April 4, 1950 J. A. MORTON ET AL 2,502,531

ELECTRON DISCHARGE DEVICE

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FIG. 1

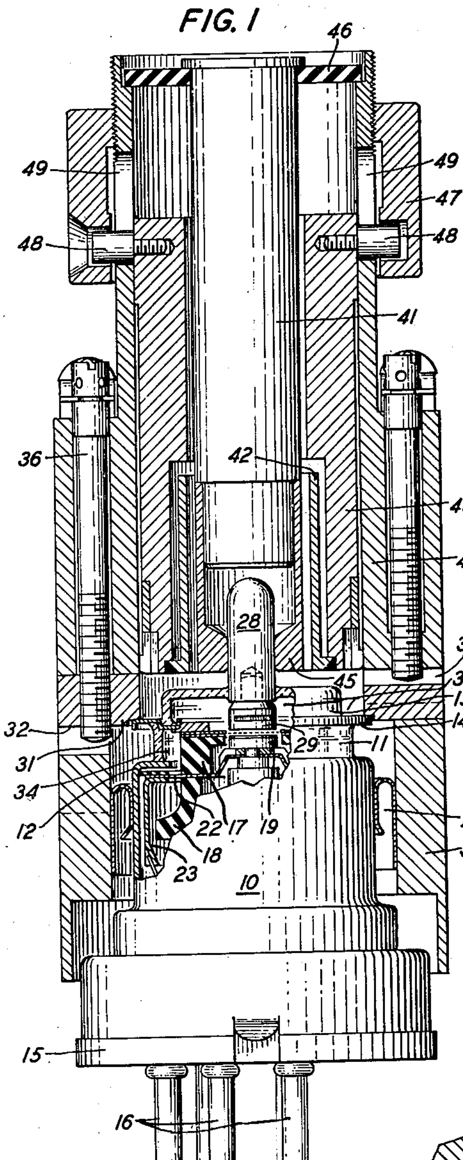


FIG. 2

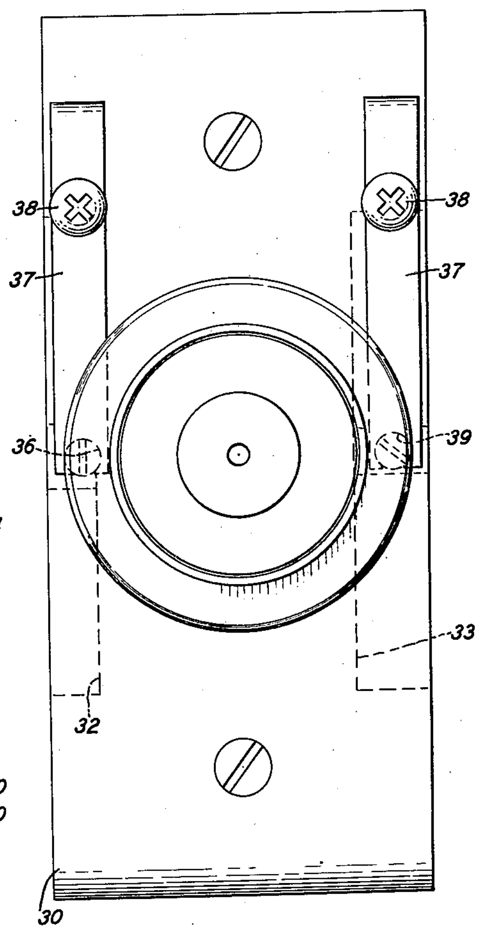
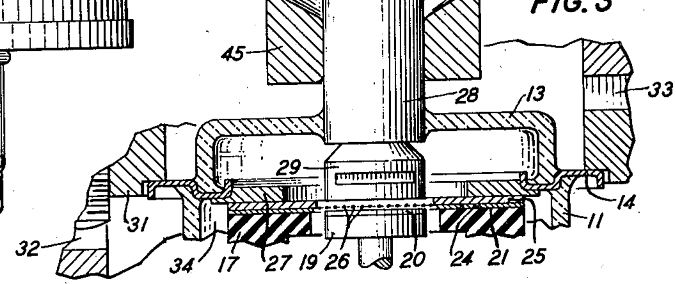


