Nov. 26, 1940. W. C. HAHN 2,222,902

HIGH FREQUENCY APPARATUS

Filed May 27, 1939 4 Sheets-Sheet 1

Fig. 1.

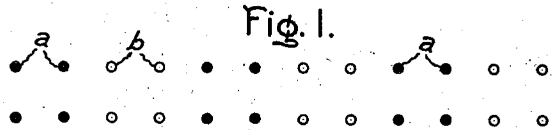


Fig. 2.

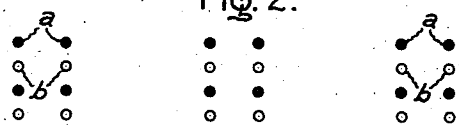


Fig. 3.

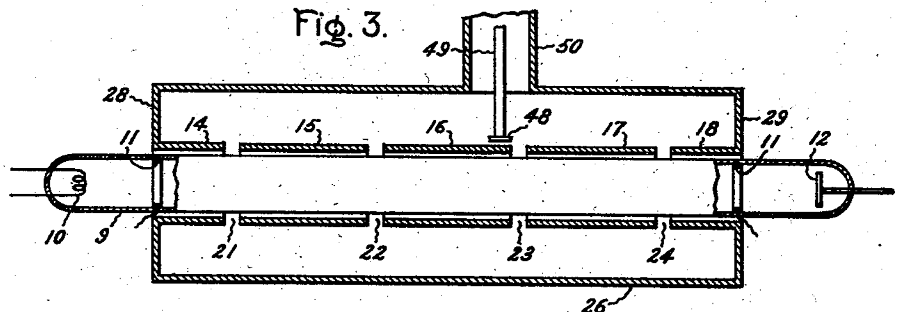


Fig. 4.

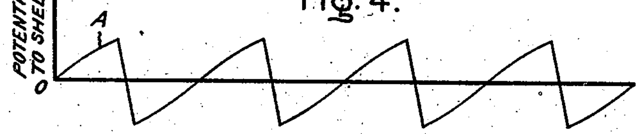


Fig. 5.

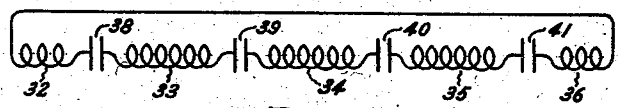


Fig. 6.

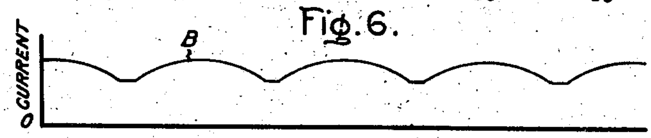
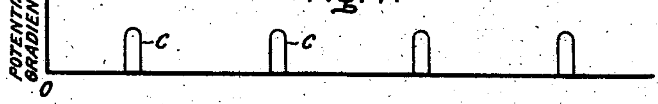


Fig. 7.



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Nov. 26, 1940. W. C. HAHN 2,222,902

HIGH FREQUENCY APPARATUS

Filed May 27, 1939 4 Sheets-Sheet 2

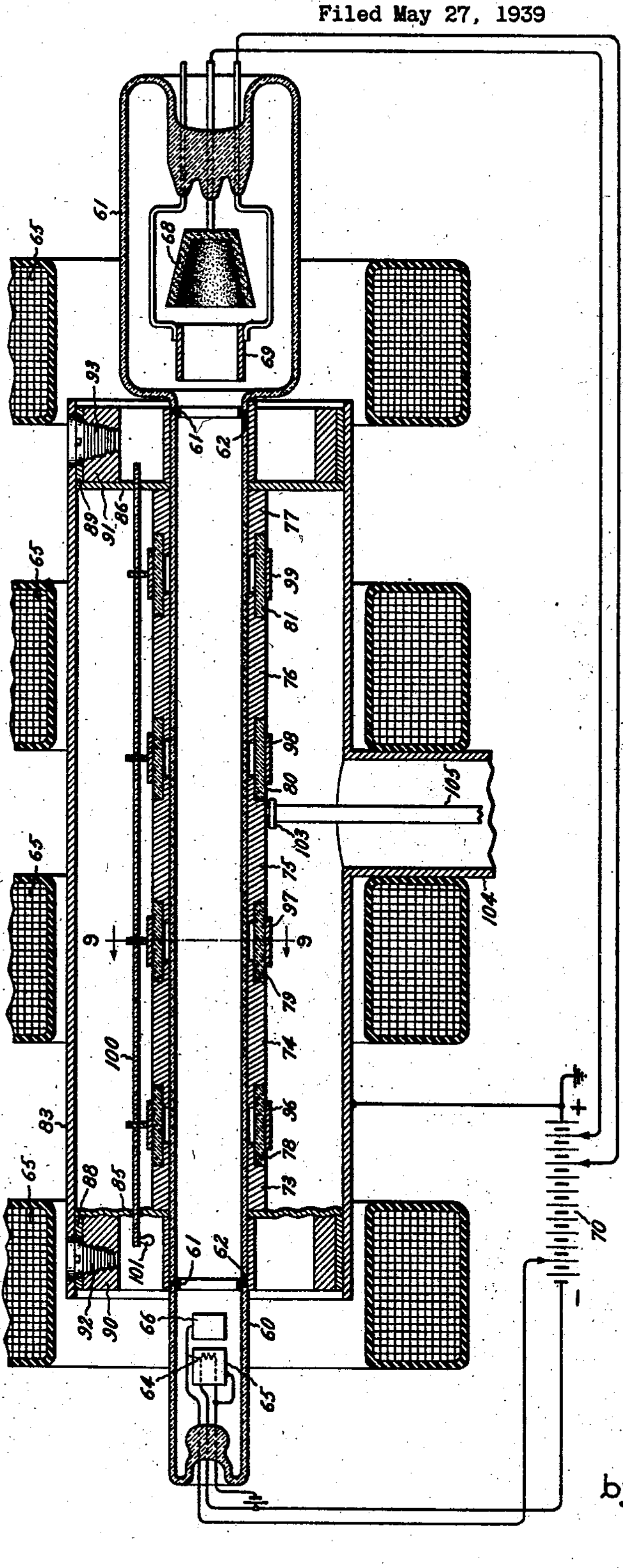

Fig. 8.

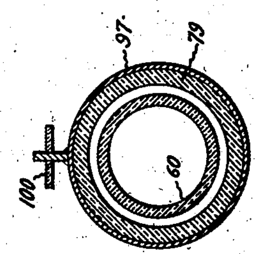

Fig. 9.

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Nov. 26, 1940. W. C. HAHN 2,222,902

HIGH FREQUENCY APPARATUS

Filed May 27, 1939 4 Sheets-Sheet 3

Fig. 10.

