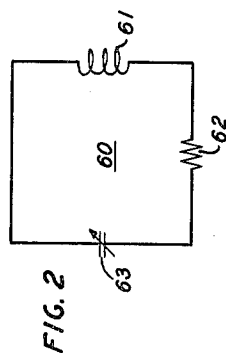
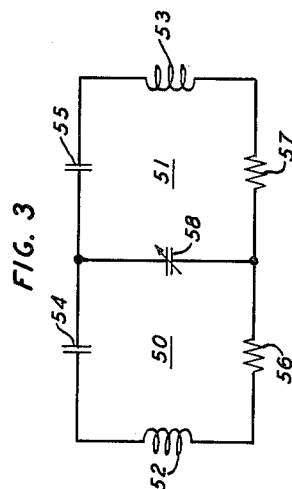
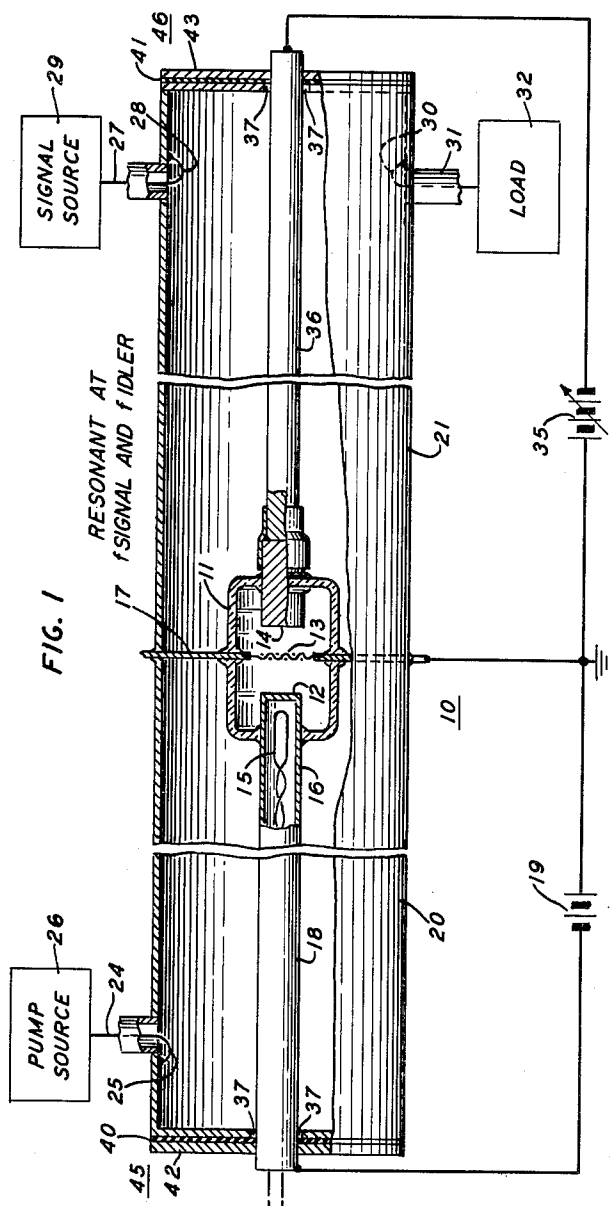


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T. J. BRIDGES ETAL
TRIODE PARAMETRIC AMPLIFIER

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TRIODE PARAMETRIC AMPLIFIER

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This invention relates to electron discharge devices and more particularly to such devices of the thermionic space-charge-limited control type.

In conventional space-charge-limited control type tubes, such as triodes, the tube may be thought of as operating essentially as a variable transconductance, that is, operation is dependent upon a control grid, the voltage of which, under dynamic or varying conditions, establishes a variable electric control field which changes the plate current in a predetermined manner for either generating or amplifying signal energy. The transconductance, designated g_m , is therefore an important figure of merit for a conventional vacuum tube because it gives an indication of the magnitude of plate current change per volt of grid-potential change. Disadvantageously, the transconductance parameter g_m is directly affected by the size of the tube and the cathode, generally decreasing as the frequency of operation for which the tube is designed increases and the tube and electrode sizes decrease. As a consequence, gain falls off markedly at the higher frequencies.

