

July 11, 1939.

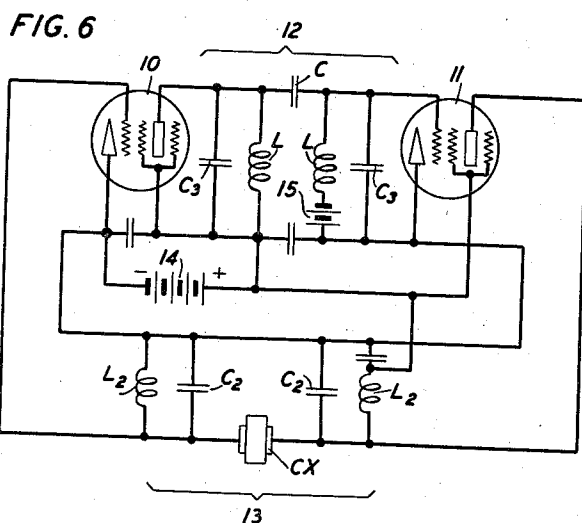
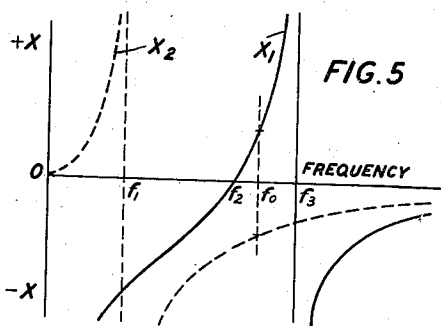
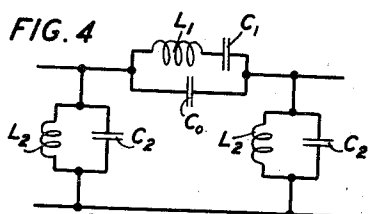
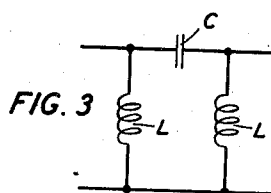
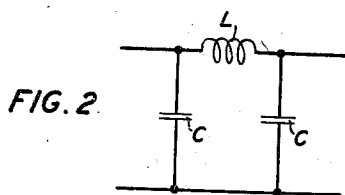
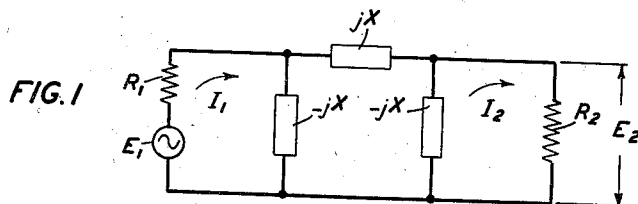
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2,165,517

