

Oct. 11, 1949.

L. C. PETERSON

2,484,643

HIGH-FREQUENCY ELECTRONIC DEVICE

Filed March 6, 1945

5 Sheets-Sheet 1

FIG. 1

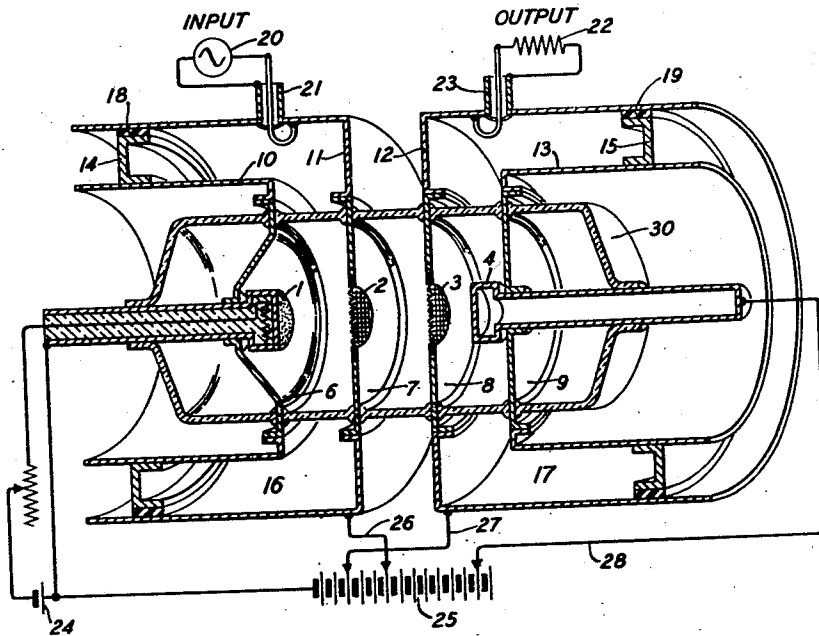
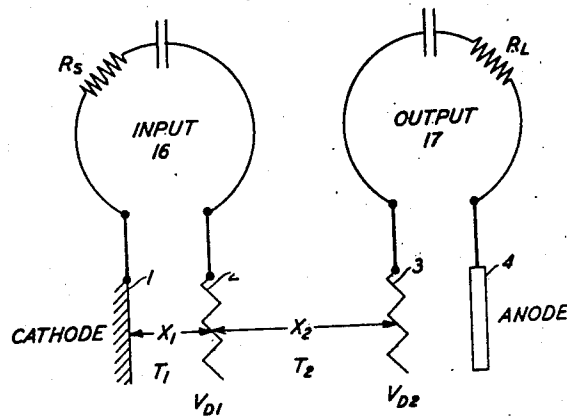


FIG. 2



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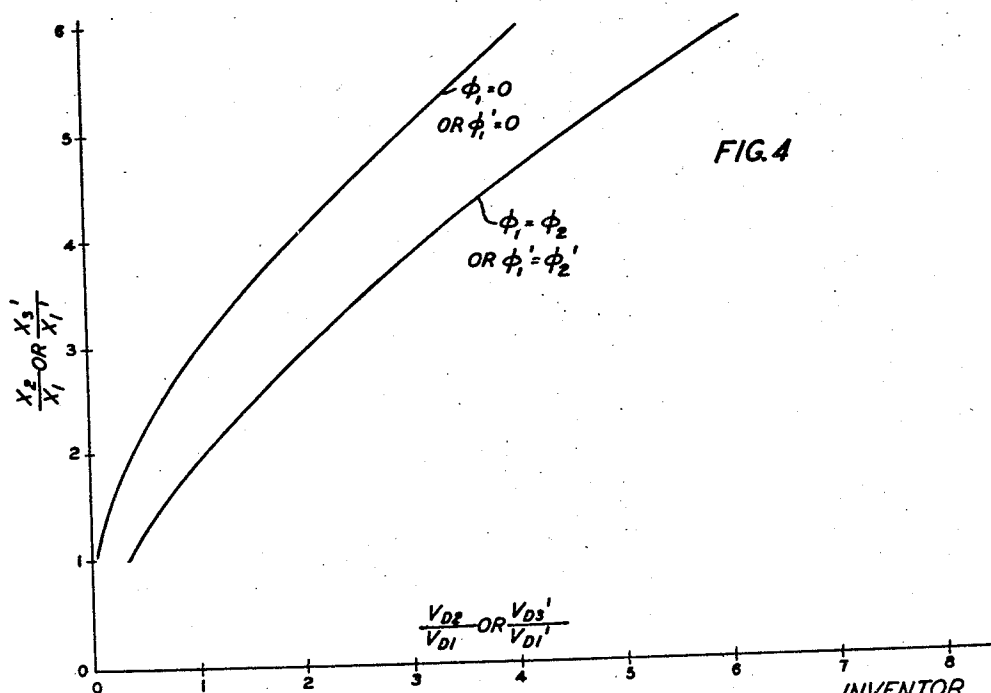
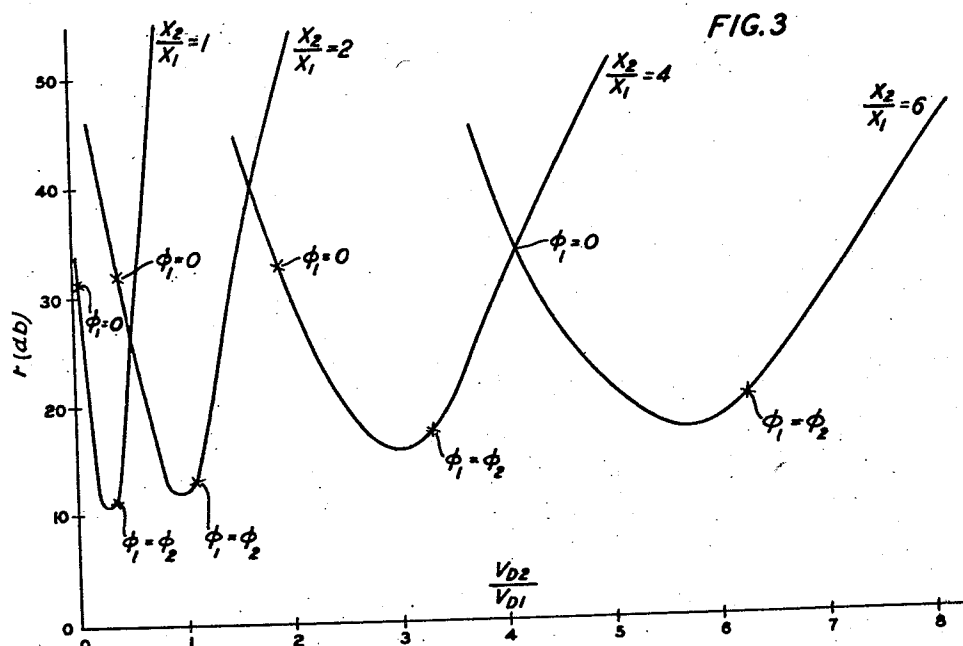
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HIGH-FREQUENCY ELECTRONIC DEVICE