With constantly increasing interest in the use of the ultra-high frequency spectrum for electronic communication applications, the problems encountered in designing conventional space-charge-limited control tubes for such applications have likewise increased many fold. The maximum frequency at which such tubes can be used advantageously as amplifiers and oscillators has been determined heretofore by one or more of the following factors:

(1) The physical size and spacing of the tube electrodes, decreasing the spacing of the tube electrodes increases the interelectrode tube capacitances and lead inductances;

(2) Power losses resulting from the skin effect;

(3) I^2R losses caused by capacitance-charging currents;

(4) Limitations of the amount of heat that can be dissipated from electrodes of small dimensions; and

(5) Electron transit-time which, when it becomes a fractional part of the period of the signal, reduces the magnitude of the transconductance and causes it to have an imaginary component, as well as causes the input admittance to have a conductive or in-phase component that loads the cathode-grid circuit.

One significant approach taken to improve high frequency operation of these tubes has been to minimize further the interelectrode capacitances, lead inductances, resistance and radiation losses by utilizing built-in or sealed-off resonant circuits. Attention has therefore been directed toward constructing sealed-off tubes wherein the electrodes are an integral part of a closed cavity resonator or coaxial line resonator. Such tubes have become known as "disk-seal" tubes; two basic versions of which have become known as the "pencil" tube, preferably using coaxial line resonators, and the "lighthouse" tube utilizing cavity resonators.

Although power gain of the order of 10-14 decibels has been obtained at 3000 megacycles with present "lighthouse" tubes, for example, values of only the order of three or four decibels are more representative and there is considerable variation in the results obtained among tubes. This, in part, is the result of variations in the

transconductance from tube to tube resulting from the very close manufacturing tolerances. The higher values of gain are the result of feedback through the plate-cathode capacitance, which disadvantageously reduces the bandwidth. Accordingly, from a reproducible manufacturing standpoint, an upper frequency limit of approximately 1500 megacycles appears to be the best that can be obtained at present with "lighthouse" tubes of the above-described space-charge-limited control type. It is primarily because of the fact that further improvement on the aforementioned specialized tubes appears to have reached a limit, that attention in the electronic art has been diverted, to a large degree, to the fields of velocity modulation and solid state types of devices for high frequency applications. The latter devices, especially of the so-called parametric amplifier type, have exhibited low noise at very high frequencies.

Disadvantageously, however, solid state devices exhibit very low power gain and velocity modulation devices are generally quite bulky and require high voltages, with many versions of the latter type necessitating costly and critical beam focusing arrangements. Accordingly, if the upper frequency limit of space-charge-limited control tubes could be raised substantially for a given power level in a reproducible manner, the many advantages of such tubes in regard to compactness, ruggedness and ability to produce high power would make their importance increase many fold in future high frequency electronic application.

It is therefore a general object of this invention to improve the gain at high frequencies in thermionic vacuum tubes of the space-charge-limited control type in a manner independent of the transconductance parameter.

It is a further object of this invention to improve the gain at high frequencies in such tubes in a more reproducible manner.

It is an additional object of this invention to achieve high frequency amplification or oscillation in a tube of uniquely simple and practical construction.

These and other objects of our invention are realized in one illustrative embodiment thereof wherein a vacuum tube triode of the space-charge-limited control type comprises an evacuated envelope within which are positioned a cathode, grid and plate, spaced and biased with respect to each other so as to establish space-charge regions therebetween. Two cavity resonators are associated, respectively, with the cathode-grid and grid-plate regions of the triode. Thus far described, the illustrative embodiment bears a superficial structural resemblance to a typical "lighthouse" tube described above. However, as will presently be seen, there is a sharp demarcation between the instant invention and any of the aforementioned tubes in terms of both structure and function.

