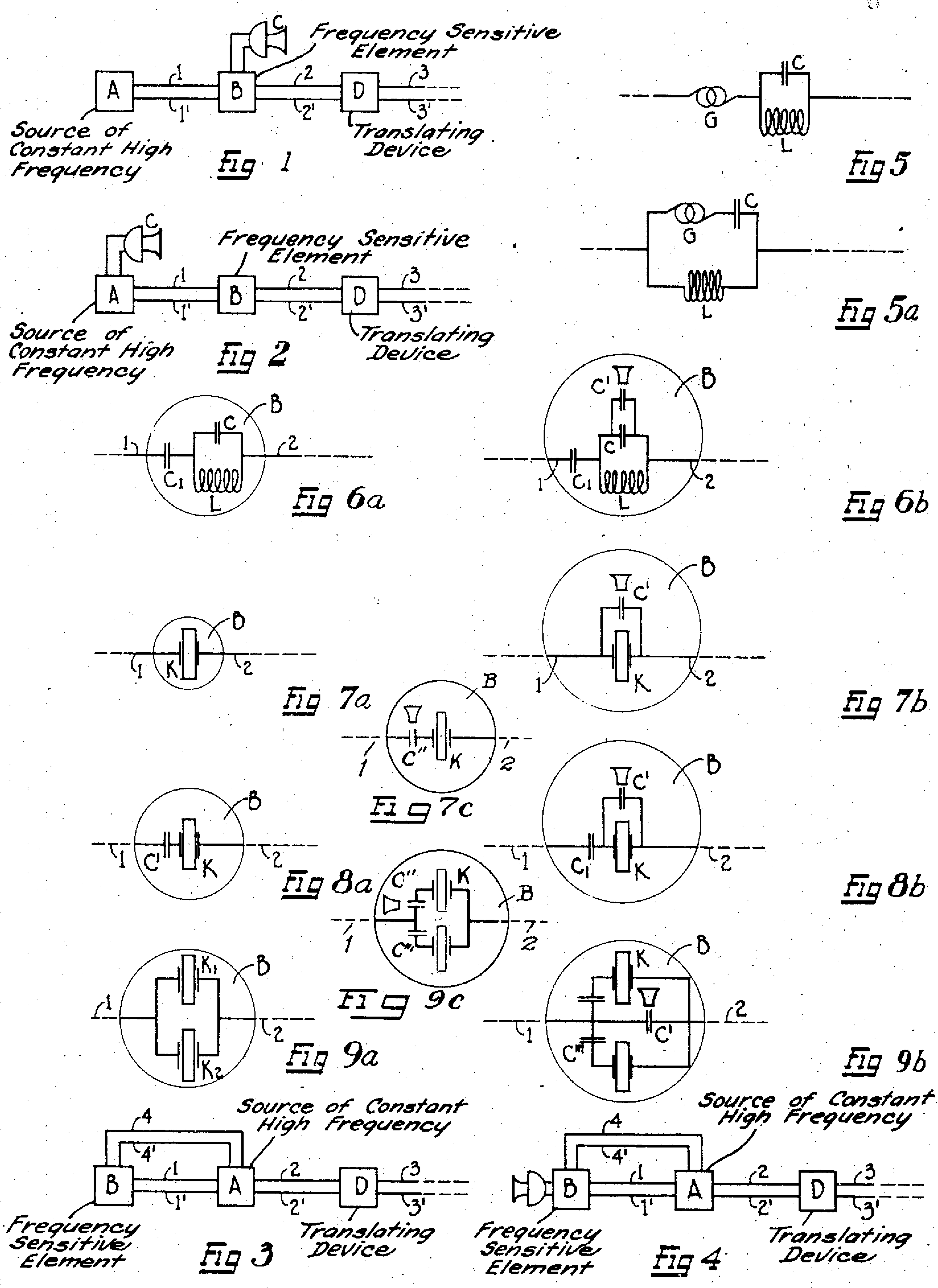
Nov. 10, 1942. J. S. STONE 2,301,828

FREQUENCY SENSITIVE ELEMENTS

Filed April 12, 1940 4 Sheets-Sheet 1



A = Source of Constant H.F.
B = Frequency Sensitive Element
C = Condenser Transmitter
D = Translating Device

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FREQUENCY SENSITIVE ELEMENTS