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5 Sheets-Sheet 2



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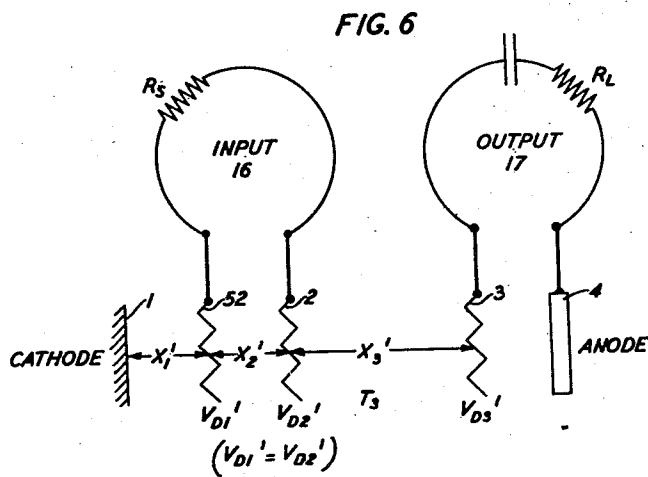
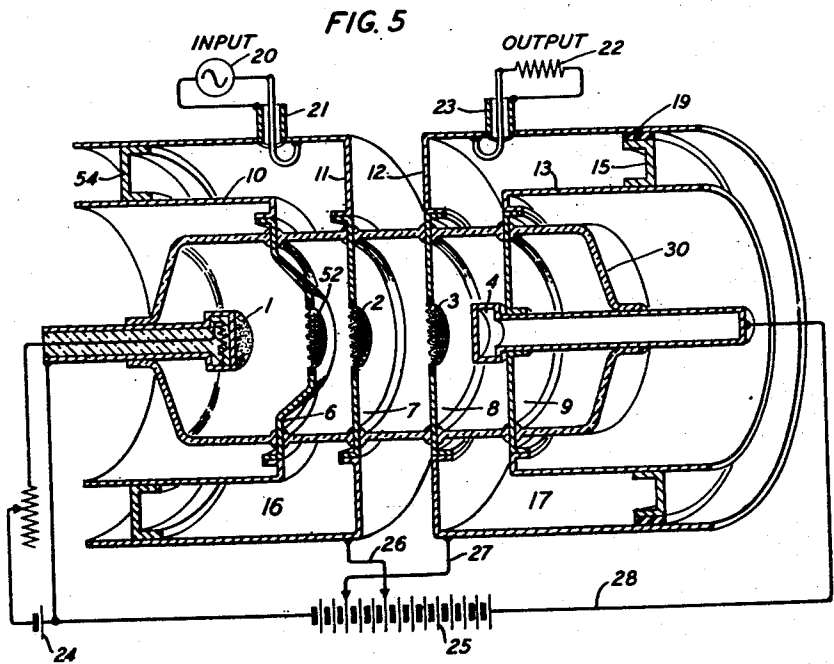
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HIGH-FREQUENCY ELECTRONIC DEVICE

Filed March 6, 1945

5 Sheets-Sheet 3



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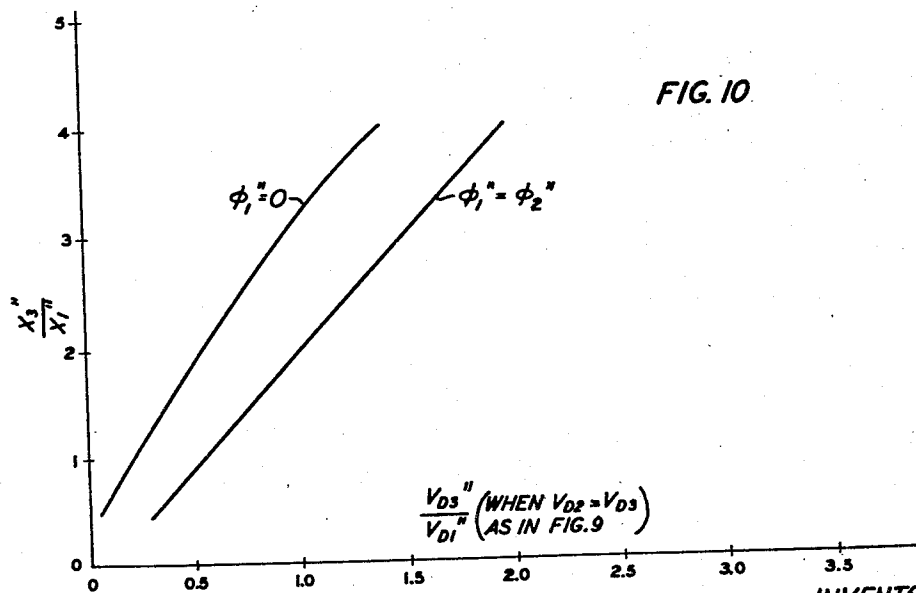
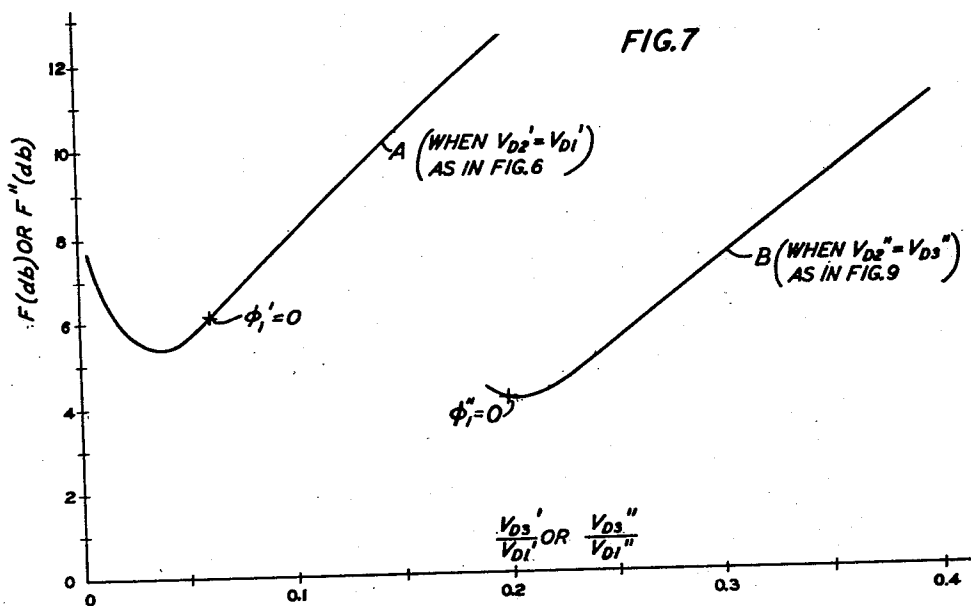
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HIGH-FREQUENCY ELECTRONIC DEVICE

Filed March 6, 1945

5 Sheets-Sheet 4



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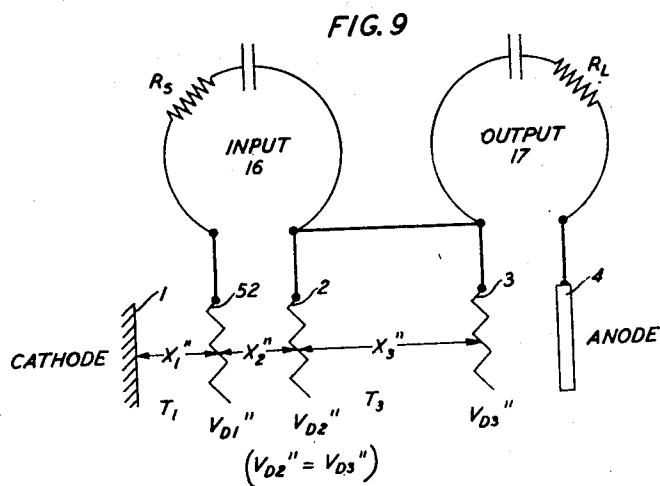
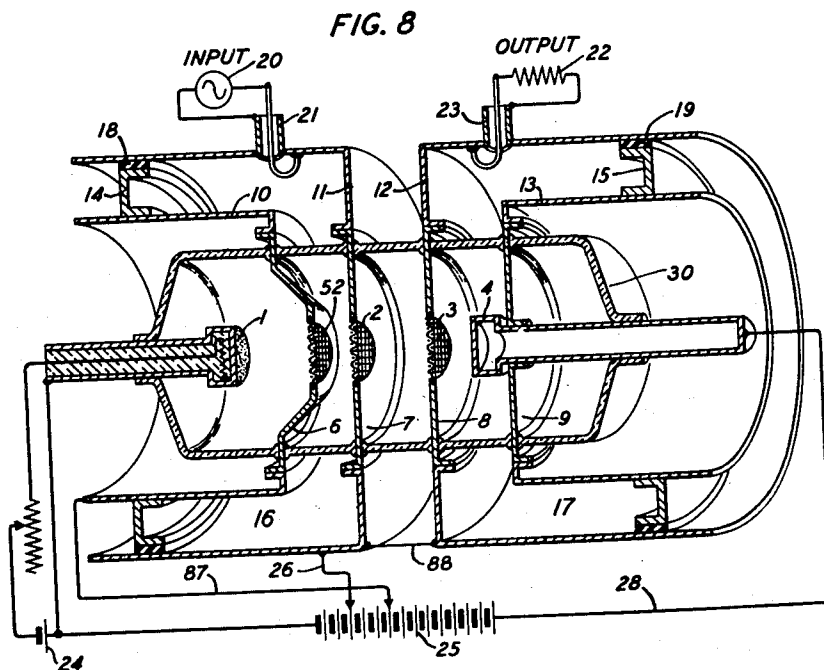
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HIGH-FREQUENCY ELECTRONIC DEVICE

