May 28, 1963 W. P. DYKE ET AL 3,091,719

MICROWAVE TRANSDUCER

Filed April 14, 1959 3 Sheets-Sheet 1

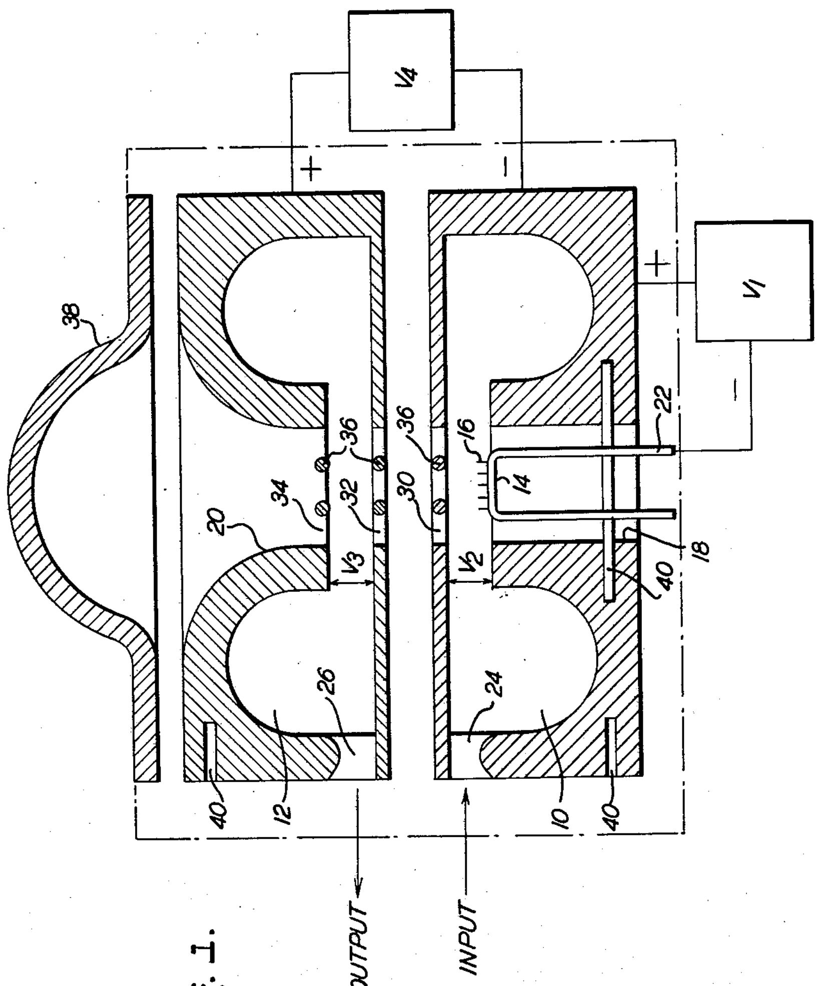


FIG. 1.

INVENTORS.
WALTER P. DYKE
JOSEPH E. HENDERSON
FRANCIS M. CHARBONNIER

BY Harold T. Stowell
Harold L. Stowell
ATTORNEYS

May 28, 1963 W. P. DYKE ET AL 3,091,719

MICROWAVE TRANSDUCER

Filed April 14, 1959 3 Sheets-Sheet 2

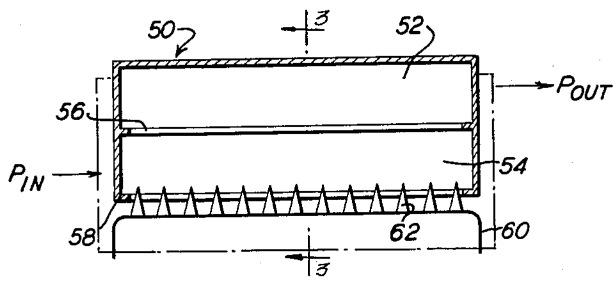


FIG. 2.

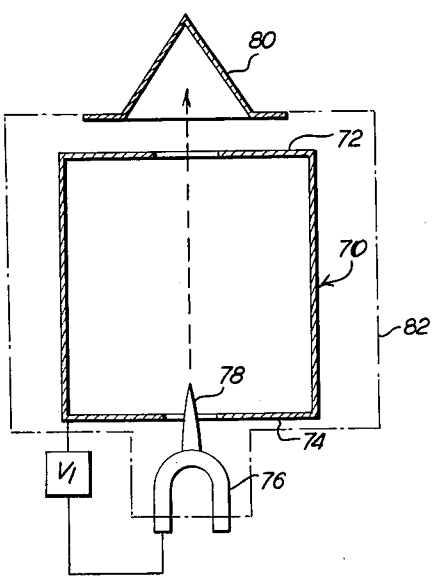


FIG. 4.

