In accordance with one particular embodiment of the present invention, which has been constructed for the generation of 34 kilomegacycle energy in the output cavity **18**, the output cavity has been constructed to have a length from top to bottom of 0.664", a width from front to back of 0.123", a depth of 0.28" and a slot width of 0.110". It will be appreciated, of course, that the slot width is not particularly critical but may be as wide as is necessary to accommodate the particular electron beam which is being utilized. In the particular embodiment above mentioned, a 2.8 millimeter beam diameter has been used.

To clarify the operation of the system of FIGURE 1, it is advantageous to consider the waveguide device **18** as having a physical length along the longitudinal axis **19** of exactly 3 half wavelengths at the ultramicrowave frequency which is to be generated. This characteristic is illustrated by the curve **26** of FIGURE 1*b* which represents three half-waves of a standing wave within the resonator **18**. In this particular embodiment, the cavity is designed to resonate in the TE_{103} mode. This means, of course, that the electric field vector of the waves within the cavity extend between the front and rear walls of the cavity and thus substantially parallel to the direction of travel of the beam electrons. When a high velocity beam electron passes through such an electric field parallel to the electric field vector, the beam electron is decelerated in proportion to the intensity of the electric field through which it passes. Thus, if the electron beam **36** is synchronously deflected from top to bottom along the resonator **18**, in step with an electromagnetic field which travels along the resonator, the beam electrons traversing the resonator will be, at all times, coincident with the maximum decelerating portion of the electric field in the resonator.

In accordance with a preferred form of the invention, the resonator **18** supports a standing wave rather than a traveling wave. In a standing wave resonator, as is well understood in the art, a wave arriving at one end of the resonator is reflected with a 180° phase reversal between the impinging wave and the reflected wave. To maintain synchronism between the deflecting electron beam and the wave in the resonator it is therefore necessary to sweep the electron beam sinusoidally up and down along the resonator with the sweep amplitude being somewhat larger than the length of the resonator. That is, the beam sweeps beyond the top end of the resonator and "dwells" there for a time period equal to one half cycle of the harmonic frequency which is being generated within the resonator. Then, when the electron beam starts the return sweep downwardly along the resonator, it arrives at the top end of the resonator and begins to pass through the upper portion of the resonator precisely in synchronism of the decelerating electric field maximum of the reflected wave within the resonator.

More precisely, the vertical motion of the electron beam may be considered in terms of a cycle of the input deflection frequency f. The beam sweeps from the beam axis **10** to the top end of the resonator in a time

$$\frac{T}{K}=\frac{1}{fK}$$

wherein

$$T=\frac{1}{f}$$

is the period of the input deflection signal. It then leaves the resonator. After a "dead time" or dwell time outside the resonator, it returns at a time

$$t=\frac{T}{2}-\frac{T}{K}$$

If n is equal to the number of waveguide wavelengths at the harmonic frequency mf between the axis **10** and the top end of the resonator **18** it can be shown that the frequency mf generated in the resonator is a harmonic of f given by $mf=knf$. Here n and k are related by

$$k-4=\frac{2\varphi+1}{n} \quad (1)$$

$\varphi=0, 1, 2, \ldots$

$4n=1, 2, 3, \ldots$

We have found that the output frequency of the linear waveguide structure **18** of the apparatus of FIGURE 1 can be determined from equations governing the beam position and field distribution with the equations being integrated to determine the available power that can be generated for various possible generated harmonics. FIGURE 3 illustrates the position of the electron beam **36** and the field distribution **26'** for a cavity **18** which has a length equal to one waveguide wavelength at the frequency to be generated. By consideration of the relationship arising from the configuration of FIGURE 3, the power generated by a cavity having a length equal to even multiples of one-half wavelength may be theoretically determined. FIGURE 4 shows the beam position and field distribution which exists in a cavity whose length is an odd multiple of one half-wavelength at the frequency to be generated. From the relationships arising out of FIGURE 4, the power generated by cavities having lengths equal to various odd multiples of one half-wavelength may be calculated.