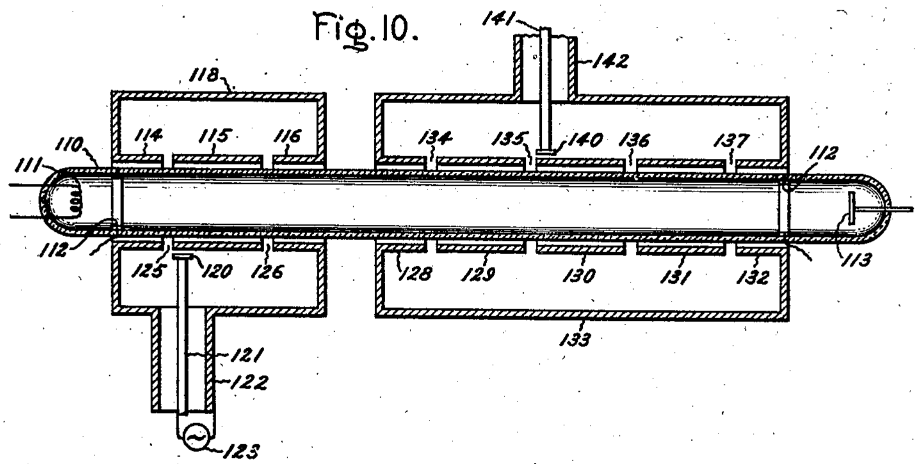


Fig. 11.

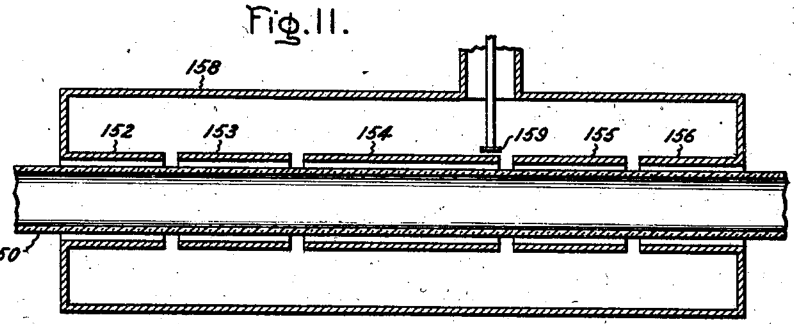
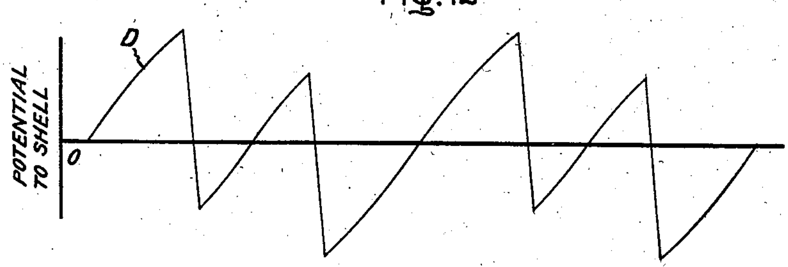


Fig. 12



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Nov. 26, 1940. W. C. HAHN 2,222,902

HIGH FREQUENCY APPARATUS

Filed May 27, 1939 4 Sheets-Sheet 4

Fig. 13.

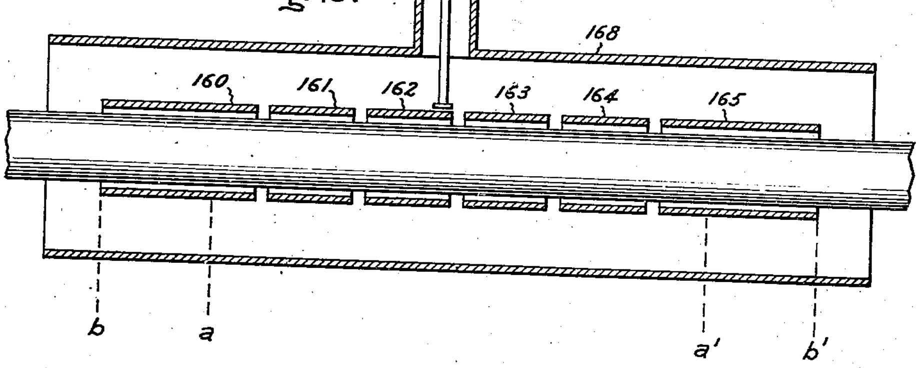


Fig. 14.

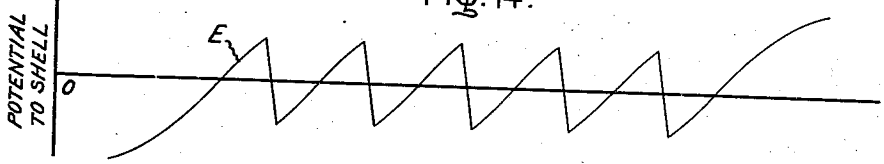


Fig. 15.

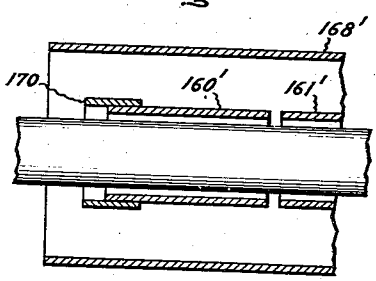
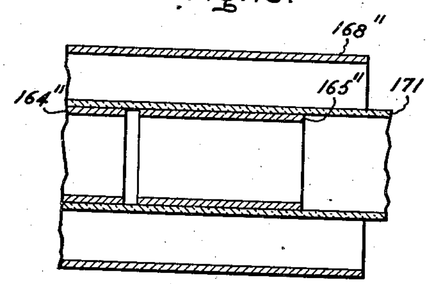


Fig. 16.



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Patented Nov. 26, 1940

2,222,902

UNITED STATES PATENT OFFICE

2,222,902

HIGH FREQUENCY APPARATUS

William C. Hahn, Scotia, N. Y., assignor to General Electric Company, a corporation of New York

Application May 27, 1939, Serial No. 276,172

14 Claims. (Cl. 250—36)

The present invention relates to ultra-high frequency apparatus utilizing the principles of velocity modulation described in my copending application Serial No. 153,602 filed July 14, 1937. More specifically, the invention relates to improvements in devices of the general structural form described and claimed in my copending application Serial No. 211,123 filed June 1, 1938. However, while the devices disclosed in the latter application are described mainly as oscillators, the improved structures to be described herein are considered to be useful not only for generating oscillations, but also for purposes of amplification, etc.

It is a primary object of the invention to provide ultra-high frequency apparatus capable of realizing high power output. In this connection, an important feature of the invention consists in the use of an arrangement in which an electron beam is caused to traverse an extended series of mutually spaced electrode elements which are so dimensioned and spaced as to constitute in themselves the primary parts of a resonant electrical system and which are so correlated to the beam velocity as to assure the occurrence of cumulative effects at the various inter-electrode gaps.

In a further aspect, the invention may also be viewed as comprising an improved method of operating high frequency electronic apparatus to obtain the results outlined in the preceding paragraph.