FIG. 3



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ELECTRON DISCHARGE DEVICE

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FIG. 4

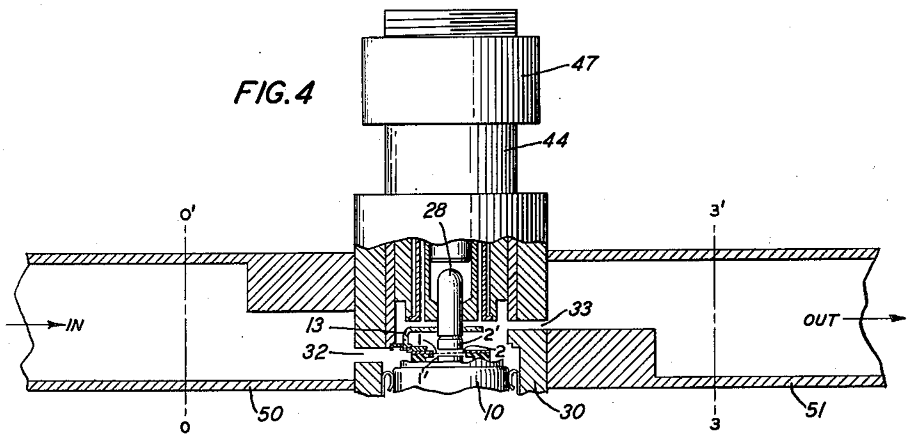


FIG. 5

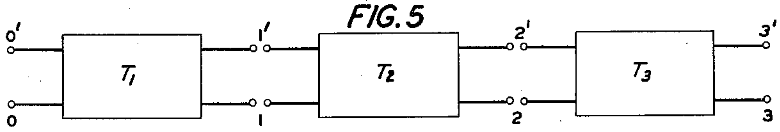


FIG. 6

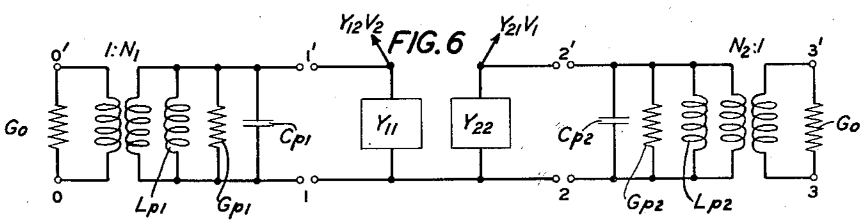


FIG. 7

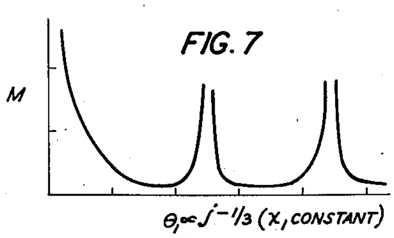


FIG. 8

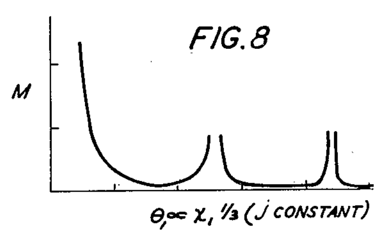


FIG. 9

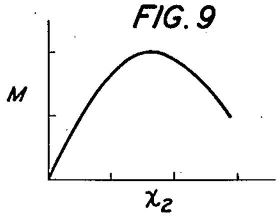
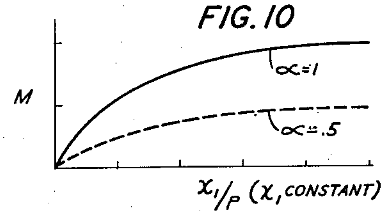


FIG. 10



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UNITED STATES PATENT OFFICE

2,502,531

ELECTRON DISCHARGE DEVICE

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Application January 6, 1949, Serial No. 69,564

4 Claims. (Cl. 315—5)

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This invention relates to electron discharge devices of the space charge type and more particularly to such devices especially suitable for use as broad band microwave amplifiers.

Two common performance desiderata for amplifiers are large gain and substantial uniformity of gain over a wide range of frequencies. As will be pointed out presently, a figure of merit for evaluating the performance of an amplifier is the gain-band product, which may be defined broadly here as a measure of the frequency band over which a gain of at least a specified magnitude is obtained.