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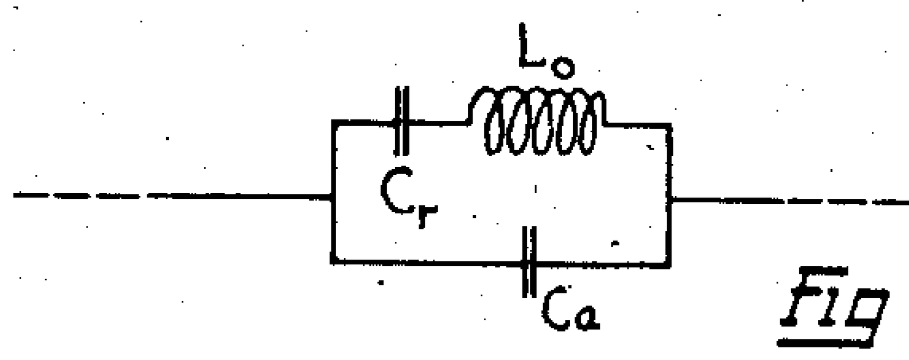

Fig 10

$C_rL_o = \frac{1}{\omega_o}$, $C_a = 162C_r$

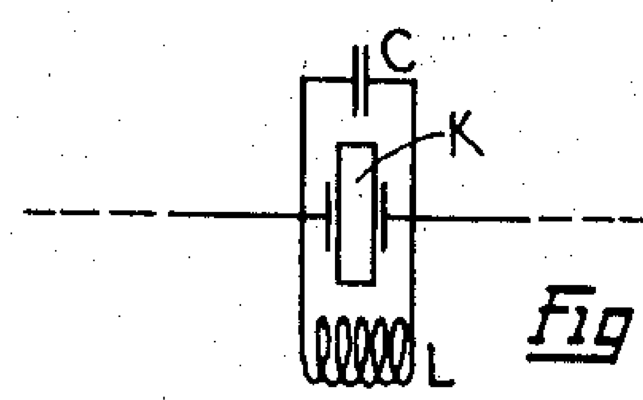

Fig 11a

