June 17, 1941. R. H. VARIAN 2,245,627

STABILIZATION OF FREQUENCY

Filed June 24, 1938 4 Sheets-Sheet 1

FIG 1

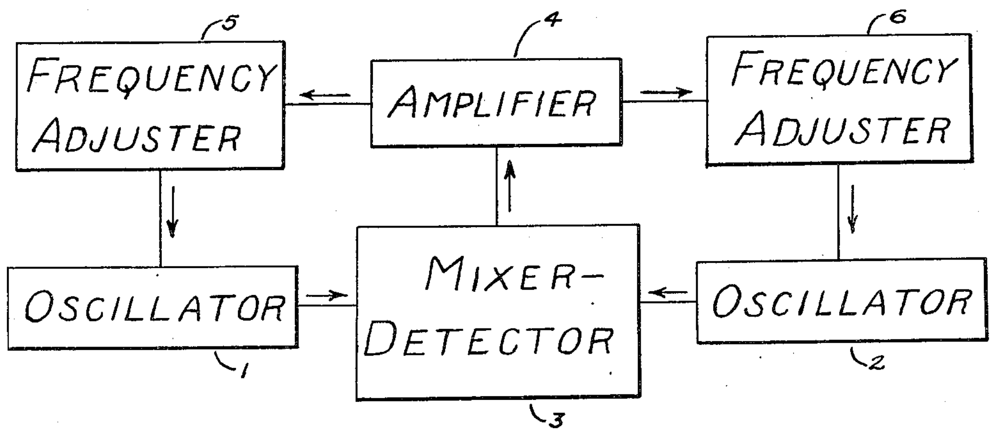

FIG 2

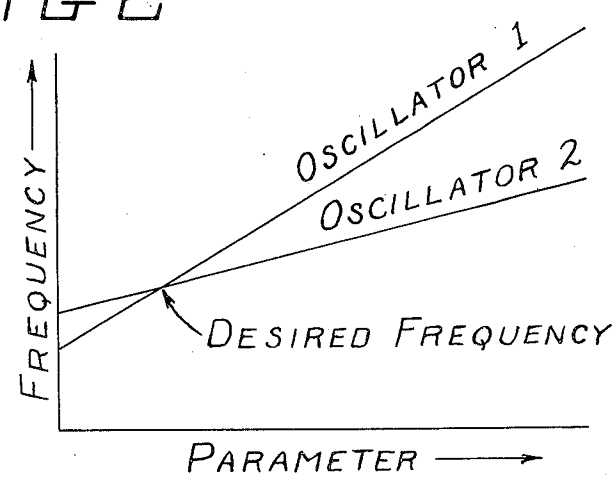