For relatively low frequencies, including frequencies corresponding to wavelengths of a substantial part of a meter, the device parameters and the correlation thereof determining the gain and the gain variation with frequency are now fairly well known. However, for frequencies in the microwave region, say frequencies of about 1000 megacycles and higher, although many of the device parameters and the broad qualitative relation thereof entering into the determination of the performance may be known, the operating characteristics of microwave space charge type discharge devices of presently known constructions are far below obviously desirable standards. For example, to the best of applicants' knowledge, the maximum gain-band product for the best devices of prior art constructions is about 65 megacycles per second at frequencies of the order of 1000 megacycles, the gain being of the order of 13 decibels at 1000 megacycles and 3 decibels down at 998.4 and 1001.6 megacycles.

One general object of this invention is to improve the performance of space charge type electron discharge devices. More specifically, one object of this invention is to attain a substantially maximum gain-band product for broad band microwave amplifiers.

In one illustrative embodiment of this invention, a discharge device comprises a cathode, a control electrode or grid and an anode having juxtaposed parallel plane surfaces. The device is particularly adapted for use in the so called grounded grid or grid return type of circuit, with wave-guide input and output circuits.

It has been ascertained that the performance of such a device is determined uniquely by the transadmittance, active and passive output capacitance, input conductance, and input loss conductance. It has been ascertained further that the physical parameters of the discharge device can be correlated consistent with practical considerations and mechanical and thermal limitations so that a maximum figure of merit, specifically a maximum gain-band product is realized.

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The improved performance obtained by the invention may be appreciated from the fact that in specific devices of the construction hereinafter described gain-band products of about 1800 megacycles per second at frequencies of the order of 4000 megacycles per second, the gain being 10 at 4000 megacycles and 3 decibels down at 3910 and 4090 megacycles, have been obtained consistently.

In accordance with one broad feature of this invention, in a space charge type wide band amplifier, the significant parameters are correlated so that the gain-band product is substantially maximized whereby optimum performance is realized.

In accordance with another feature of this invention, in such a discharge device, the cathode current density and the electrode construction and spacing are made such that the electronic figure of merit, as hereinafter defined, is substantially a maximum.

In accordance with a further feature of the invention, is a discharge device of the general construction described hereinabove, the portion of the enclosing vessel significantly affecting the passive part of the output capacitance is so constructed and associated with the anode that the ratio of the passive to active parts of the output capacitance is minimized.

The invention and the above-noted and other features of this invention will be understood more clearly and fully from the following detailed description with reference to the accompanying drawing in which:

Fig. 1 is an elevational view, partly in section of an electron discharge device and associated circuit coupling elements therefor, illustrative of one embodiment of this invention;

Fig. 2 is a plan view of the apparatus illustrated in Fig. 1;

Fig. 3 is a fragmentary sectional view to an enlarged scale showing details of a portion of the discharge device and parts of the coupling to the input and output of the device;

Fig. 4 is a diagram illustrating one manner of association of the device and input and output wave guides therefor;

Fig. 5 is a block diagram analog of the combination illustrated in Fig. 4;

Fig. 6 is a schematic or equivalent circuit representation of this combination; and

Figs. 7 to 10 inclusive are graphs showing qualitatively the relation between certain parameters and a performance criterion for an electron discharge device of the construction illustrated in Fig. 1.

Referring now to the drawing, the electron discharge device illustrated in Fig. 1 is of the parallel plane electrode type adapted for grounded grid operation and comprises an evacuated enclosing vessel having a metallic portion 10, a cylindrical insulating portion 11 hermetically bonded or sealed to a flange 12 on the metallic portion 10 and a dished insulating portion 13, the several portions being in coaxial relation. The cylindrical and dished insulating portions 11 and 13 are bonded or sealed hermetically to opposite faces of an annular metallic disc 14, for example of Kovar, through which electrical connection may be established to the control electrode or grid, as will appear presently. The metallic portion 10 is joined hermetically to a base 15 having terminals 16 therein through which connection to the cathode may be made.

Mounted within the enclosing vessel is a unitary assembly, for example of the construction disclosed in the application Serial No. 777,312, filed October 1, 1947 of J. A. Morton and L. J. Speck, now Patent No. 2,455,381 granted Dec. 7, 1948 which comprises a pair of ceramic members 17 and 18 and a cathode supported from the member 17. As shown clearly in Fig. 3, the cathode includes a stem, for example of molybdenum having a disc head portion 19 to which a nickel disc 20 is affixed. The face of the disc 20 is coplanar with the surface 21 of the insulating member 17 and is coated with a good electron emitting material, such as a mixture of barium and strontium oxides. The cathode and the heater element therefor, not shown, are connected to the terminal prongs 16 by suitable conductors, also not shown. A radio frequency connection is established between the cathode and the vessel portion 10 by an annular metallic member 22 from which a metallic cylinder 23, coaxial with and in juxtaposition to the vessel portion 10 and defining a condenser therewith, depends.

