Oct. 21, 1941. W. P. MASON 2,259,528

CRYSTAL CONTROLLED OSCILLATOR FOR ULTRA-HIGH FREQUENCIES

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FIG. 1

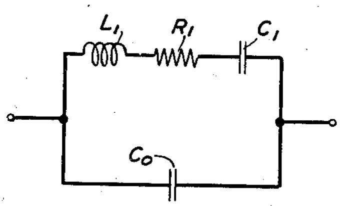


FIG. 2

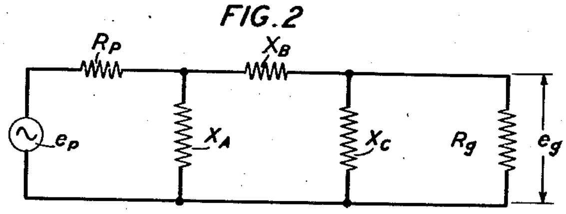
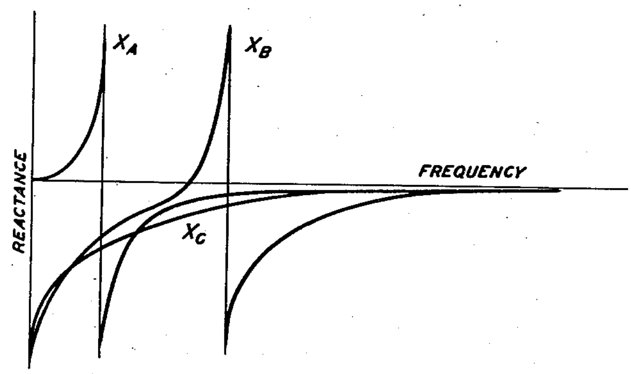


FIG. 3



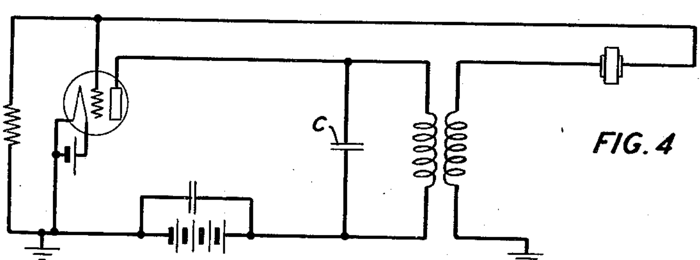


FIG. 4

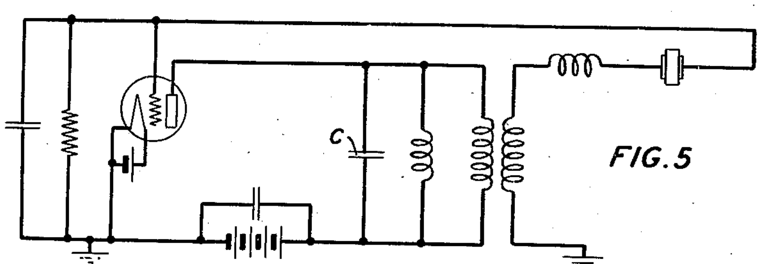


FIG. 5

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FIG. 6A

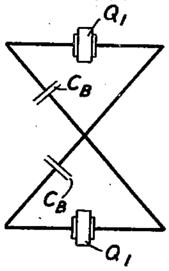


FIG. 6B

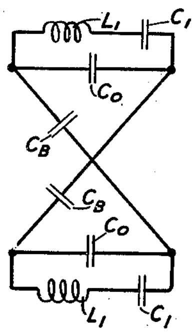


FIG. 7A

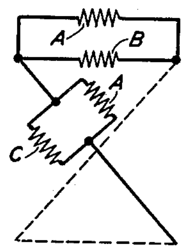


FIG. 7B

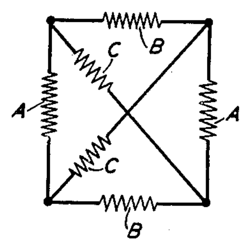


FIG. 8

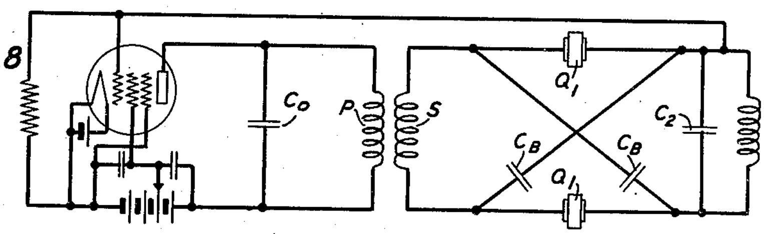


FIG. 9

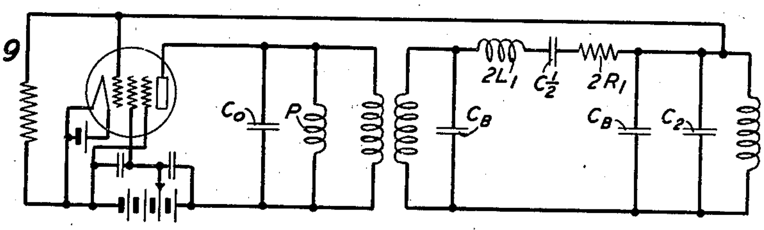


FIG. 10

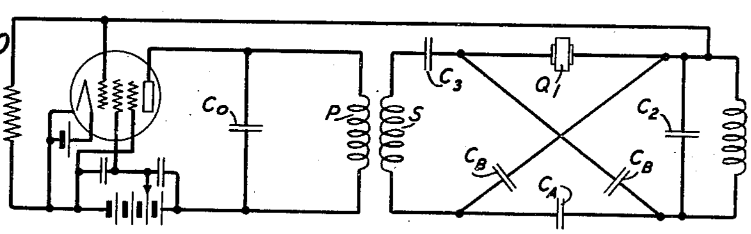
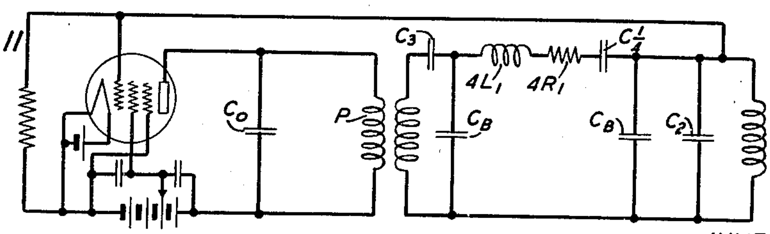


