

June 1, 1948.

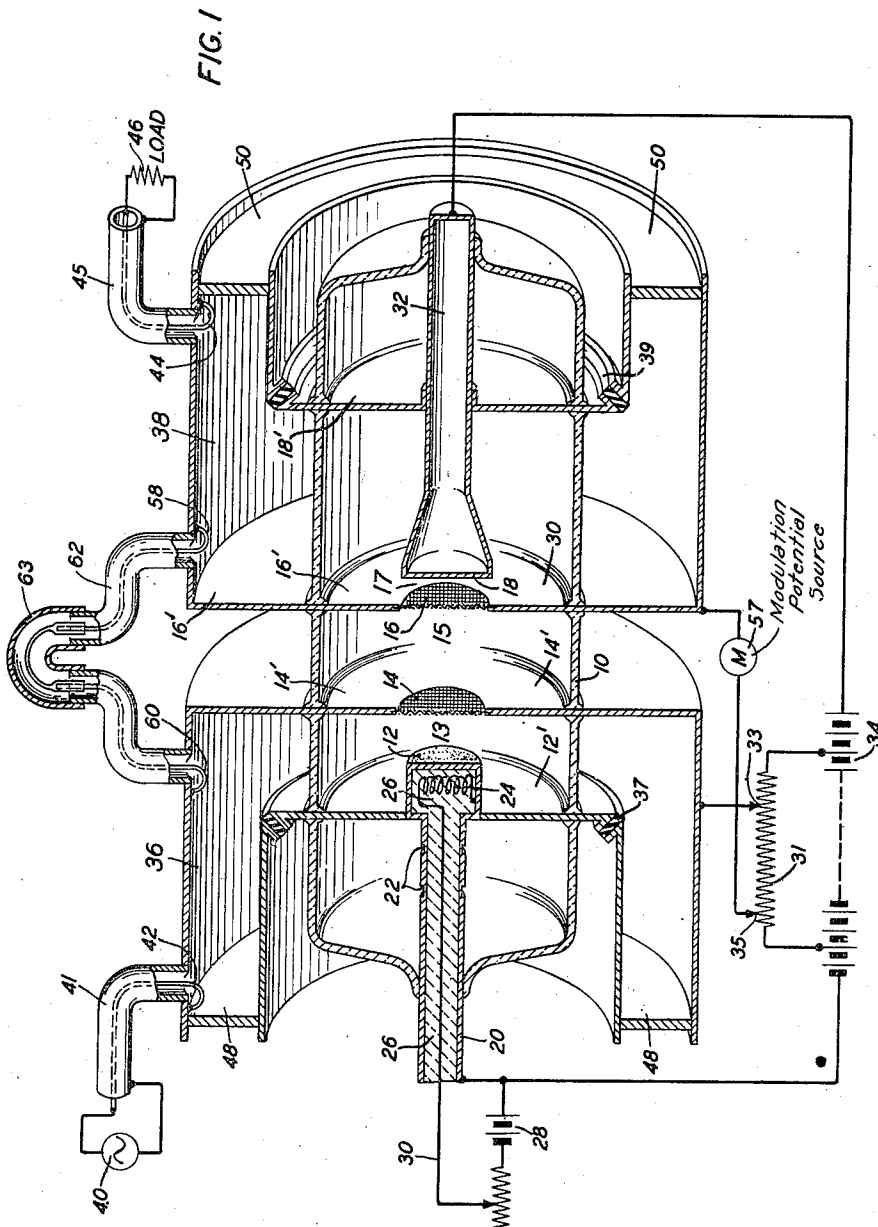
L. C. PETERSON

2,442,662

HIGH-FREQUENCY TRANSLATING APPARATUS

Filed April 15, 1942

5 Sheets-Sheet 1



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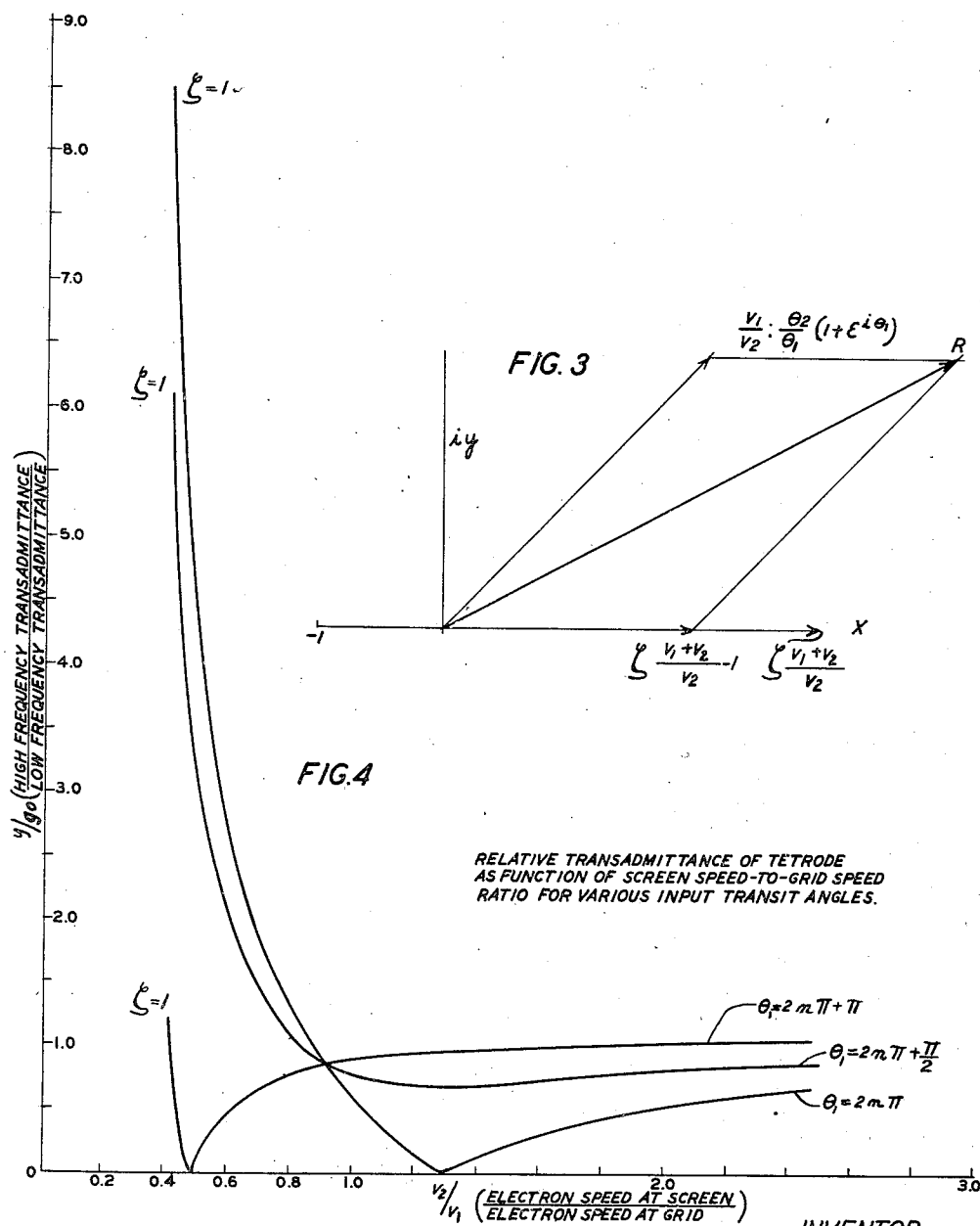
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HIGH-FREQUENCY TRANSLATING APPARATUS