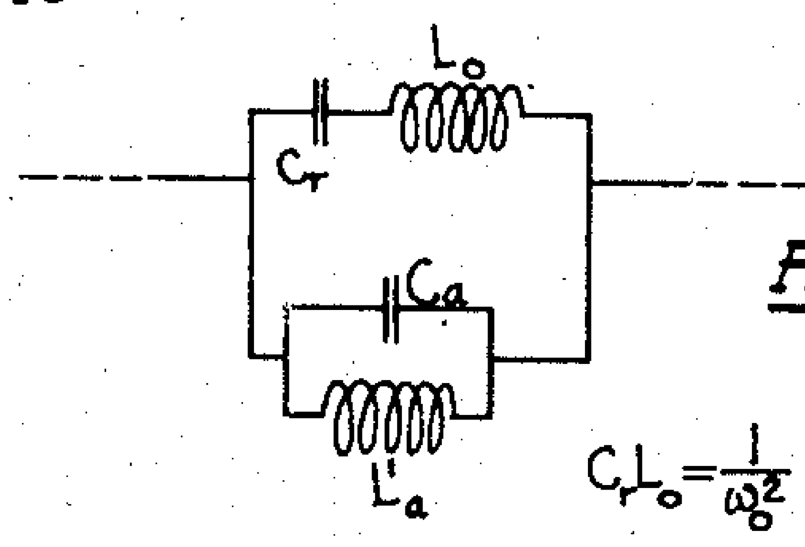

Fig 11

$C_rL_o = \frac{1}{\omega_o^2}$, $C_aL'_a = \frac{1}{\omega_o^2}$

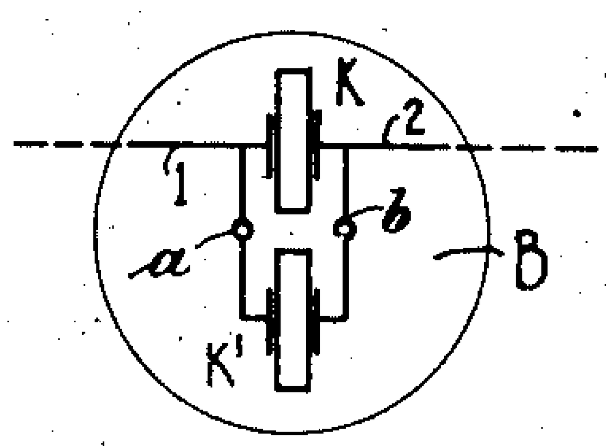

Fig 12a

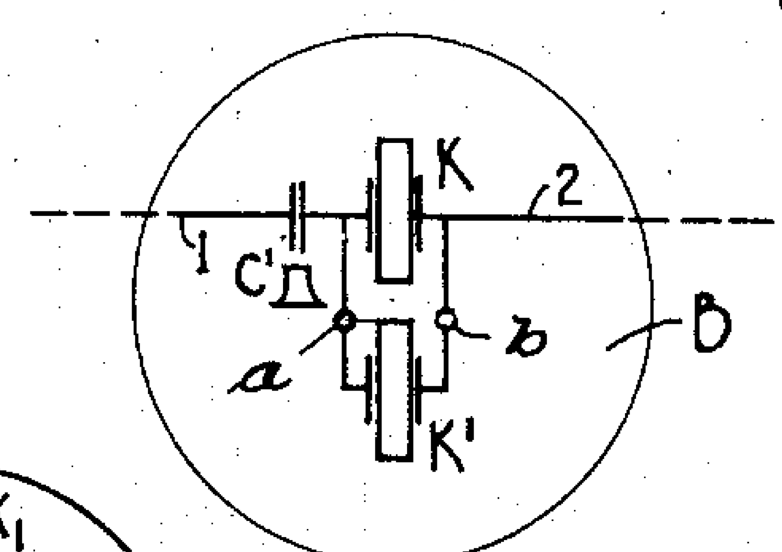