FIG. 11



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CRYSTAL CONTROLLED OSCILLATOR FOR ULTRA-HIGH FREQUENCIES

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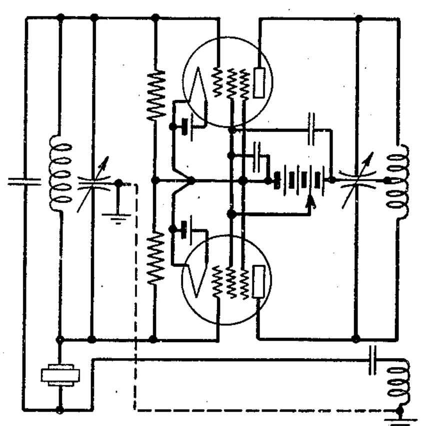
FIG. 12



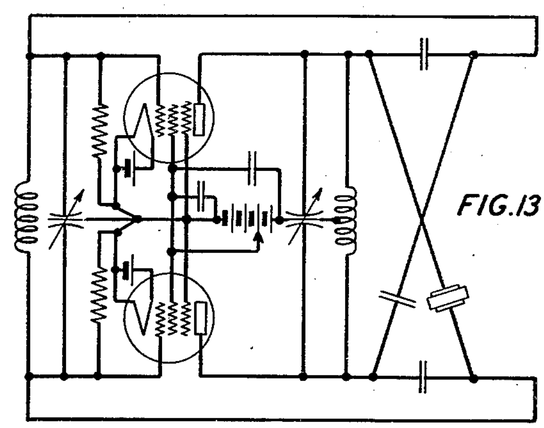


FIG. 13

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Patented Oct. 21, 1941

2,259,528

UNITED STATES PATENT OFFICE

2,259,528

CRYSTAL CONTROLLED OSCILLATOR FOR ULTRA-HIGH FREQUENCIES

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Application January 5, 1939, Serial No. 249,388

9 Claims. (Cl. 250—36)

This invention relates to ultra-high frequency oscillators and, more particularly, to such oscillators as comprise in each instance an electron discharge repeater tube with associated circuits cooperating with it to regeneratively produce a sine wave under the frequency control of a piezoelectric crystal.

An object of the invention is to utilize piezoelectric crystal control, with its inherently superior characteristics as to frequency stability, in the production of ultra-high frequency waves, while also utilizing a circuit as a whole which is very much simpler, and employing fewer tube and impedance elements than has been found possible heretofore in the frequency range here concerned, and crystal elements of such a size and configuration as to make possible the accurate frequency dimensioning heretofore made possible only in connection with a radically different order of frequency.

Another object of the invention is to generate a wave of frequency as high as 150 megacycles a second utilizing direct control by a piezoelectric crystal.

Another object of the invention is to generate oscillations under conditions such that there is a maximum output at the frequency of maximum stability.

It is a still further object of the invention to generate ultra-high frequency waves, including those having frequencies of the order of 120 to 150 megacycles per second, by utilizing mechanical harmonics of the crystal, and, therefore, without the employment of stages of harmonic generation succeeding the primary generation of a relatively low frequency fundamental; and this without substantial sacrifice of frequency stability, simplicity and economy of circuit elements, and ease of operation as compared with the generation of the fundamental wave alone in the prior art systems, as above, which employ harmonic generators to build up a comparable ultra-high frequency from a prime fundamental frequency crystal controlled source or as compared with the generation of a wave by direct crystal control within a frequency range where the use of harmonic frequencies is not necessary in order to achieve the desired frequency.

During the last few years vacuum tubes of moderate power output have been developed which extend the commercially usable frequency spectrum into the ultra-high frequency region. Point-to-point station transmitters operating at 120 megacycles and 150 megacycles, especially aircraft transmitters, are examples of such equipment. These transmitters, and they are merely typical of many of like requirements, require frequency stabilities of their component oscillators which are attainable only with crystal control. Because of the unavailability of crystals having operating frequencies of this order of value, which therefore has negatived the possibility of directly controlling the frequency of an oscillator generating waves of this order of frequency, recourse has been had in the past to the expedient of using prime crystal oscillators working under 20 megacycles followed by a number of stages of harmonic generation to build up the eventual, desired frequency.

By means of this invention it is practicable to directly control the frequency of an oscillator by crystal resonance at a frequency as high as 150 megacycles. This resonance is at a mechanical harmonic of the crystal, which crystal is therefore considerably thicker than it would be if it had to vibrate at a fundamental frequency in this ultra-high frequency region, and hence can be ground and adjusted with much greater facility. A particular oscillator whose properties are to be described later in this specification uses the fifteenth mechanical harmonic of a crystal and produces a frequency of 120 megacycles. The type of crystal there used, and which was found most effective, is of a cut disclosed and claimed in Lack-Willard-Fair application Serial No. 728,640 filed June 2, 1934, which eventuated into Patent 2,218,200, October 15, 1940, and described also in a paper by Willard beginning on page 250 of the Bell Laboratories Record for April 1936, vol. 14, No. 8, in which see especially the extreme right-hand circuit in Fig. 6. There is also a description of this cut of crystal, which is known to the assignee corporation as the AT cut crystal, in a paper by Lack, Willard and Fair, "Some Improvements in Quartz Crystal Elements" in the Bell System Technical Journal for July 1934, vol. 13, pages 453 to 463. Because of the high order of the harmonic the crystal in these tests was thicker than, and could be ground and adjusted much more easily than, crystals that have been commonly used in commercial fields, even at frequencies of a far lower range than that here exemplified. A mechanical harmonic tends to have the same temperature coefficient of frequency as the fundamental which in the instance of the AT crystal can be made lower than two parts per million per degree centigrade.