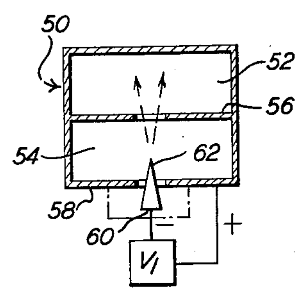


FIG. 3.

INVENTORS
WALTER P. DYKE
JOSEPH E. HENDERSON
FRANCIS M. CHARBONNIER

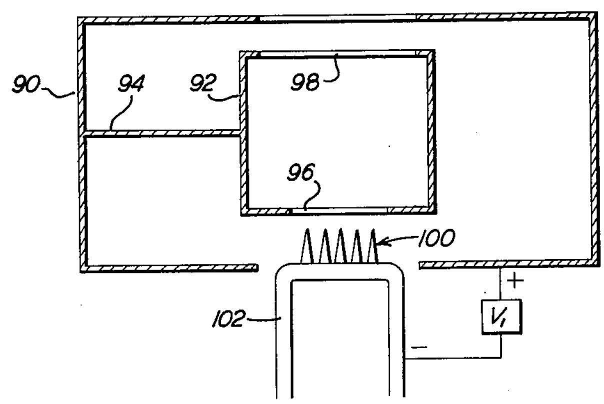
BY Harold T. Stowell
Harold L. Stowell
ATTORNEYS

May 28, 1963 W. P. DYKE ET AL 3,091,719

MICROWAVE TRANSDUCER

Filed April 14, 1959 3 Sheets-Sheet 3

FIG. 5.



INVENTORS.
WALTER P. DYKE
JOSEPH E. HENDERSON
FRANCIS M. CHARBONNIER

BY Harold T. Stowell
Harold L. Stowell
ATTORNEYS

United States Patent Office 3,091,719 Patented May 28, 1963

1

3,091,719

MICROWAVE TRANSDUCER

Walter P. Dyke, McMinnville, Oreg., Joseph E. Henderson, Seattle, Wash., and Francis M. Charbonnier, McMinnville, Oreg., assignors, by mesne assignments, to Field Emission Corporation, McMinnville, Oreg., a corporation of Oregon

Filed Apr. 14, 1959, Ser. No. 806,334
9 Claims. (Cl. 315—5.41)

The present invention relates to electron discharge devices and, more particularly, to devices in which a field emission cathode is operated to effect the emission of a modulated current with microwave frequency components. The applications of this invention include the generation and/or amplification of microwave radiation, the generation of frequency harmonics and/or the frequency conversion of a microwave frequency signal, frequency mixing and/or amplitude modulation at microwave frequencies, and microwave switching and duplexing.

At ultrahigh frequencies, interelectrode capacitances and the inductance of internal leads determine the highest possible frequency to which a vacuum tube can be tuned. These tubes usually will not oscillate up to this limit, however, because of dielectric losses, transit time and other effects. In low frequency operation, the actual time of flight of electrons between the cathode and the anode is negligible in relation to the duration of the cycles. At 1000 kc., for example, transit time of 0.001 microsecond, which is typical of conventional tubes, is only $\frac{1}{1000}$ cycle. But at 100 mc., this same transit time represents $\frac{1}{10}$ of a cycle, and a full cycle at 1000 mc. These limiting factors establish about 3000 mc. as the upper frequency limit for negative-grid tubes.

With most tubes of conventional design, the upper limit of useful operation is around 150 mc. For higher frequencies, tubes of special design are required. About the only means available for reducing interelectrode capacitances is to reduce the physical size of the elements, which is practical only in tubes which do not have to handle appreciable power. However, it is possible to reduce the internal lead inductance materially by miminizing the lead length and by using two or more leads in parallel from an electrode.

In the operation of the conventional tubes the potential on the grid tends to reduce the electron velocity during the more negative half of the cycle, while on the other half cycle the positive potential on the grid serves to accelerate the electrons. Thus the electrons tend to segregate into groups, those leaving the cathode during the negative half-cycle being collectively slowed down, while those leaving on the positive half-cycle are accelerated. After passing into the grid-plate space only a part of the electron stream follows the original form of the oscillation cycle, the remainder travelling to the plate at differing velocities. Since these contribute nothing to the power output at the operating frequency, the efficiency is reduced in direct proportion to the variation in velocity, the output reaching a value of zero when the transit time approaches a half-cycle.