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FIG 3

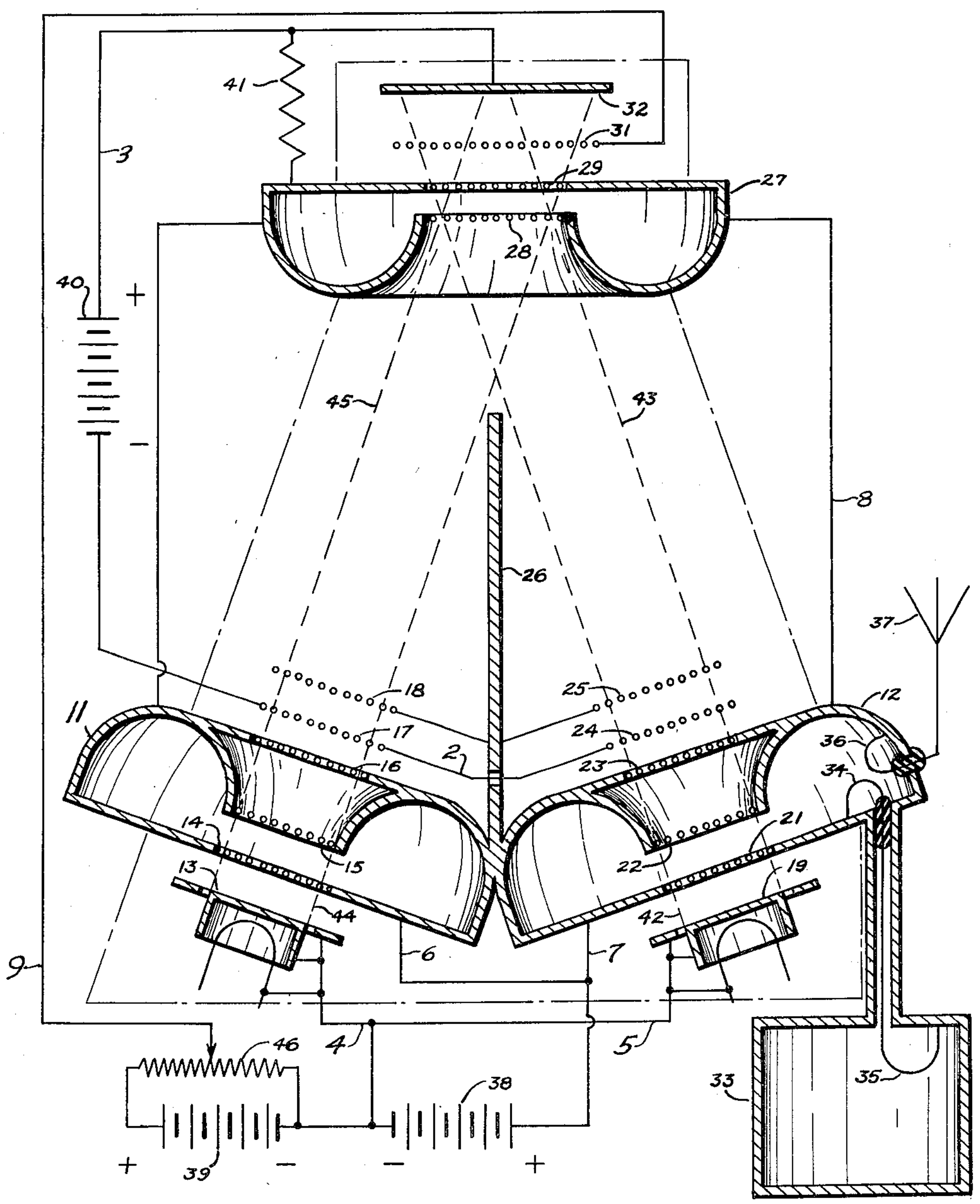

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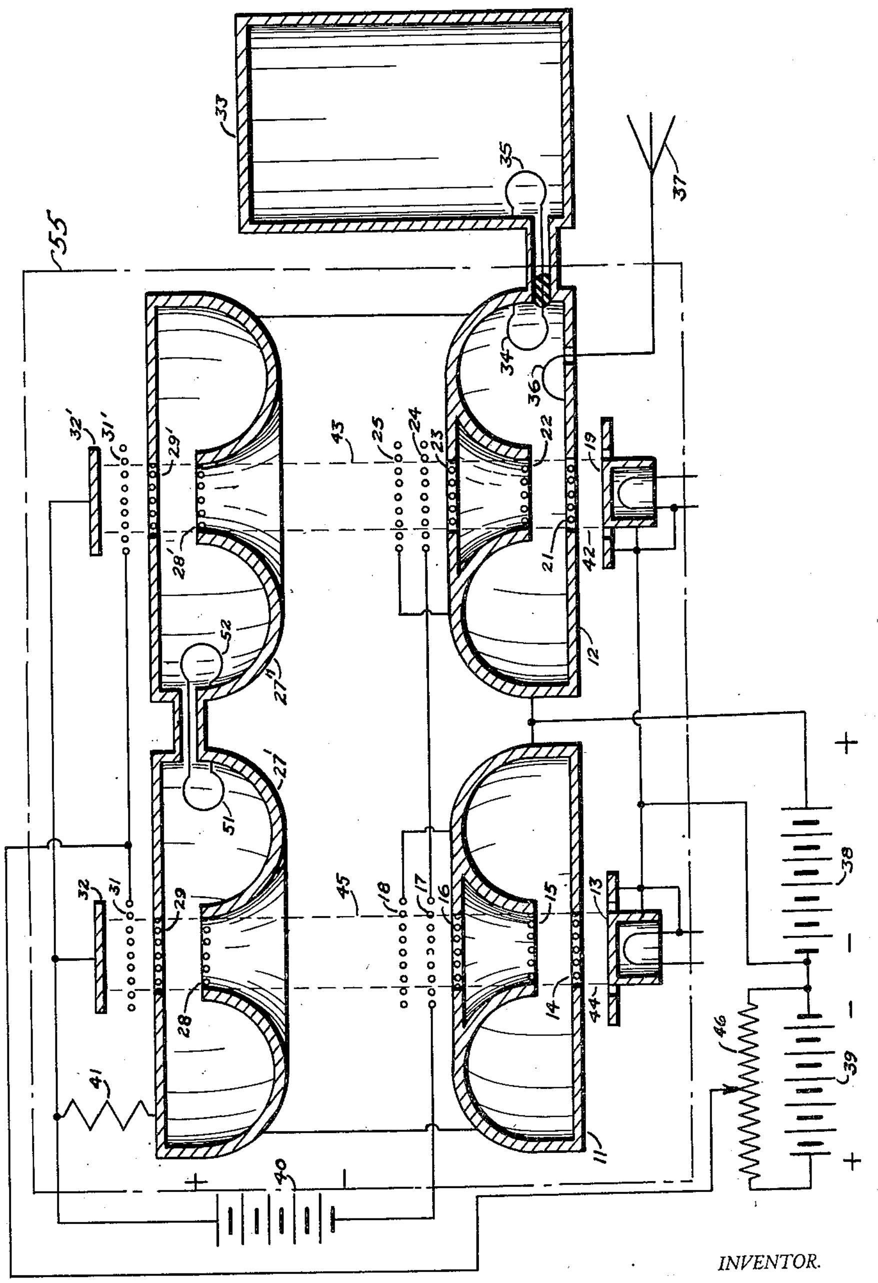
FIG 4