The type of circuit used in this invention and which was found capable of developing the characteristically large mechanical harmonics with very great effectiveness, was postulated on particular characteristics of piezoelectric crystals at the very high frequencies here concerned.

The invention will be more fully explained in the following description when taken in connection with the accompanying drawings in which:

Fig. 1 represents the equivalent electrical circuit of a piezoelectric crystal;

Fig. 2 represents the equivalent electrical circuit of a common generic type of oscillator of the prior art, the genus including a common type of piezoelectric crystal controlled oscillator;

Fig. 3 is a graphical representation of the characteristics of the piezoelectric crystal as used in the circuit of Fig. 2;

Figs. 4 and 5 illustrate, respectively, a type of crystal controlled oscillator circuit of the invention and a slight variant thereof, also of the invention;

Figs. 6A and 6B illustrate, respectively, a circuit means for balancing out the static capacitance of a piezoelectric circuit and the equivalent electrical network thereof, while Figs. 7A and 7B illustrate a network theorem indicating how the circuit of Fig. 6A or 6B may be differently represented;

Figs. 8 and 9 illustrate, respectively, a form of the invention employing the balanced circuit of Figs. 6A and 6B and the equivalent electrical circuit thereof;

Figs. 10 and 11 are similar, respectively, to Figs. 8 and 9 but indicate how one of the two crystals thereof may be avoided if replaced by an equivalent condenser;

Fig. 12 illustrates another form of the circuit of the invention; and

Fig. 13 illustrates another and preferred form of the circuit of the invention.

As normally operated, and therefore under circumstances where the crystal effectively replaces a reactive element of a prototype vacuum tube oscillator, and without regard to the particular pair of tube electrodes between which the crystal is connected, a piezoelectric crystal must exhibit a positive reactance, and this capability depends upon the "Q" of the crystal and the coupling coefficient of the electrical and mechanical systems embodied in the crystal. Specifically such coupling of a harmonically vibrating crystal varies inversely as the order of the mechanical harmonic. It, therefore, becomes increasingly difficult to excite the harmonic vibrations, where a positive crystal reactance is required and, in fact, harmonics higher than the fifth cannot usually be excited with conventional circuit arrangements.

More specifically, it may be shown that in order for a positive reactance to occur in the crystal it is necessary that the following relations be true:

$$\frac{k^2}{2} > \frac{1}{Q} \text{ or } Q > 2r$$

where Q is the ratio of reactance of a coil in the electrical representation of the crystal to its resistance, k the electro-mechanical coupling factor, and r the ratio of the shunt capacitance of the crystal to its series capacitance in the equivalent circuit of the crystal shown in Fig. 1 and, therefore, is an inverse measure of the coupling to the crystal. These two relations which are derived in applicant's paper, "An Electromechanical Representation of a Piezo Electric Crystal" in the Proceedings of the Institute of Radio Engineers, October 1935, pages 1252 to 1264, are both stated here as equally well providing convenient devices for indicating the difficulty of achieving positive reactances in crystals by conventional means. The ratio of capacitances for the fundamental vibration of an AT crystal as usually mounted is of the order of 1000 to 1. It has been shown experimentally and theoretically that the value r increases as the square of the harmonic and hence $2r$ for the fifth harmonic would be 50,000. The Q of a crystal is usually not much larger than this so that this harmonic is about the highest harmonic that can be used in the conventional oscillator circuit.

The circuit of the present invention is such that a positive crystal reactance is not required. It actually consists of a high frequency tube, preferably a pentodetube, with tuned grid and plate circuits conjugately coupled to a capacitance bridge of which the crystal forms one arm. For this circuit the crystal impedance does not have to have a positive reactance and it has been found possible to control the frequency of an oscillator with harmonics up to the twenty-third or higher. As a practical matter, the operation of the bridge principle where the bridge is a capacitance bridge, as in this invention, allows the bridge to become unbalanced with the crystal maintaining a negative reactance by the action of a harmonic resonant frequency changing the reactance from the balancing value.

The stability obtainable for this oscillator is about the same as can be obtained with ordinary circuits at a much lower frequency. The stability with plate voltage change is of the order of .05 cycle per megacycle per volt. The temperature coefficient of the crystal is, as above explained, under two parts per million per degree centigrade. Without regulation of voltage or temperature, the frequency should be stable to plus or minus .00025 per cent or better and with temperature regulation the stability can be increased. The use of the capacitance bridge feedback in the oscillator circuit of the invention has certain incidental benefits besides the capability, imputed thereto, of the crystal functioning as a negative reactance. Because of the bridge principle there is a balancing out of the paralleling (that is static) capacitance of the crystal or, which amounts to the same thing, a shifting of it to a new position in the equivalent electrical circuit. This by itself promotes the stability of the circuit as enabling a feedback to occur only during the dynamic phase of operation of the crystal with a resultant greater dependence of the frequency on the elastically vibratory characteristics of a crystal, which confers on a circuit controlled by a crystal its unusually high stability qualities. Not only does the circuit enable a crystal to exercise control at a very high, harmonic frequency because of the avoidance of the limitation to positive crystal reactance, inherent in prior circuits of the same order of frequency, but this condition does not at all depend on the size of the harmonic above the fifth harmonic, which is usually cited as the lower limit at which positive reactance can occur. That is, as the order of harmonic becomes indefinitely higher, the crystal does not tend to become inductive but merely changes its capacitance and unbalances the circuit sufficiently to produce oscillations.