OSCILLATION GENERATOR

Filed June 28, 1938

2 Sheets-Sheet 1



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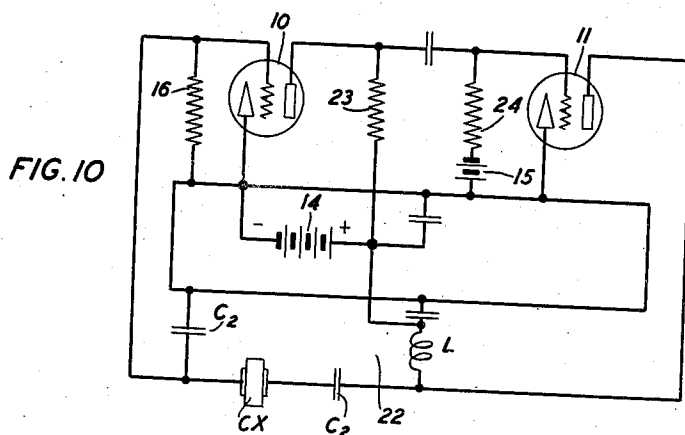
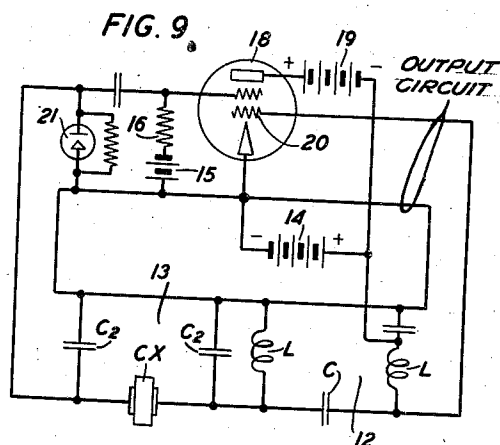
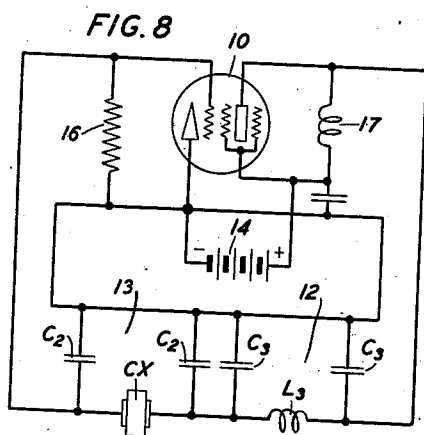
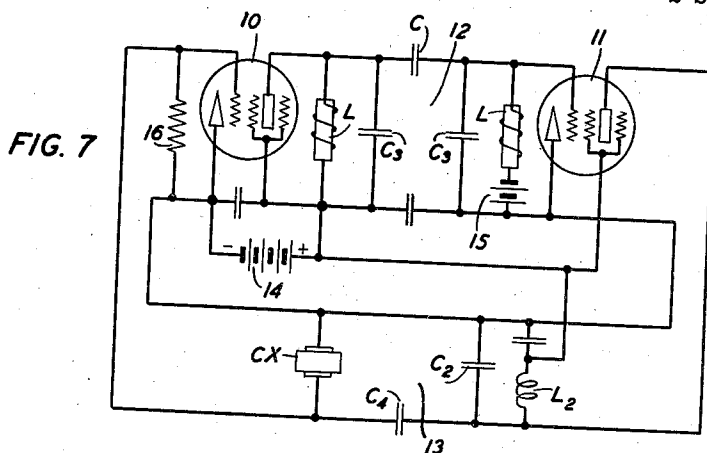
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OSCILLATION GENERATOR

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2 Sheets-Sheet 2



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OSCILLATION GENERATOR

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14 Claims. (Cl. 250—36)

This invention relates to vacuum tube oscillation generators and more particularly to the stabilization of the oscillation frequency of such generators against variation with changing excitation voltages. Objects of the invention are to improve the frequency stability of vacuum tube feedback oscillators; to diminish the effect of the internal capacities of the vacuum tubes upon the stability of the system; and to provide for the stabilization of the frequency of piezoelectric crystal controlled oscillators.

The frequency deviations that accompany changes of the electrode potentials or of the cathode temperature in many types of vacuum tube oscillators are known to have their origin in the resulting variation of the internal resistances of the vacuum tube. In order that these deviations may be eliminated or substantially reduced it is necessary that the oscillator circuit be of such configuration and proportions that the oscillation frequency is independent of the magnitudes of the tube resistances and is determined wholly by the linear impedance elements of the circuit. Various circuits having this property are disclosed in U. S. Patents 1,896,781, February 7, 1933, and 1,976,570, October 9, 1934, to F. B. Llewellyn.

In the present invention, use is made of a unique phase shift characteristic of certain simple four-terminal reactance networks. These networks comprise essentially three reactances disposed in the form of a π -network and of such character and proportions that all three become equal in magnitude at an assigned frequency but with the series reactance of opposite sign to the shunt reactances. Under this condition, the network produces a phase shift of 90 degrees when connected between resistive terminal impedances, which is constant regardless of the values of the resistances.

The oscillators of the invention comprise one or more vacuum tubes and a plurality of phase shifting networks of the type described above all connected in tandem to form a closed feedback path. The vacuum tubes each produce fixed phase shifts of 180 degrees, although in certain forms the phase shift may be zero. The several phase shifting networks are each designed to produce stable phase shifts of 90 degrees at the assigned oscillation frequency and are combined in such manner as to provide a total phase shift of zero in the closed loop circuit, thereby establishing a necessary condition for self-oscillation. Because of the character of the coupling networks, the zero phase shift condition is independ-

ent of the internal resistances of the vacuum tubes and the resulting oscillations are therefore stable in frequency.