The features which I desire to protect herein are pointed out with particularity in the appended claims. The invention itself, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the drawings in which Figs. 1 and 2 comprise imaginative representations useful in explaining the invention; Fig. 3 is a schematic illustration of an oscillator embodying the invention; Fig. 4 is a graphical representation of potential distribution from point to point along the oscillator; Fig. 5 is a diagram of a circuit which is in some respects functionally equivalent to the structure of Fig. 3; Figs. 6 and 7 are graphical representations of current and longitudinal potential gradient distribution respectively; Fig. 8 illustrates the application of the invention in connection with a practical oscillator construction; Fig. 9 is a sectional view taken on line 9—9 of Fig. 8; Fig. 10 is a schematic illustration of an amplifier utilizing the invention; Figs. 11, 13, 15 and 16 represent structural variations of the invention and Figs. 12 and 14 are graphical representations respectively applicable to the structures of Figs. 11 and 13.

Before proceeding to a detailed description of the invention it will be helpful to consider briefly the principles of velocity modulation as the same are set forth in my application Serial No. 153,602, above referred to.

In the said application, it is pointed out that if a uniform stream of electrons is caused to traverse a region which is subjected to cyclically variable potential gradients, the various elements of the beam will be differently affected as to velocity. That is to say, electrons which traverse the region when the gradient in it is positive, will be accelerated, while electrons which enter the region during a period of negative potential gradient will be decelerated. Thus, if the potential applied to the said region is of cyclically reversible character, the portion of the beam issuing from the region will be characterized by alternate components of high and low velocity.

The condition referred to in the foregoing is illustrated in Fig. 1 wherein the black dots *a* may be taken to represent relatively fast electrons and the light dots *b* to represent relatively slow electrons. At the instant the beam emerges from the gradient-containing space, the charge density distribution in it may still be substantially uniform as shown. However, at a somewhat later time, if no further disturbance of the beam is permitted, a regrouping of electrons will occur as a result of the tendency of the faster electrons to catch up with the slower ones. Thus, Fig. 2 represents the condition of the beam of Fig. 1 after the same has traversed a drift space of substantial length; that is, after an appreciable time has elapsed. It will be noted that in the condition shown the beam is "charge density modulated" in the sense of being characterized by unequal space distribution of electrons.

My present invention makes use of the phenomenon described above in that it employs the expedient of successively producing velocity modulation of an electron beam and thereafter converting the velocity modulation into charge density modulation for the accomplishment of certain desired results.

Referring particularly to Fig. 3 there is shown in schematic form an exemplary embodiment of the invention. This includes an elongated discharge tube 9 having a cathode 10, two or more high voltage accelerating electrodes 11 and an anode 12 for producing an electron beam through the tube. Outside the tube there are provided a series of conductive electrode elements, numbered

14 to 18 inclusive, which are arranged along the beam path and in juxtaposition thereto. In the particular arrangement illustrated, the said conductive elements are in the form of hollow tubular members which are mutually spaced to permit the establishment of potential gradients in the gaps between them. By this means, the elements are enabled to influence the beam at various displaced points (21 to 24) along its axis.

Outside the tubular elements 14 to 18, a further conductive structure is provided in the form of a tubular shell 26 which is concentric with the elements. The shell 26 is connected at its extremities to the elements 14 and 18 by means of wall parts 28 and 29.

In connection with my present invention, the structure so far described may be viewed in two aspects. In the first, it comprises an electrode system for influencing the electron beam which traverses the tube 9. In the second the structure may be considered as a resonant feed-back system for assuring effective coupling between elements last traversed by the electron beam and those initially traversed by it. (This latter statement applies especially, of course, when the apparatus as a whole is to be employed as an oscillator.) The dimensional and electrical correlation of the various parts of the structure should be such as to assure that they function satisfactorily in both the capacities referred to.

The end specified in the foregoing paragraph is attained when the apparatus is brought to a condition of operation such as is indicated in Fig. 4. The saw tooth curve A of this latter figure represents the variation of the potential drop from the elements 14 to 18 to the shell 26 as one proceeds along the axis of the tube. If the condition illustrated actually prevails, the functioning of the system as a whole simulates that of a resonant circuit of the general form illustrated in Fig. 5.

In the figure last referred to there is shown a series of alternately positioned inductive elements 32 to 36 and capacitive elements 38 to 41, these elements being assumed to be so matched as to produce resonance. In the relationship illustrated, the inductive elements represent the electrodes 14 to 18, viewed as components of an impedance network, and the capacitive elements represent the end-to-end capacitive coupling between adjacent electrodes. During resonant operation of either the network of Fig. 3 or that of Fig. 5, there will be an alternate rise and fall of potential level as one proceeds from point to point along the network.

The representation of Fig. 5 is, of course, only an approximation to the arrangement of Fig. 3 since the elements 14 to 18 may not properly be viewed as of purely inductive character. They are, on the contrary, more in the nature of short sections of transmission line having distributed constants. However, it may be shown that under a particular condition of resonance, to be specified in the following, the potential variation along the electrode structure (as measured to the shell 26) is in the general form noted in Fig. 4. That is to say, as one proceeds along the electrode structure from the wall member 28, the potential rises continuously until an interelectrode gap (21) is reached. At the gap the potential reverses abruptly as a result of the presence of the lumped capacitance which couples the juxtaposed electrode elements 14 and 15. This condition is repetitive for each combination of electrode elements and gaps. The corresponding current distribution along the electrode structure is shown by curve B of Fig. 6, which indicates that the current attains a maximum value at the center of each electrode element and is a minimum in the interelectrode gaps.

Referring now more particularly to the reaction of the electrode structure on the beam itself, it will be understood that with the potential relationship shown in Fig. 4 the gap gradients assume a form such as is indicated by the curve C of Fig. 7. In this connection it will be noted that there exists a sharp rise in gradient at the extremity of each element, which is followed by an abrupt drop as the edge of the next element is approached. At any given instant the gradients in the various gaps are similarly directed. They are reversed every half cycle and return to their original condition at the beginning of the next cycle.

An electron which traverses any one of the gaps 21 to 24 at a time when a potential gradient exists across it is obviously affected as to velocity. It is desired for the purposes of my present invention that any given electron shall be similarly affected as it traverses each of the gaps, so that cumulative effects may be obtained. That is to say, it is desired that an electron which is accelerated in the first gap shall be similarly accelerated in each of the remaining gaps, and, on the other hand, that a decelerated electron shall be repetitively decelerated.

This result will obtain if the transit time of a given electron through a single electrode element corresponds approximately to some integral number (including one) of complete cycles of the potential variation across the gaps. In order to meet this condition, there must be appropriate correlation of the dimensional and electrical characteristics of the various parts. The means to be employed in securing this correlation are briefly outlined in the following.