Fig 12b

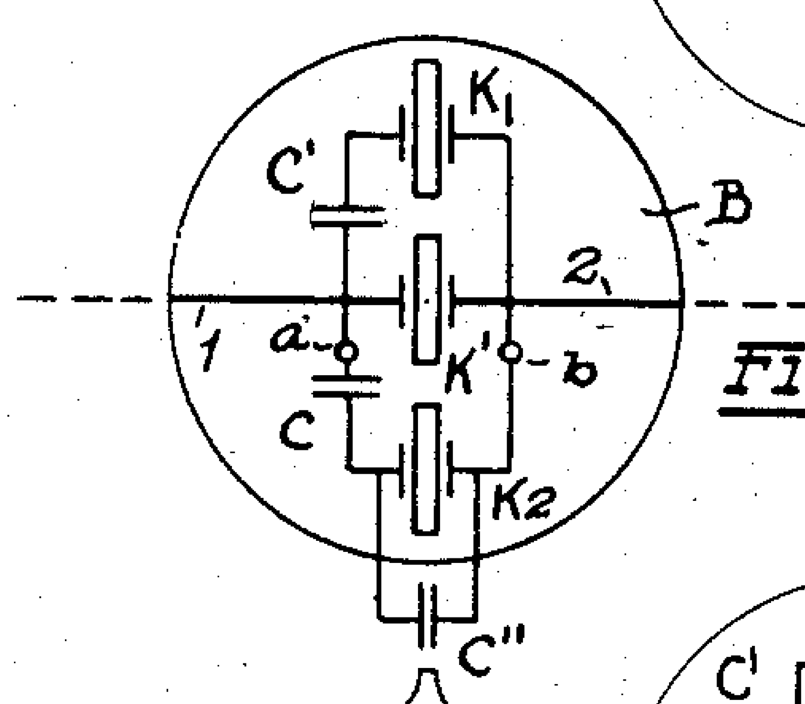

Fig. 13c

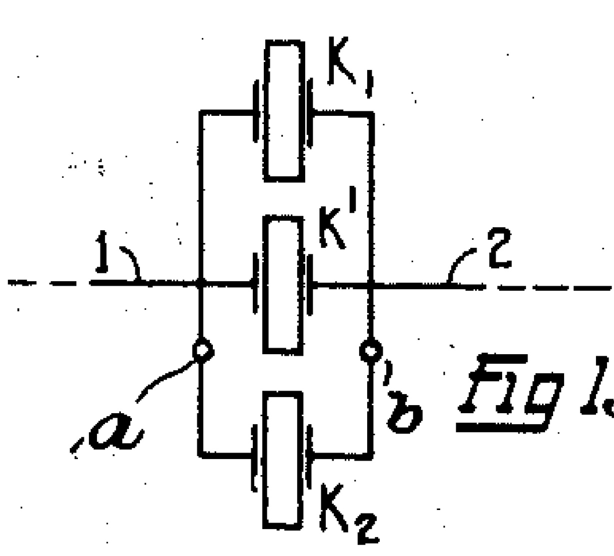

Fig 13a

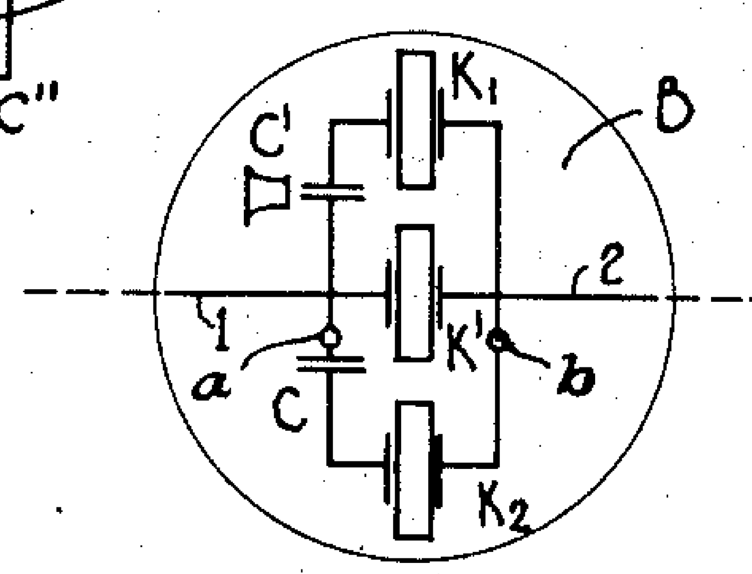

Fig 13b

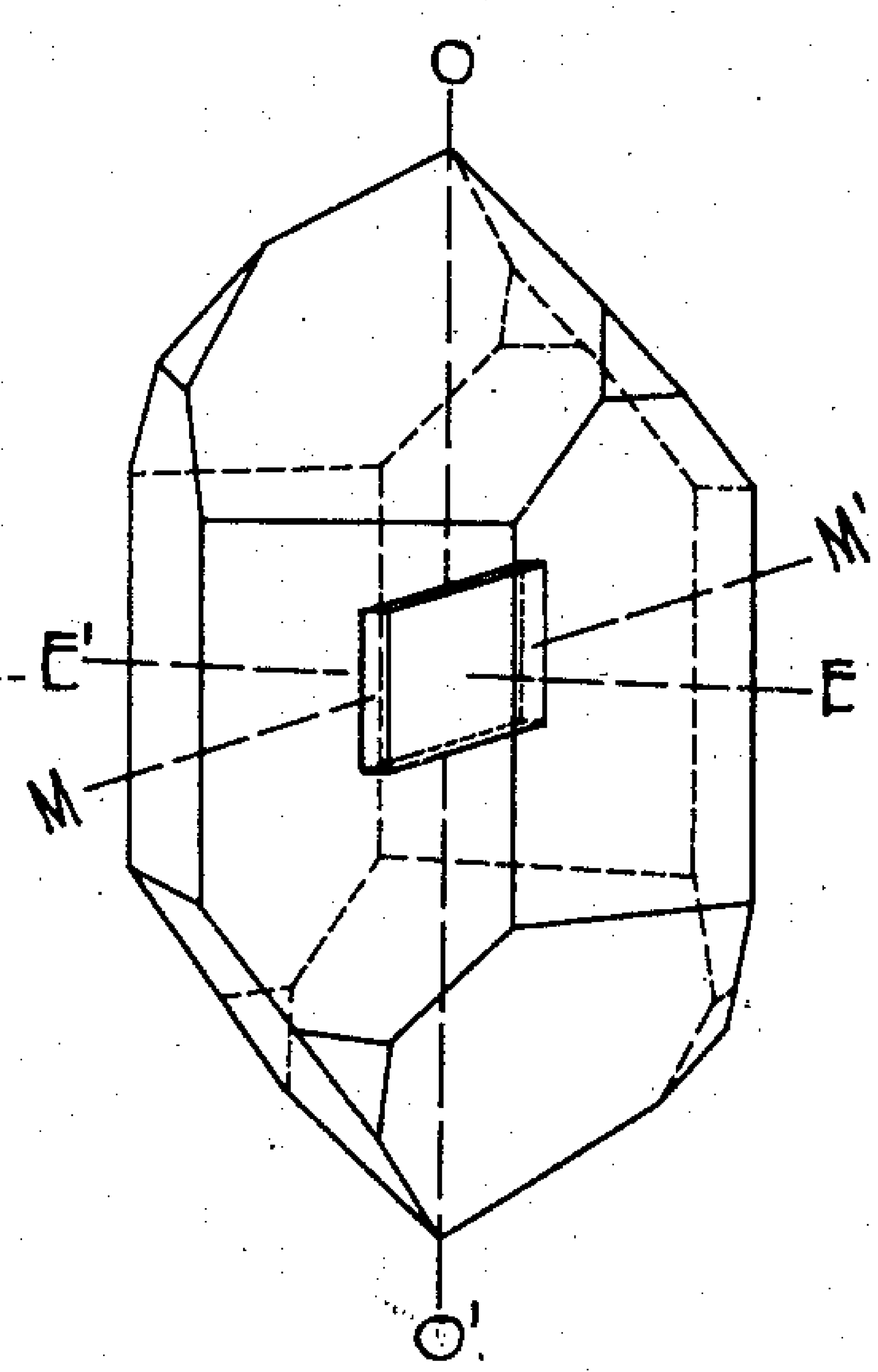

Fig 17