This effect is turned to advantage in velocity-modulated tubes in that the input signal voltage on the grid is used to change the velocity of the electrons in a constant-current electron beam, rather than to vary the intensity of a constant-velocity current flow as in the method in ordinary tubes.

The velocity modulation principles is used in a number of ways, leading to the design of the conventional klystron, magnetron, and travelling wave tubes.

These devices use thermal cathodes and accordingly are subject to a certain number of disadvantages which typically include the following: (1) low current density emission, resulting in small total current and small power when the emitting surface is scaled down to the dimensions required at the microwave frequency range; (2) the need for a "drift space" for bunching of the electron emission through velocity modulation; (3) debunching tendency due to space charge, requiring a magnetic field to maintain the required collimation of the electron beam; debunching also decreases efficiency and lowers harmonic content; (4) necessity of heater power supply and means for heat dissipation; (5) sensitivity to mechanical shock; (6) requirement of cathode warm-up time; and (7) phase instability, since the output phase depends on the applied voltage and on the distance the beam travels during interaction with fields or while bunching in the drift region; conventional devices employ distances of several wave lengths, and hence phase stability is achieved only if voltage is very accurately controlled.

2

The purposes of this invention are to produce a class of new electron discharge devices ultilizing the properties of a field emission cathode to obtain very high current densities from small emitting areas, so that insertion into small cavities or waveguide structures is practical and yields the following distinctive characteristics for devices embodying the principles of the invention:

(1) elimination of the necessity for a drift space, permitted by the bunching of the electron emission at the emitting surface through field modulation;

(2) considerable reduction of space charge effects and particularly space charge debunching in the electron beam;

(3) substantial reduction or complete elimination of the heater power requirement;

(4) elimination of delays due to warm-up time, since the current voltage response of the field emission cathode is instantaneous;

(5) increase in mechanical strength due to the small mass and monocrystalline structure of the cathode emitter tips;

(6) utilization of the non-linearity of the field emission current-voltage relationship to obtain a very high degree of bunching and therefore a very high efficiency, and/or to perform such non-linear operations as harmonic generation, frequency mixing or conversion, and amplitude modulation, when one or more of the frequencies involved are in the microwave frequency range.

Certain other objects and advantages of the invention will be apparent from the following detailed description when considered with reference to the attached drawings in which:

FIGURE 1 is a diagrammatic sectional elevation of an electron discharge device embodying the principles of the invention;

FIGURE 2 is a diagrammatic sectional elevational view of another embodiment of the invention;

FIGURE 3 is a diagrammatic sectional view of the device illustrated in FIGURE 2 taken along line 3—3;

FIGURE 4 is a diagrammatic sectional elevational view of another embodiment of the invention; and

FIGURE 5 is a diagrammatic sectional elevational view of a further embodiment of the invention.

While the basic principles of the invention may be incorporated into various designs, the essential features thereof are contained in the electron discharge device illustrated in FIGURE 1. The specific embodiment consists generally of two resonant cavities 10 and 12, and a field emission cathode 14 provided with a plurality of individual projections or needles 16. Each of the cavities 10 and 12 is provided with a central cylindrical bore or opening 18 and 20, respectively, and are arranged in axial alignment with one another. The field emission cathode 14 is positioned within the opening 18 and is mounted on a support filament structure 22.

The cavity **10** is provided with a waveguide input **24**, and the cavity **12** is provided with a waveguide output **26**.

Gaps **30**, **32**, and **34** are provided in the cavities **10** and **12**. Grid wire inserts **36** are mounted in the gaps, if desired, for the purpose of confining the various electric fields to their respective cavities.

A secondary electron suppressor and ion trap electrode **38** is disposed in axial alignment with the openings **18** and **20** and is operative to collect the electrons emitted from surfaces of the needles **16** of the cathode **14**, and also any secondary electrons and ionized particles which may be produced within the tube. The walls of the electrode **38** may be cooled by any suitable cooling means, if necessary.

The interaction gaps which contain the grids **30**, **32**, and **34**, may be bounded by metal surfaces formed such that the electric fields in the gaps are essentially parallel to the path of the electrons thereby enabling a maximum transfer of power from the electron beam to the field. Due to the resultant collimating effect on the transient electrons, no magnetic focussing field is required; however one may be used, if desired.