In this connection it is convenient first to determine an appropriate length for the various elements 15, 16 and 17 (these being each twice as long as the elements 14 and 18). For purposes of calculation it is expedient to express this length as an angle θ_g, measured in such units that one complete wavelength (at the desired operating frequency) is equal to 360°. θ_g may be determined by the following equation (which in turn is derived from the more elementary known relationship between the beam velocity and the velocity of propagation of an electromagnetic wave):

$$\theta_g=\theta_b\frac{\sqrt{V}}{505} \qquad (1)$$

wherein V represents the d-c voltage of the beam and θ_b represents the angular part of a complete cycle which is required at such voltage for the transit of an electron completely through one electrode element.

It has previously been implied that θ_b must be equal to 360° (2π radians) in order to bring about a desired cumulative action of the various interelectrode gaps on the beam. However, for reasons which will be explained more fully hereinafter, it is expedient in designing the apparatus for oscillation generation to use a value fractionally less than 360°, the exact figure being determined by the number of gaps involved. A preferred value for any given number of gaps may be selected from the following table, for which a justification will be given at another place:

Table I

Number of gaps	θ_b
	Degrees
2	270
3	306.4
4	322
5	329.4
6	334.7
7	338.4
8	341.2

Inasmuch as the output power tends to increase with the beam voltage, it is appropriate to choose the highest convenient value for V. In order to illustrate the method of calculation, let it be assumed that six gaps are to be employed, and that a d-c voltage of 8,000 volts is to be used. Using these values in Equation 1, θ_G turns out to be 59.2°.

The length of the electrode elements being thus tentatively fixed, it is desirable next to determine the interelectrode capacity required to effect resonant operation of the system (i. e., such operation as to produce the voltage distribution shown in Fig. 4). In this connection it may be noted from Fig. 4 that the capacitive drop across a given gap must be equal to twice the voltage appearing between either of the adjacent electrode extremities and the shell 26. Furthermore, since the current flow observed at the extremity of any electrode is identical with that across the contiguous gap, it may be reasoned that the gap capacitance should be made to equal twice the electrode-to-shell impedance at the gap boundary. (It will be understood that the gap capacitance may be controlled either by properly adjusting the form of the electrodes at their extremities or by providing capacitance increasing means adjacent the gap, as will be later explained in connection with Fig. 8.)

In order to determine the electrode-to-shell impedance, recourse must be had to transmission line theory, since as has been previously specified, the electrode elements tend to function as transmission line sections. Applying the relevant formula in this connection we may write for the impedance at any point:

$$Z=Z_0, \tan h(\alpha+j\theta) \qquad (3)$$

where Z_0 is the characteristic impedance of the type of line under consideration; α is the attenuation constant; and θ is the electrical angle measured from a current maximum.

In the present case considerations of symmetry indicate the occurrence of current maxima at the centers of the various electrode elements, as shown in Fig. 6. In order to determine the impedance at the end of an element, therefore, the angle θ may be taken as the length of a half element or

$$\frac{\theta_g}{2}$$

Also, attenuation can be neglected, so that Equation 3 may be rewritten:

$$Z=Z_0 \tan h\frac{j\theta_g}{2}=jZ_0 \tan \frac{\theta_g}{2} \qquad (4)$$

Setting this quantity equal to one half the capacitive impedance of the gap, we have

$$jZ_0 \tan \frac{\theta}{2}=\frac{j\lambda_0}{4\pi C_g c} \qquad (5)$$

where λ_0 is the desired wavelength of operation, C_g is the gap capacitance, and c is the velocity of light.

For a practical construction, wherein the diameter of the discharge tube is ¾ inch, that of the electrode elements is 1 inch and that of the shell is 2 inches, Z_0 is about 41.6 ohms. Therefore, using the previously calculated value of θ_g (59.2°) and solving Equation 5, it appears that for an operating wavelength of 20 centimeters, C_g should be about 2.24 m. m. f.

The discussion up to this point has been mainly concerned with the operation of the apparatus of Fig. 3 viewed solely as a circuit network and without regard to the mode of its excitation. The latter factor will now be brought into the picture by investigating the cooperative reaction of the electrode elements with the electron beam of the tube 9.

In considering the effect of the electrode structure on the beam let it be assumed that a radio frequency voltage of value V_g is by some means impressed across the gap 21. The velocity modulation produced by such voltage is then $V_g B_1$, where B_1 is a factor which takes into account the geometry of the gap, the operating wave length, and the average velocity of the beam.

In accordance with the explanation given in connection with Figs. 1 and 2, the velocity modulation thus produced will cause at least some charge density modulation to exist in the beam issuing from the drift space defined by the electrode element 15. The amount of R. F. conduction current (I) thus developed will be a function of the velocity modulation ($V_g B_1$), of the total beam current (I_0), of the D. C. beam voltage (V), and of the electrode length (θ_b). A complete expression for this quantity may be written as follows:

$$I=j\frac{I_0 V_g B_1 \theta_b}{2V} \underline{/\theta_b} \qquad (6)$$

As the modulated beam traverses the second interelectrode gap 22 it will induce in the electrode structure a radio frequency current corresponding to the conduction current I but opposite to it in sign.

The actual current thus induced may be written

$$I=-IB \qquad (7)$$

where B is a factor which takes into account the characteristics of the gap. For reasons which need not be elaborated here, B may be taken as equal to the quantity B_1 previously employed above. Consequently, the complete expression for the conduction current induced in the electrode structure is

$$I_i=\frac{-jI_0 V_g B_1^2 \theta_b}{2V} \underline{/\theta_b} \qquad (8)$$

Now, let it be further assumed that the gap 22 is also subjected to a radio frequency voltage V_g, similar in amplitude and phase to the voltage predicated across the gap 21. Under these conditions the apparent admittance of the gap 16 is

$$A=\frac{I_i}{V_g}=\frac{-jI_0 V_g B^2 \theta_b}{2VV_g} \underline{/\theta_b}=\frac{-jI_0 B^2 \theta_b}{2V} \underline{/\theta_b} \qquad (9)$$

This equation may be simplified by grouping the quantities

$$\frac{I_0 B^2 \theta_b}{2V} \text{ as } G_m$$

whereupon we have

$$A=-jG_m \underline{/\theta_b} \qquad (10)$$

The foregoing analysis pertains mainly to the interaction of the beam and electrode system where only two gaps are involved. It must be remembered, however, that in the system under consideration the complete electrode structure involves the use of n gaps each spaced $\theta_b°$ (in the beam) apart. Each part has a radio frequency voltage across it and tends to produce a modulating reaction on the beam. Furthermore, each of the electrode elements provides a drift space between two gaps. Thus, the total reaction of the beam on the electrode structure may be derived as follows:

As we have seen, the first gap produces a velocity modulation V_gB_1 which in turn results in an apparent admittance at the second gap of $-jG_m\underline{/\theta_b}$. (This is on the postulated condition that the gradient in the second gap is in the same direction as in the first.) The admittance of the third gap, due to the voltage across the first, is $-j2G_m\underline{/2\theta_b}$. Similarly, for the fourth gap, the admittance is $-j3G_m\underline{/3\theta_b}$, etc.