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5 Sheets-Sheet 2



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5 Sheets-Sheet 3

FIG. 2

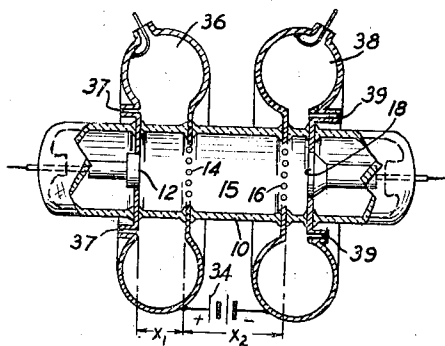


FIG. 5

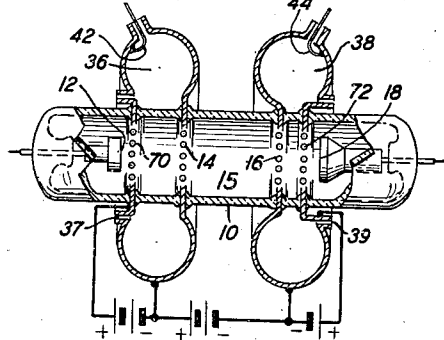


FIG. 6

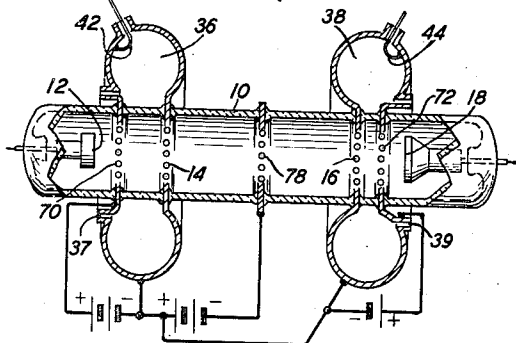


FIG. 8

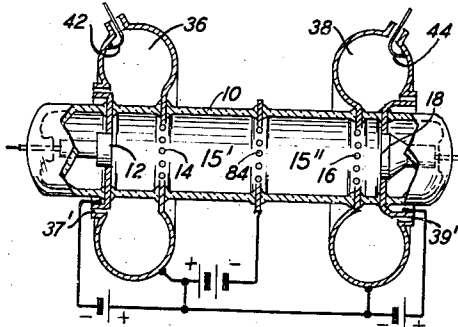


FIG. 7

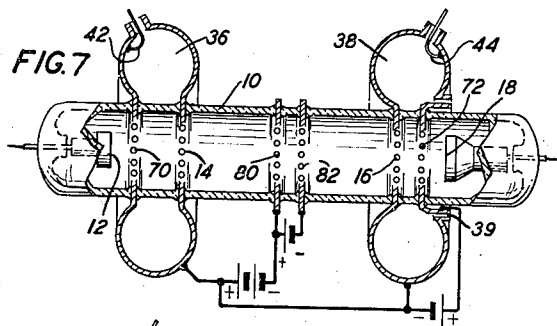
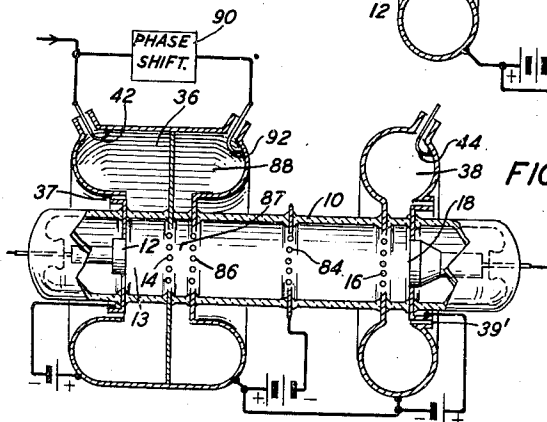


FIG. 10



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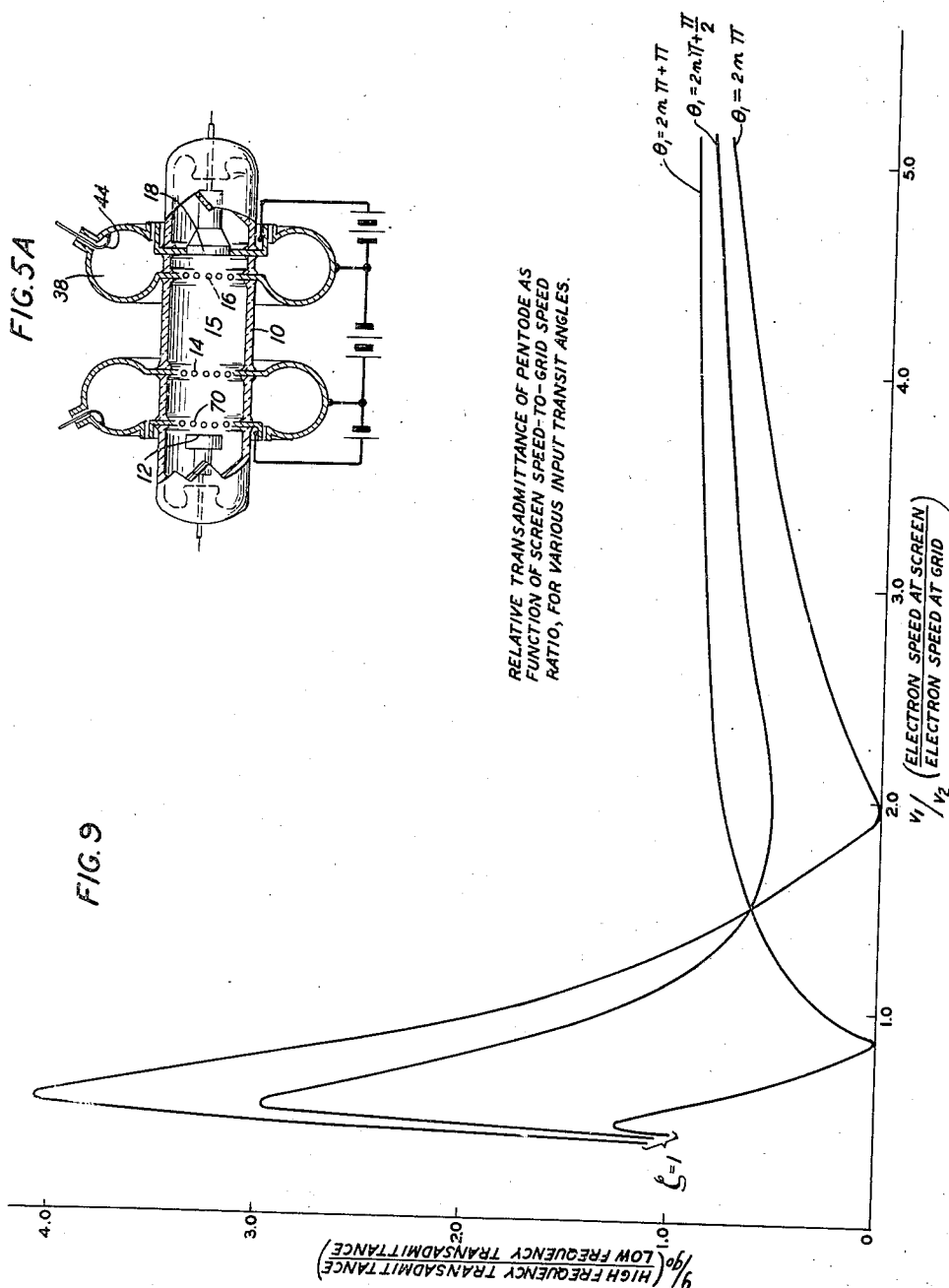
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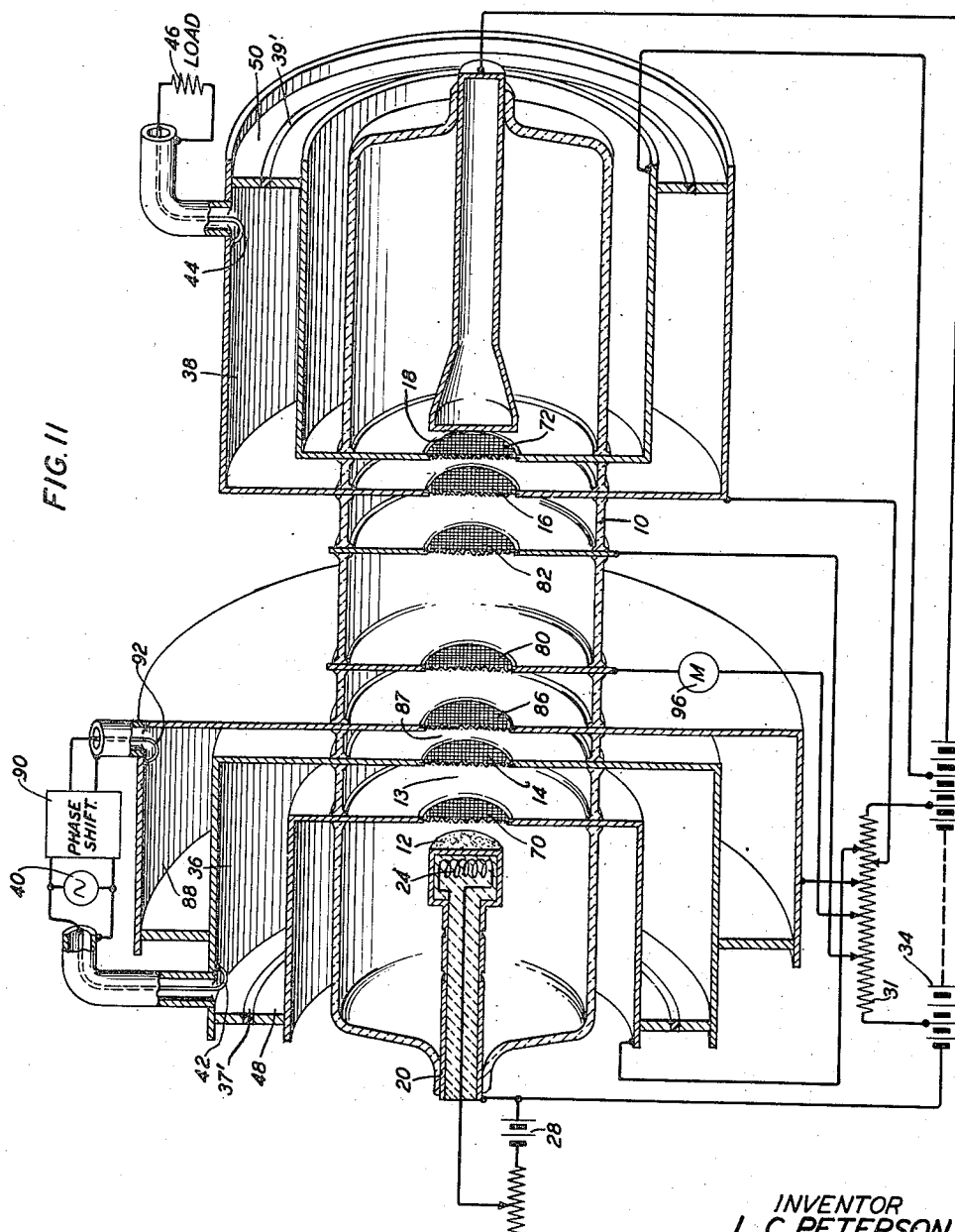
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HIGH-FREQUENCY TRANSLATING APPARATUS