In the preferred forms of the invention one of the phase shifting networks is made to have a very rapid frequency variation of the phase shift at the 90-degree point and the other networks are designed to provide slowly varying phase shifts. The network with the strong characteristic then becomes the principal frequency determining element and the others make up the necessary total phase shift while maintaining the condition for frequency stability. The rapid phase shift characteristic is preferably obtained by the use of a piezoelectric quartz crystal as one of the reactances of the network, as described in detail hereinafter.

It is well known that a relatively high degree of frequency stability is obtained with crystal controlled oscillators of simple circuit configuration, but that, nevertheless, the frequency deviations may be noticeable and troublesome when extreme accuracy is required. The present invention provides improved frequency stabilization of such oscillators in a simple manner and permits the substantial elimination of residual frequency variations.

Other features of the invention and its mode of operation will be more fully understood from the following detailed description and by reference to the accompanying drawings, of which:

Fig. 1 is a schematic diagram explanatory of certain network principles used in the invention;

Figs. 2, 3 and 4 illustrate different forms of networks used in the circuits of the invention;

Fig. 5 illustrates properties of the network of Fig. 4; and

Figs. 6 to 10, inclusive, are circuit diagrams of a number of oscillator circuits in accordance with the invention.

A circuit comprising a resistive wave source and a resistive load coupled by a phase shifting network of the type used in the oscillators of the invention is shown schematically in Fig. 1. The resistances of the source and the load are denoted by R_1 and R_2 , respectively, the source having a voltage E_1 . The coupling network consists of a π section, each branch of which includes only pure reactance elements. The configurations of the branches are not illustrated and, for the present, may be left undetermined, but it is assumed that they are such as to permit the impedances of the shunt branches to take the same value, $-jX$, at an assigned frequency and for the

series branch impedance to take the value $+jX$ at the same frequency. Under this condition, the output voltage E_2 across resistance R_2 has the value given by the equation

$$\frac{E_2}{E_1} = \frac{-jXR_1}{R_1R_2 + X^2}$$

The two voltages are in quadrature and the quadrature phase relationship is obviously independent of the values of R_1 and R_2 . For the particular signs of the reactances indicated, the output voltage lags 90 degrees behind the input voltage. Reversing the signs of all three reactances reverses the phase of the output voltage causing it to lead the input voltage by 90 degrees.

Simple forms of phase shifting networks are shown in Figs. 2 and 3, the former having a positive series reactance provided by an inductance and the latter a negative series reactance provided by a capacity. The two shunt branches in each network are alike and, therefore, have equal reactances at all frequencies. The network of Fig. 2 produces a lagging output voltage and that of Fig. 3 produces a leading output voltage. The quadrature relationship is produced in each case at the frequency of the resonance of the series branch with a single one of the shunt branches.

The networks should, preferably, be of such character that a quadrature phase shift in either direction is produced at not more than one frequency. With this restriction, it is possible to depart considerably from the simple configurations of Figs. 2 and 3 by increasing the complexity of each branch. An example of such modification is shown in Fig. 4 wherein the series branch comprises a series resonant circuit L_1C_1 shunted by a capacity C_0 and the shunt branches comprise similar antiresonant circuits L_2C_2 . The series branch is proportioned to have a positive or inductive reactance in the neighborhood of the assigned frequency and the shunt branches are proportioned to have negative reactances at this frequency. The frequency variations of the two reactances are shown by the curves of Fig. 5, the solid line curves representing the series branch reactance X_1 and the dotted line curves representing the shunt reactances X_2 . The series branch exhibits a resonance at a frequency f_2 and an anti-resonance at a higher frequency f_3 and has a positive reactance in the intervening range. The shunt branch reactance is negative or capacitive above the anti-resonance frequency f_1 which preferably lies well below the resonance of the series branch. The frequency for a lagging phase shift of 90 degrees must necessarily lie in the interval between f_2 and f_3 and is determined by the equality of X_1 and X_2 , as indicated at f_0 in the figure. The particular value of this frequency may be varied by adjustment of the shunt capacities C_2 or of the series capacity C_0 . A second frequency of phase quadrature exists below the anti-resonance frequency of the shunt branches, but in this case the phase shift is in the opposite direction.