Now, consider the effect of the voltage across the second gap. The admittance created across the third gap as a result of the modulation produced by this voltage is $-jG_m\underline{/\theta_b}$; that across the fourth gap is $-j2G_m\underline{/2\theta_b}$, etc. Adding the admittances for all gaps, one obtains the total admittance as—

$$A_{tot}=-j(n-1)G_m\underline{/\theta_b}-j2(n-2)G_m\underline{/2\theta_b}-j3(n-3)G_m\underline{/3\theta_b}\ \ldots\ -j(n-1)G_m\underline{/(n-1)\theta_b} \quad (11)$$

Of this admittance, the negative conductance component is

$$G_t=G_m\{(n-1)\sin\theta_b+2(n-2)\sin 2\theta_b+3(n-3)\sin 3\theta_b\ \ldots +(n-1)\sin(n-1)\theta_b\} \quad (12)$$

For satisfactory oscillator operation, a condition desired to be fulfilled is that the current required to initiate oscillation shall be a minimum. This condition provides a means of calculating the preferred value of θ_b.

In this connection it will be noted that in Equation 12 the quantity G_m, as defined, contains the beam current I_0 as a factor. The quantity G_t may, therefore, be viewed as being the product of two components, of which one, G_m, is mainly a function of the beam current I_0 and the other,

$$\frac{G_t}{G_m}$$

is mainly a function of the angle θ_b. Since the value of G_t required for oscillation is fixed by the consideration that it shall be equal to the internal losses of the device (such losses being fixed in turn by the physical characteristics of the system), we may determine the best value for the angle θ_b approximately by plotting the quantity

$$\frac{G_t}{G_m}$$

as a function of θ_b for a fixed value of n. For each value of n selected, the point of maximum of the quantity

$$\frac{G_t}{G_m}$$

will define the value of θ_b for which a minimum value of G_m, and consequently of I_0, will be required to produce oscillator operation. The results obtained by this determination have already been given above in the form of Table I.

The significance of the foregoing may be summarized by saying that most effective feedback action and consequently most satisfactory oscillator operation will obtain when the beam voltage is adjusted to bring about a value of θ_b corresponding to the values indicated in Table I. It will be appreciated, of course, that no change in results will occur if the value of θ_b is increased by 360° or by some integral multiple of that angle. Thus, if a six gap system is to be used and voltage considerations make it necessary to employ an electrode length greater than, say, 500°, satisfactory results may be obtained by using 335° (from Table I) plus 360°, or 695°. It will be understood from a consideration of Table I, however, that in each case the electrode length is such that the average electron transit time through the electrode will be on the order of the time consumed by an integral number of complete cycles of potential variation (at the desired operating frequency of the apparatus) and will depart therefrom by only a fraction of the period of a quarter cycle of such variation.

The particular mode of operation described in the foregoing is that which is calculated to produce a voltage distribution along the electrode system of the character illustrated in Fig. 4. It will be understood, however, that a system of the type under consideration actually comprises a plurality of coupled circuits (each represented by one electrode and its associated parts) and that it, therefore, possesses a number of possible modes of resonance. Furthermore, at least certain of these modes will produce modulation effects generally similar to the effects considered above. I therefore wish to point out that it is in no sense a departure from my invention to so modify the operating conditions of the apparatus as to procure operation in a mode of resonance different from the zero order mode and to produce a voltage distribution different from that shown in Fig. 4, as long as modulation effects are still obtained thereby.

The discussion so far has been concerned mainly with the problem of assuring satisfactory operation of the apparatus as an oscillating system without regard to the ultimate disposition of the high frequency power thus realized. It will be understood, however, that connection to an external utilization circuit, such as a radiating antenna, may be accomplished by coupling to the electrode system in any appropriate manner. Thus, in the arrangement shown in Fig. 3, a plate-like element 48 is positioned adjacent to one extremity of the electrode element 16 so as to be capacity coupled thereto at a point of voltage maximum. (The central electrode element is preferably utilized for this purpose for the reason that its use tends to prevent operation of the system in any mode of oscillation other than the preferred or zero order mode). Connection of the element 48 to an external circuit may be made by means of a concentric transmission line arrangement comprising an inner conductor 49 and an outer tubular conductor 50.

One advantage of the construction just described consists in its extreme mechanical simplicity and flexibility of use. As a result of the use of a plurality of identical electrode elements the problem of assuring balanced operation of the various elements is very much simplified. Furthermore, due to the method of design of the electrode system, one may avoid the use of inconveniently small electrode parts such as are usually required for ultra-short-wave operation. (This is a consequence of the previously described possibility of adding to the theoretically correct electrode length any desired number of

360° units without thereby altering the operating characteristics obtained.)

In transmitting devices, the use of a plurality of cascaded gaps, each subjected to a relatively moderate voltage, permits the attainment of operating efficiencies materially higher than can be obtained in previously available constructions without the use of unsafe voltage concentrations.

In receiving devices, the same method of cascading greatly increases the effective voltage amplification which may be obtained and thus raise the limit of internal losses which can be tolerated. This latter factor is of considerable importance in that it avoids the necessity of employing special low loss materials in all parts of the apparatus. In particular, it permits certain glasses to be employed in place of a more expensive dielectric such as quartz in the tube envelope where the occurrence of high frequency dielectric losses would ordinarily require that the latter material be utilized.

The invention has so far been described solely by reference to a schematic representation of the same, but in Fig. 8 it is shown as being embodied in a practical structure. In the arrangement referred to there is illustrated an electron beam tube which comprises an evacuated envelope having an elongated shaft portion 60, and an enlarged anode-containing portion 61'. This envelope may be suitably constituted of quartz or of low-loss glass.

The shaft portion 60 encloses means for producing an electron beam, such as a known type of electron gun. The combination shown comprises a filamentary cathode 64, which is indicated in dotted outline, and a cylinder 65 which may be used for confining the electrons to a concentrated beam. This cylinder may be either connected directly to the cathode as shown or maintained at a few volts negative or positive with respect to it. In order to accelerate the electrons to a desired extent there is provided an accelerating electrode 66 which is spaced from the cathode and which may be biased to a suitable positive potential, say, several hundred volts.

In order that the intermediate portion of the beam path may be maintained at a desired potential level there are provided a pair of intermediate electrodes 61, which suitably comprise rings of conducting material such as colloidal graphite applied to the inner wall surface of the envelope. These are connected with external elements by means of appropriate lead-in connections 62. A number of magnetic focusing coils 65, distributed along the envelope, serve to maintain the beam in focus during its passage through the discharge space.

After traversing the envelope, the electron beam is collected by an anode 68 which is in the form of a hollow conical structure, suitably consisting of graphite. A tubular electrode 69 in the nature of a suppressor grid serves to prevent secondary electrons emitted by the anode from returning to the discharge space.