Filed April 15, 1942

5 Sheets-Sheet 5



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UNITED STATES PATENT OFFICE

2,442,662

HIGH-FREQUENCY TRANSLATING
APPARATUS

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Application April 15, 1942, Serial No. 439,059

7 Claims. (Cl. 179-171.5)

1

This invention relates to high frequency discharge devices for the production, amplification, and conversion of ultra-high frequency waves and particularly to devices of this character whose operation is in large part dependent on the inertia effects of moving electric charges.

The principal object of the invention is to secure efficient amplification of waves of ultra-high frequency, for example in the 3000-megacycle range, using moderately low voltage electron tubes.

An additional object of the invention is to secure efficient control of these ultra-high frequency waves with comparatively simple structures.

An additional object is to provide means and methods for efficient operation at ultra-high frequencies of structures which are in some respects conventional having been developed for use at much lower frequencies at which charge inertia effects may be neglected.

It is a feature of the invention that both charge density variations and velocity variations of a stream of moving charges take part in the operation of the apparatus. It is another feature that the effects, at an output circuit, of both charge density variations and velocity variations imparted to a stream of moving charges at an input circuit are combined in a favorable phase relation.

It is another feature of the invention that space-charge repulsion or dispersion effects, heretofore regarded as constituting unavoidable limitations on the efficiency of velocity variation devices, are found to provide a source of unforeseen advantages and are turned to good account.

It is another feature of the invention that the potentials and geometrical dispositions of the electrodes of a device constructed in accordance therewith are so correlated with signal frequencies, charge transit time and space-charge repulsion effects that a transadmittance is secured which greatly exceeds not only the transadmittance obtainable with the best available apparatus at ultra-high frequencies, but also the transadmittances obtainable with the same apparatus at "low frequencies"; i. e., at frequencies such that inertia and transit time effects are of no importance.

The phenomena which take place in so-called velocity variation devices are commonly explained on the assumption that space-charge repulsion effects may, to a first approximation at least, be ignored. In such devices an electron stream is projected in succession through an input gap, a

2

drift space and an output gap. High frequency signal energy is imparted to the stream at the input gap, and it is commonly conceived that initially this energy appears wholly in the form of velocity differences between electrons, without substantial differences in the density of the stream from point to point thereof. Under these conditions the faster electrons will obviously tend to overtake the slower ones so that a grouping or bunching of electrons will result. It is conceived that the faster electrons may actually overtake and pass the slower ones so that the electron stream, were it to extend over a great distance, would appear characterized by regions of high electron density separated by intervening regions of much lower electron density, each electron of the stream, however, preserving unchanged the actual velocity with which it emerged from the input gap. It is pointed out in these explanations that the output circuit, in order that it may efficiently abstract the signal frequency energy from the stream, should be placed along the path of the stream at a point of maximum charge density, preferably the first of such points.

It is recognized that this is an idealized picture which is not wholly borne out in practice on account of space-charge dispersion or so-called "debunching" effects. These effects, which are due to the mutual repulsive forces between electrons, are conceived to impede or retard the formation of electron groups as above described with a consequent alteration of the optimum position at which the output gap should be placed and a reduction in the efficiency of the apparatus.

Another theory is based on the assumption that space-charge effects are controlling; that due to the repulsive forces between electrons the faster ones, as they begin to overtake the slower ones, will, instead of passing them, be reduced in speed as by elastic collision with an interchange of momentum. In accordance with this theory it is suggested that waves of density travel along the moving stream, each particular electron undergoing a movement which is compounded of a steady average velocity and an oscillatory movement superposed thereon. As before, it is suggested that the output circuit should be placed along the path of the stream at a point where a density maximum, preferably the first density maximum, exists. The positions along the stream path at which these density maxima are believed to occur differ from the positions of the density maxima which arise from

fast electrons overtaking slow ones, space-charge effects being neglected.

In one of its aspects the invention is based upon applicant's recognition that the true state of affairs is not in accord with either of the above idealized pictures but lies somewhere in between; i. e., some of the fast electrons pass unimpeded by the slower ones while others of the fast electrons are retarded by elastic collisions, so that the charge grouping is in part due to the unimpeded progress of fast electrons by slow ones and in part due to the interchange of their momenta as they approach one another. Thus the problem is presented as to how best to take advantage of the charge grouping due to space-charge repulsion effects without undue sacrifice of the charge grouping due to velocity variation, and, if possible, to bring these two different effects into favorable phase relation.

This problem is solved by the invention. In the solution the moving electron stream is retarded and compressed in an axial direction in such a manner that the electron groups are much more closely spaced in the vicinity of the output circuit than in the vicinity of the input circuit. Space-charge repulsion effects are progressively built up along the electron stream from its input end to its output end well beyond the point heretofore considered possible. As a result, not only are the two types of charge grouping due, respectively, to momentum interchange and to passage of fast electrons by slow electrons, caused to be greatly in excess of what is possible in the absence of retardation, but, in addition, these two effects are brought into a favorable phase relation so that they are cumulative.

The invention both in its mode of operation and in its specific details will be explained in conjunction with the following description of certain preferred embodiments thereof, taken in connection with the appended drawings in which:

Fig. 1 is a diagrammatic cross-sectional view of a comparatively simple structure which, by reason of the electrode arrangement shown and the potentials applied, embodies certain features of the invention;

Fig. 2 is a simplified explanatory diagram of parts of the apparatus of Fig. 1;

Fig. 3 is a vector diagram of assistance in understanding the mode of operation of the invention;

Fig. 4 is a set of curves depicting the performance of apparatus according to Fig. 1;

Fig. 5 is a simplified diagram of a modification of Fig. 2, in which a constant current is injected into the input region, and Fig. 5a is a modification thereof;

Fig. 6 is a simplified diagram of a modification of Fig. 5 wherein the drift space is provided with an auxiliary space-charge controlling electrode;

Fig. 7 is a simplified diagram of another modification of Fig. 5 showing a plurality of space-charge controlling electrodes;

Fig. 8 is a simplified diagram showing the inclusion of a space-charge controlling electrode in a structure like that of Figs. 1 and 2;

Fig. 9 is a set of curves depicting the performance of apparatus according to Fig. 8;

Fig. 10 is a simplified diagram showing the addition of an auxiliary input gap to the apparatus of Fig. 8; and

Fig. 11 is a diagrammatic cross-sectional view of apparatus embodying a number of the features separately shown in others of the figures.