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STABILIZATION OF FREQUENCY

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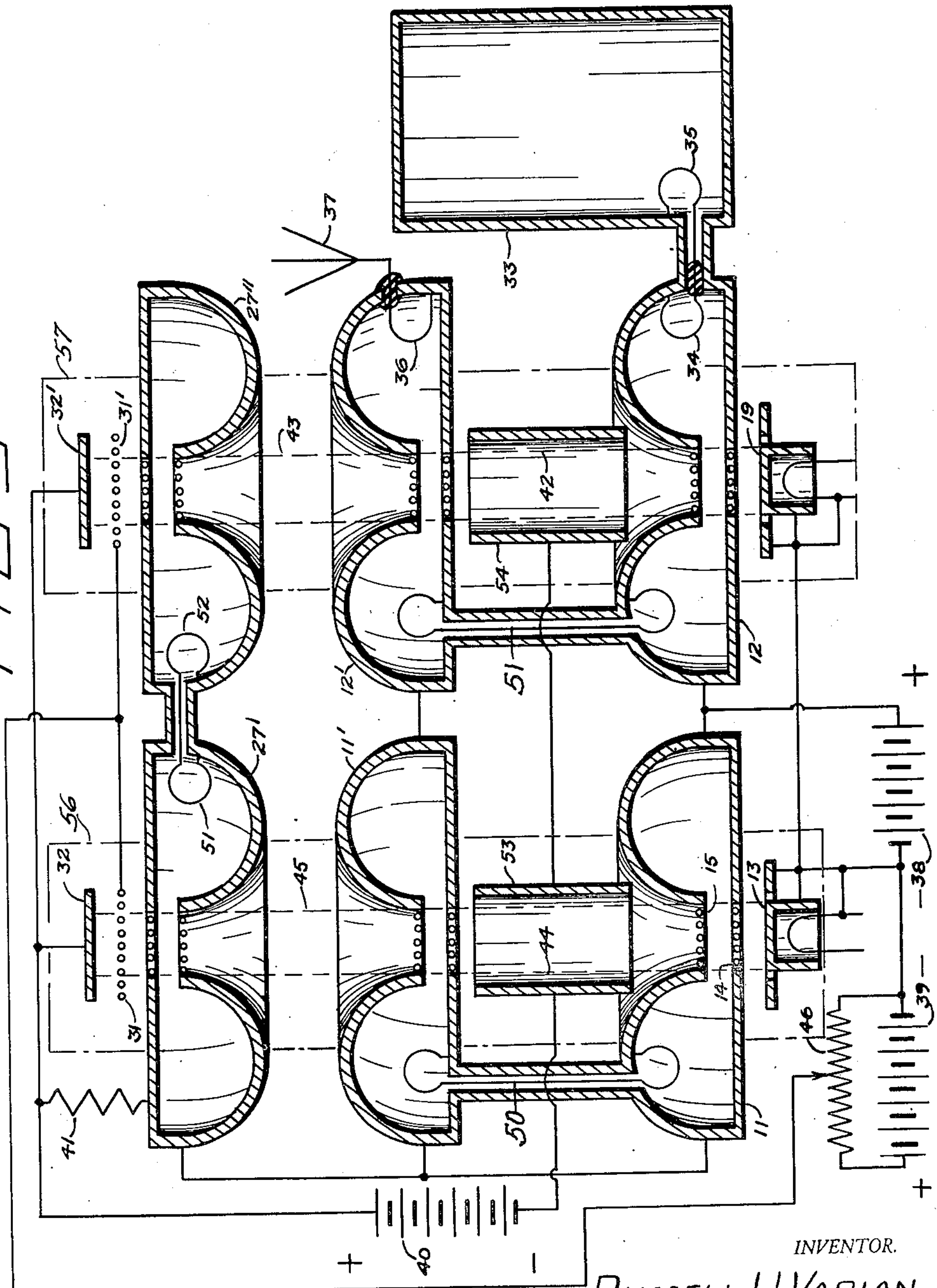
FIG 5



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UNITED STATES PATENT OFFICE

2,245,627

STABILIZATION OF FREQUENCY

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Application June 24, 1938, Serial No. 215,639

14 Claims. (Cl. 250—36)

This invention relates, generally, to the stabilization of frequency in electromagnetic oscillators, and particularly to the stabilization of frequency in electron beam oscillators of the type designated as the "klystron." This invention is related to copending applications Serial No. 92,787, W. W. Hansen, High efficiency resonant circuit, filed July 27, 1936 (now Patent No. 2,190,712, dated February 20, 1940); Serial No. 168,355, R. H. Varian, Electrical translating system and method, filed Oct. 11, 1937; and Serial No. 201,898, R. H. Varian and W. W. Hansen, Radio transmission and reception, filed April 14, 1938.