Considering an even multiple cavity **18** as per FIGURE 3, if during operation the beam is not deflected past the ends of the cavity the average power generated is:

$$P_g=\frac{1}{T}\int_0^T AEbI \sin\left[\frac{2\pi y_m}{\lambda_g}\sin \omega t\right] \sin n\omega t dt \quad (2)$$

Wherein A is a beam-to-field coupling factor dependent on electron transit time through the cavity, P_g is the generated power, T is the radio frequency period of the generated harmonic, λ_g is the waveguide wavelength of the generated harmonic signal, y_m is the y coordinate of the maximum beam deflection at the resonator **18**, b is the cavity length or height along the longitudinal axis **18** and n is the harmonic number of the generated harmonic energy. No restriction is made of the cavity length other than that it is an even multiple of

$$\frac{\lambda_g}{2}$$

By integration of Equation 2, the power output can be shown to be:

$$P_g=AEbIJ_n\left(\frac{2\pi}{\lambda_g}y_m\right); \text{ for } n \text{ odd}; \left.\begin{array}{l}\text{cavity length an even}\\ \text{number of half wave-}\\ \text{lengths}\end{array}\right.$$

$$P_g=0; \text{ for } n \text{ even}$$

(3)

Thus, it is demonstrated that a cavity which is an even number of half wavelengths long will generate power only at odd harmonics. The generated power for all of the even harmonics is zero so long as the cavity or resonator **18** has a length corresponding to an even number of half wavelengths. It can be shown that solution of the same equation for the configuration of FIGURE 4 in which the cavity has a length corresponding to an odd number of wavelengths gives the opposite results. That is, if the cavity has a length equal to an odd number of half wavelengths, the power generated at all of the odd harmonics is zero and the power at all of the even harmonics is the same as given by the first alternative of Equation 3. Thus, a cavity which is an even number of half wavelengths long can generate any odd harmonic to which it is tuned, and a cavity which is an odd number of half wavelengths in length can generate any even harmonic and no odd harmonics.

The even-odd relationship illustrated above arises from the symmetry of the electric field within the cavity **18** in which the undeflected beam is located. Thus, if the electron beam axis **10** passes through a point of pure even symmetry of the fields within the standing wave resonator **18** no odd harmonics can be generated, and conversely for the case where the beam axis **10** passes through a point of pure odd symmetry. This characteristic holds true even if the electron beam axis **10** is not located centrally between the ends of the output cavity **18** or even if the beam is deflected past the top and bottom ends of the output cavity **18**.

In FIGURE 5 is plotted the 4th harmonic power which may be generated by an output cavity **18** which is a single half wavelength in length (curve **44**) and for an alternative cavity having a length of three half wavelengths (curve **46**). It can be shown that when the electron beam **38** (FIGURE 6) is deflected beyond the ends of the resonator **18'**, the output power may decrease or may continue to increase. For the

$$\frac{3\lambda_g}{2}$$

cavity (FIGURE 4) the power decreases sharply because of the decrease in the current which is interacting with the electromagnetic fields in the cavity. For the

$$\frac{\lambda_g}{2}$$

cavity (curve **44**) the power continues to increase in spite of loss of interaction current because the beam position and the position of the electric fields within the cavity are caused to have better synchronism throughout the deflection cycle. As shown in FIGURE 5, the ordinate represents the ultramicrowave power developed in the output waveguide **18'** of FIGURE 7 and the abscissa represents the ratio

$$\frac{y_m}{\lambda_g}, y_m$$

being the maximum beam deflection as shown by the electron beam position **38** and λ_g being the waveguide wavelength within the cavity.

In FIGURES 7 and 8, there is illustrated a further embodiment of the present invention which embodies a very substantial increase in the power generating capacity of an apparatus of the type described. Specifically, the apparatus of FIGURES 7 and 8 differs from the embodiment of FIGURE 1 primarily in that a sheet-like electron beam rather than a cylindrical electron beam is used. FIGURE 7*a* is a cross section view taken in the plane of beam deflection of the apparatus and FIGURE 7*b* is a front view of the output resonator **62** of FIGURE 7*a*. As shown in FIGURE 8, the electron gun utilized in this embodiment is a substantially rectangular structure adapted to produce an electron beam **76** having a substantially rectangular beam cross section, with the beam width being several times greater than the beam thickness. To that end, the electron gun **52** is provided with an elongated beam forming aperture **74** in the wall **72** through which the beam electrons exit from the electron gun. The rectangular cross section electron beam **76** passes from the electron gun through a resonant cavity deflection means **54** (FIGURE 7*a*) and through a post-deflection acceleration means **60** so that the deflected beam sweeps up and down in the plane of the paper along the output resonator **62**.