Filed March 6, 1945

5 Sheets-Sheet 5



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UNITED STATES PATENT OFFICE

2,484,643

HIGH-FREQUENCY ELECTRONIC DEVICE

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Application March 6, 1945, Serial No. 581,290

3 Claims. (Cl. 315-39)

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This invention relates to high frequency translating devices of the electronic type, particularly such devices as high frequency amplifiers and radio receivers employing multi-element tubes and operating at frequencies where the effect of electron transit time may be an important factor.

An object of the invention is to make possible such devices having superior performance characteristics by virtue of a reduction in the interfering noise which originates in the electron tubes and tends to obscure the signal at the output of the device.

A related object is to make possible such devices having in operation a relatively high signal to noise ratio.

Another object is to make possible such devices having in operation relative low noise energy at the output terminals. In the use of high frequency devices such as amplifiers and radio receivers it is well known that an important limiting factor is the inherent noise which tends to obscure the signal desired at the output. Certain of this noise originates in the electron tubes due to irregularities in the electron stream. Random emission at the cathode and the interception of electrons by electrodes along the path of the stream are important sources of such irregularities. In addition to these fluctuations there are those in the external circuits to which the vacuum tube may be connected. These fluctuations, which have been called Johnson fluctuations, are caused by Brownian movements of electrons in conductors.

One proposed method of noise reduction has involved a favorable adjustment of the phase and magnitude of the input circuit impedance and the introduction of external impedances between the tube elements of such phases and magnitudes as to effect noise reduction.

Another proposed method of noise reduction is one in which a favorable electron transit time across the input region of the tube is employed.

Both of these methods have limitations and objectionable features.

According to this invention a still different method of minimizing noise is utilized, namely, that of adjusting the space-charge conditions over a portion of the electron path between the input and output regions in an appropriate manner. The nature of the invention will be more fully understood from the following description and the accompanying drawings of which:

Fig. 1 illustrates an embodiment of the invention in a high frequency amplifier employing cavity resonator input and output circuits and

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a tetrode type of tube operating on the space-charge control principle;

Fig. 2 is a schematic representation of the arrangement of Fig. 1 useful in explaining the invention;

Fig. 3 shows calculated performance curves giving values of Noise Figure for a typical arrangement such as that of Fig. 1;

Fig. 4 shows curves useful in determining the adjustment of a device such as either Figs. 1 and 2 or Figs. 5 and 6;

Fig. 5 illustrates an embodiment of the invention in a device somewhat similar to that of Fig. 1 but employing an electron gun type of tube operating on the velocity variation principle and in which the two control electrodes are at the same direct current potential;

Fig. 6 is a schematic representation of the arrangement of Fig. 5;

Fig. 7 shows calculated performance curves giving values of Noise Figure for typical arrangements such as those of Figs. 5 and 8 respectively;

Fig. 8 illustrates an embodiment of the invention in a device similar to that of Fig. 5 except that the two control electrodes are at different direct current potentials;

Fig. 9 is a schematic representation of the arrangement Fig. 8; and

Fig. 10 shows curves useful in determining the adjustment of devices such as that of Figs. 8 and 9.

Noise components from the several sources such as those mentioned above are statistically independent and enter into the total noise at the output of the device in different ways though they all reach the output as irregularities in the electron stream in the region where energy is transferred from it to the output circuit. Parts of the noise from irregularities originating at the cathode and at the control electrode excite the input circuit and are amplified by the tube. This component has sometimes been termed induced input noise. Other components are introduced farther along in the path of the electron stream. The so-called Johnson noise previously referred to originating in the circuit preceding the tube input is amplified with the signal as is any noise entering the device with the signal input. It is evident, therefore, that the minimum total noise at the output of the device is dependent upon the amount of Johnson noise at the input, how that is amplified and also upon the amount of noise originating within the device and how that is treated. In other words for similar

noise sources the output noise depends upon the amplification or gain of the device as a whole which applies to the input Johnson noise and also upon the amplification or other treatment of the internally generated noise. The output signal of course depends upon the over-all gain or amplification of the device. Since the relative freedom from noise may be an important if not controlling factor in determining the intelligibility of the signal it is obvious that a criterion of the utility of the device is not simply its capability to amplify or impart gain to the signal but rather involves its capability to do so without adding excessive interfering noise energy. Actually, within limits, the ratio between signal energy and noise energy at the output of the device is as important as magnitude of output signal. This fact is so recognized that a term Noise Figure has been employed to indicate the merit of signal translating devices such as amplifiers and radio receivers. This Noise Figure is essentially a measure of how much noise the device adds to the Johnson noise already present in the signal at the input. For a discussion of this term reference may be made to an article "Noise figures of radio receivers" by H. T. Friis, published in Proceedings of the I. R. E. for July 1944, pages 419-422. The Noise Figure (F) of a network is defined by Mr. Friis as the ratio of the available signal-to-noise ratio at its input terminals to the available signal-to-noise ratio at its output terminals. Thus a low Noise Figure or a high output signal-to-noise energy ratio is desirable. The applicant has found that in high frequency operation the Noise Figure of a vacuum tube (a form of network) may be reduced, or in other words, the effect of noise from sources within the tube in obscuring a signal may be minimized, by providing a proper space-charge condition within the tube.

To demonstrate this effect, mathematical expressions have been obtained for the Noise Figure by following the general procedure and type of analysis outlined in an article "Vacuum tube networks" by F. B. Llewellyn and L. C. Peterson, published in Proceedings of the I. R. E. for March 1944, pages 144-166. In this article expressions are obtained for the output of a vacuum tube network due to signal input. In order to obtain similar expressions for output due to noise sources within the network voltages and currents from the several such sources must be considered also and additional terms representing those impressed voltages must be included.

As has already been remarked these noise sources are: irregular emission from the cathode and random capture of electrons from the passing stream by electrodes through which it passes.

An important concept in carrying out the mathematical analysis referred to is that of equivalent noise voltage which may be defined as that fictitious noise voltage which when inserted in series with the signal generator impedance attached to a network input produces the same noise output as is produced by all the noise sources within the network. The importance of this concept is twofold. In the first place, a means is provided whereby the noise sources within the network are represented by a single equivalent noise source outside the network and, secondly, this noise source is placed exactly where the signal enters the network. The noisy network has thus been replaced by a noiseless network with a noise generator and a signal generator working into it in series with the signal genera-

tor impedance. Noise calculations are thus put on the same basis as signal calculations. The total noise of the system has been referred to the input, which is the place where the signal enters and the signal and noise may be directly compared.