In the operation of the device, the intermediate electrodes 61 may be maintained at ground potential, the cathode 64 at one-thousand to several-thousand volts below ground, and the anode 68 at one-thousand to several-thousand volts above the cathode. The suppressor grid 69 should be biased fifty to several hundred volts negative with respect to the anode 68. These potential relationships may be established by means of a suitable source of potential, an exemplary such source being conveniently represented in the drawing as a battery 70.

The combination of elements so far described comprises means for producing a unidirectional electron beam of substantially constant average intensity and velocity. Outside the envelope there is provided an electrode arrangement for affecting the beam at radio frequencies. This arrangement includes a series of tubular electrode elements (numbered 73 to 77 inclusive) which are disposed at spaced intervals along the axis of the envelope 60. These elements, which should consist of a conductive material such as copper, are maintained in spaced relationship by means of a number of interfitting insulating rings, 78 to 81. For use at ultra-high frequencies, these rings are preferably constituted of a material which has relatively low dielectric losses, for example, quartz.

The electrode elements referred to are concentrically enclosed within a conducting shell 83 which extends along substantially the entire length of the envelope shaft. A connection between the end elements 73 and 77 and the shell 83 is provided by means of circular metal diaphragms 85 and 86 which extend transversely to the axis of the envelope. These diaphragms may be made of flexible character to allow for heat expansion of the electrode parts. In the arrangement shown, the diaphragms 85, 86 are equipped with circular flanges 88 and 89 which are adapted to interfit with the inner surface of the shell 83. In order to assure a satisfactory engagement of parts, the flanges are preferably cut at various points (not illustrated) so as to be readily expansible and are respectively associated with split rings 90, 91, which can be spread by means of tapered screws 92, 93. By tightening these screws the flanges can be forced outwardly into tight-fitting contact with the shell.

It will be understood that the electrode elements 73 to 77 and the shell 83 correspond in nature and function with the similar items described in connection with Fig. 3. That is to say, the elements 73 to 77, considered alone, constitute electrodes for mutually reacting with the beam, while in cooperation with one another and with the shell 83, they form a feedback system for assuring oscillatory operation of the system as a whole. The longitudinal dimensions of the electrode elements are so correlated with the average velocity of the electron beam traversing the envelope shaft 60 as to assure effective reaction therewith at a desired frequency of operation of the apparatus.

In accordance with the principles previously set forth, it is necessary, in order to obtain the desired operation of the system, that the end-to-end capacities between the various electrode elements be so adjusted as to secure resonance with the elements themselves. In order that this adjustment may be made with the desired fineness, there are provided a series of conductive bands 96 to 99 which are slidingly supported on the insulating rings 78 to 81 in regions overlapping the gaps which separate the electrode elements. The gap capacity is obviously a function both of the size and of the position of these rings. Consequently, by making the rings of appropriate longitudinal extent and by regulating their position, it is possible to adjust the interelectrode capacity to any desired value within reasonable limits.

Under certain circumstances it may be desirable to change the normal frequency of operation of the oscillating system. To this end the capacity-controlling rings 96 to 98 are mechanically connected with a movable rod 100 (constituted of a suitable dielectric material, such as quartz) which can be moved longitudinally of the discharge envelope so as simultaneously to alter the position of the various rings. An externally accessible actuating element 101 makes such adjustment readily practicable. It will be understood that each adjustment of the gap capacity to alter the resonant frequency of the system requires a corresponding adjustment of the effective electrode length (as referred to the beam). This latter adjustment is made by varying the beam velocity to an appropriate degree.

Radio frequency power may be taken from the oscillating system by means of a plate-like member 103 which provides capacity coupling to one extremity of the electrode element 75. This member is associated with concentric conductors 104 and 105 which constitute a transmission line system for connection to an external circuit.

The foregoing has included an explanation of the principles of my invention as applied to the generation of oscillations. I wish it to be understood, however, that the invention is equally applicable in connection with high frequency amplifiers, and in Fig. 10 I have shown schematically one type of amplifying apparatus.

In the arrangement illustrated, there is provided an electron-beam-producing means including an elongated envelope 110 which encloses a cathode 111, high voltage accelerating electrodes 112, and an anode 113. (In a practical construction this may be replaced by a tube of the character shown in Fig. 8.) Surrounding the end of the beam path which is nearer the cathode there is provided an input system comprising an electrode arrangement of the general type previously described herein. This comprises a series of tubular elements 114, 115 and 116, successively arranged along the beam axis and concentrically surrounded by a conductive shell 118. The element 115 is of such length that the electron transit time therethrough corresponds as nearly as possible to a complete cycle of potential variation at the desired operating frequency. A resonant condition of the system as a whole is obtained by balancing the capacitive coupling which exists between the ends of the element 115 and the adjacent elements 114 and 116 against the distributed constants of the various elements.

In order to energize the electrode system thus described so as to produce a desired modulation of the electron beam, there is provided in proximity to one end of the electrode element 115, a plate-like member 120 which serves as an input coupling means. The member 120 is connected through a pair of concentric conductors 121 and 122 to an exciting source such as an oscillator 123. The energy supplied by the oscillator 123 serves to excite the electrode system to resonant operation so that in-phase voltages are developed across the gaps 125 and 126 in accordance with the principles already explained.

Inasmuch as the losses of the system are supplied externally from the power source 123, it is unnecessary that the electrode system itself exhibit negative conductance such as is required for oscillator operation. Consequently, the length of the electrode 115 may be made precisely 360° (or as near thereto as is practical). Of course, if energy feedback is desired for any reason, the electrode element 115 can be made somewhat less than 360° in length.

The effect of the electrode structure thus described is to produce superimposed velocity modulation effects at the gaps 125 and 126. As a result of this modulation the beam issuing from the right hand extremity of the element 116 is characterized by variations in electron velocity from point to point along its length. In accordance with principles already explained, these velocity variations are converted into charge density variations as the beam progresses along the axis of the envelope 110.

At a point somewhat displaced from the input electrode structure there is provided a further electrode system adapted to serve for output purposes. Like the input structure, this comprises a series of electrode elements 128 to 132 which are enclosed within a cylindrical conducting shell 133 and which are separated by a plurality of gaps 134 to 137.

The action of the charge density modulated beam in traversing any of the interelectrode gaps is to induce a current flow in the electrode structures which bound the gaps. For present purposes it is desired that the currents induced at the various gaps be unidirectional and additive at any given instant, this end being best served when the length of the individual electrodes corresponds to the spacing between two adjacent charge density maxima in the beam. It will be found that this condition is fulfilled when the electrode length is 360° in terms of beam velocity so that the average electron transit time through the electrode corresponds to one full cycle of the potential variation. The effect of the beam in traversing the various gaps 134 to 137 will be cumulative under the conditions stipulated so that R. F. currents of relatively great magnitude may be caused to flow along the electrode structure. As a result of this factor, large amounts of power may be drawn from the system without damping it unduly.