An advantage in the use of crystals vibrating at mechanical harmonics besides those cited having to do with the attainment of a frequency not heretofore attainable except by undue complication of circuits is that thereby the coupling with respect to spurious or "hop" frequencies goes down very fast as the order of harmonics increases so that if it is carried to the fifteenth harmonic or above, the circuit becomes substantially immune to "hops."

Preliminarily to a description of the invention as embodied in practical circuits, certain observations will be made and certain analyses undertaken to better frame, and lead up to, the invention proper.

In order that the crystal may be useful in an ultra-high frequency oscillator it is necessary that its Q shall be high and remain high in this range. By a variety of means, not of particular pertinency here, applicant has measured the Q of a number of crystals, some of which were later used in the experimental work pertaining to this invention. The fundamental frequencies of the crystals varied from 800 kilocycles to 20 megacycles. Since no measurements have been published on how the Q's of crystals, especially ultra-high frequency crystals, vary with frequency, these measurements were undertaken with the thought that if there is a systematic variation with the frequency it would be brought to notice thereby. The Q of a crystal has already been defined in general terms but it may be better defined with respect to the equivalent circuit of the crystal as shown in Fig. 1. Here C_0 designates the static capacitance of the crystal while the effect of the motional impedance of the crystal, that is, the impedance under the dynamic conditions attending its practical operation, is represented by the series resonant circuit L_1, C_1 and R_1. The Q of the crystal is therefore, in terms of this circuit, expressible as the ratio $2\pi f_R L_1/R_1$ where f_R is the resonant frequency.

The measurements indicated that although the Q of different crystals had differed over a considerable range, between 30,000 and 100,000, there was no significant trend with frequency. Incidentally the same tests of Q brought out the fact of the ratio of capacitances for the fundamental frequencies being around 1000 to 1, as above pointed out.

In view of the proposal in accordance with the invention, of using harmonics of these crystals, the Q's were measured at the harmonic frequencies. Quite significantly it was found that the crystals uniformly showed an increasing Q with an increase in the order of the harmonic. It is thought that the variation in Q of shear vibrating crystals is due to very minute cracks on the surface which cause a small amount of friction when the crystal vibrates. This is borne out by the fact that etched or polished crystals usually have a higher Q than non-treated crystals. This is probably also the explanation of the higher Q in the harmonically vibrating crystal for a harmonically vibrating crystal is similar to a number of crystals in parallel with a correspondingly increased number of vibrating surfaces. All of the internal surfaces are whole and free from cracks. If most of the resistance is associated with the outside surfaces, as is reasonable, it follows that a harmonically vibrating crystal, and therefore a crystal with a large number of internal faces, should have less dissipation than the fundamental vibrating crystal. At the high order harmonics the Q seems to approach an asymptote of 400,000 to 500,000, which is probably the Q associated with the internal dissipation. This data indicates that so far as internal dissipation is concerned the Q of the crystal is independent of the frequency but that if one goes from a condition for which the Q is controlled by the surface dissipation to a condition where the Q is controlled by the internal dissipation, the Q will increase. This increase of Q, which is not unsubstantial but of the order of several hundred per cent comparing the higher Q's with the fundamental, is, per se, a strong argument, additional to those already adduced, for the development of ultra-high frequency by use of the mechanical harmonic method as in accordance with the present invention, as compared with the prior art method of developing an ultimate like frequency by use of stages of harmonic generation.

It is a matter of interest to observe how the impedance of a harmonic crystal varies with the order of the harmonic, this also involving proof of the above necessary relations for a positive reactance crystal, namely $k^2>2/Q$ or $Q>2r$. It has been shown in applicant's paper "An Electro-Mechanical Representation of a Piezo-Electric Crystal Used as a Transducer" in the Proceedings of the Institute of Radio Engineers, vol. 23, October 1935, pages 1252 to 1264, that the impedance of a piezo-electric crystal is given by the expression

$$Z_c=\frac{-j(1-k^2)}{\omega C_0}\left[\frac{1-f^2/f_1^2+\dfrac{j}{Q(1-k^2)}}{1-f^2/f_2^2+j/Q}\right] \qquad (1)$$

where C_0 is the static capacitance of the crystal, f_1 the resonant frequency, and f_2 the anti-resonant frequency. Also,

$$f_1^2=f_2^2(1-k^2)$$

Inserting this value and expressing the equation in the form of a resistance and reactance we find

$$Z_c=\frac{\dfrac{k^2}{Q}-j\left[1-k^2-\dfrac{f^2}{f_2^2}(2-k^2)+\dfrac{f^4}{f_2^4}+\dfrac{1}{Q^2}\right]}{\omega C_0\left[\left(1-\dfrac{f^2}{f_2^2}\right)^2+\dfrac{1}{Q^2}\right]} \qquad (2)$$

The reactance term will have a maximum value when

$$f^2=f_2^2\left(1-\frac{1}{Q}\right)$$

At that frequency the impedance of the crystal will be

$$\frac{\dfrac{k^2Q}{2}+j\left(\dfrac{k^2Q}{2}-1\right)}{\omega C_0} \qquad (3)$$

Hence in order that the crystal shall exhibit a positive reactance

$$\frac{k^2Q}{2}>1 \text{ or } k^2>\frac{2}{Q} \qquad (4)$$

These expressions may be put in a more usable form by expressing the relationship in question in terms of the ratio of capacitance r, instead of in terms of the coupling factor. As is pointed out in the above paper by applicant in the Proceedings of the Institute of Radio Engineers, the following equation expresses the relation of said capacity ratio and coupling factor

$$r=\frac{1-k^2}{k^2}$$

By substitution of the value of k derived from this equation, in the last preceding equation, the expression $Q>2(1+r)$ for the crystal, to exhibit a positive reactance, may be derived. For practical purposes, since r is always large as compared with the numeric 1, this expression may be represented approximately by $Q>2r$. This is the expression that has been made use of in the statement of invention to appraise the invention from the standpoint of the difficulty of generating an ultra-high frequency when using a crystal in a position requiring it to have a positive reactance. As then stated, with practicable values of Q and r, the highest order harmonic which will show a positive reactance for an AT cut crystal is of the order of the fifth harmonic.