Our invention is based upon the discovery that amplification or generation of oscillatory energy can be effected in a space-charge-limited control triode designed for high frequency operation by utilizing the principles of parametric amplification. Briefly, these principles are based upon the time-varying change of a capacitive reactance, induced by the application of radio-frequency power, referred to hereinafter as pumping power, at a frequency preferably twice the frequency of the signal to be amplified, to a space-charge medium defining the dielectric region of the effective variable capacitor.

The instant invention makes use of the fact that the dielectric constant of a medium containing space-charge is a function of the space-charge density and, therefore, the values of the interelectrode capacitances of an electron tube are themselves dependent upon the amount of space-charge present between the electrodes. This characteristic is advantageously utilized in a unique manner in accordance with the principles of this invention to

achieve parametric amplification. More specifically, the space-charge density in the grid-plate region of the triode is modulated in a manner which gives rise to a time-varying grid-to-plate capacitance which is used as the requisite reactive element. The time-varying grid-to-plate capacitance presents a frequency dependent negative resistance therebetween, the largest negative value of which occurs at the signal frequency. If the value of the negative resistance is adequate and the load is made one of the positive resistances, the small total resistance of the system results in large signal amplification being realized with a low noise content.

In accordance with an aspect of this invention, parametric amplification is effected by modulating the space-charge density in the grid-plate region of the triode through the expedient of applying radio-frequency pump power, preferably at a frequency twice the signal frequency, to the resonator associated or communicating with the cathode-grid region of the tube and applying radio-frequency signal energy to the resonator associated with the grid-plate region of the tube. The parametrically amplified signal energy is abstracted from the grid-plate cavity resonator.

In accordance with another aspect of this invention, the space-charge density in the grid-plate region is increased to a magnitude sufficient to effect optimum parametric amplification by applying a negative potential to the plate electrode. This has the effect of confining more electrons within the grid-plate region at any given time and, hence, increases the space-charge density in this region. The amplifier or oscillator may be operated in either the degenerate or non-degenerate mode, as discussed in greater detail hereinafter. Oscillation or amplification can be obtained depending on the magnitude of the pumping power with no external feedback circuitry required, such as in the aforementioned tubes of conventional design. In addition, operation of the novel triode described herein is not dependent on the transconductance parameter as in conventional space-charge-limited tubes; in fact there is no transconductance in the instant tube since a negative plate is utilized and, hence, no plate current is drawn.

Accordingly, it is a feature of this invention that a thermionic vacuum tube of the space-charge-limited control type depends upon a time-varying capacitance instead of upon transconductance for producing amplification.

It is a more specific feature of this invention that radio-frequency pump energy of a predetermined frequency is applied to the cathode-grid region in a manner whereby the space-charge density of the grid-plate region is modulated resulting in a time-varying grid-to-plate capacitance which in turn produces a negative resistance.

It is another feature of this invention that signal energy of a second predetermined frequency is applied to the cavity resonator associated with the grid-plate region of such a tube.

It is a further feature of this invention that a negative potential is applied to the plate for enhancing the modulated space-charge density in the grid-plate region and thereby increasing the magnitude of the time-varying grid-to-plate capacitance of such a tube.

A complete understanding of this invention and of the above-noted and other features thereof may be gained from a consideration of the following detailed description taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a cross-sectional view of an illustrative embodiment of this invention;

FIG. 2 is a schematic resonant circuit equivalent to the device depicted in FIG. 1 when operating in the degenerate mode; and

FIG. 3 is a schematic resonant circuit equivalent to the device depicted in FIG. 1 when operating in the non-degenerate mode.

Referring now to FIG. 1, there is depicted an illustrative embodiment of a vacuum tube triode 10 embodying

the principles of this invention. Positioned within an evacuated envelope 11, which for example may be of glass or any other suitable wave permeable material, is an indirectly heated cathode 12, control grid 13 and an anode 14, these three elements being axially aligned and in spaced relationship. The cathode 12 is heated by a suitable filament 15 positioned within a cylindrical heater sleeve 16, with the leads of the filament brought to the outside of the tube, as shown schematically, through a cylindrical member 18, of conductive material. The triode thus far described may take any basic known form of the close-spaced type designed for high frequency operation. The most important structural requirement of the triode utilized, in accordance with the principles of the instant invention, is that it have a foraminous grid structure which assures substantially complete passage of the electrons therethrough during transit toward the plate.