Other possible modifications will be obvious, for example, one of the shunt inductances in Fig. 3 may be replaced by a three-element combination like the series branch of Fig. 4. Furthermore, it is not necessary that the two shunt branches be alike, but simply that they have equal reactances at the assigned frequency of phase quadrature.

The three-element combination $L_1C_1C_0$ in Fig. 4 will be recognized as corresponding in configura-

tion to the equivalent impedance network of a piezoelectric quartz crystal. Accordingly, a piezoelectric crystal may be used in this position. The effect of substituting the crystal is to make the frequency range in which the branch has an inductive reactance extremely small and to provide an extremely rapid variation of the phase shift with frequency in this range.

Referring again to Fig. 1, it may be shown readily that the impedance measured at the input terminals of the phase shifting network is purely resistive at the frequency of phase quadrature and has the value X^2/R_2 . A second network, not necessarily similar but having a quadrature phase shift at the same frequency, may therefore be inserted ahead of the network shown without either affecting the phase shift of the other at the common frequency of phase quadrature. Furthermore, the two networks may produce phase shifts in opposite senses if desired.

Stabilized oscillator circuits in accordance with the invention making use of combinations of the quadrature phase networks will now be described. It will be understood that the examples illustrated do not comprehend all of the possible circuits provided by the invention, but are simply illustrative of a number of the preferred circuit configurations.

The oscillator circuit shown in Fig. 6 comprises two vacuum tubes 10 and 11 coupled in tandem by reactance networks 12 and 13 to form a closed feedback loop. Network 13, which is the principal frequency determining unit is of the general type shown in Fig. 4, the series branch being constituted by a quartz piezoelectric crystal CX and the two shunt branches by similar parallel combinations of inductances L_2 and capacities C_2 . As explained in connection with Fig. 5, the shunt branches of network 13 are proportioned to be anti-resonant at a frequency well below the crystal resonance. Network 12 coupling the input of tube 11 to the output of tube 10 is generally similar to that shown in Fig. 3, but the shunt branches are modified by the addition of small capacities C_3 in parallel with each of the inductances. Tubes 10 and 11 are preferably of screen grid types to avoid any effects from internal feedback. A common source 14 provides plate and screen current for both tubes and a separate source 15 provides a negative bias for the grid of tube 11. The remaining elements of the circuit comprise blocking and by-pass condensers which should be large enough to have negligibly small impedances at the operating frequency. The shunt inductances in the two networks serve to provide conductive paths for the grid and plate currents of the tubes.

Since each of the two vacuum tubes produces a fixed phase shift of 180 degrees, together they contribute zero total phase shift in the closed loop. The network 13 produces a lagging phase shift of 90 degrees at a frequency for which the crystal CX has a positive reactance equal in magnitude to the negative reactance of either of the two equal shunt branches. At this frequency, the phase shift is independent of the values of the terminal resistances constituted by the plate circuit of tube 11 and the grid circuit of tube 10. To provide for self-oscillation of the system at the frequency so determined, the network 12 must produce a leading phase shift of 90 degrees. This phase shift is provided and is made independent of the tube resistances by proportioning the network in the manner described so that each shunt branch has an inductive reactance

equal to the reactance of the series branch capacity at the oscillation frequency. The anti-resonance frequencies of the shunt branches must be higher than the oscillation frequency, but preferably should be lower than the second harmonic of this frequency.

The circuit of Fig. 6 can oscillate only at the frequency determined by the quadrature phase shifts of the two networks and, since the phase quadrature in each case is independent of the tube resistances, the oscillation frequency is stable. Each network is provided with shunt capacities at both ends in which the grid and plate capacities of the tubes may be included. The stability is, therefore, unaffected by the presence of the tube capacities. Furthermore, the effect of the shunt capacities is to diminish the impedance presented to the tubes by the networks at harmonics of the oscillation frequency and thereby to reduce harmful modulation effects.