Referring now to the figures, Fig. 1 illustrates

one form of apparatus embodying the principles of the invention as applied to a system in which a compact air-tight envelope serves to define an evacuated space in which the working electrons may be thermionically produced and undergo their proper movements, the comparatively large cavity resonators which serve as tuned circuits being disposed outside of the envelope. If preferred, the cavity resonators or other tuned circuits may be contained entirely within the envelope, though, since it is now possible to make substantially perfect metal-to-glass seals, the structure shown is preferred on account of its compactness and the ease with which adjustments may be made. A cylindrical evacuated envelope 10 having ends tapered for the purpose of strength is provided. Within this envelope there are mounted in axial succession a cathode 12, a grid 14, a screen 16, and a collector anode 18. The cathode may comprise a flat plate 12 suitably treated on its outer face with thermionically emissive material. It may be mounted on and supported by a metal sleeve 20 which projects through the end wall of the envelope 10 to provide an electric connection. Suitable means, such as slots 22 or regions of reduced cross section may be provided to reduce the flow of heat from the cathode to the exterior of the envelope and thus effect economies in materials and in the energy required to maintain the cathode at the temperature of emission. The sleeve 20 protruding through the end wall of the envelope, may be sealed into the latter in air-tight fashion. The cathode may be maintained at a suitable temperature for emission of thermions by a heater element 24 mounted immediately behind it, and preferably embedded in a suitable refractory plastic material 26 which substantially fills the mounting sleeve 20. This heater element 24 may have heating current fed to it from an external source 28 by way of a conductor 30 passing through the sleeve 20, the sleeve itself constituting the return current path.

Since the function of the cathode is merely to provide a stream of electrons which shall be comparatively uniform both in velocity and in density, and whose density is substantial, any cathode construction which meets these requirements may be employed.

The anode 18, whose function is to collect the electrons after their high frequency energies are largely spent, may be similarly mounted in the opposite end of the envelope 10 being supported, for example, on a conducting member 32 which is sealed in the envelope wall, over which operating anode potential may be supplied as from a suitable potential source 34.

Spaced along the path of the electron stream between the cathode 12 and the anode 18 are disposed a control electrode or grid 14 and a screen electrode 16. Each of these electrodes may be in the form of a wire mesh screen, a perforated plate, an array of slats or the like. The primary consideration dictating the electrode structure is that it shall act to the least extent possible as an obstacle to the electrons of the stream, and yet behave as an electric shield of high quality, segregating the cathode-grid space 13 and the screen-anode space 17, respectively, from the central grid-screen space 15. The grid 14 and the screen 16 may each be mounted centrally in an aperture of a plate or disc 14', 16' of conducting material which extends through the envelope wall 10 to provide means of coupling these electrodes with an external circuit, for

example, a cavity resonator. Similar plates or discs 12', 18' may extend radially outward from the cathode sleeve 20 and the anode support 32, respectively, to provide a similar coupling means with the appropriate cavity resonator.

Input and output cavity resonators may be connected to the electrodes of this structure in any suitable manner, the arrangement which is preferred on account of its simplicity being that shown in the figure, wherein a first or input cavity resonator 36 is coupled to the cathode 12 and the grid 14, while a second or output cavity resonator 33 is coupled to the screen 16 and the anode 18. Blocking condensers 37, 39 may be inserted at convenient points, for example, at the peripheries of the discs 12', 18', so that a steady potential difference may be established between adjacent electrodes without substantially reducing the effectiveness of the resonators at the signal frequency. To this end these condensers should be of capacitance values such as to present but a negligible impedance at the operating frequency. They may conveniently be formed by providing adjacent portions of the plates with parallel flanges, a thin annular strip of insulating material being placed between. With this arrangement the space 15 between the grid 14 and the screen 16 is substantially free of signal frequency fields, and to this extent is similar to the so-called "drift space" of velocity variation devices. However, it is by no means free of steady fields.

Signal energy may be supplied to the input cavity resonator 36 from a high frequency signal source which is symbolically represented by the generator 40 by way of a coaxial line 41 to a coil or loop 42 which extends within the cavity 36 through a hole in the cavity wall to link a small amount of the magnetic field within the cavity. Signal energy may be withdrawn from the system by a similar loop 44 similarly coupled by a line 45 to the output resonator 33 and supplied to any suitable load, symbolically represented by the resistor 46. The resonators 36, 33 may be tuned by adjustment of the position of conducting rings 43, 50. As is well known, when resonators of this type are excited, high frequency electric fields exist across the input region 13 defined by the reentrant cathode 12 and the grid 14 and also across the output region defined by the screen 16 and the anode 18. These electric fields are established in a substantially axial direction, both of the envelope 10 and of the electron stream flowing from the cathode 12, through the grid 14 and the screen 16 to the anode 18. They interact with the electrons of the stream in their movements between these electrodes and across these regions to cause variations in their energies.

It is preferred that the electron transit angle across the input region 13 should be fairly long, i. e., of the order of a full cycle of the signal frequency or more, and also that this input region 13 be substantially space-charge limited, i. e., that the velocities and accelerations of the electrons at the cathode surface be substantially zero, the space-charge density within this region having a high value.

The output region 17 defined by the screen 16 and the anode 18 is preferably of a short electrical length. This result may be achieved by making its geometrical length short and the anode potential high or by any compromise between these conditions. As shown, the space 17 is considerably shorter than the input space

13, while the anode potential is substantially in excess of the potential of any other electrodes in the tube.

In accordance with the principles of the invention and with a preferred arrangement thereof the potential of the grid-screen space 15 should fall steeply from the grid 14 to the screen 16. A suitable arrangement is one in which this space is of twice the length of the input region 13, the screen 16 being maintained at a potential equal to one-quarter of the grid potential, measured with respect to the cathode.

Suitable values for the spacings and potentials of the apparatus of Fig. 1 are:

15	Length of cathode-grid space-----inches--	0.06
	Length of grid-screen space-----do-----	0.12
	Length of screen-anode space-----do-----	0.03
	Cathode potential-----volts--	0
	Grid potential-----do-----	60
20	Screen potential-----do-----	15
	Anode potential-----do-----	400

These potentials may be applied to the electrodes of the device in any suitable manner, as by connections to a suitable source 34. Since the potentials of the grid 14 and the screen 16 are fairly critical, means may be provided for experimental adjustment of these potentials to correct values, as for example by a potentiometer 31 connected across at least a part of the source 34 and movable taps 33, 35 which are connected, respectively, to the grid 14 and to the screen 16.

In the operation of the apparatus, electrons, thermionically emitted by the cathode 12 are drawn toward the grid 14, pass through the latter at considerable velocities and travel at continually reduced velocities to the screen 16, pass through the screen and are immediately accelerated by the anode potential to cross the screen-anode space 17 with great rapidity and are finally collected by the anode 18 and returned through the potential source 34 to the cathode 12. During successive half cycles of the signal applied to the loop 42, the signal frequency electric field which is established between the cathode 12 and the grid 14 is successively added to and subtracted from the steady electric field which appears between these electrodes due to the applied steady bias potentials. In the case of tubes with close-spacing between the cathode and grid, with the consequence that the transit angle across the input gap is small it follows that at instants when the fields are additive, electrons pass through the grid 14 with greater than average velocity and at instants when it subtracts they pass through with less than average velocity. Associated with these velocity variations there also exists a variation in the number of electrons passing the grid, i. e., in the charge density of the stream. Thus, in general, the grid effects both velocity variation and density variation of the electron stream, though these two sorts of stream variations are by no means necessarily or usually in any favorable phase relation. In the case of tubes with greater spacing between the cathode and grid with the consequence that the transit angle across the input gap is not small, the simple phase relations described above no longer apply. Nevertheless, the general effect is the same when proper account is taken of the phase shifts, and the grid again affects both velocity variation and density variation of the electron stream.

In conventional velocity variation devices electrons whose velocities have been varied in ac-

cordance with the signal are next allowed to traverse a field-free drift space in which the faster electrons tend to overtake the slower ones so that, at a distance from the grid, they will have become partially segregated into groups or bunches. At the beginning of the bunching process the forward electrons of each bunch are the slowest and the rearward ones the fastest, while the bunch as a whole travels with the mean or normal speed of the stream. It has been conceived by some that, ideally, the faster electrons eventually overtake and pass the slower ones and proceed in turn to catch up with the slower electrons of the next group ahead, so that the proper point at which to place the output circuit, i. e., the point of maximum charge density, is the point at which the fast electrons have overtaken but not yet passed the slower ones.

It has been recognized that as this process proceeds and the density of the bunches becomes greater and greater, the completeness of the bunching process will be impeded, delayed, and reduced by mutual repulsive forces between electrons; i. e., a space-charge dispersion or so-called "debunching" effect will come into play. However, this has been generally regarded as indicating merely that the output circuit should not be placed exactly at the point dictated by elementary considerations but rather at a point somewhat further along the stream path.