The Noise Figure mentioned may be defined in terms of equivalent noise voltages as the ratio between the mean square of the total equivalent noise voltage (excluding that originating in the load impedance) and the means square of the noise voltage originating in the signal generator impedance only. The noise originating in the signal generator impedance is the Johnson noise which is amplified or otherwise treated by the device or network the same as the signal input. If several statistically independent fluctuation current or voltages such as those due to noise are simultaneously present in the same circuit the mean square of the total is given by the sum of the mean squares of the individual ones. Thus if

E_{E_s} = equivalent noise voltage originating in the signal generator impedance

E_n = equivalent noise voltage from sources within the network

then, the mean square of the total equivalent noise voltage is

$$E_{E_s}^2 + E_n^2$$

and the noise figure may be expressed,

$$F = \frac{E_{E_s}^2 + E_n^2}{E_{E_s}^2} = 1 + \frac{E_n^2}{E_{E_s}^2}$$

which is the general form in which the noise figure is derived for presentation in the following description. However, as the internally generated noise E_n is from a number of different sources and is expressed in terms representing each source there results a number of terms rather than the single one

$$\frac{E_n^2}{E_{E_s}^2}$$

Since the equivalent noise voltages of each source depends upon the impedance looking back toward the input of the device and since the gain of the device with respect to the voltage from each source is dependent upon the same impedance it is evident that the calculation of the various components of the total noise is quite complicated.

It can be shown that over a narrow band width the noise currents or voltages may be considered to be sinusoidal so that mathematical treatment according to the methods outlined in the article "Vacuum tube networks" in the March 1944 Proceedings of the I. R. E., and previously referred to is legitimate and in this way the equivalent noise voltages may be calculated and an expression for the noise figure obtained. Such analysis is lengthy and complicated and its presentation here is not warranted. However, by making application to specific tubes, circuits and operating conditions relatively simple expressions are obtained and it is made apparent that the basic principle of operation is the same for various applications.

Consider now the embodiment of the invention in the tetrode arrangement shown in Fig. 1 which illustrates a simple type of high frequency amplifier. In this figure the tetrode comprises the indirectly heated cathode 1, the control grid electrode 2, the screen grid electrode 3 and the anode 4 enclosed in the evacuated envelope 30. The four electrodes are mounted in alignment

in the metallic discs 6, 7, 8 and 9 which pass through the envelope and connect the electrodes to the resonant cavity members 10, 11, 12 and 13, respectively. The metallic members 14 and 15 with insulating rings 18 and 19 are slidable axially between the concentric metallic members 10 and 11 and 12 and 13, respectively, to provide closure and frequency adjustment of the input and output cavities 16 and 17. The insulating rings 18 and 19 serve to insulate the electrodes for direct voltages but are arranged to provide capacitances to furnish low impedance high frequency paths between the concentric metallic members across the insulation. The input cavity resonator 16 is bounded by electrodes 1, 2, discs 6, 7, concentric members 10, 11 and the slidable members 14 and 18. The output cavity resonator is bounded by electrodes 3, 4, discs 8, 9, concentric members 12, 13 and the slidable members 15 and 19. A high frequency input as from source 20 may be coupled to the input resonator

16 through the coaxial line 21 as shown or in any other suitable manner. A load circuit represented by the resistor 22 may be coupled to the output resonator 17 through the coaxial line 23 as shown or as desired. The cathode is heated indirectly from the direct current source 24. The grid, screen and anode are biased with respect to the cathode according to their requirements through the leads 26, 27 and 28 respectively. It will be noted that the screen 3 may be biased to a lower potential than the grid 2 if necessary to provide the desired space-charge condition in the grid-screen region.

When the input resonator 16 is excited at high frequency the alternating voltage appearing between the cathode 1 and grid 2 exerts space charge control in the region therebetween and varies the density of the electron stream passing on to the anode in accordance with the input excitation. The density varied stream in passing between the screen 3 and the anode 4 induces in the output resonator 17 and the load 22 high frequency energy corresponding to the input excitation but with noise components from sources in the tube added.

To realize best the benefits of the applicant's invention the grid electrodes should be accurately parallel to the cathode and the grid mesh should be fine in order to disturb the electron trajectories as little as possible. Also the cathode emission should be uniform over its surface. Like other high frequency output circuits the screen-anode spacing should be small enough so that the electron transit angle is moderately small to prevent loss in gain. It will be seen that the cathode-control grid spacing may advantageously be made such that under operating conditions the electron transit time across that space is $1\frac{1}{4}$, $2\frac{1}{4}$ or $3\frac{1}{4}$, etc. cycles of the operating frequency to minimize input loading in that manner while realizing at the same time the noise reduction according to the present invention.

Fig. 2 is a schematic representation of the arrangement of Fig. 1. Its purpose is to illustrate mathematical symbols used and with Figs. 6 and

9 to facilitate comparison of the different circuit arrangements. In this figure the electrodes 1, 2, 3 and 4 are shown spaced along the path of the electron stream. The input and output cavity resonators 16 and 17 are indicated with the capacitances to provide direct current insulation between the electrodes. R_s and R_L are the high frequency resistances of the tuned input and output circuits as measured at the tube terminals. x_1 is the distance between the cathode and the control grid, x_2 is the distance between the control grid and the screen grid, V_{D1} is the effective direct current potential of the control grid with respect to the cathode and V_{D2} is the effective direct current potential of the screen grid with respect to the cathode. T_1 and T_2 are the direct current electron transit times across the regions indicated.

After an analysis of the type referred to, the expression for Noise Figure of the arrangements of Figs. 1 and 2 is found to be

$$F = 1 + \frac{2.4}{R_s} \frac{1}{3} \frac{\epsilon^2 R_s^2}{\eta I_D} \omega^4 \frac{(\Phi_2 - \Phi_1)^2}{(\Phi_2 - \Phi_1)^2 + \Phi_2^2 - 2(\Phi_2 - \Phi_1)\Phi_2 \cos \theta_1} + \frac{19.3(1 - \alpha_1)}{\alpha_1} \frac{I_D}{4R_s} (R_s \theta_1)^2 \frac{\Phi_1^2}{(\Phi_2 - \Phi_1)^2 + \Phi_2^2 - 2(\Phi_2 - \Phi_1)\Phi_2 \cos \theta_1} + \frac{19.3(1 - \alpha_2)}{\alpha_2} \frac{I_D}{4R_s} (R_s \theta_1)^2 \frac{1}{(\Phi_2 - \Phi_1)^2 + \Phi_2^2 - 2(\Phi_2 - \Phi_1)\Phi_2 \cos \theta_1} \quad (1)$$

where:

R_s =resistance of the input circuit in ohms as seen at the tube terminals at the operating frequency with the tube disconnected.

R_e = R_s plus the tube input resistance in ohms at the operating frequency.

ϵ =permittivity of vacuum ($=10^{-11}/36\pi$).

η =constant $=10^6 e/m$.

e =electron charge, 1.59×10^{-19} coulomb.

m =electron mass, 9.03×10^{-28} gram.

I_D =direct electron current density leaving the cathode, in amperes/cm.²

ω =angular frequency, radians per second ($=2\pi f$).

f =operating frequency, cycles per second

Φ_1 =direct current space charge function=

$$1 - \xi_2 \left(1 + \frac{\sqrt{V_{D1}}}{\sqrt{V_{D2}}} \right)$$

Φ_2 =direct current space charge function=

$$\frac{T_2 \sqrt{V_{D1}}}{T_1 \sqrt{V_{D2}}}$$

ξ_2 =space charge factor of the region between the control grid and the screen grid=

$$3 \left(1 - \frac{T_0}{T_2} \right)$$

V_{D1} =effective direct current potential of the control grid with respect to the cathode, in volts.