It will be noted that suitable R.F. chokes **40** are disposed in the cavities **10** and **12** to reduce radiation losses.

The components of the device illustrated in FIGURE 1 must obviously be maintained in an evacuated environment and accordingly an envelope structure is indicated generally by dashed lines. Since the actual envelope structure may assume a variety of configurations, the illustration thereof is merely schematic.

In operation of the device illustrated in FIGURE 1 as an amplifier, at D.C. or pulsed voltage V_1 is applied between the grids **30** and the field emitter cathode **14** until the desired level of field current is drawn due to the action of the resultant electric field at the needle tips **16** of the cathode.

An R.F. voltage V_2 is impressed across the interaction gap of cavity **10** through the input **24** and thereby establishes an oscillating electric field within the cavity. This latter electric field is superposed on the field established by the voltage V_1 and cause the field current or electrons emitted from the cathode **14** to be modulated in phase therewith. It will be appreciated that both voltages V_1 and V_2 contribute to the cathode emission, and that the wave shape of the beam current may be varied over a wide range by adjusting the relative amplitudes of these two voltages. The rate of emission of the electrons from the surface of the needles **16** of the cathode **14** is largest when the oscillating electric field established by V_1 and V_2 is maximum. Since the voltage V_2 is alternating, electrons are drawn off from the cathode in bunches in phase with the applied electric field. Due to the fact that electron bunching is achieved at the cathode surface during the emission process, no drift space is required and the cavities **10** and **12** can therefore be disposed immediately adjacent one another. As a result, high electron density of the bunches of electrons is conserved during the short transit period between the cavities **10** and **12**.

Upon reaching the cavity **12**, which in the case of amplification is tuned to the fundamental frequency, the electrons are decelerated establishing an opposing electric field of voltage V_3.

In this process, energy from the D.C. or pulsed field set up by the voltage supply V_1 is transferred by the electron beam to the R.F. field across the interaction gap of the output cavity, at the frequency of voltage V_2 which is thereby amplified. Because the electrons are tightly bunched initially, and since there is no extensive drift space in which space charge forces can cause debunching of the transient electrons, the energy transfer from cavity **10** to cavity **12** is extremely efficient.

A post acceleration voltage V_4 may be employed to further increase the energy of the transient electrons, and hence the output voltage V_3 which is made large with respect to the R.F. input voltage V_2, yielding a desirably high voltage and power gain.

It will be appreciated that due to the short transit distance between the cavities **10** and **12** and the predominance of field emission in directions close to the axes of the needles **16** of the cathode **14**, the resultant beam of bunched electrons caused to be emitted therefrom will travel through the gaps **30**, **32**, and **34** and will be finally collected at the electrode **38**.

The device described in the foregoing description is useful as an amplifier. However, when the cavity **12** is tuned to a harmonic of the fundamental frequency and when the proper values are selected for the relative amplitudes of the voltages V_1 and V_2, the device operates as a frequency multiplier, the efficiency of which is improved over conventional frequency multipliers by the highly non-linear field emission current-voltage characteristic and by the short transit distance during which space charge debunching is avoided. The conversion of the harmonic content of the beam requires maintenance of the initial bunching during transit, which is readily accomplished in the device of the invention, but is difficult in the conventional klystron type tubes due to their relatively long drift space. It is immediately apparent that the same device will also function as a detector of microwave frequency radiation.

FIGURES 2 and 3 show another device incorporating the principles of the invention and specifically disclose an embodiment of the invention wherein the cavities **10** and **12** of the device of FIGURE 1 are replaced by the broad band waveguide structure **50**. The waveguide **50** is divided into two guide sections, an upper section **52** and a lower section **54**, by a partition **56** having an elongated slot formed therein which extends substantially the entire length of the waveguide structure **50**. The lower section **54** of the waveguide **50** is provided with a bottom wall **58** having a slot formed therein which is substantially coextensive with the slot in the partition **56**.

As in the device of FIGURE 1, the embodiment of FIGURES 2 and 3 utilizes a field emission cathode structure including cathode **60** provided with a plurality of individual projections or needles **62**. The needles **62** are disposed so that at least a portion of the length thereof extends into the slot formed in the bottom wall **58**.

Suitable potential is impressed on the cathode **60** by the application of a source of potential V_1 which is connected between the lower waveguide section **54** and the cathode **60**.