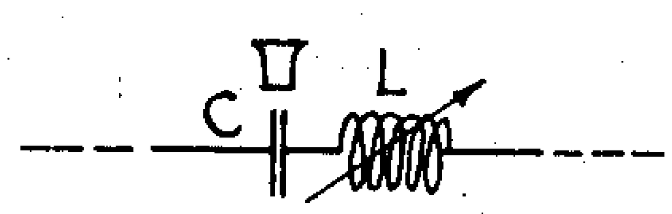

Fig 14

$C' = \frac{\omega_o^2}{\omega_o^2 - \omega^2} C$

where $\omega_o^2 = \frac{1}{CL}$

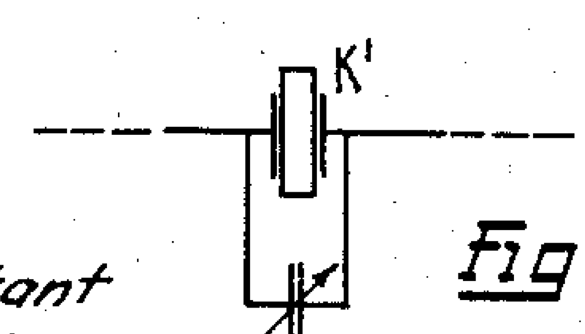

Fig 15