V_{D2} =effective direct current potential of the screen grid with respect to the cathode, in volts.

T_0 =direct current electron transit time between the control grid and the screen grid under the condition of zero space charge, in seconds.

T_1 =direct current electron transit time between the cathode and the control grid, in seconds.

T_2 =direct current transit time between the control grid and the screen grid, in seconds.

θ_1 =direct current transit angle between the cathode and the control grid, in radians ($=\omega T_1$).

α_1 =transmission factor of the control grid.

α_2 =transmission factor of the screen grid.

It may be remarked that when the grids are of the desired fine mesh and fine wire, effective

direct current potentials such as V_{D1} and V_{D2} above and as discussed in the I. R. E. article "Vacuum tube networks" previously referred to are very near to the actual impressed direct current potentials and the two may be considered the same for the purpose of this discussion.

In this expression the second term represents the noise contribution of the cathode, the third term represents the noise contribution of the control grid and the fourth term represents that of the screen grid.

It can be seen that the Noise Figure is reduced when $\Phi_1 = \Phi_2$ for then the second term representing the cathode noise becomes zero, and also that it is reduced by the third term becoming zero when $\Phi_1 = 0$. This shows that space charge may entirely smooth out either the noise contributed by the cathode or that contributed by the positive control grid but not both simultaneously.

To ascertain the presence of optimum values of Noise Figure and their dependence upon various factors the above Equation 1 may be simplified by substituting some practical values for parameters designated in general terms. For this purpose the following typical figures have been substituted:

$$R_s = 0.5 \text{ ohm}$$

$$R_c = 1.0 \text{ ohm}$$

$$I_D = 15 \times 10^{-3} \text{ amp.}$$

$$f = 3 \times 10^9 \text{ (10 cm. wavelength)}$$

$$\cos \theta_1 = 0 \text{ (as this corresponds to a transit time to give minimum input loading)}$$

$$\alpha_1 = .80$$

$$\alpha_2 = .80$$

giving to a close approximation:

$$F = 1 + 60 \frac{(\Phi_2 - \Phi_1)^2}{\Phi_2^2 + (\Phi_2 - \Phi_1)^2} + 3 \frac{\Phi_1^2}{\Phi_2^2 + (\Phi_2 - \Phi_1)^2} + \frac{4}{\Phi_2^2 + (\Phi_2 - \Phi_1)^2} \quad (2)$$

From this expression values of F have been plotted in Fig. 3 against the ratio V_{D2}/V_{D1} for several different values of the ratio x_2/x_1 . As indicated on Fig. 2, V_{D1} and V_{D2} are the direct current potentials of the control grid and screen grid respectively while x_1 is the distance in centimeters between the cathode and the control grid and x_2 is the distance in centimeters between the control grid and the screen grid. On the curves of Fig. 3 are indicated the points where $\Phi_1 = 0$ and where $\Phi_1 = \Phi_2$.

It may be noted from Fig. 3 that minimum values of F occur. Also it may be noted that the minimum points fall very close to the points on the curves where $\Phi_1 = \Phi_2$.

It is shown, therefore, that by space charge adjustment a favorable noise condition can be obtained and it is apparent from Fig. 3 that by suitable proportioning of the electrode spacings and biasing voltages a space charge adjustment may be had whereby the Noise Figure as expressed in Equations 1 and 2 is minimized.

In practice such a desirable operating condition may be determined experimentally by measuring in a known manner the gain of the device put energy separately, plotting the gain-to-noise or the signal-to-noise ratio against screen grid potential and then adjusting the screen grid potential to give the maximum value of that ratio. Such a procedure starting with a circuit adjusted for the usual mode of operation where the control grid is very nearly the same potential as the cathode and the screen potential is near that of

the anode or plate may be as follows: First without altering the screen grid potential raise the potential of the control grid. Depending upon a number of factors, the gain and the noise may change to a greater or lesser extent. Experiments show that the noise does not increase as rapidly as might be expected when the transit angles between the cathode and control grid and between the control grid and screen grid are moderately large, even though the positive grid captures a portion of the electron current. The grid potential may be adjusted to the position of minimum input loading as will be indicated by a maximum signal output. Having set the control grid potential at a positive value, proceed to decrease the screen grid potential. As the screen grid potential is lowered the gain or the signal output begins to increase at a considerably faster rate than the noise output. Eventually the noise output begins to rise rapidly until at last a "Kipp" point is reached where the space charge suddenly breaks and a virtual cathode is formed with some of the electrons returning to the cathode. Before this point is reached the place of maximum value of signal-to-noise ratio will have been passed. By plotting the signal-to-noise output ratio or the gain-to-noise output ratio as the screen grid potential is varied the point where it is maximum is observable and the optimum operating condition so determined.

Another method of obtaining a favorable adjustment of the space charge is to use the curves of Fig. 4. These curves are from the same data as the curves of Fig. 3 and show values of the ratio V_{D2}/V_{D1} (screen grid voltage to control grid voltage) for various values of the ratio x_2/x_1 (control grid-screen grid spacing to cathode-control grid spacing) to make the space charge functions Φ_1 and Φ_2 equal and to make the function $\Phi_1 = 0$. As has been mentioned these are conditions for zero cathode noise contribution and zero control grid noise contribution respectively. As shown in Fig. 3 the minimum value of the noise figure is between the $\Phi_1 = \Phi_2$ point and the $\Phi_1 = 0$ point but is very close to the $\Phi_1 = \Phi_2$ condition. Therefore when the spacing ratio x_2/x_1 is known the optimum voltage ratio V_{D2}/V_{D1} may be approximately selected from Fig. 4. Ordinarily the ratio should be selected from the curve showing values for $\Phi_1 = \Phi_2$ as that is the condition for cancellation of the cathode noise. Under some conditions a lower noise figure may be had by selecting a ratio between that curve and the one showing values for $\Phi_1 = 0$.

Consider now a velocity variation type of tube as shown in Fig. 5 to which the same principles apply and of which the same type of analysis may be made. A difference from the tetrode is that the input gap defined by the electrodes between which the high frequency input voltage is applied is very short so that expressions for noise components involving the electron transit angle in that region may be neglected. In Fig. 5 most of the elements are similar to those of Fig. 1 and are similarly designated. The principal difference between Fig. 1 and Fig. 5 is that in Fig. 5 the high frequency input circuit is not connected to the cathode 1 and the control grid electrode 2 but to two control grid electrodes 52 and 2. Thus while in Fig. 1 the high frequency input voltage varied the density of the electron stream directly by space charge control at the cathode, in Fig. 5 a steady electron stream from the cathode reaches the input gap between the two control grid electrodes 52 and 2 where the high frequency

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field acts to vary the velocities of the electrons in accordance with the input voltage. Due to the velocity variations, density variations develop in the electron stream by the time it has traversed the drift space between the electrodes 2 and 3 and reached the output gap between the electrodes 3 and 4 as is characteristic of velocity variation devices. Because in this arrangement the electrodes 52 and 2 are held at the same direct current potential it is not necessary to insulate the cavity members 10 and 11 as by the insulating ring 18 in Fig. 1, therefore in Fig. 5 the adjusting slider 54 alone connects these members for both direct current and alternating current.