The impedance of the crystal CX imparts to the phase shift characteristic of network 13 a very rapid frequency variation at the oscillation frequency which has the effect of increasing the stability of the system. Network 12, on the other hand, is characterized by a slow variation of the phase shift in the neighborhood of the oscillation frequency. This has the advantage of making the adjustment of the system non-critical. In the oscillator circuit shown in Fig. 7, the principal frequency determining network 13 is modified to permit the use of a shunt connected crystal and the compensating network 12 is suitably modified to take account of the change. A high resistance 16 is provided to act as a grid leak path for tube 10. The network 13 is basically similar to the type shown in Fig. 3. At the operating frequency the crystal CX has an inductive or positive reactance equal to the negative reactance of the series branch capacity C_4 and the other shunt branch L_2C_2 is proportioned to have the same inductive reactance as the crystal at this frequency. The network produces a leading quadrature phase shift and the compensating network 12 must, therefore, produce a lagging quadrature phase shift in order that oscillation may take place.

The shunt inductances in network 12 are made large enough to be anti-resonant with the shunt capacities at a frequency well below the oscillation frequency and the series capacity C is likewise made large enough to have a negligible impedance. The tubes are then in effect coupled solely through the shunt capacities which, in combination with the high internal resistance of screen grid tube 10, produce a substantially constant lagging phase shift of 90 degrees. It is desirable that the shunt coils have low dissipation and that the grid of tube 11 have a sufficiently great negative bias to prevent any grid current being drawn. Preferably also, the shunt capacities C_3 should be fairly large and, while this may result in a considerable attenuation of the voltage, the gain of the two tubes is usually sufficient to ensure adequate feedback. Modifications of this type of shunt reactance coupling are obvious.

When a single vacuum tube of the ordinary type is used it produces a fixed phase shift of 180 degrees and the external network must provide an equal phase shift of 180 degrees in order that the total phase shift in the feedback loop may be zero. In the circuit shown in Fig. 8 the required 180-degree phase shift is produced by means of two quadrature phase-shift networks connected in tandem, each proportioned to provide a phase

shift of 90 degrees in the same direction at the oscillation frequency. It has already been pointed out that two or more of the quadrature phase shift networks may be connected in tandem, provided that all produce the quadrature phase shift at the same frequency.

The total phase shift at that frequency is then also independent of the terminal resistances. The frequency stability of the circuit of Fig. 8, therefore, requires only that the two networks be each proportioned for quadrature phase shift at the oscillation frequency.

Network 13, which includes the piezoelectric crystal CX, is the principal frequency controlling network. Both this network and the compensating network 12 are of the general type represented by Fig. 2. The function of the compensating network in this case is to supplement the phase shift of network 13 so that together they compensate the 180-degree phase shift of the vacuum tube at the oscillation frequency. Plate current is supplied to the tube through a shunt inductance 17. This inductance may be made large enough so that its admittance is negligible or its effect may be compensated for by an appropriate adjustment of the adjacent shunt condenser in network 12.

Instead of using two tubes in tandem, as in Figs. 6 and 7, to make the phase shift contribution of the tubes equal to zero, a single tube having a negative amplification constant may be used. A stabilized oscillator circuit employing such a tube is shown in Fig. 9. In this circuit the tube 18 includes, in addition to the usual anode, an auxiliary or space charge anode 20 located between the control grid and the cathode. The output circuit is connected between the auxiliary anode and the cathode. The action of a positive voltage superimposed on the bias voltage of the control grid is to rob the auxiliary anode of some of the electrons that would otherwise go to it and thereby to diminish the auxiliary anode current. This is the reverse of what occurs in an ordinary tube and corresponds to a reversal of the phase of the output current. Plate batteries 14 and 19 and grid bias battery 15 may be adjusted to give suitable voltages for the realization of the effect in substantial degree. To avoid the flow of grid current during operation and the possible disturbing effects thereof, an unbiased diode 21 may be connected across the tube input as shown. This serves to provide the amplitude limiting action on the oscillation currents which is usually produced by the current flow in the amplifier grid path.

The external network comprises two quadrature phase-shift networks 12 and 13, which produce phase shifts in opposite directions, respectively. Network 12 is of the type shown in Fig. 3 and the principal frequency controlling network 13 is of the type shown in Fig. 2, modified to substitute a piezoelectric crystal CX for the series inductance.