Seated upon an annular spacer 24, in turn seated upon the surface 21 is a control electrode or grid which comprises an annular disc 25 and parallel wires 26 extending across the aperture in the disc and equally spaced from the emissive face of the cathode. The grid frame or disc 25 bears against a metallic ring 27 which is joined to the disc 14, whereby electrical connection to the grid or control electrode may be established.

The anode comprises a stem 28 hermetically sealed to the insulating portion 13 of the enclosing vessel, and a button 29 having its face toward the grid and cathode planar and parallel thereto. The stem 28 may be of Kovar and the button of copper.

The electron discharge device is positioned in a cylindrical recess in the body 30 of a metallic coupler, the vessel 10 being held coaxially within the recess by an annular metallic spring member 40 fitted to the vessel and the wall of the recess surrounding the vessel and the disc 14 bearing against a shoulder 31 in the coupler. The latter is provided with a pair of windows 32 and 33, the window 32 leading to the input gap between the cathode and grid by way of the resonator 34 and the window 33 leading to the output gap between the grid and the anode by way of the resonator 35. Suitable wave guides, not shown in Fig. 1, may be coupled to the input and output windows 32 and 33 respectively.

The input coupling including the window 32 and cavity 34 may be tuned and the coupling adjusted by a single screw 36 threaded into the body 30, projecting into the window 32 and longitudinally movable against the action of a lever spring 37 fixed adjacent one end by a screw 38. The output coupling including the window 33 and cavity 35 similarly may be tuned and the coupling adjusted by a single screw 39 extending into the window 33 and acting against a second lever spring 37.

Associated with the anode is a tuner and choke assembly including coaxial cylindrical metallic members 41, 42, 43 and 44, for tuning the grid-anode cavity. Specifically, the anode stem 28 is closely fitted into a central aperture in the end 45 of the member 41, the latter being supported from an insulating disc 46 which is fixed upon the outer end of the member 44. The member 43 carries the choke member 42 and is fitted slidably within the outer member 44. It is movable longitudinally by rotation of the adjusting nut 47 threaded to the outer member 44 and coupled to the member 43 by screws 48 which are slidable in slots 49 in the outer member. The juxtaposed portions of the members 41, 42 and 43 define a quarter wavelength choke joint which serves to prevent loss of energy from the output cavity. The latter is tunable by motion of the members 43 and 45.

An amplifier including a device such as illustrated in Fig. 1 and appropriate input and output circuits may be considered as composed of three transducers in tandem as illustrated in Figs. 4 and 5. The input transducer T_1 extends from a region 0—0′ in the input wave guide 50 where only the dominant wave exists to immediately adjacent the electron stream at the region 1—1′ at the grid-cathode gap. It includes the external input cavity portion and that portion of the discharge device up to the region 1—1′. Similarly, the output transducer T_3 extends from a region 3—3′ in the output wave guide 51 where only the dominant wave exists to immediately adjacent the electron stream at the region 2—2′ at the grid-anode gap. It includes the external output resonator portion and that portion of the discharge device up to the region 2—2′. The active transducer T_2 includes the electron stream and the active portions of the electrodes, that is, those portions which interact directly with the electron stream. It extends from the region 1—1′ to the region 2—2′.

For many practical cases, the combination of transducers may be considered as in Fig. 6 wherein the input and output transducers are represented by ideal transformers the turns ratios of which are real and independent of frequency and the shunt admittance of the device consists of lumped constant circuit elements. This representation is permissible for cases where the combined circuit has no series and only one shunt resonance near the operating frequency band. It is not strictly accurate for cases such as double tuned circuits having two resonances near the frequency band of interest. However, such complication of the circuit may be considered as a circuit broad-banding problem, the broad banding producing an improvement which does not depend upon the discharge device per se if there is no feedback. Thus, the single circuit configuration may be used as a basis for comparing performance of the discharge devices even in the complicated circuit cases.