In the copending applications cited there are described a number of embodiments of related inventions which have come to be known by the names "rhumbatron," "klystron," "buncher," "catcher," and "reflex klystron." These names are used in the present specification. They are defined as follows: "Rhumbatron"; i. e. a resonant circuit characterized by an electromagnetic field bounded by a substantially closed conducting surface, and in which energy is transferred to or from the electromagnetic field by inductive loops or capacitive elements in the field or by a beam of electrons projected through the field. "Klystron"; i. e. an electrical converter composed of two or more "rhumbatrons" excited and coupled by a beam of electrons projected through the fields contained in the "rhumbatrons." "Buncher"; i. e. in a "klystron" the "rhumbatron" nearest the emitter of the electron beam, in which the electrons are alternately accelerated and decelerated at the frequency of oscillation of the "klystron," and "catcher"; i. e. in a "klystron" the "rhumbatron" farthest from the emitter of the electron beam, in which energy of the "bunched" electron beam is converted into electromagnetic field energy. "Reflex klystron"; i. e. an oscillator operating on the "klystron" principle but with only one "rhumbatron" which acts as both "buncher" and "catcher," an electron beam being projected through the "rhumbatron" in one direction and reflected back into the "rhumbatron" by an additional electric field between two grids outside the "rhumbatron."

The principal object of the present invention is to provide novel means and method for stabilizing the frequency of an electromagnetic oscillator, the general method of frequency stabilization used in this invention being applicable to oscillators of conventional form as well as to those of the "klystron" type.

Another object of the present invention lies in the provision of a general system of frequency stabilization for vacuum tube circuits operating at ordinary frequencies using in the component parts of the system known vacuum tube circuits.

Still another object of the invention is to provide a method and means for frequency stabilization in oscillators operating at frequencies of the order of 10^8 or more cycles per second.

Other objects and advantages will become apparent from the specification, taken in connection with the accompanying drawings wherein the invention is embodied in concrete form.

In the drawings,

Fig. 1 is a generalized diagram illustrating the principle of our invention.

Fig. 2 is a graph for assisting in the explanation of the theory of the invention.

Fig. 3 is a diagram showing the application of the present invention to a pair of "klystron" oscillators with a single detector.

Fig. 4 is a diagram substantially equivalent to Fig. 3 except that two detectors closely coupled are used instead of a single detector.

Fig. 5 is a diagram substantially equivalent to Fig. 4 except that the oscillators and the means of controlling them are of a different form.

Similar characters of reference are used in all of the above figures to indicate corresponding parts.

Referring to Fig. 1 there are two oscillators 1 and 2 which operate at a common frequency which is to be held constant. The two oscillators 1 and 2 are preferably identical except for their frequency-parameter characteristics. One oscillator, let it be assumed for example oscillator 1, changes its frequency more in proportion to the variation of a given parameter than the other oscillator 2. This difference in characteristics may be obtained by making the tuned circuits of oscillator 2 with less resistance giving a higher "Q", that is, ratio of reactance to resistance, than the tuned circuits of oscillator 1.

The difference in characteristics of oscillators 1 and 2 is illustrated in Fig. 2. The greater slope of the line of oscillator 1 indicates a greater change in frequency of oscillator 1 than of oscillator 2 corresponding to a given change in some stated parameter such as voltage for example.

The two oscillators 1 and 2 deliver a portion of their outputs to a mixer-detector 3 which operates on the heterodyne principle. The mixer-detector 3 delivers a voltage or current which is a function of the difference in phase between the oscillations of oscillators 1 and 2.

The output of mixer-detector 3 is amplified by an amplifier 4 which in turn controls two frequency adjusters 5 and 6. The frequency adjusters are made so that they change the frequency of the two oscillators 1 and 2 in accordance with the output of amplifier 4. In any given instance, amplifier 4 may or may not be necessary. If it is not necessary, the output of mixer-detector 3 may be used directly to control the frequency.