A different mode of operation for such devices is proposed in W. C. Hahn Patent 2,240,183, April 29, 1941, wherein the space-charge dispersion effects are treated as controlling. It is there suggested that as the faster electrons tend to overtake the slower ones they will be progressively retarded by the latter, the slow ones in turn being progressively accelerated by the faster ones. On the assumption that the phenomena are elastic in nature an interchange in momentum is said to occur, the roles of fast electrons and slow ones being interchanged, the final effect being that of a density wave traveling along the path of the stream. An analogy is drawn to a rubber rod along which elastic waves move back and forth while the rod is being translated as a whole in the direction of its length. Thus, according to the teachings of the Hahn patent there are at any instant a succession of regions of maximum density in which the velocity is low, interspersed with regions of reduced density in which the velocity is high. Each successive density maximum is conceived to be like the others and it is suggested that the output circuit may be placed to coincide with any one.

Now it is a fact that neither of these two modes of conceiving the operation of devices of this character is complete. There is, in fact, always some elastic interchange of momentum while at the same time some of the fast electrons which find themselves between two density maxima or groups succeed in passing through the group ahead of them from rear to front as though space-charge repulsion effects were not present. These two different effects tend, in general, to offset each other so that the results obtainable in the past with devices of this character are notoriously inferior to those predicted by either theory.

In accordance with the invention, these two effects are so controlled as to aid each other instead of opposing each other while at the same time each one separately is caused to be substantially greater than it could be if it stood alone. These results are secured by the proper correlation of the electrode spacings and poten-

tials with the space charge present in the device in the manner now to be explained.

For the sake of simplicity of explanation, let it be assumed that the apparatus is a plane parallel electrode arrangement such as that diagrammatically depicted in Fig. 2, wherein a cathode 12, a grid 14, a screen 16, and an anode 18 serve the purposes of the similarly designated electrodes of Fig. 1. If it be assumed further that the total length of the beam from the cathode to the anode is small as compared with its diameter the effects of radial spreading may be neglected. These assumptions are simplifying idealizations which, however, are not far from the reality as it exists in a practical embodiment such as that shown in Fig. 1. In the figures of the drawing, the spacings between the several elements of the tube structure are shown extended for the sake of clearness. It is evident that they may be shortened in relation to the diameter of the elements in order to maintain a more homogeneous electron stream or may even be lengthened provided that undue dispersion of the beam does not result.

In Fig. 2, as in the other simplified diagrammatic figures, namely Figs. 5, 6, 7, 8, and 10, batteries are shown to indicate the preferred potential differences between the more important electrodes, cathode and anode potential supply sources being omitted in the interests of simplicity.

Consider a velocity-varied electron stream of comparatively high average density issuing from the control grid 14 of Fig. 2. Since the screen electrode 16 is maintained at a potential, measured with respect to the cathode 12, which is considerably less than that of the grid 14, an electric field exists between these electrodes of a character such as to retard the electrons of the stream. With a screen potential of only one-fourth of that of the grid potential, the retarding field is such as to reduce the electron velocities at the screen 16 to one-half of their values at the grid. As a result, in the absence of an alteration in beam cross section, the average beam density at the screen 16 is twice, and the average electron spacing one-half, of what these quantities are at the grid 14. The stream has been subjected to a progressive axial compression. It is under these new conditions that the bunching process is now to take place.

Without necessary subscription to any particular theory, it is felt that the bunching phenomena which take place under these new conditions are somewhat as follows:

Consider a region of the stream path at which bunching has just commenced. In the case of a signal input of the purely velocity variation variety, this point may be a point somewhat removed from the input means, i. e., the grid 14 of Fig. 1. In the case of combined velocity variations and density variations, this point may be immediately to the right of the grid. At this point, wherever it may be, the incipient groups of electrons are spaced apart by a distance determined by the mean speed of the stream and the signal frequency, while the actual velocity of each electron is compounded of a steady or D. C. component and a signal frequency or A. C. component. The groups themselves are advancing with a "group velocity" equal to the average velocity of the stream. An electron lying between two adjacent incipient charge groups has, in general, a speed which differs from the average stream speed. Suppose this electron to be

somewhat ahead of the mid-point between two adjacent incipient charge groups. It will normally be traveling with a velocity greater than the average stream velocity and at the same time it will be repelled by the charge group ahead of it more strongly than it is urged forward by the charge group behind it. These repulsive forces offset each other only for an electron which lies midway between the two charge groups and which may have a velocity which is forward or backward with respect to the group, depending on the phenomena which have taken place in the input region. These repulsive forces represent potential energy, which is reduced to a minimum when the electron is equally spaced between adjacent charge groups. At the same time, by virtue of the alternating components of its speed and momentum, the electron under consideration has kinetic energy relative to the stream as a whole. These potential and kinetic energies are related in such a way as to promote a tendency for the electrons to oscillate to either side of some point lying between the two adjacent charge groups, for example, the mid-point, and this energy of oscillation will have a definite value. To a first approximation this oscillation energy is given by

$$E = \frac{1}{2} K x_1^2$$

where x_1 is the maximum value of the oscillatory excursion of the electron from the point about which it oscillates and K is an equivalent elastic constant which, again to a first approximation, is proportional in a plane parallel electrode arrangement such as that here under discussion to the average density of the beam.

Under these conditions, the amount of bunching or grouping associated with the particular electron under consideration is related to the difference between the distance separating it from the nearer group and the distance separating it from the farther group.

Consider next the modification of this state of affairs which exists when the stream as a whole has been reduced in velocity, its density increased and its group spacing reduced by the influence of the retarding field which is established between the grid 14 and the screen 16. If no signal frequency energy is abstracted until after the beam enters the output region 17 defined by the screen 16 and the anode 18, then, at the entrance plane of this output region, i. e., just as the stream is about to enter the screen 16, the energy of oscillation has the same value as before. In other words, the oscillation energy is conserved during the travel of the stream along the drift space and against the retarding field which is established therein. Assuming, for example, that the electrode potentials have the values recommended for Fig. 1, namely, the screen potential is one-quarter of the grid potential, then the average velocity of the stream at the plane of the grid 14 will have been halved; its mean density will have been doubled and the spacing between adjacent electron groups will have been halved. The equivalent elastic constant will be twice its prior value. With conservation of the oscillation energy this requires that the oscillatory excursion of the electron on either side of its position of equilibrium be reduced by the factor $\sqrt{2}$. Since, however, the spacing between adjacent groups has been reduced by a factor 2, it is easily seen that a substantial enhancement or increase in the

amount of bunching or grouping will have resulted; in other words, the ratio of the peak or maximum value of the electron stream density to the average value is greater, where the beam has been axially compressed, than the same ratio at the input gap.

The electron stream with its electron bunches or groups, substantially enhanced in the manner described above, now passes through the screen and travels rapidly across the output region 17 defined by the screen 16 and the anode 18. The anode potential is preferably maintained at a relatively high value such that, despite the comparatively low electron velocity at the screen 16, the electron transit angle in the output region 17 is but a small fraction of a cycle at the signal frequency. The passage of the segregated electron groups across this output region generates and maintains an electromagnetic field within the output cavity resonator 38 in well-known manner, from which signal frequency energy, greatly amplified by the apparatus described above, may be abstracted by the loop 44 and delivered to the load 46.

If it were not for the phenomenon of space charge the electrons of the stream would continue throughout the length of the drift space without modification of the original velocities with which they emerge from grid 14 by reason of the presence of other electrons or electron groups within the space. With these electrons grouping or bunching would take place on a purely kinematic basis, i. e., unaffected by interchange repulsions. In apparatus of conventional design this kinematic grouping is offset and impeded by the space-charge repulsion grouping. By proper selection of electrode spacings and operating conditions in accordance with the principles of the invention these two effects are both increased in magnitude and rendered cumulative.