In order to couple the output system to an appropriate utilization circuit there is provided a capacitative coupling member 140, this being associated with a concentric transmission line consisting of elements 141 and 142. It will be understood that if the impedance of the load circuit including the transmission line elements 141 and 142 is properly matched to the characteristics of the output electrode system, the current induced in the electrode system may be caused to develop a very high voltage across the load.

In the structures so far described the various high frequency electrodes have been shown as being all of identical form. While this arrangement is preferred because of the higher operating efficiency which it realizes, it is not an essential attribute of my invention, and in Fig. 11 I have shown an alternative embodiment in which it is not utilized.

In this case a tube 150, shown broken away, is assumed to serve as a confining means for an electron beam (of which the source is not indicated). The beam successively traverses a series of tubular electrode elements 152 to 156, these being in turn surrounded by a conducting shell 158.

The electrodes 153 and 155 are taken to be on the order of 360° in length (so that the electron transit time therethrough corresponds approximately to a full cycle of the operating potential), while the electrode 154 is on the order of twice this length. The electrode sections 152 and 156 are preferably made one half as long as electrode 154, and the interelectrode gap capacitances are matched to the distributed constants of the electrodes in accordance with the principles already described. When this condition is established and the system is operating in an excited condition as a result of the pressure of an electron beam therethrough, the instantaneous potential distribution along the electrode structure will be approximately as indicated by the irregular saw-tooth curve D of Fig. 12. Under these circumstances cumulative effects are obtained at the various gaps, as previously explained.

The negative conductance which is requisite to oscillator operation can be secured by shortening the various electrodes to the necessary degree. As an alternative to shortening all the electrodes, certain electrodes only may be shortened. For example, the electrodes 153 and 154 may be made 360° in length and the electrodes 152, 154 and 156 shortened by the appropriate amount. With an arrangement such as that last specified, the length of electrode 154 is preferably set at about 360° and the length of electrodes 152 and 156 at one half this value. Power may be taken from the system by means of a capacitive element 159 coupled to one extremity of electrode 154.

A still further possible variation of structure is that shown in Fig. 13. In this case the high frequency electrodes (numbered 160 to 165) are not terminally connected to the outer shell (168) as in the arrangements previously described. On the contrary, terminal coupling is accomplished by providing the end electrodes 160 and 165 with extensions, measured from a to b and a' to b' respectively, which constitute quarter wavelength transmission line sections or, alternatively, odd multiple quarter-wave sections.

Under these circumstances, standing waves may be established along the electrodes 160 and 165, which waves have voltage minima at a and a' respectively. The resultant voltage distribution along the electrode system is as indicated by the saw-tooth curve E of Fig. 14. It will be seen that as far as modulating action is concerned, the arrangement of Fig. 13 is substantially the same as that of the construction of Fig. 3. However, some longitudinal potential gradients will exist at the open ends b and b' of the quarter-wave sections and will add to the mutual reaction of the beam and the electrode system. If calculations in a given case indicate that this factor is of appreciable value, it should, of course, be taken into account in designing the system.

If desired for mechanical reasons, the construction of Fig. 13 may be combined with that of Fig. 3 by utilizing the direct electrical connection of the former figure at one end of the electrode system and employing transmission line coupling at the other end. Also, the coupling means of Fig. 13 may be further modified by providing some form of lumped capacitance at the electrode extremities to permit shortening of the quarter-wave sections.

An arrangement such as that of Fig. 13 may be variably tuned by the use of means for varying the effective length of the terminal electrode. This feature is illustrated in Fig. 15 in which the parts 160', 161', and 168' (shown broken away) correspond in nature and function with the similarly numbered elements of Fig. 13.

For the purpose stated in the preceding paragraph the extremity of the electrode 160' is provided with a sleeve 170 which can be moved axially as desired. This sleeve may be used to adjust the dimensions of the quarter-wave transmission line section to cause it to function effectively for a plurality of different frequencies at which it is desired to operate the system as a whole.

Another attribute of the construction of Fig. 13 is that it permits the high frequency electrodes to be placed within the discharge tube so as to be separated from the cooperating conductive shell by the wall of the tube. This may be done, for example, in the manner indicated in Fig. 16 wherein the electrodes are shown at 164'' and 165'' and the shell at 168''. The wall of the envelope is indicated at 171. This construction is especially advantageous when design considerations make it desirable to position the electrode surfaces relatively close to the beam.

While I have described my invention by reference to particular embodiments thereof, it may be understood that numerous additional modifications may be made by those skilled in the art without departing from its principles. I, therefore, intend to cover in the appended claims all such variations as fall within the true spirit and scope of the foregoing disclosure.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. In electronic apparatus having means for producing an electron beam, a resonant electrode system including a conductive structure surrounding the beam for an appreciable portion of its path length, a conductive tubular element positioned within said structure so as to be axially traversed by the beam, the length of said element being so correlated to the beam velocity that the average electron transit time through the element is on the order of the time consumed by an integral number of complete cycles of potential variation at the desired operating frequency of the apparatus and departs therefrom by no more than the period of a quarter cycle of such variation, and a pair of electron-permeable conductive elements positioned adjacent the extremities of said tubular element to provide a pair of gaps to be traversed by the beam, the capacitance across said gaps being matched to the distributed constants of said tubular element and said structure, whereby upon operation of the said electrode system in a state of resonance the instantaneous potential gradients occurring across said gaps have a common direction.

2. In electronic apparatus having means for producing a beam of electrons, a resonant electrode system including a series of tubular electrode elements arranged in mutually spaced relation to provide a plurality of gaps which are successively traversed by the beam, said elements being dimensionally correlated to the beam velocity so that the average electron transit time through each element is on the order of the time consumed by an integral number of complete cycles of potential variation at the desired operating frequency of the apparatus and departs therefrom by no more than the period of a quarter cycle of such variation, and an elongated conductive structure concentrically surrounding the said tubular elements, the capacitance across each of the said gaps being matched to the distributed constants of the elements and the conductive structure, whereby upon excitation of the said electrode system, the potential gradients occurring across the various gaps at any given instant are similarly directed.

3. An electronic apparatus having means for producing a beam of electrons, the combination

which includes a series of tubular electrode elements arranged in mutually spaced relation to provide a plurality of gaps which are successively traversed by the beam, said elements being dimensionally correlated to the beam velocity so that the average electron transit time through each element is on the order of the time consumed by an integral number of complete cycles of potential variation at the desired operating frequency of the apparatus and departs therefrom by no more than the period of a quarter cycle of such variation, an elongated conductive structure concentrically surrounding the said tubular elements and means associated with the said elements at said gaps for matching the capacitance of the gaps to the distributed constants of the elements and the conductive structure, whereby upon excitation of the resonant electrode system which is formed by said elements and said conductive structure, the instantaneous potential gradients occurring across the various gaps are similarly directed.