In the operation of the system, the oscillators 1 and 2 are adjusted to operate in synchronism at some desired frequency. Then if some parameter, such as voltage, changes, the two oscillators will both tend to change slightly in frequency. The oscillator 1 will tend to increase its frequency, for example, more than oscillator 2, so there will first occur a phase difference between the outputs of the two oscillators. This phase difference in mixer-detector 3 will control a voltage or current which when amplified controls the two frequency adjusters 5 and 6 that introduce into oscillators 1 and 2 controlling currents or voltages that tend to return their frequencies to the desired frequency. If this controlling voltage or current is strong enough in its action to keep the two oscillators synchronized, they must be synchronized at the original frequency since the relative change in frequency of the two oscillators as a function of correction voltage is the same as it is for the parameter tending to cause a departure from the initial frequency. These controlling currents or voltages are sufficient to keep the oscillators 1 and 2 in synchonism although a phase difference remains between the oscillations of the oscillators.

In systems operating at the frequencies used with thermionic vacuum tubes all the elements of Fig. 1 can be made in ways already known in the art. The general system is new and the combination of elements is new, but the specific elements themselves when employing vacuum tubes are old. Specifically, it is known in the art how to combine the waves of two oscillators and to produce a voltage or a current which is a function of the phase angle between the two oscillator waves. It is also known how to use such a voltage or current to control a circuit which will determine the frequency of an oscillator, for example by changing the circuit capacitance. Inasmuch as the wiring diagrams applicable at ordinary frequencies to the several elements 1 to 6 inclusive shown in Fig. 1 can be supplied from the known prior art without further invention as to details, the detailed wiring diagrams for an ordinary vacuum tube circuit have been omitted for brevity and convenience.

In systems operating at frequencies of the order of 10^8 or more cycles per second, the known vacuum tube circuits of the prior art are not suitable. Accordingly, for the practice of the present invention three arrangements, Figs. 3, 4, and 5, adapatable to high frequency operation are herein presented.

In Fig. 3, there are two "rhumbatron" oscillators or hollow oscillatory circuit members or resonators 11 and 12 of a general form and mode of operation described in copending application Serial No. 218,064, filed July 8, 1938, W. W. Hansen, S. F. Varian and Russell H. Varian. In oscillators of this type, "bunching" and "catching" are performed in the same hollow resonator. In connection with "rhumbatron" 11 there is an electron emitter 13 and there are grids 14 to 18 inclusive. Similarly connected with resonator 12 are an electron emitter 19 and grids 21 to 25 inclusive. Between the two groups of grids there is an electrostatic shield 26. The action of cavity resonators or hollow oscillatory circuit members 11 and 12 in serving both functions of "bunching" and "catching" electrons is due to the use of repelling grids 17 and 24. These grids are connected to the negative side of a battery 40 by leads 1 and 2 and act as reflectors in that they return a part of the electron streams back into the resonators 11 and 12 from which the streams came. By the time these returned electrons again reach grids 15 and 22, sufficient "bunching" has taken place to cause them to deliver enough energy to resonators 11 and 12 to maintain oscillation therein.

A third hollow or cavity resonator 27 with which are associated grids 28 to 31 inclusive and a plate 32 is placed as shown facing the other two resonators 11 and 12. A fourth resonator 33, intended to operate at a harmonic of its fundamental frequency as described in Serial No. 201,898, is coupled through coupling loops 34 and 35 to resonator 12. No attempt is made to represent resonator 33 in actual proportions relative to the other parts of the drawings. Another loop 36 is shown used to take energy out of the system for any adaptable load such as an antenna 37. Batteries 38, 39, and 40 supply the energy for the system. Battery 40 has its positive side connected to the resonators through lead 3 and a resistor 41. Lead 3 also connects with plate 32. The battery 38, acting through leads 4, 5, and 6, 7, 8 connected to the emitters 13, 19 and the resonant circuit members 11, 12 and 27, respectively, provides the necessary electron accelerating potential. Battery 39 and connected potentiometer 46 are connected by lead 9 to the electron velocity discriminating grid 31. The usual evacuated container enclosing the resonators, its appurtenances, and arrangements for adjustment are omitted from the figure as they may be found in the cited copending applications. This container is shown in schematic form in outline in dot-dash lines in Fig. 3 and designated 10 in the drawings.

The system shown in Fig. 3 operates in accordance with the principles set forth in connection with Figs. 1 and 2. In Fig. 3 "rhumbatrons" 11 and 12 together with their associated parts correspond respectively to oscillators 1 and 2 in Fig. 1. Resonator 27 and its accessories correspond to mixer-detector 3. No amplifier is shown in Fig. 3. The plate 32 and grids 17 and 24 constitute the frequency adjusters corresponding to parts 5 and 6 in Fig. 1. Oscillator 12 is connected by coupling loops 34 and 35 with resonator 33 for the purpose of making the "Q" or ratio of reactance to resistance of oscillator 12 greater than that of oscillator 11. Other means of influencing the "Q" of the oscillator can be used. For example, the two resonators 11 and 12 could be made identical in all respects except resistance. Thus resonator 12 could be made of copper and resonator 11 could be made of copper with an interior coating of metal of higher electrical resistance.