Fig. 6 is a schematic representation of the arrangement of Fig. 5 showing mathematical symbols used. The input and output circuits with their resistances R_s and R_L and cavity resonators 16 and 17 are indicated. It may be noted that a capacitance to provide direct current insulation between tube electrodes is used in the output resonator circuit only. x_1' is the distance between the cathode and the first control electrode. x_2' is the length of the input gap, the distance between the two control electrodes 52 and 2. x_3' is the length of the drift space, the distance between the second control electrode 2 and the first output electrode 3. The output region or gap is between the electrode 3 and the anode 4. V_{D1}' , V_{D2}' and V_{D3}' are the effective direct current potentials with respect to the cathode of the grid electrodes 52, 2 and 3, respectively. In the Fig. 5 arrangement

$$V_{D1}' = V_{D2}'$$

T_3 is the electron transit time across the drift space between electrodes 2 and 3. As in other arrangements shown it is important that the tube electrodes be lined up accurately parallel, that the grids be fine so that the potential pockets around the individual grid wires exercise a negligible influence upon the uniformity of the electron stream and that the cathode possess very uniform emission properties.

When this velocity variation circuit of Figs. 5 and 6 is analyzed as was the tetrode circuit of Figs. 1 and 2 a closely approximate expression for the Noise Figure is found to be

$$F' = 1 + 2.4 \frac{R_s C_2^2}{g_0} \omega^2 \left(\frac{\Phi_1'}{\Phi_2'} - 1 \right)^2 + 19.3 \alpha_1 (1 - \alpha_1) I_D R_s \left(\frac{\Phi_1'}{\Phi_2'} \frac{x_1'}{x_2'} - 1 \right)^2 + 19.3 (1 - \alpha_2) \alpha_1 \alpha_2 I_D R_s \left(\frac{x_1'}{x_2'} \right)^2 \left(\frac{\Phi_1'}{\Phi_3'} \right)^2 + 19.3 \frac{(1 - \alpha_3) \alpha_1 \alpha_2}{\alpha_3} I_D R_s \left(\frac{x_1'}{x_2'} \right)^2 \frac{1}{\Phi_3'^2} \quad (3)$$

where:

R_s = resistance of the input circuit in ohms as seen at the tube terminals at the operating frequency with the tube disconnected.

C_2 = capacitance of the input gap in farads per square centimeter.

g_0 = conductance in mhos of the region between the cathode and the input gap

$$\left(g_0 = \frac{3}{2} \frac{I_D}{V_{D1}'} \right)$$

I_D = direct electron current density leaving the cathode in amperes/cm.²

V_{D1}' = effective direct current potential in volts with respect to the cathode of the control electrodes defining the input gap.

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V_{D3}' = effective direct current potential in volts with respect to the cathode of the first output electrode.

ω = angular frequency in radians per second ($\omega = 2\pi f$).

f = operating frequency in cycles per second.

Φ_1' = direct current space charge function =

$$1 - \xi_3 \left(1 + \frac{\sqrt{V_{D1}'}}{\sqrt{V_{D3}'}} \right)$$

Φ_2' = direct current space charge function =

$$\frac{T_3 \sqrt{V_{D1}'}}{T_1 \sqrt{V_{D3}'}}$$

Φ_3' = direct current space charge function =

$$\frac{x_1}{x_3} \xi_3 \left(1 - \frac{\xi_3}{3} \right) \frac{1 + \frac{\sqrt{V_{D3}'}}{\sqrt{V_{D1}'}}}{\frac{\sqrt{V_{D3}'}}{\sqrt{V_{D1}'}}}$$

ξ_3 = space charge factor of the drift space =

$$3 \left(1 - \frac{T_0}{T_3} \right)$$

T_0 = direct current electron transit time in seconds of the drift space under the condition of zero space charge.

T_1 = direct current electron transit time in seconds between the cathode and the first control electrode.

T_3 = direct current electron transit time in seconds of the drift space.

α_1 = grid transmission factor of the first control electrode.

α_2 = grid transmission factor of the second control electrode.

α_3 = grid transmission factor of the first output electrode.

x_1' = distance in centimeters between the cathode and the first control electrode.

x_2' = distance in centimeters between the two control electrodes.

x_3' = length in centimeters of the drift space.

In this expression (3) the second term represents the cathode noise contribution, the third the noise from the first control grid 52, the fourth the noise from the second control grid 2, and the fifth the noise from the first output grid 3. It may be seen from the expression (3) that the contribution from the cathode noise depends upon the square of the frequency while that from the positive grids is independent of frequency. This situation differs from that of the space-charge controlled tetrode of Figs. 1 and 2 where the cathode noise contribution increases as the fourth power of the frequency and the positive grid contributions according to the square of the frequency. This difference in behavior is a reflection of the fact that the transmittance of the velocity variation tube is directly proportional to the frequency. It may be seen, also, that at any one frequency the Noise Figure F' depends only upon Φ_1' , Φ_2' and Φ_3' which in turn depend only upon the space-charge condition in the drift space. Further, the same space-charge conditions which determine the space-charge controlled tetrode noise behavior are also involved in the noise behavior of this velocity variation tube. From the expression (3) it is apparent that the cathode noise contribution represented by the second term becomes zero when

$$\Phi_1' = \Phi_2'$$

Also it is apparent that the noise contribution of the first control grid represented by the third term is zero when

$$\Phi_1' = \frac{\Phi_2' x_2'}{\alpha_2 x_1'}$$

or practically (because

$$\frac{x_2'}{x_1'}$$

is small) when

$$\Phi_1' = 0$$

and that the noise contribution of the second control grid is cancelled when $\Phi_1' = 0$.

Again it is apparent that the simultaneous elimination of the noise from all three of these sources is not possible. The Noise Figure may be calculated from the expression (3) for various space charge conditions. The curve A of Fig. 7 shows the results of such calculations on a typical tube and circuit indicating a minimum value of the Noise Figure F' as the ratio of the voltages V_{D3}'/V_{D1}' is varied to change the space charge condition in the drift space. This curve is based on a circuit operating at a wavelength of 10 centimeters, having an input circuit with a moderate Q (reactance/resistance ratio) of 250 and a tube with the following characteristics and fixed operating conditions as denoted in the expression (3):

$$x_1' = 2.54 \times 10^{-1} \text{ cm.}$$

$$x_2' = 2.54 \times 10^{-2} \text{ cm.}$$

$$x_3' = 2.54 \times 10^{-1} \text{ cm.}$$

$$\alpha_1 = \alpha_2 = \alpha_3 = 0.80$$

$$V_{D1}' = 250 \text{ volts, resulting in}$$

$$I_D = 140 \times 10^{-3} \text{ amps./cm.}^2$$

The curve shows a minimum value of the Noise Figure F' for V_{D3}'/V_{D1}' approximately .04. With the assumed value of $V_{D1}' = 250$ volts this means that the direct current potential at the exit of the drift space with respect to the cathode is about 10 volts. Other calculations show that at a shorter wavelength (higher frequency) with other fixed conditions the same, the Noise Figure minimum is higher and is shifted toward a higher value of the direct current exit potential of the drift space, also, that the effect of lowering the Q of the input circuit is principally to increase the Noise Figure without changing the position of the minimum with respect to V_{D3}'/V_{D1}' and that the minimum occurs close to the value of V_{D3}'/V_{D1}' for which $\Phi_1' = 0$ where, as has been mentioned, the noise contributions of the grid electrodes approach zero. In this connection it may be noted that in the case of the tetrode the minimum value of F' was found to be close to the voltage ratio where $\Phi_1 = \Phi_2$. This difference is because with the typical tetrode structure of the Fig. 2 type the major noise source proved to be the cathode while with the typical velocity variation structure of the Fig. 6 type the major noise source proves to be the input grid electrodes. The minimum values of F and F' are actually between the points where $\Phi_1 = 0$ and where $\Phi_1 = \Phi_2$ (or where $\Phi_1' = 0$ and where $\Phi_1' = \Phi_2'$) and is closer to one or the other depending upon whether cathode noise or grid noise preponderates.