In connection with the shortly to be treated oscillator circuit adapted for use with ultra-high frequency harmonic crystals, as in accordance with the invention, it is useful to consider, relatively thereto, the properties of two types of oscillator circuits of use for low frequency crystals. A very common type of circuit of the prior art, perhaps the most common, is illustrated generically by Fig. 2. In this figure the oscillator circuit is represented as a network comprising the reactances X_A, X_C, and X_B simulating respectively the anode-cathode, grid-cathode and grid-anode reactances of an oscillator tube, R_g represents the input impedance external to the tube and R_p represents the output impedance in series with the anode source e_p. Of course, impedances R_g and R_p are principally resistive. This circuit, which may be specifically exemplified in either the well-known Hartley or Colpitts forms, as well as other well-known forms, is characterized by the necessity of the network itself producing the 180 degree phase shaft offsetting the 180 degree phase shift produced in the tube, so that the wave fed back to the grid from the anode is in the same phase as the phases for contiguous wave cycles, this resulting in a perpetuation of the oscillations induced by an initial wave impulse. This generic type of circuit is to be distinguished from alternative generic types wherein, for example, two tubes are employed to achieve the equivalent over-all zero phase shift. In this Fig. 2 circuit the crystal, since this application has to do with crystal controlled oscillators, may constitute a portion (and probably the principal portion in view of the relatively small internal reactance which is characteristic, or which can be made characteristic, of modern tubes) of either one of the three reactances shown, the precise positioning determining the particular type of crystal controlled oscillator concerned.

If we consider the circuit of Fig. 2, the conditions for zero over-all gain and zero over-all phase shift, these being the conditions for oscillation, are given by the two following equations taken from a paper by F. B. Llewellyn in the Proceedings of the Institute of Radio Engineers, vol. 19, page 2063, December 1931:

$$\frac{R_p}{R_g}=-\left[\frac{X_A}{X_A+X_B}\right]\left[\mu+\frac{X_B+X_C}{X_C}\right] \tag{5}$$

$$R_pR_g=\frac{X_AX_BX_C}{X_A+X_B+X_C} \tag{6}$$

In these equations μ is the amplification factor of the tube and the other quantities the resistances and reactances corresponding to the elements shown in the figure. These equations assume that the tube introduces a phase shift of 180 degrees. In case two tubes are used in tandem to produce the requisite phase shift as above, or if a coupled transformer is used for the same purpose, (as will be disclosed) the sign of μ in the first equation would have to be reversed, and for two tubes the value of μ would be measured by the ratio of the potential applied to the anode of the second tube to the potential applied to the grid of the first tube.

For the circuit of Fig. 2 μ would ordinarily be greater than

$$\frac{(X_B+X_C)}{(X_C)}$$

regardless of sign. If

$$\frac{(X_B+X_C)}{(X_C)}$$

were assumed to be of opposite sign to μ and greater in magnitude, it could readily be shown that the resulting conditions would not satisfy the last above equation so that the circuit would not oscillate under these conditions. Since

$$\frac{R_p}{R_g}$$

in Equation 5 must be positive, it follows that the quantity

$$\frac{X_A}{X_A+X_B}$$

must be negative. Writing

$$\frac{X_A}{X_A+X_B}=K$$

there results

$$X_B=-\frac{(1+K)}{K}X_A$$

This shows that X_B must be of opposite sign to X_A. Also the relation

$$\frac{X_A}{X_A+X_B}=-K$$

shows that X_B must be greater in magnitude than X_A.

Introducing the above value of X_B into Equation 6 we have

$$R_pR_g=-\frac{X_A^2(1+K)}{X-\frac{X_A}{X_C}} \tag{7}$$

Since

$$X_A^2$$

is positive, the right-hand side of Equation 7 can only be made positive if X_A is the same sign as X_C and $K\,X_C<X_A$. It accordingly appears not only that X_B must be opposite in sign to and greater than X_A but that X_A and X_C must be of the same sign. It also appears from the other conditions above established taken with the above equation for R_pR_g that the sum of X_A and X_C must be smaller in magnitude than X_B.

Since we do not know R_p and R_g explicitly, the frequency cannot be calculated definitely from these equations, unless R_p, R_g and the distributed capacitances of the tube are evaluated as functions of the voltage and current conditions in the tube. Ways for minimizing the variations with tube and circuit conditions are, however, evident from the above equations, especially Equation 6. For example, this equation may be satisfied by making the sum of the reactances substantially zero and the product of the tube resistances, especially the grid resistance, correspondingly very large. As shown in Fig. 3, this condition, so far as concerns the reactances, may be realized where a tuned circuit constitutes the X_A arm, as is customary, and with the X_B arm constituted substantially wholly by a crystal as is also customary, by tuning said X_A arm to a frequency considerably lower than the crystal resonance frequency. The crystal will operate on the positive slope of its resonance curve and will be large as compared with X_A and X_C, the frequency being determined very closely by the condition that $X_A+X_B+X_C=0$. A change in R_pR_g caused by a change in potential anywhere in the circuit will produce only a small frequency change because of the large value already existing for this product. The maximum frequency stability for variations of voltage for this type of oscillator circuit very obviously occurs for a minimum energy output, contrary to the teachings of the circuit of the invention.