Two performance criteria for amplifiers are the gain and the band width, the latter being defined as the magnitude of the frequency interval within which the gain is within some specified range. The band width as treated hereinafter will be considered as that interval within which the voltage gain is within a factor of

$$\frac{1}{n}$$

times the maximum, the maximum occurring at the approximate midband frequency. In general, the form of the band characteristic is dependent upon the Q of the input and output circuits. If the Q's of these circuits are equal, that is, the band is shaped equally by the input and output circuits, the gain decreases 6 decibels per octave in band width; if the Q of the input circuit is much smaller than that of the output circuit, the gain decreases 3 decibels per octave of band widening.

In an amplifier including a discharge device such as illustrated in Fig. 1 and operated in a grounded grid or grid return type of circuit, the Q of the input circuit is ordinarily much smaller than that of the output circuit. For this case, it can be shown that the amplifier performance can be evaluated from the relation

$$\Gamma_0^2 B=\left(\frac{|Y_{21}|^2}{4\pi G_{11}C_{22}}\right)\left(\frac{C_{22}}{C_{22}+C_{p2}}\right)\left(\frac{G_{11}}{G_{11}+G_{p1}}\right).F \quad (1)$$

where

Γ_0=insertion voltage gain at midband frequency.
B=band width, 3 decibels down.
Y_{21}=transfer admittance of the discharge device.
G_{11}=input conductance of the discharge device.
C_{22}=grid to anode capacitance of the discharge device.
C_{p2}=passive part of output circuit capacitance.
G_{p1}=loss conductance in input circuit.

For capacitances in micromicrofarads and transadmittance in micromhos, the gain band product Γ_0^2B, is in megacycles per second.

It will be noted that in the right-hand side of the equation, the first factor is the electronic figure of merit of the discharge device alone and is dependent upon only the parameters of the device; the second term is a degradation factor, due to the effect of adding passive capacitance to the active capacitance in the device; and the third term also is a degradation factor due to losses in the input circuit. The third factor can be minimized by the use of low loss insulating materials in the input path and low loss connections to the cathode and the grid.

The factor F is a band definition matching factor which depends only upon the characteristics of the input and output circuits and the band width. If the input and output circuits are matched and the band width is taken between the 3 decibels down points, this factor is unity.

The transfer admittance Y_{21} is substantially constant over band width usually employed; it varies slowly with frequency and approaches the transconductance at $f = 0$. In a device of the construction illustrated and described, a transconductance of the order of 50,000 mmhos at an anode circuit of about 25 megacycles is obtained.

The product Γ_0^2B is a figure of merit for the amplifier, that is, the greater this product the better the performance or rating of the amplifier. As has been pointed out herinabove, the third term or factor on the right-hand side of Equation 1 can be maximized. A large value for the second term obtains if C_{p2} is small in comparison to C_{22}. This will be discussed in some detail presently. The first term, as has also been pointed out hereinabove, depends upon only the parameters of the electron discharge region, all of which can be operated upon. Maximizing of this first term will be understood from the following considerations. Subject to the assumptions in and on the basis of the analysis for triodes presented in "Vacuum Tube Networks" by Llewellyn and Peterson, IRE Proceedings, March 1944, page 144, it can be shown that the intrinsic gain-band product for the discharge device may be expressed in two forms, to wit:

$$M=K\left[\frac{1}{X_1}\right]\left[\frac{F_1^2(\theta_1)}{\theta_1F_3(\theta_1)}\right][\theta_2F_2^2(\theta_2)\sqrt{V_p}] \quad (2)$$

$$=K'\left[\frac{1}{j}\right]\left[\frac{F_1^2(\theta_1)}{\theta_1^4F_3(\theta_1)}\right][\theta_2F_2^2(\theta_2)\sqrt{V_p}] \quad (3)$$

where

K and K' are functions only of frequency
X_1 is the cathode to grid spacing in centimeters
θ_1 is the cathode to grid transit angle in radians and equals

$$\frac{126}{\lambda}\left[\frac{X_1}{j}\right]^{1/3}$$

j is the cathode current density in amp./cm.^{2}
θ_2 is the grid-anode transit angle in radians and equals

$$\frac{6300X_2}{\lambda\sqrt{V_p}}$$

X_2 is the grid to anode spacing in centimeters
λ is the wavelength in centimeters
V_p is the anode direct voltage, and
$F_1(\theta_1)$, $F_2(\theta_2)$ and $F_3(\theta_1)$ are functions of the respective transit angles θ_1 and θ_2.