Thus as in the case of the tetrode a favorable noise condition may be had by space charge adjustment. The optimum condition is had when the electrode spacings and biasing voltages are such that the Noise Figure F' as defined by the expression (3) is a minimum. The adjustment may be determined experimentally by arranging

to measure the noise energy output and the gain or the signal energy output of the system and adjusting for maximum ratio of signal to noise output. As in the case of the tetrode, with other

- 5 operating conditions normal the potential at the exit of the drift space (V_{D3}') may be adjusted to maximum signal to noise ratio. Also as in the case of the tetrode (because the space charge functions Φ_1' and Φ_2' are similar to the space
- 10 charge functions Φ_1 and Φ_2) the curves of Fig. 4 may be used to determine a favorable adjustment it being necessary only to consider x_3'/x_1' , V_{D3}'/V_{D1}' , Φ_1' and Φ_2' rather than x_2/x_1 , V_{D2}/V_{D1} , Φ_1 and Φ_2 . When applying these curves to the
- 15 velocity variation arrangement, ordinarily the voltage ratio V_{D3}'/V_{D1}' for a given spacing ratio x_3'/x_1' is selected from the curve giving values for $\Phi_1 = 0$ which is the condition for cancellation of the grid noise. Under some conditions a lower
- 20 Noise Figure may be had by selecting a ratio between that curve and the one showing values for $\Phi_1' = \Phi_2'$.

A slightly different form of velocity variation device is shown in Figs. 8 and 9, Fig. 9 being a schematic representation. The difference between this device and the one shown in Figs. 5 and 6 is that the electrodes bounding the drift space are at the same direct current potential which is, in general, lower than the direct current potentials of the first control or input electrode and the anode. Thus the electron stream is retarded across the input gap and accelerated across the output gap.

Most of the elements of Fig. 8 are the same as those of Fig. 5 and are similarly designated. Differences are: on account of the direct current potential difference between the input electrodes 52 and 2, the insulating member 18 is used with the slider 14 to insulate the cavity members 10 and 11, the appropriate direct current potential from source 25 is applied to the electrode 52 through conductor 87 and the electrode 3 derives its direct current potential through conductor 88 connected to the electrode 2 rather than directly from the source 25 as in Fig. 5. The device operates generally like that of Fig. 5 in the usual velocity variation manner.

Fig. 9 is a schematic representation of the arrangement of Fig. 8 showing the mathematical symbols used. It is similar to Fig. 6 except for the insulating capacitance in the input circuit formed by the insulating ring 18 of Fig. 8 and the direct current connection joining the electrodes 2 and 3. It may be noted that in Fig. 9 $V_{D2}'' = V_{D3}''$, while in Fig. 6 $V_{D2}'' = V_{D1}'$. As in the previous arrangements shown, it is assumed that the electrodes are parallel, the grids fine and the input circuit tuned. Also, as in the velocity variation device already described, it is assumed that the transit angle across the input gap is small so that any effect of space charge may be disregarded in that region. After a mathematical analysis such as has been applied to the other arrangements shown, the Noise Figure is found to closely approximate:

$$F'' = 1 + 2.4 \frac{R_s C_s^2}{g_0} \omega^2 \left(\frac{\Phi_1''}{\Phi_2''} - 1 \right)^2 +$$

$$19.3 \alpha_1 (1 - \alpha_1) I_D R_s \left(\frac{\Phi_1''}{\alpha_2 \Phi_2''} \frac{x_1''}{x_2''} \right)^2 +$$

$$19.3 (1 - \alpha_2) \alpha_1 \alpha_2 I_D R_s \left(\frac{x_1''}{x_2''} \right)^2 \left(\frac{\Phi_1''}{\Phi_2''} \right)^2 +$$

$$19.3 \frac{(1 - \alpha_2) \alpha_1 \alpha_2}{\alpha_3} I_D R_s \left(\frac{x_1''}{x_2''} \right)^2 \left(\frac{1}{\Phi_2''} \right)^2 \quad (4)$$

where:

R_s =resistance of the input circuit in ohms as seen at the tube terminals at the operating frequency with the tube disconnected.

C_2 =capacitance of the input gap in farads per square centimeter.

g_0 =conductance in mhos of the region between the cathode and the input gap

$$\left(g_0 = \frac{3}{2} \frac{I_D}{V_{D1}''}\right)$$

ω =angular frequency in radians per second.

Φ_1'' =direct current space charge function

= $1-2\zeta_3$.

Φ_2'' =direct current space charge function=

$$\frac{T_3}{T_1} \frac{V_{D1}''}{V_{D3}''}$$

Φ_3'' =direct current charge function=

$$4 \frac{x_1''}{x_3''} \zeta \left(1 = \frac{\zeta_3}{3}\right)$$

ζ_3 =space charge factor of the drift space=

$$3 \left(1 = \frac{T_0}{T_3}\right)$$

T_0 =direct current electron transit time in seconds of the drift space under the condition of zero space charge.

T_1 =direct current electron transit time in seconds between the cathode and the first control electrode.

T_3 =direct current electron transit time in seconds of the drift space.

V_{D1}'' =effective direct current potential in volts with respect to the cathode of the first control electrode.

V_{D3}'' =effective direct current potential in volts with respect to the cathode of the first output electrode.

x_1'' =distance in centimeters between the cathode and the first control electrode.

x_2'' =distance in centimeters between the two control electrodes.

x_3'' =length in centimeters of the drift space.

α_1 =grid transmission factor of the first control electrode.

α_2 =grid transmission factor of the second control electrode.

α_3 =grid transmission factor of the first output electrode.

I_D =direct electron current density leaving the cathode in amperes/cm.²

In this expression (4) the second term corresponds to the cathode noise contribution, the third to the noise from the first control grid and the fourth to the noise from the second control grid.

It may be observed that the cathode noise is cancelled when

$$\Phi_1'' = \Phi_2''$$

and that the noise from the control grids is cancelled when

$$\Phi_1'' = 0$$

These cancellation points may be found immediately from the curves of Fig. 10 which have been obtained by calculating Φ_1'' and Φ_2'' as the ratio V_{D3}''/V_{D1}'' is changed for several assumed values of the ratio x_3''/x_1'' and plotting the values of

$$\frac{V_{D3}''}{V_{D1}''}$$

at which $\Phi''=0$ and $\Phi_1''=\Phi_2''$ for the different values of x_3''/x_1'' . The minimum of the Noise

Figure F'' occurs, in general somewhere within the domain between the two curves $\Phi_1''=0$ and $\Phi_1''=\Phi_2''$. When the grid noise predominates the minimum point will be closer to where $\Phi_1''=0$ than to where $\Phi_1''=\Phi_2''$. As an illustration the Noise Figure has been calculated for different values of V_{D3}''/V_{D1}'' assuming a circuit operating at a wavelength of 10 centimeters, the input circuit having a moderate Q (reactance/resistance ratio) of 250 and the following tube characteristics and fixed operating conditions as denoted in the expression (4)

$$x_1'' = 2.54 \times 10^{-1} \text{ cm.}$$

$$x_2'' = 2.54 \times 10^{-2} \text{ cm.}$$

$$x_3'' = 2.54 \times 10^{-1} \text{ cm.}$$

$$\alpha_1 = \alpha_2 = \alpha_3 = 0.80$$

$$V_{D1}'' = 250 \text{ volts resulting in}$$

$$I_D = 140 \times 10^{-3} \text{ amperes/cm.}^2$$

The results of these calculations are shown in Fig. 7 curve B. The curve shows a minimum value of F for V_{D3}''/V_{D1}'' approximately .2. It may be noted that this is close to the point where $\Phi_1''=0$ and to the point in curve $\Phi_1''=0$ of Fig. 10 for $x_3''/x_1''=1$. With the assumed value of $V_{D1}''=250$ volts this means that the direct current potential of the drift space with respect to the cathode is about 50 volts. Other calculations at a shorter wavelength show the noise figure minimum shifted to the right toward the curve $\Phi_1''=\Phi_2''$.