Considering first the operation of resonator 12, a beam of electrons 42 is projected from emitter 19 through grids 21, 22, and 23 into the space between grids 23 and 24. Grid 24 is maintained at a negative potential relative to grid 23 by means of battery 40 acting through leads 1 and 2. The greater part of electron beam 42 is reflected in the space between grids 23 and 24 and the electrons are turned back into resonator 12. The electron beam 42 is bunched in its course from grid 21 to the space between grids 23 and 24 and back to grid 22, and the beam energy is absorbed by resonator 12 when the electrons re-enter the space between grids 22 and 21 after being reflected by the field between grids 23 and 24. The difference of potential between grids 23 and 24 determines the distance the electrons of beam 42 travel toward grid 24 before they are reversed and consequently the time allowed for beam bunching. Any change in the potential of grid 24 due to varying the potential of battery 40 will cause a corresponding change in the phase in which the electron bunches re-enter resonator or oscillatory circuit member 12 and will influence to some extent the frequency of oscillation of the resonator 12 circuit.

Part of the electrons of beam 42 manage to go through grid 24, after which they are accelerated by the relatively positive grid 25 maintained at the same potential as members 11, 12 and 27 and projected as a beam 43 which is much less dense than beam 42. Beam 43 passes through grids 28 to 31 inclusive and is detected on plate 32, producing thereby a current through resistor 41. This will be evident when it is noted that the spread in the velocities of the electrons of beam 43 as the electrons approach grid 31 is a function of the amplitude of oscillation in resonator 27. Grid 31 is so biased from potentiometer 46 with respect to the emitter voltage that relatively few electrons of gun velocity can penetrate this grid and reach plate 32. With lead 9 connected to the center of potentiometer 46 as shown, the grid 31 is maintained slightly positive with respect to emitter 19 thereby causing a space charge to build up in front of this grid causing all but the faster electrons to turn back. Consequently, an increase in the spread of electron velocities as electrons approach grid 31 due to an increase in the amplitude of oscillations in member 27, will result in an increase in the number of electrons passing through grid 31 and reaching plate 32. Hence, in use, there is a rectified component of current passing through resistor 41 and this current is a function of the amplitude of oscillation of hollow resonator 27.

In resonator 11 a beam of electrons 44 is acted upon in the same way as described for resonator 12. Part of beam 44 reaches resonator 27 as beam 45. If resonators 11 and 12 are initially oscillating in synchronism i. e. at the same frequency and at a definite phase angle, i. e. the oscillations in one having a definite angular phase difference with those in the other, then, resonator 27 will be excited at some definite intensity, and a definite current will be produced in resistor 41 by plate 32. Now if some parameter of the system, such as the voltage of battery 38, changes, the frequency of resonators 11 and 12 will tend to change as described before with reference to Figs. 1 and 2. The tendency to change frequency will be greater for the circuit of low "Q" than for the one of higher "Q", that is, resonator 11 will tend to change frequency more than resonator 12. The immediate result will be relative phase displacement between the beams 43 and 45 and this will produce a change in current in resistor 41 and in the resulting voltage on grids 17 and 24. This voltage change will change the flight time for the electron beams 42 and 44 and will introduce a tendency to change the frequency of resonators 11 and 12 which tendency will be in direction to oppose the tendency toward change of frequency as a result of the variation of the system parameter, i. e. the voltage of battery 38 for example. The final result will be that the two oscillators 11 and 12 will continue to oscillate in synchronism, but with a different phase angle between their oscillations. Since they can only oscillate in synchronism if they have been individually corrected to the same frequency, and since the relative frequency displacement as a function of the correction voltage applied to grids 17 and 24 is the same as the relative frequency displacement as a function of the disturbing parameter, the point at which the oscillators can have the same frequency is the initial frequency. The system thus has stable characteristics. A disturbance tending to change the system frequency is allowed to produce a phase change which is developed to a magnitude sufficient to counteract through the action of grids 17 and 24 the disturbing effect of parameter variation, and to hold the two oscillators in synchronism at the desired frequency. The potentiometer 46 connected with battery 39 is used to adjust directly the detector action of grid 31 and indirectly the phase correction effect of grids 17 and 24. This stabilizes the frequency at the normal conditions of operation.

Fig. 4 shows an arrangement similar to the one shown in Fig. 3. An evacuated envelope is shown schematically in dot-dash lines at 55. The principles of operation are the same in the two arrangements except that in Fig. 4 two resonators 27′ and 27″ are used to perform the functions of resonator 27 in Fig. 3. When only one resonator 27 is used, the combination of the signals from beams 43 and 45 are combined by the interaction of the two electron beams in the single resonator, but when two resonators 27′ and 27″ are used, the combination of signals is accomplished by coupling loops 51 and 52. Either resonator 27′ or 27″ may be used as the detector resonator in connection with plate 32 and the adjacent grids. As shown in the drawings, both rhumbatrons are used as detectors. Electrically Figs. 3 and 4 are substantially equivalent. Mechanically Fig. 4 is easier to construct inasmuch as two separate structures, one containing resonators 11 and 27′ and the other containing resonators 12 and 27″ can be used. The connection between coupling loops 51 and 52 can be made as long as may be convenient.