The system of FIGURES 7 and 8 is generally similar to that of FIGURE 1 with the exception that the electron beam thickness is several times smaller than the beam

width and the various structural elements of the system have a correspondingly increased dimension normal to the plane of FIGURE 7*a*. That is, as shown in FIGURE 7*b*, the output resonator **62** has a width somewhat larger than its height from top to bottom and several times greater than its thickness from the front screen **66** to the back screen **64**. In a preferred form of the embodiment of FIGURES 7 and 8, substantially the entire front wall of the resonator **62** is comprised of tungsten screen having 100 x 100 wires per inch with this screen being gold plated to provide for maximum conductivity of the high frequency currents in the resonator walls. As shown in FIGURE 7*a*, the system is provided with a Faraday cup collector **70** which preferably is connected to the same potential level as the electron gun **52** so that the beam electrons are decelerated prior to collection.

In FIGURE 8 there is shown a further variant of the apparatus of FIGURE 7 in which the post-deflection acceleration means takes the form of two spaced apart cylindrical metal plates **86** and **88** each having a major area **90** formed of small apertured metal screening such as the 100 x 100 tungsten mesh mentioned heretofore. The sheet-like electron beam **76** passes through the deflection cavity **54** through an elongated entrance aperture (not shown) in the front wall of the deflection cavity with the entrance aperture having substantially the same dimensions as the cross-sectional dimensions of the electron beam **76**. As shown in FIGURE 8, the top wall **78** and the bottom wall of the deflection cavity have a width in the direction perpendicular to the electron beam direction substantially greater than the front to back dimensions of the deflection cavity. The rear or beam exit wall **82** of the deflection cavity is provided with a substantially rectangular aperture **84** which preferably has a height slightly greater than twice the thickness of the electron beam **76** and which has a length substantially corresponding to the width of the electron beam. Thus the exit aperture **84** permits deflection of the beam within the cavity and exit of the deflected electrons from the cavity along the maximum deflection lines **96**.

The top to bottom dimension of the screened apertures in the post-deflection acceleration plates **86** and **88** is, of course, designed to accommodate the maximum deflection of the electron beam. Post-deflection acceleration is accomplished by biasing the first acceleration screen **86** to −15 kv. as indicated at **94** and by connecting the second acceleration plate **88** to ground potential as indicated at **92**. Accordingly, since the first acceleration plate **86** is connected to the same potential as the electron gun **52**, the electron beam **76** has a relatively low velocity during its passage from the gun **52** through the deflection cavity **54** and to the first deflection plate **86**. Between the plates **86** and **88** there is extremely high potential gradient for abruptly accelerating the deflected beam electrons to a velocity corresponding to a kinetic energy of 15 kv. Accordingly, by deflection of the beam while the beam electrons have a relatively low velocity and thereafter accelerating the beam electrons to a high velocity the radio frequency power input required for deflection of the beam is minimized while, at the same time, the kinetic energy of the beam electrons traversing the output resonator **62** is maintained at a high level.

The fabrication of complex structures for the low millimeter and submillimeter wavelength regions is a difficult problem because of minute dimensions and close tolerances involved. Thus, for the output resonator of the exemplary apparatus of FIGURE 1, we have, in practice, used rectangular TE_{10} mode waveguide configurations which have the advantage of structural simplicity. For this type of waveguide it can be shown that the output power of the apparatus of FIGURE 1 is dependent upon the front-to-back height of the resinator **18** between the screen walls **24** and **22**. This dependence is, in part, a function of the electron transit time coupling factor "A" of the foregoing Equation 2. We have determined that, in a system using a TE_{10} mode resonant waveguide structure, the maximum output power is obtained when the electron transit time through resonator **18** is an odd multiple of a half cycle of a radio frequency cycle within the waveguide, i.e., $\textcircled{H}=\pi, 3\pi, 5\pi \ldots$ Accordingly, where a rectangular cross section output resonator **18** is to be employed, it is definitely not advantageous to minimize the electron transit angle $\textcircled{H}$, or the front-to-back waveguide dimension. Rather, best results can be obtained by constructing the resonator to have a height dimension dependent upon the beam particle velocity. This means that the useful structures are not limited to small heights. The front-to-back dimension may be relatively quite large providing that it is related to the electron transit velocity in a manner to make the transit time an odd multiple of a half-cycle at the generated frequency. Additionally, we contemplate that the use of ridged waveguide structures for the output resonator **18** can appreciably increase the power generated by systems such as those of FIGURES 1 and 7.