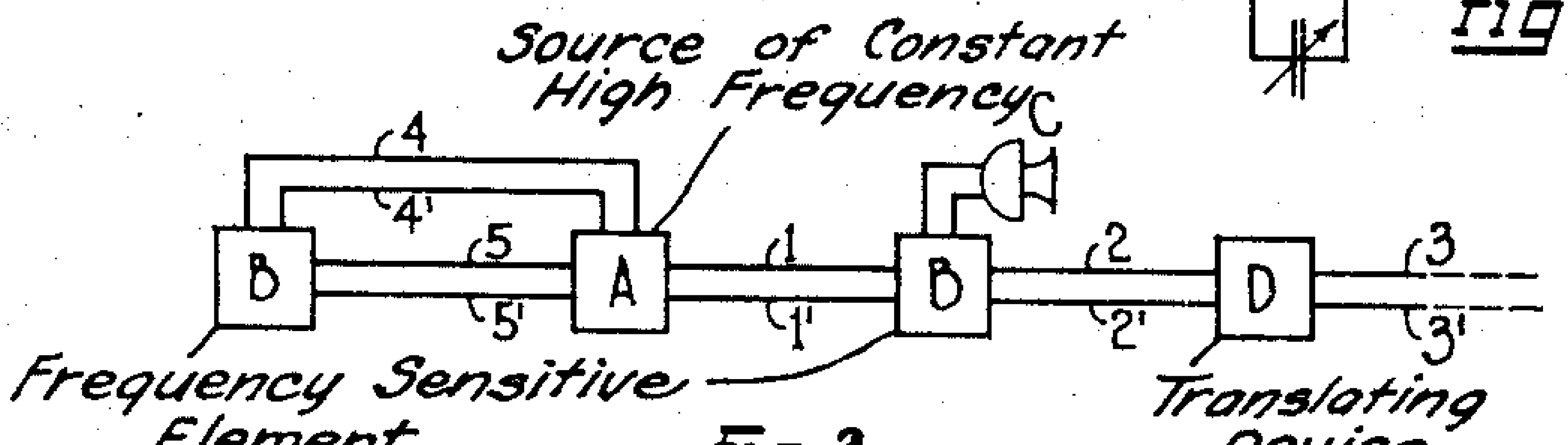

Fig 3a

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FREQUENCY SENSITIVE ELEMENTS

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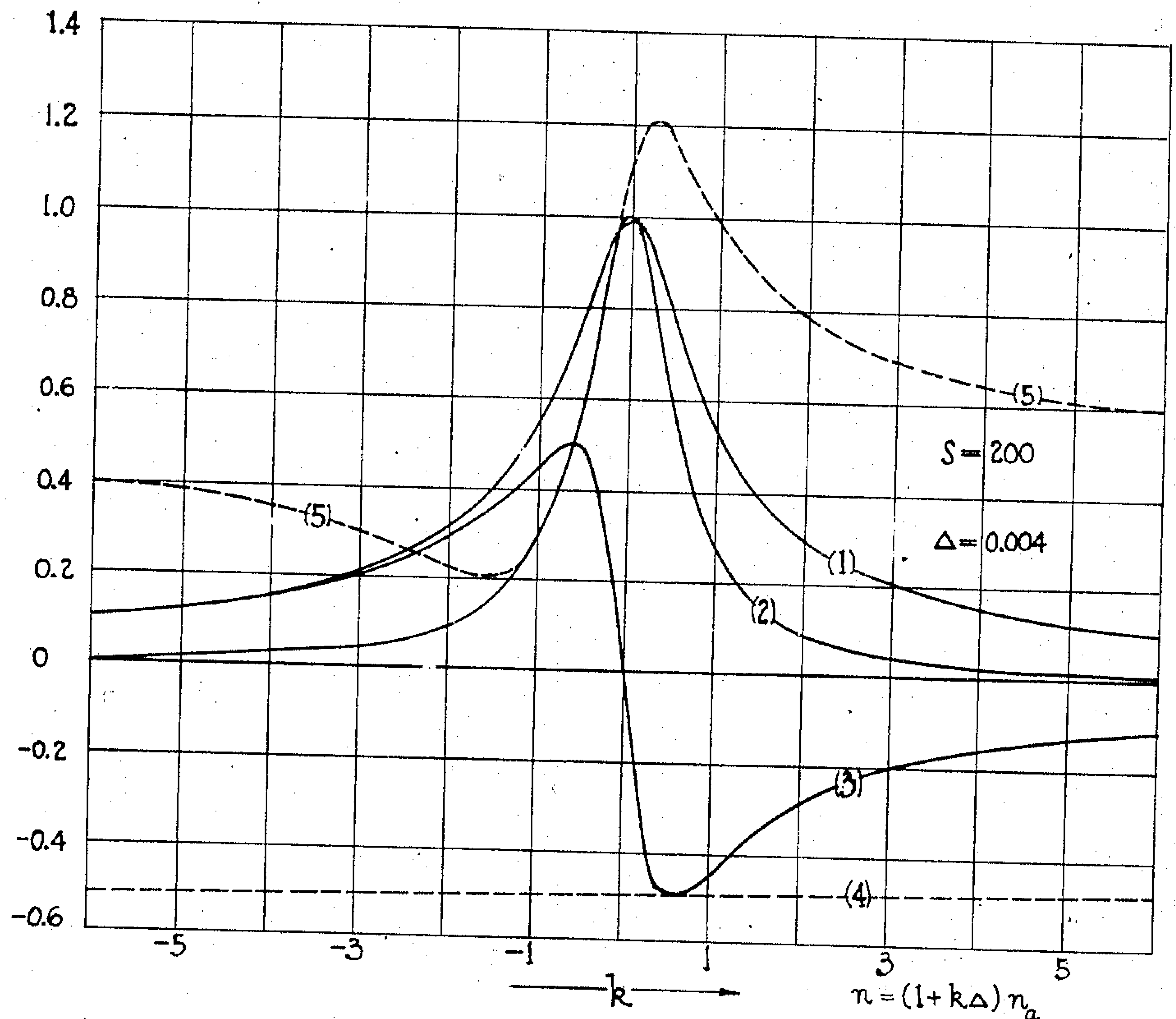