The lower waveguide section **54** is energized by a source of R.F. power as illustrated diagrammatically by an arrow designated as P_{in}. The upper waveguide section **52** is provided with a suitable output terminal illustrated diagrammatically by an arrow designated as P_{out}.

The vacuum envelope indicated by dashed lines is intended to merely illustrate the evacuated regions of the device rather than represent the actual envelope configurations.

In operation, a D.C. or pulsed voltage V_1 is applied to the cathode **60** and establishes a resultant electric field of a value which is usually (but not necessarily) just slightly below the value necessary to draw a continuous stream of electrons from the surface of the cathode needles **62**. R.F. power P_{in} is added to the lower waveguide section **54** establishing an electric field therein which varies as a function of the total applied voltages V_1+V.

Electron emission from the cathode **60** is caused by and is in phase with the R.F. voltage V and is tightly bunched upon emission and, accordingly, no drift space is necessary for bunching purposes. The emergent electrons receive most of their energy from the power supply V_1 and release their energy to the electric field which their transit causes in the upper waveguide section **52**, thereby amplifying the latter field. As the input R.F.

field advances along the input or lower waveguide section 54, an amplified wave advances at the same rate and in the same direction along the output or upper waveguide section 52. The amplified wave provides the output power as designated by P_{out}.

It will be readily apparent to those skilled in the art that the gain and bandwidth of the devices described may be varied by the resonance of the resonant structures employed. Waveguides provide very wide bandwidth but relatively low gain; however, loaded waveguides having intermediate impedances exhibit improved values of both gain and bandwidth and therefore may be useful in applications where a higher gain is desired.

The principles of the invention are retained, and the functions performed by the embodiments of FIGURES 1, 2 and 3 are extended to include frequency mixing, frequency conversion, and amplitude modulation of a carrier signal at microwave frequencies, when the bias voltage V_1 applied to the cathode is modulated at a low or I.-F. frequency β. In this case, the field at the cathode surface contains two A.C. components, one at frequency β and the other at the frequency ω of the microwave input signal, and because of the non-linearity of the field emission current-voltage relationship the emitted current contains components at all frequencies $m\omega \pm n\beta$ (where m and n are zero or integers) from which power may be extracted in the manner described above. By a simple modification, the input structure in FIGURES 1, 2 and 3 may also be provided with two distinct input couplings, each connected with a separate source of microwave power. For instance, one signal may come from a reception antenna and the other from a local oscillator at a neighboring frequency, in which case the device functions as a mixer and yields an I.-F. signal at the difference frequency which can be amplified by conventional means.

The principle of field emission bunching may also be utilized in single cavity devices as illustrated in FIGURE 4. The device illustrated in FIGURE 4 includes a resonant cavity 70 having slotted upper and lower walls 72 and 74, respectively. A field emission cathode structure is employed and comprises a field emission cathode 76 having either one or several projections or needles 78. The cathode structure is inserted into the slotted lower wall 74 of resonant cavity 70 so that at least a portion of the surface of the needle 78 projects into the cavity.

The slot formed in the upper wall 72 of the cavity is provided with a suitable grid structure which is transparent to the flow of electrons and is effective to maintain the electric fields within the cavity 70.

A Faraday cage or electrode 80 is disposed in alignment with the slots formed in the upper and lower walls 72 and 74 of the resonant cavity 70 and is spaced in parallel relationship with the upper wall 72. The Faraday cage 80, in addition to collecting the electrons subsequent to their travel through the cavity 70, also acts as an ion trap.

A suitable potential is impressed on the cathode 76 by the application of a source of potential V_1 which is connected between the lower slotted wall 74 of the cavity 70 and the cathode 76.

The vacuum envelope indicated by dashed lines is intended to merely illustrate the evacuated regions of the device rather than represent the actual envelope configuration.

In operation, the voltage V_1 is applied to the cathode 76 and establishes a resultant electric field of a value sufficient to draw a continuous beam of electrons from the surface of the cathode needles 78.

The electrons drawn off from the cathode will be caused to travel along the path generally indicated by the dashed arrow. The device described and illustrated is a microwave oscillator. As a result of emission shot noise, the emitted electron beam contains noise components with a continuous frequency spectrum. The cavity is excited by the noise component whose frequency coincides with the resonant frequency of the cavity, and a regenerative process takes place in which the cavity field produces both velocity modulation and density modulation in the beam, which in turn transfer additional energy to the R.F. field in the cavity, when the cavity dimensions are adjusted to provide the correct beam transit time.