A first quarter wave coaxial cavity resonator 20, which preferably is of a highly conductive material, communicates with the cathode-grid region of the triode and a second coaxial cavity resonator 21 of similar material communicates with the grid-plate region of the triode. It is thus seen that the grid 13 provides a common boundary wall separating the two cavity resonators. A conductive disk 17 forms an extension of the grid 13 in the region between the envelope 11 and the outer common wall of the resonators 20 and 21. Grid 13 preferably is grounded, in accordance with the principles of this invention, as in a conventional grounded grid circuit. Accordingly, the cathode 12 is shown as being biased slightly negatively with respect to the grid by the voltage source 19.

The coaxial cavity resonator 20, in accordance with an aspect of this invention, is designed to be resonant at a frequency preferably twice the resonant frequency of the cavity resonator 21 when operating in the degenerate mode. As will be further described hereinafter, the device of FIG. 1 may also be operated in the non-degenerate mode wherein the signal frequency is not exactly one-half the pump frequency. Cavity resonator 20 has applied thereto, through a suitable transmission line 24 and coupling loop 25, radio-frequency pump power from a source 26. Similarly, signal energy is applied to cavity resonator 21 through a transmission line 27 and a coupling loop 28 from a signal source 29. It is to be understood of course that the device depicted in FIG. 1 may be also operated as an oscillator in accordance with the principles of this invention, in which case there is no signal source associated with the resonator 21. The amplified output power or generated oscillatory energy is abstracted from cavity resonator 21 by way of a coupling loop 30 through a transmission line 31 to a suitable load 32. Inasmuch as the tube acts as a negative resistance during operation as a parametric amplifier, in accordance with this invention, the load should comprise a suitable positive resistance providing a close impedance match in order to obtain optimum performance.

In accordance with our invention, parametric amplification is dependent upon causing the grid-to-plate capacitance of the triode to act as a time-varying capacitance in response to the modulation of the space-charge density in this region at the pump frequency. In order to insure a maximum variation of this capacitance effect, which concomitantly assures the realization of optimum gain, the plate 14 of the triode, in accordance with an aspect of this invention, is biased negatively with respect to the grid 13. This results in the electrons in the grid-plate region being reflected back to the grid thereby increasing the number of electrons in this region at any given time and, as a consequence, increasing the space-charge density in this region. The plate 14 is maintained at the desired negative potential with respect to the grid 13 by means of the negative voltage applied thereto from the adjustable voltage source 35 through a solid cylindrical member 36

of good conductivity, which extends axially through the cavity resonator 21 and projects slightly from one end thereof for facilitating a direct-current connection thereto.

The extreme opposite ends of coaxial resonators 20 and 21 each forms a plate of a bypass capacitor. Two mica spacers 40 and 41 separate the end walls of cavity resonators 20 and 21, respectively, from two conductive condenser plates 42 and 43. Air gaps 37 separate the end walls of cavity resonators 20 and 21 from the conductive cylindrical members 18 and 36, respectively, which pass therethrough. The end wall of cavity resonator 20 together with the mica spacer 40 and the conductive plate 42 thus comprises a cathode-grid bypass or isolating capacitor 45. The end wall of cavity resonator 21 together with the mica spacer 41 and the conductive plate 43 comprises a grid-plate bypass capacitor 46.

Our invention can thus be seen to be distinct from prior conventional space-charge-limited tubes, such as of the "lighthouse" and "pencil" types, in the following particulars:

(1) By reason of the resonant frequencies of the cavity resonators associated, respectively, with the cathode-grid and grid-plate regions of the triode;

(2) By reason of the utilization of radio-frequency pump power applied to the cathode-grid region to effect amplification of the signal energy;

(3) By reason of both applying and abstracting signal energy from the cavity resonator associated with the grid-plate region of the triode when operating as an amplifier; and

(4) By reason of the utilization of a negative plate potential with respect to the grid for increasing the space-charge density of the grid-plate region of the triode.