Fig 18

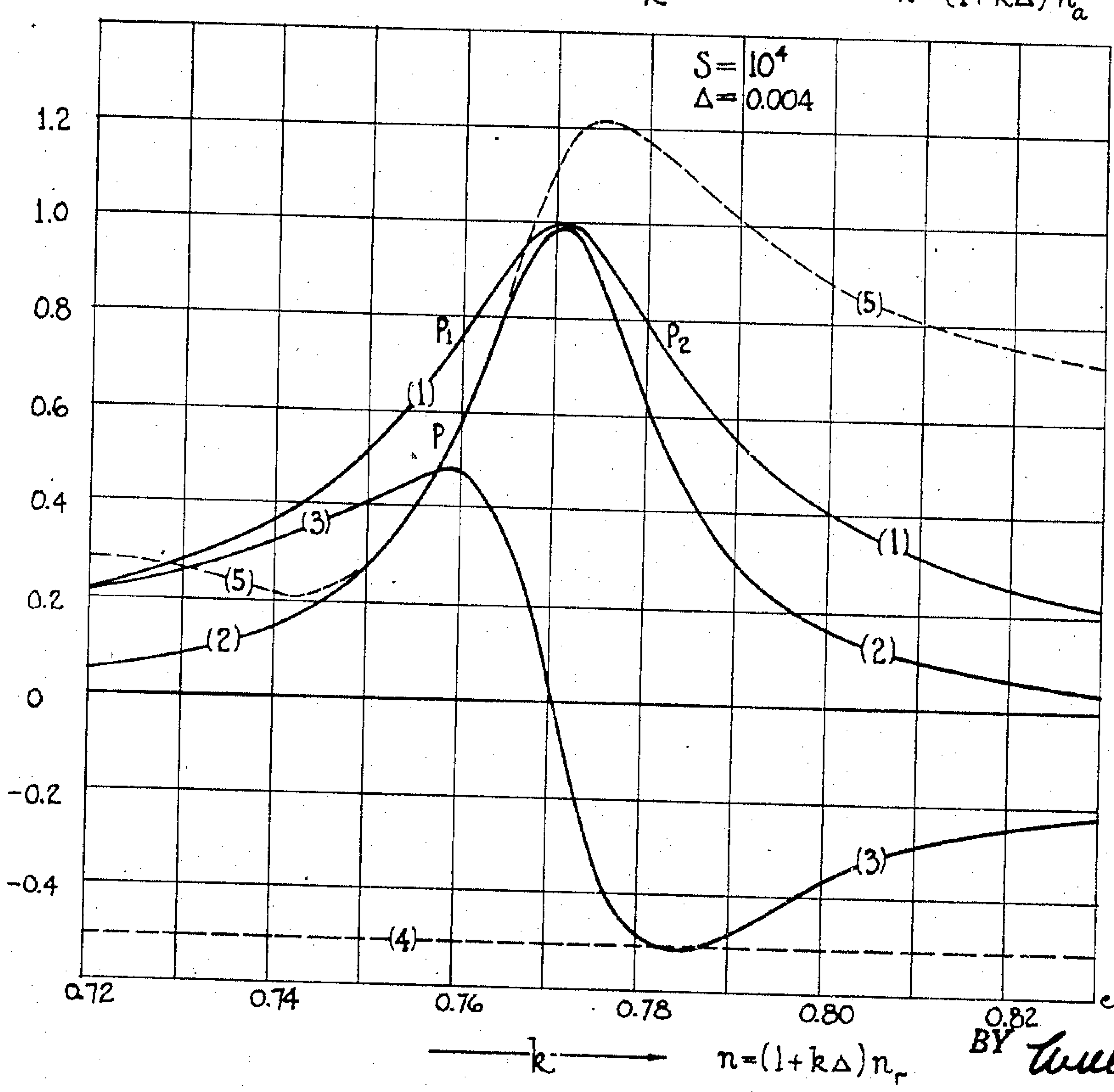

Fig 19

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FREQUENCY SENSITIVE ELEMENTS