It will be noted that in Equation 2, the current density j is involved only in the second factor on the right-hand side, this factor being a function of θ_1, which as indicated above, varies as

$$\left(\frac{1}{j}\right)^{1/3}$$

The relationship between gain-band product and the current density j is illustrated qualitatively in Fig. 7. As is evident from this figure, maxima for the gain-band product appear for several values of θ_1, the first occurring at a point where θ_1 approaches 0, that is, where j is very large. The other maxima, it can be shown are of primary interest only in narrow frequency band cases and, hence, need not be investigated further here. Thus, the current density should be as large as possible, consistent of course, with long cathode life. In a device of the construction illustrated in Fig. 1, a current density j of 180 ma./cm.^{2} has been found satisfactory, the cathode life being several thousand hours.

It will be noted further from Equation 3 that the cathode to grid spacing X_1 is involved only in the second factor, which is a function of θ_1. The relationship between gain-band product and X_1 is illustrated qualitatively in Fig. 8 from which it will be seen that, as in the case of Fig. 7, several maxima are indicated. The first occurs where θ_1 approaches zero, which, of course, requires X_1 to be very small. The other maxima may be neglected here for the same reasons noted in the discussion of Fig. 7.

As a practical matter, it is mechanically impossible to make the parameter X_1 zero. Thus, in an actual device the cathode to grid spacing should be the smallest that can be obtained mechanically consistent with maintenance of parallelism of the cathode and grid and with reasonable tolerances. In connection with this matter, a further factor is to be noted. One of the assumptions in the analysis upon which relations 2 and 3 are based is that the grid dimensions are infinitesimally small in comparison to the cathode to grid spacing. In any real device, however, the grid dimensions are finite so that the gain-band product is degraded somewhat from the ideal, specifically by a factor F_4 which is a function of the grid transmission factor, α,

$$\alpha=\frac{P-d}{P} \tag{4}$$

and the ratio

$$\frac{X_1}{P}$$

where

P is the pitch distance between the grid wire centers, and

d is the grid wire diameter.

The relation between gain-band product and this function is illustrated qualitatively in Fig. 10, wherein the plots are for a fixed value of X_1. From this figure, it will be noted that the grid dimensions P and d should be as small as mechanically possible and in relation to produce a large value of α, specifically no less than 0.5.

In a typical device of the construction illustrated in Fig. 1, the optimum relations consistent with practical limitations are realized with a spacing X_1 of 0.0007 inch, a grid pitch P of 0.001 inch, and a grid wire diameter of 0.0003 inch. For these values, it will be noted, the grid transmission factor α is 0.7.

From relations 2 and 3, it will be noted that the anode to grid spacing X_2 is involved only in the third factor, which is a function of the output transit angle θ_2. The relation between gain-band product and X_2 is illustrated qualitatively in Fig. 9. It is characterized by a definite maximum which occurs at $\theta_2=2.9$ radians. This relatively large value of θ_2 for the maximum gain-band product is explainable by the facts that the capacitance C_{22} varies as

$$\frac{1}{X_2}$$

whereas the coupling coefficient of the electron stream to the gap at first decreases more slowly than the capacitance as X_2 is increased. Consequently the ratio

$$\frac{Y_{21}^2}{C_{22}}$$

in Equation 1 increases until the spacing X_2 becomes relatively large, that is, as θ_2 approaches 2.9 radians. It will be understood, of course, that θ_2 depends upon the anode voltage and the operating frequency. For example, in a device of the construction illustrated in Fig. 1, for a voltage of 250 volts and a frequency of 4000 megacycles per second, the optimum spacing X_2 is 0.022 inch. A large spacing may be advantageous in that by virtue of the correspondingly small capacitance, a high maximum frequency limit on the device is attainable. However, the circuit degradation factor, that is, the second factor on the right-hand side of Equation 1, may become enough larger to affect the smaller C_{22} as the capacitance C_{22} is decreased by increasing the spacing X_2.

Also, if the spacing X_2 is increased and the anode voltage maintained constant, in order that the anode may draw the desired current, it may be necessary that the grid be operated positive so that excessive grid current would obtain. Thus, in the construction of an actual device a number of practical considerations must be balanced in correlating the factors entering into the determination of the optimum spacing X_2. Some departure from the optimum value of θ_2 without too great a decrease in the gain-band product may be tolerated in some cases. As an indication of the decrease, it may be noted that in a device of the construction illustrated in Fig. 1 for which the optimum values of θ_2 and X_2 were as given above, values of θ_2 and X_2 of 1.6 radians and 0.012 inch respectively resulted in 78 per cent of the theoretical maximum gain-band product.