Fig. 5 shows a system which is substantially equivalent to that shown in Fig. 4 except for mechanical differences. Evacuated envelopes are shown schematically at 56 and 57. In Fig. 5 the oscillators are ordinary "klystrons" as shown in Serial No. 168,355 and other copending applications. Two hollow resonators are used for each oscillator. For example, 11′ and 11″ are used instead of a single resonator 11 with grids 16, 17, and 18 as shown in Figs. 3 and 4. The operation of resonators 27′ and 27″ is as described for Fig. 4, but the frequency correction in Fig. 5 is by tubes 53 and 54 which control flight time instead of by grids 17 and 24 shown in Figs. 3 and 4. The principles governing the operation of tubes 53 and 54 are explained in Serial No. 201,898, these tubes creating potential regions in which the speed of the electric stream is increased or decreased depending on the current through resistor 41.

In the operation of Fig. 5, suppose that the voltage of battery 38 increases. That will increase the velocity of the electrons in beams 42 and 44 and will cause a corresponding shift of phase between the oscillations in resonators 11 and 11' and between the oscillations in resonators 12 and 12'. These changes, due to the feed back couplings 50 and 51, will tend to change the frequencies of the two oscillators 11 and 12, the latter less in proportion than the former. The shifts in phase mentioned will also manifest themselves by a shift in phase of the electron bunches obtaining in the electron beams 43 and 45 and the amplitude of oscillation in resonators 27' and 27'' will be correspondingly affected. The resultant detected signal at plate 32 will change the voltage on tubes 53 and 54, and consequently will change the time of flight of the electrons between resonators 11' and 11'' and between resonators 12' and 12'' which in turn will neutralize the disturbing effect of the variation of battery voltage.

The two oscillators 11 and 12 or 11' and 12' used in any of the systems shown in Figs. 3, 4, and 5 are preferably identical except for their "Q" or ratio of reactance to resistance. If they are identical except in this respect they will respond in the same way to any variation in parameters such as battery voltage or electron current. They will also respond in the same way to correction voltages applied for frequency stabilization. The only difference in the operation will be in the relative amount of change of frequency for a unit change in parameter. This difference is as explained with reference to Fig. 2 an important element in the operation of the system.

The effects of temperature variation are neutralized, in the systems described, by making the temperature coefficient of frequency inversely proportional to the "Q" of each oscillator. This gives a temperature characteristic of frequency of the same form as shown in Fig. 2 and correctable in the same way.

In the drawings the usual means for operating the apparatus in a vacuum have been omitted for convenience inasmuch as they will be readily understood by reference to the copending applications. Similarly, for convenience, obvious details of known types of connections have been omitted.

As many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. The method of stabilizing the frequency of an oscillator which consists of operating said oscillator in substantial synchronism with a second oscillator whose frequency variation characteristic is made different from that of the first oscillator, producing a voltage component which is substantially proportional to the product of the instantaneous voltages of said oscillators, and causing said produced product voltage to control the frequency of both of said oscillators, whereby the operating frequency of both oscillators is maintained at a substantially fixed value regardless of variations in supply voltage and current.

2. The method of stabilizing the frequency of an oscillator which consists of operating said oscillator in substantial synchronism with a second oscillator, the frequencies of the two oscillators being different functions of parameters subject to change, producing a voltage which is proportional to the product of the instantaneous voltages of the two oscillators, and causing said produced product voltage to change the frequencies of the two oscillators in the same ratio as their respective frequencies are changed by said changing parameters.

3. The method of stabilizing the frequency of an oscillator which consists of operating said oscillator in synchronism with a second oscillator whose frequency variation characteristic as a function of changing parameters is different from that of the first oscillator, detecting phase shifts occurring between the two oscillators due to changes in parameters and controlling the frequency of both oscillators in accordance with said detected phase shifts.

4. The method of stabilizing the frequency of an oscillator which consists of operating said oscillator in synchronism with a second oscillator whose frequency variation characteristic is different from that of the first oscillator, intermixing electrical energy from both oscillators, obtaining thereby a resultant difference of potential which is a function of the relative phase displacement of the oscillations of the two oscillators, variations of said phase displacement causing variations in said resultant difference of potential and using said variations in difference of potential in both oscillators to produce an effect in opposition to factors tending to prodluce the variations in the relative phase displacement of the oscillations of the oscillators.