4. Electronic apparatus comprising an elongated tubular envelope, a series of tubular conductive elements surrounding the envelope at spaced points along its length, insulating means interposed between the various tubular elements so as to establish fixed gaps between them, a conductive structure concentrically surrounding the said tubular elements and forming therewith a resonant electrode system, means associated with each of said gaps for correlating the capacitance of the gaps to the distributed constants of the tubular elements and conductive structure, thereby to permit resonant operation of the electrode system at a frequency corresponding to the desired frequency of operation of the apparatus, means within the envelope for projecting an electron beam axially thereof at a velocity which is so correlated to the dimensions of the tubular envelope as to assure the occurrence of cumulative effects at the various gaps as a result of the electrical interaction of the beam and the elements at such gaps and means coupled to the electrode system for abstracting energy therefrom upon passage of the electron beam therethrough.

5. In electronic apparatus having means for producing a beam of electrons, a series of tubular electrode elements arranged to be axially traversed by the beam, the elements being mutually spaced to provide a plurality of gaps, and the axial dimensions of the elements being correlated to the average velocity of the beam and to the desired frequency of operation of the apparatus, a conductive structure surrounding the said tubular elements and forming in combination therewith a resonant system, means associated with each of said gaps for matching the capacitance of the gaps to the distributed constants of said resonant system, and means for producing adjustment of the last-mentioned means to vary the natural frequency of operation of the apparatus.

6. In electronic apparatus having means for producing a beam of electrons, a series of tubular electrode elements arranged to be successively traversed by the beam, said elements being mutually spaced to provide a plurality of gaps and the axial dimensions of the elements being correlated to the average velocity of the beam and to the desired operating frequency of the apparatus, a conductive structure suronding the said tubular elements and forming in combination therewith a resonant system, a series of conductive bands positioned coaxially with said tubular elements at points adjacent said gaps, the said bands serving to match the capacitance of the gaps to the distributed constants of the said resonant system so as to facilitate operation of the apparatus at a desired frequency, and means for producing axial adjustment of the bands to vary the operating frequency of the apparatus.

7. In combination, means for producing a beam of electrons, a series of tubular elements arranged to be axially traversed by the beam, said elements being mutually spaced to provide a plurality of gaps between them, a conductive structure surrounding the said elements and forming therewith a resonant standing wave system by virtue of the distributed constants of the elements and the structure, means for modulating the beam prior to its traversal of the said elements thereby to produce excitation of the said resonant system, and means coupled to the said resonant system for abstracting energy therefrom upon excitation of the system.

8. A method of operating a high frequency electronic device having a series of coaxially spaced tubular electrodes and a conductive structure forming with said electrode an electrical system which is adapted to resonate at a particular frequency; which method comprises projecting an electron beam axially through said electrodes at such velocity that the electron transit time through a single electrode is on the order of the time consumed by an integral number of complete cycles of potential variation at the said particular frequency but departs therefrom by a fractional part of the period of a quarter cycle of such variation, thereby to procure mutual reaction of the beam and the resonant system resulting in modulation of the former and excitation of the latter at the said particular frequency.

9. A method of operating a high frequency electronic device having a series of dimensionally similar tubular electrodes arranged in axially spaced alignment to provide a plurality of interelectrode gaps and a conductive structure concentrically surrounding the electrodes so as to form therewith an electrical system adapted to resonate at a particular frequency; which method comprises projecting an electron beam axially through said electrodes at such velocity that the electron transit time through a single electrode is on the order of the time consumed by an integral number of complete cycles of potential variation at the said particular frequency but departs therefrom by a fractional part of the period of a quarter cycle of such variation, thereby to procure mutual reaction of the beam and the resonant system resulting in excitation of the latter, and abstracting energy from the resonant system for utilization outside the system.

10. In high frequency apparatus, the combination which includes means for producing a beam of electrons, a series of tubular conductive elements which are arranged to be axially traversed by the beam and which are mutually spaced to provide a plurality of gaps between them, at least several of the successive intermediate elements being electrically isolated in the sense of having no direct electrical connection to any other conductive part of the apparatus, a conductive structure surrounding the said tubular elements and forming therewith a standing wave resonant system by virtue of the distributed constants of the structure and the elements, the said system being maintained in excited condition during operation of the appa-

ratus by mutual reaction with the beam at the said gaps, and means coupled to the said resonant system for abstracting energy therefrom for utilization outside the system.

11. In high frequency apparatus, the combination which includes means for producing a beam of electrons, a series of tubular conductive elements which are arranged to be axially traversed by the beam and which are mutually spaced to provide a plurality of gaps between them, all of the said elements being electrically isolated in the sense of having no direct electrical connection to any other conductive part of the apparatus, a conductive structure surrounding the said elements and forming therewith a standing wave resonant system by virtue of the distributed constants of the structure and the elements, the said system being maintained in excited condition during operation of the apparatus by mutual reaction with the beam at the said gaps, and means coupled to the said resonant system for abstracting energy therefrom for utilization outside the system.

12. In high frequency apparatus, the combination which includes means for producing a beam of electrons, a series of tubular conductive elements which are arranged to be axially traversed by the beam and which are mutually spaced to provide a plurality of gaps between them, all of the said elements being electrically isolated in the sense of having no direct electrical connection to any other conductive part of the apparatus, a conductive structure surrounding the said elements and forming therewith a standing wave resonant system which is maintained in excited condition by mutual reaction with the beam at the said gaps, capacitance-increasing means associated with the end ones of the said elements to provide a desired terminal coupling between the elements and the said conductive structure without a direct electrical connection therebetween, and means coupled to the said resonant system for abstracting energy therefrom for utilization outside the system.

13. In high frequency electronic apparatus, the combination which includes means for producing a beam of electrons, an elongated hollow structure surrounding the path of the said electron beam, a series of coaxial tubular conductive elements arranged concentrically within the said structure so as to be axially traversed by the beam, all of the said elements being electrically isolated in the sense of having no electrical connection to any other conductive part of the apparatus but, nevertheless, forming a standing wave resonant system with the said conductive structure by virtue of the distributed constants of the elements and the structure, means supporting the conductive elements in mutually spaced relationship to provide a plurality of gaps between them, the said resonant system being maintained in excited condition during operation of the apparatus by mutual reaction with the beam at the said gaps, and the end ones of the said tubular elements differing from the remaining elements in being provided with extended terminal portions which produce a desired terminal coupling between the elements and the said conductive structure without a direct electrical connection therebetween.

14. In high frequency electronic apparatus, the combination which includes means for producing a beam of electrons, a series of tubular conductive elements which are arranged to be axially traversed by the beam and which are mutually spaced to provide a plurality of gaps between them, all of the said elements being electrically isolated in the sense of having no direct electrical connection to any other conductive part of the apparatus, a conductive structure surrounding the said elements and forming therewith a standing wave resonant system which is maintained in excited condition by mutual reaction with the electron beam at the said gaps, the end ones of the said elements being longer than the remaining elements so that they provide a desired terminal coupling between the elements and the said conductive structure without a direct electrical connection between them.

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