The reference in the above explanation to oscillations and oscillation energy is not to be taken as implying that a number of full oscillation cycles necessarily take place in the electron stream between the grid and the screen. There may be a number of such full cycles or there may be only a fraction of a cycle, depending on the detailed arrangement of the electrodes and their potentials. In the particular case discussed above, it is believed that there is but one density maximum; i. e., the electrons, while they have oscillatory energy in the sense that they are masses in motion under the influence of restoring forces, fail to complete the first full cycle of such oscillation and are, so to speak, caught by the output circuit just as they are about to be reflected for the first time. In other more elaborate structures constructed in accordance with further features of the invention, they may be caught on the second or third reflection, or even after a still higher number of reflections. The limiting consideration here is that if the average velocity of the stream be too greatly retarded and the stream be axially compressed with too great rapidity, electrons may actually be brought to a zero velocity at some point of the stream, in which case some electrons may be turned back relatively not only to the moving charge groups but also to the electrodes, with the formation of a virtual cathode and a sudden large reduction in the stream current. This phenomenon is fully discussed in an article published in the Bell System Technical Journal for July 1939 at page 465. It is recommended that operation of apparatus in accordance with the

invention be kept well to the safe side of such a condition.

When the phenomena described above are treated mathematically, it can be shown that the transadmittance of the device as a whole may be expressed in the following form:

$$y = A g_0 e^{-i(\theta_1 + \theta_2)} \left[\zeta \frac{v_1 + v_2}{v_2} - 1 + \frac{v_1}{v_2} \frac{\theta_2}{\theta_1} (1 + e^{i\theta_1}) \right] \quad (1)$$

where the symbols all refer to measurements made before any alternating currents are impressed on the device, that is, to measurements made on a direct current basis and

v_1 and v_2 are the steady components of the stream velocities at grid and screen, respectively;

θ_1 and θ_2 are the transit angles across the input region and the drift space, respectively,

ζ is a space-charge factor for the drift space, defined by

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

where T is the actual transit time across the drift space and T_0 is the transit time in the absence of space charge, both measured when no alternating currents are flowing,

g_0 is the transadmittance of the structure at frequencies so low that transit time effects may be neglected, A is a constant which depends on the permeability to electrons of the grid and the screen,

e is the base of naperian logarithms, and

$$i = \sqrt{-1}.$$

The procedure employed in arriving at the above mathematical expression is laborious, though straightforward. In "Electron Inertia Effects" by F. B. Llewellyn there are given general electronics equations for discharge devices having parallel plane electrodes. Solution of these equations for the cathode-grid space provides boundary conditions to be inserted in the coefficients of the same equations for the grid-screen space. Solution of these, in turn, provides boundary conditions to be inserted in the coefficients of the same equations for the screen-anode space. Solution of these last equations gives the output signal frequency current in terms of a large number of factors, among which are the electrode spacings, the electrode potentials, and the electron steam density. Division of the output signal current by the input signal voltage gives the transadmittance.

To simplify the work, various approximations may be made. Thus, in arriving at the above expression it has been assumed that in the input region **13**, space charge is high and the transit angle of the order of a full cycle or more; that in the output region the space charge is negligible and the transit angle but a small fraction of a cycle.

In the expression (1) the first two terms represent the effects of density variations imparted to the stream in the input region and the third term represents the effects of velocity variations imparted to the stream in the input region. After multiplication of the third term by g_0 , it may be rewritten in the form

$$\frac{I_0 \theta_2}{2\sqrt{V_1 V_2}} \left(\frac{1 + e^{i\theta_1}}{\theta_1} \right) \quad (2)$$

It will be observed that in the expression (2) the first variable factor is a modification of the drift tube factor which is well known in velocity variation practice and is discussed in an article by Hahn and Metcalf published in the Proceedings

of the Institute of Radio Engineers for February 1939 at page 106. In this factor the modification consists in the replacement, in the denominator, of the drift tube potential by the geometrical mean of the potentials of the screen and the grid, i. e., of the electrodes which define the drift space. The second variable factor, namely,

$$\frac{1 + e^{i\theta_1}}{\theta_1} \quad (3)$$

may be termed a modulation factor and relates the alternating current component of the velocity at the grid to the alternating component of the potential applied between grid and cathode.

It is of interest to note that the first two terms of the above expression (1) for the transadmittance are independent of the frequency of the applied signal, while to a first approximation the last term is equally so. This means that the apparatus whose performance the expression describes is useful over a wide frequency range and, within this range, shows great frequency stability. This is true as long as the frequency is within the range in which the restrictive assumptions on which the expression is based are satisfied; that is, as long as the frequency is so high that the transit angle across the input space is long and yet not so high but that the transit angle across the output space may still be short.

Regarding the three terms of the above expression (1) as vectors or complex members it will be observed that the first two terms are pure real numbers while the third term is a complex quantity whose phase angle depends solely on the transit angle across the input space. Thus these vectors may be given any desired phase relation merely by suitable adjustment of this input transit angle. They may be brought into phase coincidence by adjusting the input transit angle to an integral number of full cycles; they may be brought into phase opposition by adjusting the input transit angle to an odd number of half cycles. It is preferred, however, to adjust the input transit angle approximately to one or other of the members of the sequence $1/4$, $2/4$, $3/4$, etc. cycles, preferably the first member of the sequence. As explained in F. B. Llewellyn Patent 2,190,668, February 20, 1940, with this relation the input circuit of the apparatus, which is essentially a plane parallel diode, presents to the circuit to which it is coupled an impedance having a negative real part, i. e., a negative resistance. Such a negative resistance compensates, in part, for stray losses in the system and is believed to represent a desirable operating condition, as long as this result can be obtained without undue sacrifice. With an input transit angle of $1/4$, etc. cycles, the phase angle of the vector representing the third term of the above expression is 45 degrees. Referring to Fig. 3, in which the three vectors in question are shown in the complex plane, it will be observed that the resultant vector R is under these conditions only slightly reduced in magnitude as compared with its value when the input transit angle is a whole number of cycles, in which case all of the vectors lie along the real axis.

In Fig. 4 there are plotted a group of curves which exhibit the absolute value of the vector sum represented by the expression (1) under different conditions, i. e., as functions of the ratio of the velocity at the screen to the velocity at the grid. These curves are all taken for a structure such as that shown in Fig. 1, in which the screen-to-grid spacing is twice the cathode-to-

13

grid spacing. The parameter which distinguishes between these curves is the magnitude of the input transit angle. It will be observed that for properly chosen velocity ratios, the relative transadmittance, i. e., the ratio of the high frequency transadmittance to the low frequency transadmittance, g_0 , is quite large and that the high frequency transadmittance is thus many times greater than the low frequency transadmittance.

In the apparatus of Fig. 1 the drift space 15 between screen and the grid is substantially devoid of signal frequency fields, the output tuned circuit, i. e., the resonator 38, being connected between the screen 16 and the plate 18 while the input tuned circuit or resonator 36 is connected between the cathode 12 and the grid 14. This simplifies the discussion and the analysis.

The apparatus of Fig. 1 may be rendered regenerative or self-oscillatory by feeding back a portion of the energy of the output circuit to the input circuit in proper phase. Expedients are well known for effecting this result. For example, it may be accomplished merely by auxiliary loops 58, 60 introduced into each of the cavity resonators 36, 38 at the proper points, the loops being coupled together by appropriate means as through a coaxial line 62 whose length is adjustable as by a trombone-like sliding member 63.

It will be observed that the characteristic curves of Fig. 4 are exceedingly steep in the general region in which the electron speed at the screen is low relative to that at the grid. This exhibits the fact that the apparatus of Fig. 1 may serve excellently as a converter of oscillations, for example, either a detector or a modulator. It may conveniently be operated as a modulator by applying a signal of lower frequency than that of the principal signal derived, for example, from a suitable source 57 to the screen electrode 16 or, indeed, in any other desired fashion.

The principles of the invention are equally applicable to various modified arrangements of electrodes and of bias potentials of which Figs. 5, 6 and 7 show some in simplified schematic form, a number of them being shown additionally incorporated into a single structure in Fig. 11.

Fig. 5 shows a simplified view of an arrangement of four grids disposed in succession along the path of the electron stream from the cathode 12 to the anode 18, the input tuned circuit, for example a cavity resonator 36 being connected between the first grid 70 and the second 14, while the output tuned circuit or resonator 38 is connected between the third grid 16 and the fourth 72. With this arrangement there is no signal frequency field between the cathode 12 and the first grid 70 and substantially none between the last grid 72 and the anode 18. The cathode 12 thus serves merely as a source of electrons and the anode 18 merely as a collector of spent electrons. The first grid 70 should be disposed at such a distance from the cathode 12 and maintained at such a potential that a dense beam of fairly high velocity electrons reaches the first grid 70, the cathode being space-charge-limited without the formation of any virtual cathode at any point along the beam. The space between the first grid 70 and the second 14 constitutes the input region, signal energy being supplied as through a coupling loop 42 coupled to the input cavity 36. The space 15 between the second grid 14 and the third 16 constitutes the drift space. The electron stream is both velocity varied and density varied as it emerges from the second grid 14 and starts its travel through the drift space 15.