This device embodies the principles of the invention, which confer upon it two novel and advantageous properties. First, the cavity field creates density modulation in the beam not only as a result of velocity modulation but also directly at the cathode surface by emission bunching, thereby increasing the interaction between the beam and the cavity. Second, the device can be scaled down to very high frequency operation, because the field emission cathode is always small compared to cavity dimensions and is capable of supplying the relatively large currents required for oscillation at wavelengths in the millimeter range or even shorter wavelengths.

FIGURE 5 shows still another embodiment incorporating the principles of the invention, wherein the cavity 10 of the device of FIGURE 1 is replaced by a double gap floating drift tube cavity 90. The two interaction gaps are separated by a floating drift tube 92 positioned inside the cavity by supporting members such as 94, and provided with apertures 96 and 98 to permit passage of the electron beam produced by the field emission needles 100 mounted on a cathode structure 102. Suitable potential is impressed on the cathode by the application of a source of potential V_1. This embodiment of the invention, like the other embodiments previously described, uses the microwave frequency field at the nedles to yield a density modulated beam.

It will be readily apparent to those skilled in the art that, for a suitable choice of the height of the floating drift tube 92, the electron beam imparts to be electromagnetic field at the upper gap an amount of microwave energy which can be made either smaller or larger than the sum of the amount absorbed at the input gap and that dissipated by the cavity resonator. In the former case the embodiment of FIGURE 5 can be used as the input structure of a two-cavity device embodying the principles of the invention and suited to the amplification, frequency conversion, amplitude modulation or harmonic generation of microwave frequency signals. In the latter case the embodiment of FIGURE 5 constitutes an oscillator which can be used for the generation of electromagnetic radiation at microwave frequencies.

Since the structure illustrated in FIGURE 5 is a component fo a more inclusive system, no envelope is shown.

According to the provisions of the patent statutes, we have explained the principles and mode of operation of our invention, and have illustrated and described what we now consider to represent its best embodiments. However, we desire to have it understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically illustrated and described.

What is claimed is:

1. A microwave transducer comprising a resonator apertured for the passage of an electron beam thereacross, electrical energy input and output means for said resonator, field emission cathode means positioned to direct across said resonator a beam of electrons, and means for effecting field mission in the form of electron bunches directly upon emission from said field emission cathode and at a frequency in resonance with said resonator.

2. A microwave transducer as defined in claim 1 wherein said last mentioned means includes an alternating potential in resonance with said resonator.

3. A microwave transducer as defined in claim 1 wherein the input to said resonator is at substantially constant potential.

4. A microwave transducer as defined in claim 1 wherein said resonator includes a first and a second resonant cavity.

5. A microwave transducer as defined in claim 4 wherein said input means is coupled directly to said first resonant cavity and said output means is coupled directly to said second resonant cavity.

6. A microwave transducer as defined in claim 1 wherein said field emission cathode means is provided with a plurality of individual projections.

7. A microwave transducer as defined in claim 4 wherein the first and second resonant cavities are in juxtaposed relation.

8. A microwave transducer comprising a resonator including a first and a second resonant cavity, said resonator being apertured for the passage of electrons therethrough, electrical energy input means for establishing an oscillating electric field within said first resonant cavity, electron transparent means for confining said oscillating field within said first cavity, field emission cathode means disposed to deliver a beam of electrons across said resonator through said first and second cavities whereby the beam of electrons is bunched upon emission from said field emission cathode at the frequency of said oscillating field, and electrical enregy output means coupled to said second cavity for withdrawing energy from said resonator.

9. A microwave transducer comprising a resonant cavity apertured for the passage of an electron beam thereacross, a field emission cathode means positioned to direct a beam of electrons across said cavity whereby the beam of electrons is bunched upon emission from said field emission cathode at a frequency in resonance with said cavity, and electrical output means for withdrawing energy from said cavity at the resonant frequency thereof.

References Cited in the file of this patent

UNITED STATES PATENTS

2,217,448	Muller	Oct. 8, 1940
2,264,541	Mahl	Dec. 2, 1941
2,446,572	Bull	Aug. 10, 1948
2,513,933	Gurewitsch	July 4, 1950
2,591,316	Strutt et al.	Apr. 1, 1952
2,641,733	Harris et al.	Jan. 9, 1953
2,700,743	Park	Jan. 25, 1955
2,792,524	McArthur	May 14, 1957
2,911,560	Heil	Nov. 3, 1959
2,916,668	Dyke et al.	Dec. 8, 1959