While the principles of our invention have been described in the foregoing in connection with specific exemplary apparatus, it is to be clearly understood that such exemplary apparatus, in which the harmonic signal generating structure is a waveguide having a resonant length, is merely a special case of apparatus in accordance with broader principles. We have determined that it is not essential to utilize an output resonator **18** having a critical length equal to an integral number of half wavelengths at the harmonic frequency. Rather, it is also within the scope of the invention to use as the output member a slotted waveguide of unspecified length with the length being uncritical and variable at will to meet the contingencies of the particular application. With such an arrangement, the output member is not tuned to a specific frequency or to a specific harmonic and consequently is adaptable for broad band operations. Likewise, the untuned output waveguide does not require tuning or adjustment or critical dimensioning of its length. When such an elongated section of waveguide is used as the output member, it will produce equal amounts of harmonic output power at each end, and the two ends may be coupled together to a common load by any of various well-known microwave power coupling arrangements. The power output at each end of the untuned waveguide member at any selected harmonic frequency is given by the following expression:

$$P_n=(b/a)\sqrt{\mu/\epsilon}\sqrt{1-\frac{f_c}{n^2f^2}}I^2\left[J_n\left(\frac{KS}{2}\right)^2\right]\left[\frac{\sin\frac{n\omega t}{2}}{\frac{n\omega t}{2}}\right]^2 \quad (4)$$

Where P_n is the nth harmonic output power at each end of the slotted waveguide member;

Where a and b are respectively the width and height of a rectangular waveguide operating in the lowest normal mode; in this normal mode b is the waveguide dimension parallel to the electric field vector;

Where μ is the permeability of the dielectric (in MKS units) in the waveguide (for air μ is equal to $4\pi \times 10^{-7}$ henries per meter);

ϵ is the permittivity of the same dielectric material (for air ϵ is equal to 8.85×10^{-12} farads per meter);

f_c is the cutoff frequency of the waveguide;

n is the harmonic number;

J_n is the bessel function of the first type and the nth order;

K is equal to $2\pi/\lambda_g$, where λ_g is the waveguide wavelength;

S is the total length of deflection or sweep of the electron beam along the waveguide structure;

ω is equal to $2\pi f$; and

T is the electron transit time through the waveguide structure.

By critical inspection of the foregoing equation, it will be observed that the power output P_n is dependent upon the dielectric characteristics of the material which fills the waveguide structure. The power output can be very appreciably increased by utilizing a waveguide filling material which has a relatively high permeability and a relatively low permittivity. An ionized gas plasma can be used as the filling material for the untuned or unresonant output waveguide structure. A plasma can have a permitivity ϵ much smaller than that of air while having a permeability equal to that of air. Thus, filling the waveguide with plasma gives an increased value of μ/ϵ and, therefore, increased power output from an apparatus in which all other parameters and characteristics remain the same. The foregoing equation, and the above described structure to which it relates, defines in general terms a class of ultramicrowave signal generating devices within the scope of the invention. The equation defines the power output for apparatus in which the length of the output waveguide is immaterial provided that the ends are coupled to an appropriate microwave load or otherwise nonreflectively terminated. It will be understood that the specific exemplary systems of FIGURES 1 through 7 are special cases in which the ends of the output resonator **18** are reflectively terminated by conductive end plates. It is to be noted that Equations 1, 2, and 3 are applicable to only the special cases of FIGURES 1 to 7 in which the output resonator **18** is tuned, and are not applicable to the general case in which the output waveguide member is a broad band structure.