Our novel triode also distinguishes functionally over conventional triodes. More specifically, arrangements in accordance with our invention depend for amplification on a variable capacitance effect rather than a variable transconductance parameter utilized heretofore in conventional triode amplifiers or oscillators. The variable capacitance established between the grid and plate, which produces a negative resistance across the tube in this region, is effected by modulating the space-charge density in the grid-plate region through the expedient of applying pump power, preferably at twice the signal frequency, to the cathode-grid region of the triode. The time-varying grid-to-plate capacitance resulting from this modulation is thus utilized as the necessary reactance element required in accordance with parametric amplification.

As previously noted, a parametric amplifier, in accordance with the principles of this invention, may be operated either in a degenerate or a non-degenerate mode. In the degenerate mode of operation, only one resonant circuit 60 is used as depicted in the equivalent circuit of FIG. 2. Since both the signal and idler frequencies in this mode of operation are equal under ideal degenerate conditions, this circuit is resonant at one-half the pump frequency and can be considered as comprising an inductor 61, resistor 62 and a variable capacitor 63. The condition at which amplification ceases and oscillation commences with this circuit is given by the expression

$$\frac{\Delta C}{C} \geq \frac{2}{Q_{\text{intrinsic}}}$$

where ΔC represents the variation in capacitance from the average capacitance normally existing between the grid and plate at the triode when the space-charge density in this region is unmodulated. $Q_{\text{intrinsic}}$ represents the Q of the grid-plate cavity resonator 21 at the signal frequency, a value of 400 or higher being easily obtained in practice. C is the average capacitance of variable capacitor 63. Phase-locked pump and signal sources are desirable for stable operation in the degenerate mode since a beat frequency is observed when the signal frequency is not exactly one-half the pump frequency.

FIG. 3 depicts an equivalent resonant circuit for the tube of FIG. 1 when operated in the non-degenerate mode.

In this mode of operation, two resonant circuits 50 and 51, can be considered as comprising inductors 52, 53, capacitors 54, 55 and resistors 56, 57, respectively. These resonant circuits are coupled by a capacitive reactance, namely, the variable capacitor 58, which represents the modulated space-charge density in the grid-plate region of the tube. This equivalent variable capacitor 58 is driven at the pump frequency. One of the two resonant circuits resonates at the signal frequency while the other circuit resonates at an idler frequency. These frequencies are all distinct and are related by the frequency relationship $f_{\text{pump}} = f_{\text{signal}} + f_{\text{idler}}$. In this mode, since the signal frequency is not exactly one-half the pump frequency, it is seen that the grid-plate cavity resonator 21 of the triode of FIG. 1 must be designed to be resonant at both the signal and idler frequencies, and consequently, must be capable of supporting electric fields corresponding to these frequencies. Such dual resonant requirements are readily satisfied by design expedients well known in the cavity resonator art. For examples of such design expedients, see, for example, Proceedings of the IRE, June 1958, p. 1301, columns 2 and 3; QST, March 1959, pp. 35 through 39; and QST, August 1959, pp. 11 through 16. In the arrangement of FIG. 1, resonant circuit 21 is resonant at the idler frequency as well as the signal frequency, and can be made so by any one of the expedients shown in the above-mentioned articles, or by other expedients known in the art. Tuning screws and the like have not been shown because they are not necessary to the achievement of dual resonance, see, for example, page 35 of the March 1959 QST article.

The condition necessary for oscillation in the non-degenerate mode is given by the expression

$$\frac{\Delta C}{C} \geq \frac{2}{\sqrt{Q_1 Q_2}}$$

where Q_1 and Q_2 represent the Q 's of the grid-plate cavity resonator 21 at the signal and idler frequencies, respectively. Of course, it is to be understood that amplification is effected for any operating condition where

$$\frac{\Delta C}{C}$$

is less than the threshold value stated above for oscillation, but greater than zero. Obviously, where

$$\frac{\Delta C}{C}$$

is zero, that is, where ΔC is zero, there is no amplification since there is no variation in C , such variation being necessary for parametric amplification. It is readily apparent that maximum amplification is achieved for a value of

$$\frac{\Delta C}{C}$$

just less than the threshold value.