The feedback network may be further proportioned so that not only does each component network produce a stable phase shift of 90 degrees, but also that all of the branches of the two networks have reactances of the same magnitude at the oscillation frequency. In that case, the central impedance combination LC_2 becomes infinite at the oscillation frequency and these elements may therefore be omitted without affecting the operation of the system.

A feedback network thus modified is shown in the circuit of Fig. 10. The feedback network 22

comprises a series branch including a crystal CX and a series capacity C₂, a shunt branch constituted by a second capacity equal to the series branch capacity, and a second shunt branch including an inductance L such as to have a reactance equal to that of either of the two condensers at the operating frequency. Its relationship to that of Fig. 9 is readily seen. In this circuit the zero phase shift amplifier is provided by two normal tubes coupled in tandem through shunt resistances 23 and 24, but the negative amplification tube of Fig. 9 may also be used, if desired.

Besides having the particular reactance relationships described in the foregoing, the phase quadrature networks used in the systems of the invention are characterized by the properties of their image parameters. The image impedance of the network at either pair of its terminals is equal to the square root of the product of the open circuit and short circuit impedances measured at these terminals and the image transfer constant is equal to the hyperbolic arc-tangent of the square root of the ratio of the short circuit impedance to the open circuit impedance. Applying these relationships to the general network shown in Fig. 1, the image impedance is found to be a real quantity of value X at the assigned frequency and the transfer constant to be the hyperbolic arc-tangent of an infinitely great pure imaginary quantity.

In accordance with well-known network theory, the real character of the image impedance corresponds to a purely resistive character and indicates that the frequency for which the reactances have the special values lies within a transmission band of the network. The value and character of the image transfer constant shows that it represents a simple phase shift of 90 degrees without any accompanying attenuation. The networks are thus characterized by having image phase shifts of 90 degrees at frequencies within transmission bands or for which the image impedances are pure resistances. In the circuits of the invention, the networks operate at the frequency thus determined, for which the quadrature phase shifts are stable.

If the transmission band within which the frequency of the 90-degree image phase shift lies be very narrow, the frequency variation of the phase shift at this point will be very rapid, since the image phase shift ranges through at least 180 degrees in the band. The actual insertion phase shift when the network is connected to terminal impedances follows the image phase shift approximately and will also vary very rapidly. Conversely, if the band be wide, the phase shift produced will vary slowly with the frequency. The phase shifting networks shown in the drawings which include piezoelectric crystal elements are all characterized by a very narrow transmission band in the frequency range where the crystal reactance is inductive.

What is claimed is:

1. A vacuum tube oscillator circuit comprising amplifying means, a transmission path coupling the output and the input terminals of the amplifying means to form a closed feedback loop, and a plurality of reactance networks included in the feedback loop, each of said networks being proportioned to produce at a common assigned frequency a phase shift of 90 degrees which is stable with respect to variations of the network terminating impedances, and the networks together with the amplifying means producing a total

phase shift in the feedback loop which is zero at the common assigned frequency.

2. A common tube oscillator circuit comprising amplifying means, a transmission path coupling the output and the input terminals of the amplifying means to form a closed feedback loop, and a plurality of reactance networks included in the feedback loop, each of said networks being proportioned to produce at a common assigned frequency a phase shift of 90 degrees which is stable with respect to variations of the network terminating impedances, one of said networks being also proportioned to produce a phase shift which varies rapidly with frequency at the assigned frequency, the others being proportioned to produce slowly varying phase shifts, and the networks together with the amplifying means producing a total phase shift in the feedback loop which is zero at the common assigned frequency.

3. A vacuum tube oscillator circuit comprising amplifying means, a transmission path coupling the output and the input terminals of the amplifying means to form a closed feedback loop, and a plurality of reactance networks included in the feedback loop, each of said networks having an image phase shift equal to 90 degrees at a common assigned frequency for which its image impedances are real and finite, and the networks together with the amplifying means producing a total phase shift in the feedback loop which is zero at the common assigned frequency.

4. A vacuum tube oscillator circuit comprising amplifying means, a transmission path coupling the output and the input terminals of the amplifying means to form a closed feedback loop, and a plurality of reactance networks included in the feedback loop, each of said networks having an image phase shift equal to 90 degrees at a common assigned frequency lying within a transmission band of the network, one of said networks being proportioned to have a narrow transmission band in which the assigned frequency is included whereby its phase shift varies rapidly with frequency at the assigned frequency, the other networks being proportioned to have phase shifts which vary slowly with frequency, and the networks together with the amplifying means producing a total phase shift in the feedback loop which is zero at the assigned frequency.