An analysis similar to that above, with obvious changes to suit the new situation as by taking account of the effect on the sign and value of μ in the Equation 5, could be made with the alternative circuit employing two tubes.

As described in this application, oscillation may also be achieved by the use of a phase reversing transformer as shown in Figs. 4 and 5. Fig. 4 shows an ideal transformer in the plate circuit, introducing an 180 degree phase shift. The crystal is connected in series with the output and the grid of the tube. Fig. 5 shows the deviation from the ideal condition caused by a less than unity coupled transformer. As might be shown, this is equivalent to inserting a shunt inductance on the plate side, and a series inductance in the secondary side having the value $S\ (1-K^2)$ where K is the coupling coefficient, and an ideal transformer of impedance ratio M^2/P^2 between them, where M is the mutual inductance between windings and P the primary inductance. The capacitance C tunes the primary inductance near the crystal resonance. The said series inductance can be annulled at the crystal resonance by inserting a separate condenser or can be annulled by the crystal reactance itself, in which case the oscillator will oscillate at a frequency slightly lower than the crystal resonance. In either case the circuit can be tuned so that the reactances vanish at the operating point in the circuit and a change in the plate or grid resistance with change in any of the tube voltages will not produce any frequency change. This frequency will also be the frequency of maximum output since the gain through the circuit will be a maximum at this frequency.

It is indicated from the above description of the circuit of Fig. 4 that the point of maximum frequency stability with voltage variation could be made to come at the point of the highest power output in contradistinction with the above analyzed circuits of the prior art. However, the crystal, for the condition of maximum frequency stability, would still have to operate with a pure resistance and this condition cannot be obtained unless the crystal reactance can become zero or positive, and hence this oscillator circuit also cannot be used for high harmonic crystals. The input and output tube impedances corresponding to elements X_A and X_C of Fig. 2 would antiresonate at the crystal resonant frequency and the product of the two tube resistances would be less than with the other circuit. Under these conditions a large change in the tube resistance as effected by, for example, the voltage change, would not greatly change the frequencies since no phase change requiring a shift in frequency will occur.

It is notable that neither of the above two types of circuit can be used directly with the frequency determined by a high mechanical harmonic of the crystal. Therefore, these circuits are incapable of use at the very high frequencies contemplated by the present invention, as illustrated by the circuits to be presently described. This is, of course, by reason of the fact, as has been explained, that the crystal reactance at the necessarily high harmonics assumed does not become positive, as required, in the resonant region. A crystal vibrating at one of these high mechanical harmonics could be used to control the frequency by causing it to operate at a negative reactance, but in that case it would be difficult to locate the control in the resonance region and, even if so, the conditions for a near-maximum stability would not be subserved. That is, the crystal would function merely as an effective capacitance and would therefore, as is evident from the curve for X_B of Fig. 3, not exercise a stabilizing or controlling function in nearly as great a degree as in the above instances of the prior art where the crystal functions as an inductance.

It is noted, however, as appears from the equivalent circuit of a crystal, as shown in Fig. 1, that the reason the crystal reactance does not go positive at these high frequencies is that the series resonant arm is shunted by a condenser which has a relatively small reactance at the very high frequencies concerned. If this shunt capacitance could be removed, the remaining impedance arm would consist of a simple series circuit which would change between negative and positive reactance at the resonant frequency.

It has been shown by applicant in his paper "Resistance Compensated Band-Pass Crystal Filters for Unbalanced Circuits" in the Bell System Technical Journal for October 1937, beginning in page 423, that the static capacitance, that is, the above shunt capacitance, of a piezoelectric crystal can be removed by incorporating the crystal in a special lattice network of capacitances, as shown in Fig. 6A. Fig. 6B shows the equivalent electrical network. Fig. 6A shows two crystals Q_1 in the series arms having the same constants but they may equally well be represented as a single crystal with two sets of electrodes. Capacitances C_B are balancing capacitances. By virtue of the network theorem illustrated by Figs. 7A and 7B, and also as pointed out in applicant's paper above, the static capacitances of the crystals together with the balancing capacitances of like values can be removed to the ends of the lattice as in Fig. 7B leaving the T-network of reactances shown, said static capacitances and balancing capacitances being replaced by a pair of capacitances each at an individual end of the lattice and having a value equal to said static capacitance or balancing capacitance. In this network as disclosed in Fig. 7B the series arms B are each constituted by the resonance series arms A of the equivalent representation of the crystal as shown in Fig. 1, the shunt arms being constituted by the static capacitances of the crystal. The elements C represent generalized impedances which, for the conditions here assumed, in which the balancing capacitances are equal to the crystal shunt capacitances, would have infinite values. In the subsequent showings involving the use of this theorem they are accordingly absent. For other conditions said impedances C could have zero, as well as finite values, without affecting the operation of the principle. Of these Figs. 7A and 7B, Fig. 7A represents the generalization of Figs. 6A and 6B achieved by the use of the theorem and Fig. 7B the finally evolved circuit. Obviously, the two series arms could be replaced by a single series arm, in the place of one of them and having an equivalent impedance.