5. The method of stabilizing the frequency of an oscillator which consists of operating said oscillator in synchronism with a second oscillator similar to the first oscillator but having a different ratio of reactance to resistance and with correspondingly different frequency variation characteristics, mixing energy from both oscillators, obtaining thereby a resultant difference of the potential which is a function of phase displacement of the oscillations of the two oscillators, and causing any variation of said difference of potential, due to changes in common factors applied to both oscillators, to produce an effect in opposition to the factors producing any such change in said phase displacement, whereby said oscillators are caused to have a frequency stability greater than that possessed by either oscillator alone.

6. The method of compensating the effects of temperature variation in an oscillator which consists of operating said oscillator in synchronism with a second oscillator having a ratio of reactance to resistance different from the first oscillator and a temperature coefficient of frequency different from the first oscillator in inverse proportion to the respective ratios of reactance to resistance of the two oscillators, mixing energy from both oscillators obtaining thereby a resultant difference of potential which is a function of phase displacement of the oscillations of the two oscillators, said phase displacements being the result of frequency variation due to temperature changes, and causing said differences of potential to produce an effect in opposition to the frequency effect of said temperature changes.

7. In apparatus of the kind described, the combination of two oscillators arranged to operate in synchronism, the two oscillators having different frequency variation characteristics, a mixer-detector connected to be responsive to phase differences between the oscillations of the two oscillators, and means whereby the mixer-detector controls the frequency of the two oscil-

lators by acting on the oscillators in the same way and so as to counteract the causes tending to effect further relative change of phase between said oscillators.

8. In apparatus of the kind described the combination of two electron beam oscillators having different frequency variation characteristics, said oscillators having means for producing exciting electron beams, control electrodes along the paths of said beams for controlling said oscillators as to frequency, electron beam detector means receiving energy from said electron beams associated with said oscillators and responsive to differences of phase existing between said beams, and means connected to said detector means and operating to change the potential of said control electrodes for effecting the frequency control of said oscillators.

9. In apparatus of the kind described the combination of two electron beam oscillators having different frequency variation characteristics, two control electrodes, each oscillator being subject to frequency control by a respective one of said control electrodes, an electron beam detector acted upon directly by two electron beams from the two oscillators and responsive to differences of phase existing between said beams, and means whereby said detector changes the potential of said control electrodes for effecting frequency control of said oscillators.

10. In apparatus of the kind described the combination of two electron beam oscillators having somewhat different frequency variation characteristics, said oscillators having means for producing exciting electron beams, each oscillator containing a tube through which its respective electron beam passes, electron beam detector means receiving energy from both oscillators and responsive to differences in phase existing between said oscillators, and means whereby said detector means changes the potential of said tubes for the control of the frequency of oscillation of said oscillators.

11. In apparatus of the kind described the combination of two oscillators employing electron beams for exciting the same electron beam detector means comprising a pair of electron beam detector elements, said elements being respectively acted upon directly by the beam of a respective oscillator, coupling means between the two detector elements, means for causing the detector elements to produce a voltage which is a function of the phase difference between the oscillations of the two oscillators, and means for causing said voltage to act on said oscillators to maintain the same in synchronism.

12. In apparatus of the kind described, the combination of two oscillators operated in synchronism, a mixer-detector arranged to be excited by said two oscillators, said mixer-detector operating in response to changes in the phase difference between oscillations of the two oscillators, and means excited from said mixer-detector and operating on said oscillators so as to tend to produce frequency changes of the same sign in both oscillators so as to counteract the causes tending to vary said phase difference.

13. Apparatus of the kind described comprising two thermionic oscillators including means for producing an electron stream having appreciably different ratios of reactance to resistance, electrode means positioned for acting upon said electron stream and connected for controlling the frequency of both of said oscillators, said electrode means serving to control the frequency of each oscillator in different amount, said apparatus being of such character that the ratio of amount of control of the frequency of one oscillator relative to the other by said electrode means is substantially the same as the ratio of the amount of disturbance of frequency of one oscillator relative to the other produced by a frequency disturbing change in supply current or voltage, mixer-detector means for obtaining a voltage which is proportional to the instantaneous product of the oscillation voltages in said two oscillators, and means connected with said mixer-detector and said electrode means for actuating said frequency control electrode means by said product voltage.

14. In combination, a pair of oscillators comprising means for producing an electron stream, having different ratios of reactance to resistance and means for stabilizing the frequency thereof comprising, potential applying electrode means positioned for acting on said electron stream and connected to said oscillators for controlling the frequencies thereof for offsetting the effect of changing voltage or current parameters, said potential applying electrode means serving to vary the frequency of each oscillator in different amount depending upon the relative values of their respective ratios of reactance to resistance, and detector means connected to said oscillators and to said potential applying electrode means, so as to supply said potential applying electrode means with a voltage responsive to the instantaneous product of the oscillation voltages of said pair of oscillators.

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