14

It is then considerably reduced in velocity and subjected to a progressive axial compression in the drift space 15 in order to reduce the spacing between adjacent charge groups, as by a retarding field in the manner described in connection with Fig. 1. The fourth grid 72 may be disposed fairly close to the third grid 16 and maintained at a comparatively high potential in order that the transit angle across the output region defined by the third grid 16 and the fourth 72 may be short. After passing across the output region the electrons of the stream, from which the signal frequency energy has been largely abstracted as by the loop 44, travel to the anode 18 and are there collected. The first and second grids 70, 14 may be maintained at like potentials in which case except that the electron stream arriving at the grid 70 contains no density variation component, the action and performance of the apparatus are substantially as described above in connection with Fig. 1 and a transadmittance enhancement of comparable magnitude may be obtained.

Fig. 5A shows a modification which may be the same as Fig. 5 except for the connection of the output cavity resonator between the screen 16 and the anode 18 as in Figs. 1 and 2. Thus the advantages of the simpler output arrangement of Figs. 1 and 2 are combined with the advantages obtainable from constant speed injection as in Fig. 5. In other respects this apparatus may be similar to Fig. 1, and corresponding parts are similarly designated.

Still further enhancement of the transadmittance may be gained by maintaining the second grid 14 of Figs. 5 and 5A at a reduced potential with respect to the first grid 70 so that a retarding field exists across the input region itself as well as across the drift space. In order that the first and second grids may be maintained at different potentials without having the resonant cavity which is connected to them short-circuit the input signal voltage, a blocking condenser 37 of appropriate capacitance value may be included in the circuit. The same consideration dictates the use of a blocking condenser 39 in the circuits of the third and fourth grids. These blocking condensers may be formed as described above in connection with Fig. 1 or in any other suitable manner and should have capacitance values such that they present negligible impedance at the signal frequency.

Still further improvement is obtainable by the division of the drift space 15 between the input region and the output region into two or more parts by the interposition of additional grids therein, which grids should, in accordance with the principles of the invention, be maintained at reduced potentials with respect to the grids which define the input region, and serve to regulate the space charge density in their vicinity. Fig. 6 shows in simplified diagrammatic form an arrangement for constant injection velocity as in Fig. 5 with one additional space charge controlling grid 78 in the drift space. Fig. 7 shows an arrangement which is the same except for the fact that two intervening space-charge-controlling grids 80, 82 are disposed in the drift space. Fig. 8 shows an arrangement which resembles that of Fig. 2 but in which an additional space charge controlling grid 84 is interposed between the control grid 14 and the screen grid 16. Various permutations and combinations of these arrangements are entirely feasible within the scope of the invention.

15

In the arrangements of Figs. 6, 7 and 8, respectively, the feature which is common to all of them is the interposition of one or more space-charge-controlling grids in the drift space between the input region and the output region. Such grids provide additional sources of control of the change in average beam velocity and the amount of its axial compression. The exact nature of the improvements resulting from these modifications are not fully known although tests have shown that they exist. Without unqualified subscription to any particular theory it may be suggested that, in a broad sense at least, the nature of these effects is as follows:

Referring again to Fig. 4 which represents the characteristic curves of apparatus having the electrode arrangement shown in detail in Fig. 1 and schematically indicated in Fig. 2, i. e., devoid of auxiliary space charge controlling grids in the drift space, it will be observed that each of these characteristic curves rises more and more steeply as the stream velocity at the plane of the screen electrode is reduced up to a certain point at which the curves terminate abruptly and for which the space charge factor ξ , which was defined above in connection with Equation 1, reaches a value of unity. These terminal points represent unstable operation and correspond to conditions in which the electron velocity at some part of the stream path has been brought so low that a virtual cathode is formed with a resulting sudden reduction in the stream current. These phenomena are fully discussed in an article published in the Bell System Technical Journal for July 1939 at page 465. In view of this instability it is advisable to operate the device under conditions corresponding to a lower point on the characteristic curve such that the maximum signal frequency peak swing will not pass the threshold of instability.

When, on the other hand, one or more space-charge-controlling grids are interposed on the drift space, the relative transmittance curves may pass through a maximum value as shown in Fig. 9 before the instability point is reached. The origin of the phenomena which gives rise to the maximum values of these curves is believed to be related in a somewhat involved way to the phase relations between the velocity variation contribution and the density variation contribution to the total current in the successive sections of the drift space and also to the fact that when the axial beam compression is given two different values in different parts of the drift space, alterations may take place in the relative amounts of charge bunching due to drift action and of charge bunching due to space charge effects (in less precise but more graphic language, grouping due to coasting and grouping due to elastic repulsions). Whatever the intrinsic nature of the phenomena, it results that with the interposition of one or more space-charge-controlling grids in the drift space the characteristic curves of the resulting apparatus exhibit maximum values such as those shown in Fig. 9. It is obviously desirable that the peak or maximum value be selected as an operating point for the apparatus when used as an amplifier, since under these conditions it will be much less sensitive to small changes in electrode biases than when operated on a steeply sloping characteristic. On the other hand, when operation as a converter, a detector or a modulator is required, for which a steeply sloping characteristic is desirable, a suitable alteration in the bias potential

16

of one of the space charge controlling electrodes immediately shifts the operating point from the maximum peak to the sloping part of the characteristic and transforms the apparatus from an amplifier into a converter.

The relative transmittance curves of Fig. 9 are plotted for apparatus having the electrode configurations and spacings shown in Fig. 8, in which the drift space 15', 15'' is four times the length of the input region 13, a single space-charge-controlling grid 84 being placed at the mid-point of the drift space, the output region being electrically short as before. To facilitate the analysis the third grid 16 was taken as being maintained at the same potential as the first grid 14 so that the electron velocity of entrance into the output region 17 was the same as the velocity of exit from the input region 13, being reduced elsewhere in the drift space by the action of the space-charge-controlling-grid 84. The curves show the transmittance as a function of the ratio of the electron velocity at the space-charge-controlling grid 84 to the velocity at the control grid 14. As in the case of Fig. 4, which shows corresponding curves for the simpler structure of Figs. 1 and 2, the parameter which distinguishes the curves is the transit angle across the input region. It will be noted that the optimum conditions do not differ greatly from those for the apparatus of Fig. 1, i. e., the velocity ratio for which the transmittance maximum occurs is approximately one-half. Thus the bias potential of the space-charge-controlling grid 84 should be adjusted to approximately one-quarter that of the control grid 14. However, it is by no means necessary that the specific limitations under which the curves of Fig. 9 were obtained shall be satisfied, and various modifications of the spacings, with correspondingly different values for the potentials of the space charge grid 84 and of the output grid 16 relatively to the control grid 14 may profitably be employed.

As with the apparatus of Fig. 1, it is equally the case with the apparatus diagrammatically shown in the other figures that adjustment of the input transit angle, for example, to a value of $1\frac{1}{2}$ cycles, results in an optimum value of input loading, i. e., the system presents a negative input resistance to the circuit to which it is coupled. It is also true that this result may be secured with but a small reduction in the overall transmittance of the device from the maximum obtainable value, namely, that secured when the velocity variation vector of Fig. 3 is exactly in phase with the density variation vector.

Still further advantages result from the introduction of a further feature of the invention by which optimum values of input loading may be obtained without any sacrifice in transmittance. To this end, provision is made for effecting a preliminary adjustment in the phase displacement between the density variation signal and the velocity variation signal at the input region itself. Thus Fig. 10 shows an arrangement which is similar to that of Fig. 1 with the exception of the fact that a short velocity variation gap 87 defined by two adjacent closely spaced control grids 14, 86 is added following the principal input region 13. The second grid 86, defining the output plane of the velocity variation gap 87 may be maintained at the same potential as the principal control grid 14 so that the associated auxiliary tuning cavity 88 may be a continuous conducting surface, while, in view of the potential difference between the cathode 12 and the

17

first grid 14, a blocking condenser 37 must be interposed in the wall of the principal input tuning cavity 36 as shown. The signal is applied to the principal input gap 13 by way of a coupling loop 42 in the manner heretofore described and, in addition, it is passed through a phase-shifting device 90 of any suitable type and by way of an auxiliary loop 92 to the auxiliary velocity variation gap 87. Thus the electromagnetic field in the second cavity 88 is out of phase with that of the first cavity 36. The common cavity wall should be of high conductivity and the second grid 14 should preferably be a substantially perfect shield in order to prevent deleterious interaction between the fields. With this arrangement the phase displacement between the velocity variation component and the density variation component in the electron stream as it emerges from the auxiliary gap may be such that, even when the transit angle across the principal input gap 13 has the desired value of about $1\frac{1}{4}$ cycles, the effects of both of these variations at the output gap 17 may be brought into phase coincidence so that they stand in a directly additive relation.