Now suppose that this crystal lattice is incorporated in a Fig. 4 type of circuit so as to realize the circuit of Fig. 8. The capacitance C_2 with its related inductance not labeled has been added to provide a high impedance circuit between the grid and cathode. As will be indicated later these elements cooperate with other elements to constitute a circuit which as a whole is antiresonant at the desired frequency. Then, as in accordance with the teachings of Figs. 6A, 6B, 7A and 7B, the shunt capacitance of the crystal and the balancing capacitances may be removed to the ends of the network. Also, as explained in connection with Figs. 4 and 5, the transformer may be simulated by an ideal transformer, plus a shunt inductance cooperating with the capacity in parallel therewith to constitute a tuned circuit. The left-hand shunt capacitance, or lattice arm capacitance C_B, can be treated as joined to capacitance C_0 to tune the input coil constituted by the simulated self-inductance P of the primary winding. The right-hand shunt capacitance C_B can similarly be joined to capacitance C_2 to tune the output coil. If these two tuned circuits are made anti-resonant at the resonant frequency of the crystal, and assuming a 180 degree phase change in the transformer, the phase shift around the feedback path will be 360 degrees and the oscillator will oscillate strictly at the crystal resonant frequency. Fig. 9 illustrates the equivalent, simplified circuit analogously with Fig. 5 as compared to Fig. 4. Similarly as in Fig. 5, a series inductance could be shown to represent series leakage inductance of the transformer if such leakage is appreciable. In such event, said inductance could be annulled at the resonant frequency of the crystal by a small series capacitance so that the resultant, effective circuit would remain the same as that disclosed in Fig. 9.

The crystal network shown in Figs. 6A and 6B, and similarly in Fig. 8, has two identical crystals or a crystal with two sets of plates. This can be achieved by using one crystal with two identical sets of electrodes in the manner now used in crystal filters, as explained in applicant's Patent No. 2,094,044. It may also be achieved by using a crystal with a single set of electrodes since it can be shown that in the crystal lattice a single crystal in either position disclosed is equivalent to a balanced lattice with two crystals if the remaining crystal is substituted by a capacitance equal to the shunt capacitance of the crystal. The same result could be secured by other values of the substituted capacitance if the crystal is correspondingly changed from that here assumed.

Fig. 10 illustrates the circuit of Fig. 8 reorganized in this manner, the capacitance C_A representing the duplicate crystal substituted for from the circuit of Fig. 8. The series capacitance C_3 is intended to illustrate the neutralizing capacitance mentioned above in connection with the comment on the series leakage inductance. These circuits of Fig. 10 may be represented in the form of Fig. 11 which has the same relation to Fig. 10 that Fig. 9 has to Fig. 8. However, for this condition the equivalent single series impedance would have twice the values of the inductance and capacity as compared with Fig. 9. With respect to this Fig. 11, and equally with respect to the other figures, but having in mind especially Figs. 8, 9 and 11, where at first glance the contrary might be indicated, it is pointed out that the circuits are fully operative as disclosed and, in particular, that grounds are not necessary.

The oscillator of Fig. 10 is capable of driving the crystal at a high harmonic and of being controlled by the resonance characteristic of the crystal at that harmonic. A 180 degree phase shift is introduced by the transformer and the resonant circuits are tuned so that their antiresonant frequencies coincide with the resonant harmonic frequency of the crystal. This is the condition for maximum output and maximum stabilization against voltage changes, as has been pointed out previously.

Other circuits, in which the principles illustrated by the circuit of Fig. 10 are embodied, have been suggested by applicant. Some of these circuits are balanced and some unbalanced. At ultra-high frequencies it is often desirable to use balanced circuits and double pentode tubes have been developed for this purpose. For such systems it is desirable to use balanced oscillator circuits. Figs. 12 and 13 disclose certain of such circuits that have been used by applicant to successfully demonstrate the principles above described.

The circuit of Fig. 12 consists of two pentodes operated as an amplifier in a balanced circuit. The output is taken off across a coil which is tuned in the plate circuit by two variable condensers ganged together. This coil is coupled to an output coil which on one side is connected to ground and on the other connected through a neutralizing capacitance to the bridge containing the crystal. This bridge is formed by two ganged condensers which are connected to the two grids and to ground as shown, and by the crystal and another condenser used for balancing. An inductance is connected across between the two grids. It is obvious that if desired only one ground may be used, the other ground being replaced by a connection between the two ground points shown. This circuit is, therefore, quite analogous to that of Fig. 10 or 11, differing principally because of the use of balanced tube circuits.

The method of adjusting this circuit is quite simple and can be explained as follows. The condenser balancing the crystal is turned off its balancing value and the circuit is allowed to oscillate uncontrolled by the crystal. The two ganged capacities in the grid and plate circuit are then adjusted until the maximum output results near the desired crystal frequency. The balancing condenser is then adjusted toward balance and the oscillation will usually stop. The grid and plate capacitances are thus tuned to crystal frequency and the oscillator will then oscillate and be controlled by the crystal only.

Another and preferred circuit is shown in Fig. 13. Here the balanced pentodes have simple inductance coils on the grid and plate sides tuned by balanced condensers. The coupling between grid and plate is accomplished through the bridge containing three small condensers and the crystal. In order to obtain the 180 degree phase shift necessary to have the greatest output at the point of greatest stability, the crystal has to be included as one of the lattice arms as shown in Fig. 13. With this circuit very large outputs have been obtained at high harmonics. The crystal bridge can be balanced once for all times, and different odd harmonics can be obtained simply by tuning the output and input coils to the successive harmonics. No oscillations will be obtained except at the crystal resonant frequencies, whether the base frequency or harmonics thereof.

The use of the above Figs. 12 and 13 circuits were induced by the desire to work the oscillator into a balanced pentode amplifier. In order to make the crystal controlling at the very high frequencies contemplated, it was necessary to employ a circuit with as much gain as possible at these high frequencies. This indicated that high frequency pentodes should be used and accordingly RCA952 acorn pentode tubes were used.

With these circuits it was found possible to drive crystals at harmonics as high as the twenty-third to generate waves of frequencies as high as 150 megacycles or of two meters wave-length. Furthermore, it was found possible to attain the second electrical harmonic giving a frequency of 300 megacycles, therefore corresponding to waves of one meter wave-length. This probably does not represent the upper limit for by using circuits with more gain the loss inserted by the crystal circuit can be overcome and the oscillator be crystal controlled at even higher frequencies.