From the foregoing it is evident that the first factor in the right-hand side of Equation 1 can be maximized by correlation of the parameters of the discharge device. In general, to summarize, the cathode current density should be as large as possible, the grid-cathode spacing should be as small as is mechanically practical, the grid transmission factor should be large, and the output transit angle should be of the order of 2.9 radians.

It will be appreciated that maximizing of the first term on the right-hand side of Equation 1 consistent with the considerations mentioned, determines the value of the parameter C_{22}, which occurs in the second term as well as in the first. It is apparent that a large value for this second term requires that C_{p2} be small in comparison with C_{22}.

The term C_{p2}, as has been indicated hereinabove, is the passive part of the output circuit capacitance. A principal element entering into the determination of the magnitude of this term is the insulating or dielectric portion 13 of the enclosing vessel. This portion, it will be noted, is in the output resonator 35. The energy which will be stored in the dielectric portion 13 is a function of the coupling between this portion and the electric field within the resonator 35. To obtain a low value for this energy and, hence, a small value for C_{p2}, the insulating member 13 where it extends substantially parallel to the electric lines of the field within the resonator should be at a region of low field intensity. This condition is attained by the configuration of the member 13 illustrated in Figs. 1 and 3 together with the sealing of the member to the anode stem 28 adjacent the point upon the stem at which a voltage node appears during operation of the device. The field lines are essentially normal to the juxtaposed faces of the anode and grid at the output gap. However, beyond the gap the field lines are curved, specifically concave downward with respect to the gap, and the form thereof in the region of the insulating member 13 closely approximates the configuration of the member 13 shown in the drawing.

What is claimed is:

1. An electron discharge device comprising a control electrode structure including a planar grid, a cathode and an anode on opposite sides of said grid and having plane faces in juxtaposition thereto, the cathode current density and the electrode spacings being such that for the device the ratio

$$\frac{Y_{21}^2}{G_{11}C_{22}}$$

is substantially a maximum, Y_{21} being the transfer admittance, G_{11} the input conductance and C_{22} the grid to anode capacitance, means including said anode and grid defining an output resonator chamber, and a vessel enclosing said grid, cathode and anode including an insulating portion in said chamber extending between said anode and said control electrode structure, the configuration of said insulating portion being such that the ratio

$$\frac{C_{22}}{C_{22}+C_{p2}}$$

is substantially a maximum, C_{p2} being the passive part of the output capacitance.

2. A broad band microwave amplifier of the grounded grid type comprising a cathode having a plane electron emissive face capable when heated of producing an electron stream of density of substantially 180 ma./cm.^{2}, a control electrode having a plane grid portion opposite and parallel to said face and spaced of the order of 0.0007 inch therefrom, said grid portion having a transmission factor of the order of 0.7, and an anode having a plane surface opposite and parallel to said grid portion and spaced therefrom a distance such that within the operating band of the amplifier the grid to anode transit angle is of the order of 2.9 radians.

3. A broad band microwave amplifier of the grounded grid type comprising a planar grid, and a cathode and an anode on opposite sides of said grid and having plane faces in juxtaposition thereto, the cathode current density and cathode-grid and grid-anode spacings being such that for the amplifier the ratio

$$\frac{Y_{21}^2}{G_{11}C_{22}}$$

is substantially a maximum, Y_{21} being the transfer admittance, G_{11} the input conductance and C_{22} the grid to anode capacitance.

4. A broad band microwave amplifier of the grounded grid type comprising an enclosing vessel including a dished insulating portion and a substantially cylindrical insulating portion having one end opposite the edge of said dished portion, an annular metallic member between said insulating portions, said one end and said edge being sealed to opposite faces of said metallic member, a grid extending over the aperture in said metallic member and electrically connected to said member, said grid having a transmission factor of the order of 0.7, a cathode having a plane emissive face opposite one face of said grid and spaced therefrom of the order of 0.0007 inch, means including said cathode and grid defining an input chamber resonator, an anode including a stem extending through the base of said dished portion and sealed thereto, said anode having a plane face opposite the other face of said grid and spaced therefrom a distance such that in the operating band of the amplifier the grid to anode transit angle is of the order of 2.9 radians, and means including said anode and grid defining an output chamber resonator, said dished member conforming substantially to the electric fields in said output resonator at the region of said member, and the seal between said stem and said dished member being at substantially a voltage node region on said stem.

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