Thus, as in the previously described arrangements a favorable noise condition may be had by space charge adjustment. The optimum condition is had when the electrode spacings and biasing voltages are such that the Noise Figure F as defined by the expression (4) is a minimum. The adjustment may be determined experimentally by arranging to measure the noise energy output and the gain or the signal energy output of the system and adjusting for maximum ratio of signal to noise output. To do this the other operating conditions may be held normal while the potential of the electrodes enclosing the drift space ($V_{D3}''=V_{D2}''$) is adjusted to give maximum signal to noise ratio. Also as previously mentioned the curves of Fig. 10 may be used to determine a favorable adjustment. Ordinarily for this (Fig. 9) velocity variation arrangement the voltage ratio V_{D3}''/V_{D1}'' for a given spacing ratio x_3''/x_1'' is selected from the curve giving values of $\Phi_1''=0$ which is the condition for cancellation of the grid noise. Under some conditions it may be desirable to use a voltage ratio from the curve giving values for $\Phi_1''=\Phi_2''$ (the condition for cathode noise cancellation) or from between the two curves.

The utility and efficacy of the invention are indicated by the results of tests on a tetrode amplifier operating at a wavelength of 10 centimeters. The tetrode grids were of fine mesh using 0.3 mil. wire and the electrode spacings were $x_1=3.6 \times 10^{-3}$ inches, $x_2=10 \times 10^{-3}$ inches, $x_3=20 \times 10^{-3}$ inches. The plate voltage was 265 and the grid voltage (V_{D1}) +2. Measurements of the Noise Figure as the space charge condition was varied by changing the screen voltage (V_{D2}) to alter the ratio between the screen and grid voltages (V_{D2}/V_{D1}) showed a minimum value of Noise Figure when the screen voltage (V_{D2}) was 3. The improvement in Noise Figure by this adjustment was about 5 decibels. An improvement of 10 decibels in the Noise Figure has been had in another similar test.

What is claimed is:

1. A high frequency device comprising a cathode and means for projecting a stream of electrons therefrom along a predetermined path, a control grid, a screen electrode and an anode spaced along the said path from the cathode in the order named, the said means for projecting the stream of electrons comprising electrical potential sources connected to the control electrode, the screen electrode and the anode for biasing these electrodes with respect to the cathode, the spacings between the various electrodes and the biasing potentials applied to the electrodes from the said potential sources rendering the expressions

$$\Phi_1 = 1 - \zeta_2 \left(1 + \frac{\sqrt{V_{D1}}}{\sqrt{V_{D2}}} \right)$$

and

$$\Phi_2 = \frac{T_2}{T_1} \frac{\sqrt{V_{D1}}}{\sqrt{V_{D2}}}$$

substantially equivalent, where ζ_2 is a factor indicating the space charge condition in the region

between the said control grid electrode and the screen electrode defined by

$$\zeta_2 = 3 \left(1 - \frac{T_0}{T_2} \right)$$

where T_0 is the electron transit time in seconds across the said region in the absence of space charge and T_2 is the actual electron transit time in seconds, both measured when no alternating current is flowing, T_1 is the direct current electron transit time in seconds between the cathode and the control grid electrode, V_{D1} is the direct current potential in volts of the control grid with respect to the cathode, V_{D2} is the direct current potential in volts of the screen with respect to the cathode.

2. A high frequency device comprising a cathode and means for projecting a stream of electrons there along a predetermined path, a control grid, a screen electrode and an anode spaced along the said path from the cathode in the order named, the said means for projecting the stream of electrons comprising electrical potential sources connected to the control grid electrode, the screen electrode and the anode for biasing these electrodes with respect to the cathode, the spacings between the various electrodes and the biasing potentials applied to the electrodes from the said potential sources rendering the expression

$$\Phi_1 = 1 - \zeta_2 \left(1 + \frac{\sqrt{V_{D1}}}{\sqrt{V_{D2}}} \right)$$

substantially zero, where ζ_2 is a factor indicating the space charge condition in the region between the said control electrode and the screen electrode defined by

$$\zeta_2 = 3 \left(1 - \frac{T_0}{T_2} \right)$$

where T_0 is the electron transit time in seconds across the said region in the absence of space charge and T_2 is the actual electron transit time

in seconds, both measured when no alternating current is flowing, V_{D1} is the direct current potential in volts of the control grid with respect to the cathode, V_{D2} is the direct current potential in volts of the screen with respect to the cathode.

3. A high frequency signal translating device comprising a cathode and means for projecting a stream of electrons therefrom along a predetermined path, a control grid electrode, a screen grid electrode and an anode disposed in succession along said path, a high frequency input circuit suitable for a desired operating frequency and connected to tube input terminals of the cathode and control grid, the said means for projecting the said stream of electrons comprising electric potential sources connected to the control electrode, the screen electrode, the anode and the cathode, the spacings between the various electrodes and the biasing potentials applied to the electrodes by the said potential sources rendering the expression

$$F = 1 + \frac{2.41}{R_s} \frac{1}{3} \frac{\epsilon R_s^2}{\eta I_D} \omega^4 \frac{(\Phi_2 - \Phi_1)^2}{(\Phi_2 - \Phi_1)^2 + \Phi_2^2 - 2(\Phi_2 - \Phi_1)\Phi_2 \cos \theta_1} + \frac{19.3(1 - \alpha_1)}{\alpha_1} \frac{I_D}{4R_s} (R_s \theta_1)^2 \frac{\Phi_1^2}{(\Phi_2 - \Phi_1)^2 + \Phi_2^2 - 2(\Phi_2 - \Phi_1)\Phi_2 \cos \theta_1} + \frac{19.3(1 - \alpha_2)}{\alpha_1 \alpha_2} \frac{I_D}{4R_s} (R_s \theta_1)^2 \frac{1}{(\Phi_2 - \Phi_1)^2 + \Phi_2^2 - 2(\Phi_2 - \Phi_1)\Phi_2 \cos \theta_1}$$

a minimum, where

R_s = resistance of the input circuit in ohms as seen from the cathode-control grid connections at the operating frequency with the cathode and control grid disconnected.

R_e = R_s plus the cathode-control grid tube input resistance in ohms at the operating frequency.

ϵ = permittivity of vacuum ($= 10^{-11}/36\pi$)

η = constant $= 10^{10}/m$

e = electron charge, 1.59×10^{-19} coulomb

m = electron mass, 9.03×10^{-28} gram

I_D = direct electron current density leaving the cathode, in amperes/cm.²

ω = angular frequency, radians per second ($= 2\pi f$)

f = operating frequency, cycles per second

Φ_1 = direct current space charge function

$$= 1 - \zeta_2 \left(1 + \frac{\sqrt{V_{D1}}}{\sqrt{V_{D2}}} \right)$$

Φ_2 = direct current space charge function

$$= \frac{T_2}{T_1} \frac{\sqrt{V_{D1}}}{\sqrt{V_{D2}}}$$

ζ_2 = space charge factor of the region between the control grid and the screen grid

$$= 3 \left(1 - \frac{T_0}{T_2} \right)$$

V_{D1} = direct current potential of the control grid with respect to the cathode, in volts

V_{D2} = direct current potential of the screen grid with respect to the cathode, in volts

T_0 = direct current electron transit time between the control grid and the screen grid under the condition of zero space charge, in seconds

T_1 = direct current electron transit time between the cathode and the control grid, in seconds

T_2 = direct current electron transit time between the control grid and the screen grid, in seconds

θ_1 = direct current electron transit angle between the cathode and the control grid, in radians ($= \omega T_1$)

α_1 = transmission factor of the control grid

α_2 = transmission factor of the screen grid.

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