For tests in which great frequency stability was noted at a frequency of 120 megacycles, the output potential was 100 volts across an output impedance of 25,000 ohms when the anode potential was 250 volts and the screen potential was 100 volts. The maximum frequency variation was found to be of the order of 5 kilocycles from the point of maximum grid current to the point where oscillations cease when the grid tuning was varied. Similar results were obtained for variations of plate tuning. The overall frequency change, that is for both plate and grid tuning changes, amounted to about one hundred parts in a million. This range represented the control range of the crystal and, therefore, the maximum frequency deviation which would occur for any possible combination of circuit changes unless the bridge becomes unbalanced and the circuit oscillates uncontrolled. Of course, in the extreme tuning positions the output is very low so that the usable range is probably about half that above indicated. The change in frequency with change in anode voltage for this type of circuit is quite small at the maximum output, for reasons that have been given. When the circuit is tuned somewhat differently, that is for somewhat less than the maximum output, the variations may amount to from .05 to .1 cycle per megacycle per volt.

Using AT cut crystal plates vibrating at their fifteenth harmonics, an average coefficient of frequency over a 50° C. temperature range was found to be 1.3 parts in 10^6 per degree centigrade for one crystal and .2 part correspondingly for another crystal. No crystal was tested which had a coefficient of more than 2 parts in 10^6 per degree centigrade. One remarkable feature of these crystals was brought out by the temperature coefficient of frequency test. That is, no "hops" in frequency were experienced in any of the temperature tests. This appeared to be due to the fact that the coupling to harmonics of a low frequency mode of vibration tends to decrease with decrease in ratio of thickness to the diameter of the crystal plate. In one instance the crystal was .21 millimeter in thickness and 12 millimeters in diameter and operated on the fifteenth harmonic and hence the ratio of diameter to effective thickness was 12 to .014 or 860 to 1, and the unwanted coupling was practically zero. A crystal oscillator of a type disclosed in Fig. 12 was used in conjunction with two Western Electric 240A amplifying pentode tubes to deliver 12 watt output to a radio antenna of 120 megacycles. After five and a half hours of continuous running the frequency had changed about 800 cycles or 7 parts in 10^6. A day-by-day check indicated frequency agreement within several hundred cycles. Continuous runs indicated that the frequency variation under ordinary operating conditions should not be more than plus or minus 25 parts in a million or plus or minus 3 kilocycles at 120 megacycles.

It will be obvious that many variations of the specific circuits and structures disclosed herein may be made without departing from the spirit of the invention. Therefore, it is not proposed to limit the invention except as necessitated by the prior art or indicated by the claims.

What is claimed is:

1. An oscillation generator comprising an amplifier, a pair of input and a pair of output electrodes therefor, and a network between said pairs of electrodes comprising a piezoelectric crystal, said network exclusive of the crystal also comprising a tuned circuit connected directly between said output electrodes and a separate phase reversal means, the network being otherwise substantially reactanceless, and said crystal and said phase reversal means being connected effectively in series between said input electrodes, whereby the generator as a whole is adapted for maximum energy output coincidentally with adjustment for maximum stability of frequency as affected by voltage changes.

2. An oscillation generator comprising an amplifier, a pair of input and a pair of output electrodes therefor, and a network between said pairs of electrodes comprising a tuned circuit connected to said output electrodes and a piezoelectric crystal, said crystal being so related to its associated circuit elements in said network that, while the crystal controls the oscillation frequency, the network exhibits other than negative reactance in a resonant region corresponding to a crystal mechanical harmonic which is higher than five, said tuned circuit when taken with the capacitance between said output electrodes being tuned to a desired crystal harmonic frequency in this range.

3. The oscillation generator recited in claim 2 in which the associated circuit elements include circuit means for annulling the static or shunt, capacitance, of the crystal.

4. An oscillation generator comprising an amplifier, a pair of input and a pair of output electrodes therefor, a tuned circuit connected directly between said output electrodes, and a phase reversing transformer, its primary winding being constituted substantially by the inductance of said tuned circuit and its secondary winding and a piezoelectric crystal being connected in series between said input electrodes.

5. The circuit recited in claim 4 with the addition of a capacitance in said series circuit adapted to annul the effective series inductance consequent on the use of a non-unity coupled transformer, said transformer being non-unity coupled.

6. An oscillation generator comprising in combination, an amplifier, a pair of input and a pair of output electrodes therefor, a tuned circuit connected directly between said output electrodes, a phase reversing transformer having its primary winding constituted by the inductance of said tuned circuit, and a network comprising a capacitance bridge connected between the secondary winding of said transformer and said input electrodes, said bridge comprising at least one piezo-

electric crystal and the crystals being in such relation to the capacitative elements thereof as to tend to annul the static capacitances of said crystals.

7. The oscillation generator recited in claim 6 in which said bridge is of the capacitance lattice network type with a piezoelectric crystal effectively in at least one of the series arms thereof.

8. The oscillation generator recited in claim 6 in which said bridge is of the capacitance lattice network type with a piezoelectric crystal in one series arm thereof and a balancing capacitance in the other series arm thereof.

9. The oscillation generator recited in claim 6 in which said bridge is of the capacitance lattice network type with a piezoelectric crystal effectively in at least one of the two series arms thereof, and additional reactive means on either side of said bridge and adapted to cooperate with the equivalent shunt capacitance elements of said bridge, and, in the instance of the portion of the means on the transformer side of the bridge, with the simulated self-inductance of the primary winding of the transformer, to effectively tune the output and input circuits of said amplifier to the oscillation frequency.

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