Thus, while the present invention has been described with reference to certain specific embodiments only, it is intended that it is not so limited but is susceptible of the above mentioned changes and modifications as well as various others which will appear to those skilled in the art.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. In an ultramicrowave power generating system:

electron beam forming means to project a beam of electrons along a first axis;

deflection means for sinusoidally deflecting said beam to and fro in a single beam deflection plane;

microwave resonant means for receiving the deflected beam electrons and periodically extracting kinetic energy from the same by virtue of electromagnetic interaction between the beam electrons and the electric fields propagated within said resonant means to thereby generate ultramicrowave power;

said resonant means comprising an elongated waveguide device having a longitudinal axis substantially perpendicular to said first axis and coincident with said beam deflection plane, with the front and rear walls of said device longitudinally apertured along the regions where said walls intercept said beam deflection plane and with said device being internally dimensioned so that the electric field vector of the electromagnetc fields therein is oriented substantially parallel to the direction of travel of the beam electrons;

and said deflection means comprising a double-ridged waveguide structure having a pair of inwardly extending ridge members positioned on opposite sides of said beam axis in a manner to provide a gap therebetween, said gap having a length along said first axis approximately equal to the product of the beam velocity and the beam transit angle, and a gap width between said ridge members approximately corresponding to twice the beam deflection lateral displacement within the gap region plus the maximum beam diameter in the gap region.

2. A harmonic generating system comprising, in combination:

a fundamental frequency energy source;

a hollow conductive waveguide having a substantially rectilinear longitudinal axis and having an active length equal to an integral number of half-wavelengths at a harmonic frequency which is an integral multiple of said fundamental frequency, said waveguide being resonant at said harmonic frequency;

means to project a beam of electrons along a beam axis substantially perpendicular to the longitudinal axis of said waveguide;

said waveguide having an elongated beam entrance aperture extending rectilinearly along said waveguide in a direction parallel to the direction of wave propagation therewithin, said aperture having a length corresponding to at least about one wavelength of the harmonic frequency waves supported within said waveguide;

deflection means coupled to and driven by said fundamental frequency source for sweeping said electron beam to and fro with a substantially sinusoidal deflection motion in a single deflection plane which includes said beam axis and is aligned with said aperture;

said beam being deflected through a distance at said waveguide substantially greater than the length of said aperture so that during the time intervals when the beam enters said waveguide the beam has a scanning velocity substantially equal to the phase velocity of the harmonic frequency waves propagated in said waveguide and energy is transferred from said beam electrons to the harmonic frequency electromagnetic fields sustained within said waveguide;

and output coupling means for deriving harmonic frequency energy from said waveguide and applying the same to a load.

3. In a microwave harmonic generator, the combination of:

cathode means for providing a substantially rectangular-in-cross section sheet-like electron beam with the cross-sectional beam width being at least several times the beam thickness, said beam being normally directed along a predetermined beam axis;

a source of input energy of a fundamental frequency;

deflection means coupled to said source for sinusoidally deflecting said beam to and fro in a deflection plane which extends substantially normal to the cross-sectional width of said beam;

a hollow conductive waveguide constructed and positioned to propagate waves of a harmonic frequency linearly in a direction perpendicular to said beam axis, said waveguide having a substantially rectilinear longitudinal axis which angularly coincides with the direction of harmonic wave propagation;

said waveguide having at least one elongated beam entrance aperture having a width substantially equal to the cross-sectional width of said sheet-like beam, said aperture extending rectilinearly along the region where said waveguide intercepts said deflection plane and having a length corresponding to at least one-half waveguide wavelength of the harmonic frequency waves propagated within said waveguide;

said beam being deflected along said aperture in synchronism with the propagation of harmonic frequency waves within said waveguide, and through a deflection amplitude sufficiently greater than the length of said aperture so that said beam enters said aperture only during portions of the sinusoidal deflection period when the beam scanning velocity is approximately constant and substantially equal to the propagation velocity of the harmonic waves in said waveguide and so that said beam is swept past the ends of said aperture and thereby decoupled from said harmonic waves during those portions of the

sinusoidal deflection period when the beam scanning velocity is minimal.

4. Apparatus in accordance with claim 3 and further characterized in that the deflection means therein recited comprises a microwave cavity resonator tuned to said fundamental frequency and including a pair of inwardly extending ridge members for providing a narrow gap therebetween, said gap having a width between said ridge members slightly exceeding twice the beam displacement within the gap region and said ridge members having lengths at least exceeding the cross-sectional width of said sheet-like beam.

References Cited by the Examiner

UNITED STATES PATENTS

2,408,437	10/1946	McRae	315—5.25
2,418,735	4/1947	Strutt et al.	315—5.25
2,463,617	3/1949	Hartley	315—5.24
2,515,998	7/1950	Haeff	315—5.27
2,576,696	11/1951	Ramo	315—5.38
2,827,592	3/1958	Bramley	313—82

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