The features hereinabove described are mutually compatible and Fig. 11 shows a structure embodying a number of them. Referring to this figure the envelope 10, the cathode structure and the anode structure may be similar to those shown in Fig. 1 and each of the grids may be of similar construction and similarly mounted. The grids shown have the following functions. Starting from the cathode 12 in the direction of the projection of the stream, the first two grids in order, 70, 14 define the principal input region which, as before, may be of such a length and its grids at such a potential that the electron transit angle across it is $1\frac{1}{4}$ cycles. This part of the system is arranged for constant velocity injection into the input region as in Figs. 5, 6 and 7 although it may equally be arranged in the manner shown in Fig. 1. A resonant cavity 36 is coupled to these two grids and, in order to provide for a retarding field across this input region a blocking condenser is provided in series with the circuit formed by the cavity walls, for example, by an insulating band 37' in the ring 43 which closes the cavity 36.

Following this input region is a second much shorter region or gap 87 defined by the second and third grids 14, 86 which, as shown, may be maintained at the same potential, and to which is coupled another cavity 88 tuned to the same frequency as the first cavity 36. The signal derived from a suitable source 40 is applied directly to the principal input cavity 36 through a coupling loop 42 in the manner heretofore described and is also fed through a phase shifting device 90 of any suitable type to the second cavity 88. As in the case of Fig. 10 this arrangement provides means for an initial adjustment of the phase displacement between the two current components prior to entry of the stream into the drift space.

After emerging from the auxiliary input gap 87 the beam travels through a drift space toward the output gap and, in doing so, passes through two successive space charge controlling grids 80, 82. These grids may be maintained at like potentials so as to define a field-free space between them, but it is preferred to maintain the second grid 82 at a slightly reduced potential with respect to the first grid 80 in order that a substantial amount of axial beam compression may take place in each section of the drift space.

18

The output region defined by the last two grids 16, 72 should be of short transit angle as before and the two grids which define it may be maintained at such potentials as will produce the greatest possible amount of energy abstraction within this output region in accordance with the principles heretofore disclosed. The anode 18 serves to collect spent electrons.

For operation of the above-described apparatus as a modulator, detector, or other converter, an auxiliary signal source 96 of lower frequency than that of the ultra-high frequency source 40 may be connected to any suitable electrode, for example to the first of the space charge controlling grids 80 of Fig. 11. Various other points of application of this source are equally possible. It will be understood that for operation in this manner it is desirable so to adjust the potentials that the operating point lies on the sloping portion of the transadmittance characteristic.

Variations and departures from the particular details described above by way of illustration will suggest themselves to those skilled in the art as being within the scope of the invention as defined by the appended claims.

What is claimed is:

1. In an ultra-high frequency discharge device of the type in which transit time effects play a controlling part, the combination which comprises means for projecting a stream of moving charges along a prescribed path, signal input means disposed at a point of said path for imparting charge density variations and velocity variations to the current of said stream, a region disposed along said path and following said input means in which there occurs a grouping of said charges due to said imparted variations, an electrically conductive member in said region for establishing an electric field, an electrically conducting path connecting said member to the stream projecting means, said path including a source of steady polarizing electromotive force of such magnitude and polarity that the resulting electric field of the electrically conductive member retards without reversing all of said charges, signal output means disposed following said region at a point along said path at which the velocities of said charges have been reduced by said field, and means for adjusting the potential of said input means to a value such that the input impedance of said device has a desired value.

2. In an ultra-high frequency discharge device of the type in which transit time effects play a controlling part, the combination which comprises means for projecting a stream of moving charges along a prescribed path, signal input means disposed at a point of said path for imparting charge density variations and velocity variations to the current of said stream, a region disposed along said path and following said input means in which there occurs a grouping of said charges due to said imparted variations, means within said region for reducing the velocities of all of the moving charges by substantially the same amount to cause the charges to attain a mean velocity of the order of one-half that with which they entered the region whereby the average charge density of said stream is doubled with respect to the density with which it entered the region, signal output means disposed following said region at a point along said path at which the velocities of said charges have been reduced by said field, and means for adjusting the potential of said input means to a value such

that stream currents at said output means due to said charge density variations bear a favorable phase relation with respect to stream currents at said output means due to said velocity variations.

3. In a ultra-high frequency discharge device of the type in which transit time effects play a controlling part, the combination which comprises means for projecting at high velocity a dense stream of moving charges along a prescribed path, signal input means disposed at a point of said path for imparting velocity variations and charge density variations to the current of said stream, signal output means for converting each of said variations into an output current component, means positioned between said signal input means and said signal output means for reducing the velocities of all of said charges by substantially the same amount in order to effectively double the average charge density of said stream, and means for adjusting the transit angle across said signal input means to bring the output current components resulting respectively from the velocity variations and the charge density variations into cophasal relation, whereby said output current components are cumulative.

4. The method of operating an ultra-high frequency discharge device of the type in which transit time effects play a controlling part and having means for projecting a stream of charges along a prescribed path, a signal input electrode defining an input region, an intermediate electrode, a signal output electrode defining an output region, said electrodes being disposed in succession along said path, and means for applying bias potentials to said electrodes, which comprises adjusting the steady potential of said input electrode and the density of said stream current to values such that space charge in said input region is substantially complete, adjusting the potential of said output electrode to a value such that space charge in said output region is insubstantial, imparting signal frequency variations to the current of said stream to cause said charges to become grouped in the course of their passage to said output region, and adjusting the potential of said intermediate electrode to a value such as to produce in the vicinity of said intermediate electrode a space charge of a high value short of completeness, whereby the density of said charge groups at said output region is enhanced.

5. In an ultra-high frequency discharge device of the type in which transit time effects play a controlling part, the combination which comprises means for projecting a stream of charges along a prescribed path, signal input means defining an input region disposed along said path for imparting signal frequency velocity variations to the charges of said stream, independent signal input means disposed along said path for imparting signal frequency charge density variations to said stream, means for adjusting the potential of said first-named input means to a value such that the charge transit angle across said input region has a desired value, means for adjusting the phase displacement between said imparted velocity variations and said imparted density variations to a desired value such that the effects of both of said variations combine substantially in phase to produce dense groups of moving charges at a certain point along the path of said projected beam, and means disposed at said point for abstracting signal frequency energy from said groups.

6. The method of operating an ultra-high frequency discharge device having in the order

named a cathode, a control electrode, a screen electrode and an anode, an energy input circuit connected between said cathode and said control electrode and an energy output circuit connected between said screen electrode and said anode, and means for applying bias potentials to said electrodes, which comprises adjusting the bias potential applied to said control electrode to a value such as to produce a favorable transit angle across the space between said cathode and said control electrode and substantially complete space charge in said space, adjusting the potential of said screen electrode until the absolute value of the expression

$$\zeta \frac{v_1 + v_2}{v_2} - 1 + \frac{v_1 \theta_2}{v_2 \theta_1} (1 + e^{i\theta_1})$$

is greater than unity, where v_1 is the mean electron speed at the plane of the control electrode, v_2 is the mean electron speed at the plane of the screen, θ_1 is the charge transit angle from the cathode to the control electrode, θ_2 is the charge transit angle from the control electrode to the screen, e is the base of natural logarithms, and $i = \sqrt{-1}$, and ζ is a factor which measures the amount of space charge in the region between said control electrode and said screen electrode, defined by

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

where T is the actual transit time across said region and T_0 is the transit time in the absence of space charge, both measured when no alternating currents are flowing, and adjusting the potential of said anode to a value such that the transit angle across the region between said screen and said anode is a small fraction of a signal frequency cycle and the space charge within said region has a low value.

7. In an electron discharge apparatus which comprises, in the order named, a source of an electron stream, a signal input electrode coupled to said stream for imparting velocity variations to the electrons of the stream, a drift space in which said electrons tend, by reason of said imparted velocity variations, to become grouped, an output electrode for abstracting energy of said charge groups, and a collector of spent electrons, a source of potential connected to said input electrode and arranged to maintain said input electrode at a substantial positive potential with respect to said stream source, and a source of potential connected to said output electrode and arranged to maintain said output electrode at a small positive potential with respect to said stream source and at a substantial negative potential with respect to said input electrode, said negative potential operating to progressively increase the density of said stream as it traverses said drift space, whereby the grouping of said charges as they pass said output electrode is accentuated.

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