From the foregoing, it is readily apparent that the amplifier of the present invention operates in a mode in which the limitations on the gain of the tube are not dependent upon transconductance. Inasmuch as transconductance is eliminated as a factor, the high gain obtainable with the tube of the present invention is more reproducible from tube to tube.

It is to be understood that the specific embodiment described herein is merely illustrative of the general principles of this invention. Various other structural arrangements and modifications may be devised in the light of this disclosure by those skilled in the art without departing from the spirit and scope of this invention.

What is claimed is:

1. In an electron discharge device, an evacuated envelope, a cathode, foraminous grid and plate positioned, respectively, within said envelope in spaced relationship and biased with respect to each other for establishing space-charge regions therebetween, said plate being at a nega-

tive potential with respect to said grid, cathode cavity resonator means resonant at a first predetermined frequency communicating with the cathode-grid space-charge region of said device, plate cavity resonator means resonant at a second predetermined frequency communicating with the grid-plate space-charge region of said device, said first and second predetermined frequencies being related to satisfy the condition $f_p = f_s + f_i$, where f_p is said first predetermined frequency, f_s is said second predetermined frequency, and f_i is an idler frequency, means for applying signal energy at said second predetermined frequency to said plate cavity resonator, means for varying the grid-plate capacitance of said device at said first predetermined frequency for producing parametric amplification of said signal energy, said means including said cathode cavity resonator and means for applying radio-frequency pumping energy thereto at said first predetermined frequency for modulating said grid-plate space-charge density, and means for abstracting the amplified signal energy from said plate cavity resonator.

2. An electron discharge device comprising a cathode, foraminous grid, and anode, cathode cavity resonator means including said grid, anode cavity resonator means including said grid, means for varying the grid-anode capacitance comprising means for applying pump energy to said cathode cavity means, said cathode cavity resonator being resonant at the frequency of the pump energy, means for abstracting output energy from said anode cavity resonator means, said anode cavity resonator means being resonant at the frequency of said output energy, the pump energy frequency and the output energy frequency satisfying the condition $f_p = f_s + f_i$, where f_p is the pump energy frequency, and either or both f_s and f_i are the output energy frequencies, and means for maintaining said anode at a negative potential with respect to said grid.

3. In an electron discharge device, an evacuated envelope, a cathode, foraminous grid and plate positioned, respectively, within said envelope in spaced relationship and biased with respect to each other for establishing space-charge regions therebetween, said plate being at a negative potential with respect to said grid, cathode cavity resonator means resonant at a first predetermined frequency communicating with the cathode-grid space-charge

region of said device, plate cavity resonator means resonant at a second predetermined resonant frequency communicating with the grid-plate space-charge region of said device, said first predetermined frequency being twice said second predetermined frequency means for varying the grid-plate capacitance of said device at said first predetermined frequency, said means including said cathode cavity resonator and means for applying radio-frequency pump energy thereto at said first predetermined frequency for modulating said grid-plate space-charge density, and means for abstracting energy at said second frequency from said plate cavity resonator.

4. In an electron discharge device, an evacuated envelope, a cathode, foraminous grid and plate positioned, respectively, within said envelope in spaced relationship and biased with respect to each other for establishing space-charge regions therebetween, said plate being at a negative potential with respect to said grid, cathode cavity resonator means resonant at a first predetermined frequency f_p communicating with the cathode-grid space-charge region of said device, plate cavity resonator means resonant at second and third predetermined frequencies f_s and f_i , respectively, where $f_p = f_s + f_i$, communicating with the grid plate space-charge region of said device, means for varying the grid-plate capacitance of said device at said first predetermined frequency, said means including said cathode cavity resonator and means for applying pump energy thereto at said first predetermined frequency, and means for abstracting energy at said second frequency from said plate cavity resonator.

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