5. A vacuum tube oscillator circuit comprising amplifying means, a transmission path coupling the output and the input terminals of the amplifying means to form a closed feedback loop, and a pair of reactance networks included in the feedback loop, one of said networks having an image phase shift of 90 degrees at an assigned frequency lying within a narrow transmission band whereby its phase shift is stable with respect to variations of its terminating impedances at the assigned frequency but varies rapidly with frequency, the other of said networks being proportioned to produce a phase shift which is substantially 90 degrees at the assigned frequency and which varies slowly with frequency, and the two networks together with the amplifying means producing a total phase shift in the feedback loop which is zero at the assigned frequency.

6. A vacuum tube oscillator circuit comprising amplifying means producing a 90-degree phase shift at an assigned operating frequency, a transmission path coupling the output and input terminals of said amplifying means to form a closed feedback loop, and a reactance network included in said transmission path, said network being

proportioned to have an image phase shift at said operating frequency of 90 degrees in the opposite sense from the phase shift of said amplifier, whereby the total phase in the feedback loop is zero at the operating frequency independently of the magnitudes of the internal input and output resistances of said amplifying means.

7. A vacuum tube oscillator circuit comprising a two-stage vacuum tube amplifier, a reactance network coupling the stages of said amplifier in tandem, a feedback path coupling the output and the input of said amplifier to form a closed transmission loop, and a second reactance network included in said feedback path, said first network being proportioned to provide a phase shift which is substantially 90 degrees at an assigned operating frequency and which varies slowly with frequency, said second network comprising two shunt branches and a series branch in ladder configuration, the reactances of said branches being proportioned with respect to each other to produce a stable phase shift of 90 degrees in the opposite direction from the phase shift of said first network at said operating frequency, whereby the total phase shift in the closed transmission loop is zero at the said operating frequency independently of the resistances of the amplifier input and output circuits.

8. A vacuum tube oscillator circuit in accordance with claim 7 in which the shunt branches of said second network have equal reactances of like sign at the operating frequency and the series branch has a reactance of the same magnitude but of opposite sign at said frequency, and are proportioned to make the phase shift vary rapidly with frequency.

9. A vacuum tube oscillator circuit in accordance with claim 7 in which one of the branches of said second network is constituted by a piezoelectric crystal.

10. A vacuum tube oscillator circuit comprising an amplifying vacuum tube, a feedback path coupling the output and the input terminals of said tube to form a closed transmission loop, and a pair of reactance networks included in

tandem in said feedback path, each of said networks being proportioned to have an image phase shift of 90 degrees at an assigned oscillation frequency for which the image impedances of the two networks are pure resistances, whereby the quadrature phase shifts of the networks are independent of the internal resistances of the vacuum tube, and the two networks together with the vacuum tube producing a total phase shift in the closed loop which is zero at the said oscillation frequency.

11. A vacuum tube oscillator in accordance with claim 10 in which the two networks produce phase shifts of 90 degrees in the same direction at the oscillation frequency.

12. A vacuum tube oscillator in accordance with claim 10 in which one of the said networks includes a piezoelectric crystal as a reactance element whereby its phase shift is characterized by a rapid variation with frequency at the oscillation frequency.

13. A vacuum tube oscillator in accordance with claim 10 in which the said vacuum tube produces a zero phase shift between its input and output voltages and in which the said networks produce quadrature phase shifts in opposite directions at the oscillation frequency.

14. A vacuum tube oscillator comprising vacuum tube amplifying means having zero phase shift, a feedback path coupling the output and input terminals of said amplifying means to form a closed transmission loop, and a four-terminal reactance network included in said network, said network comprising a pair of series impedance elements constituted respectively by a piezoelectric crystal and a capacity connected in series, a second capacity connected in shunt at the outer terminal of said crystal and an inductance connected in shunt at the outer terminal of said first-mentioned capacity, all of said elements being proportioned to have reactances of equal magnitudes at an assigned oscillation frequency, the reactance of said crystal being inductive at said frequency.

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