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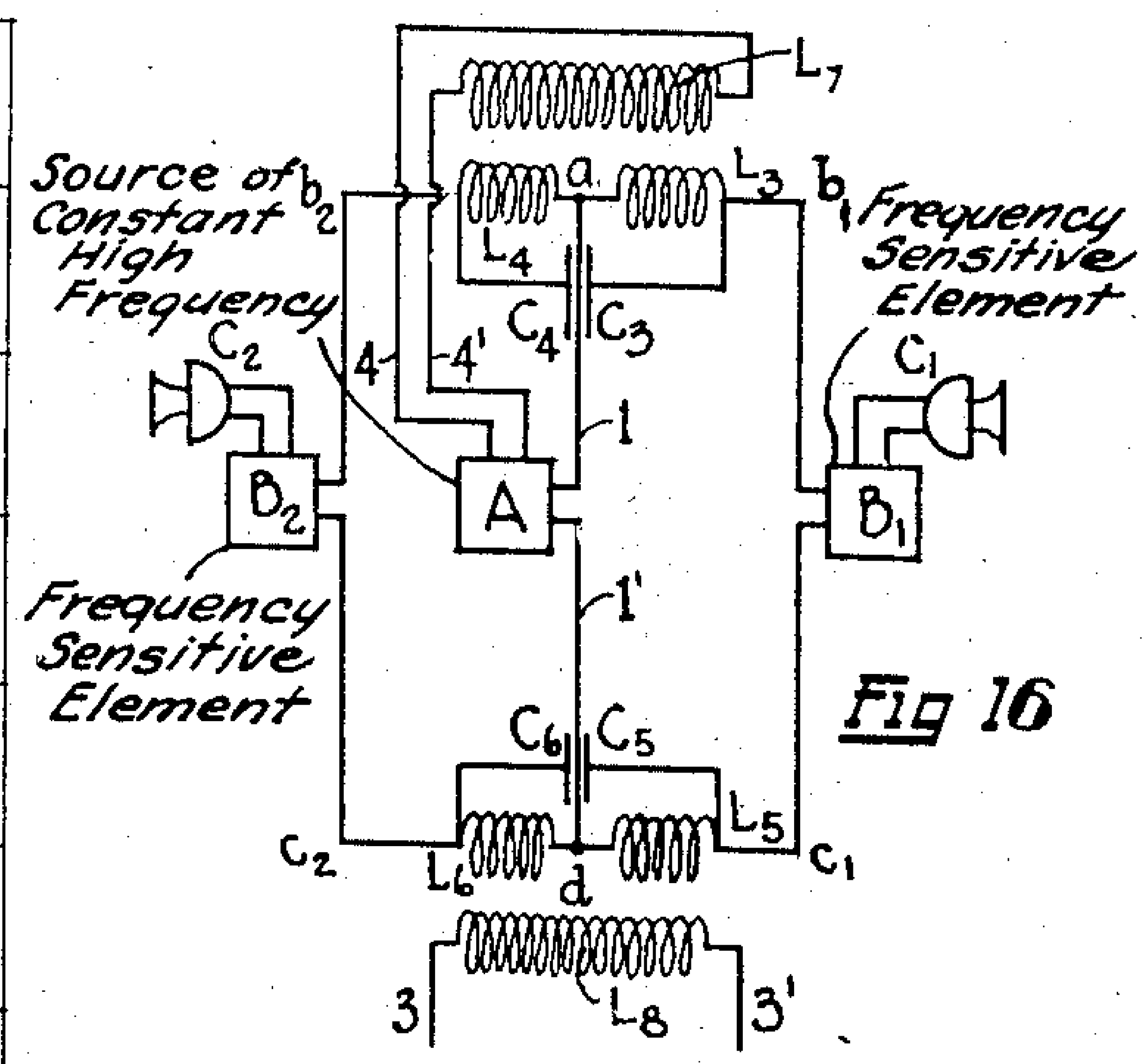

Fig 16

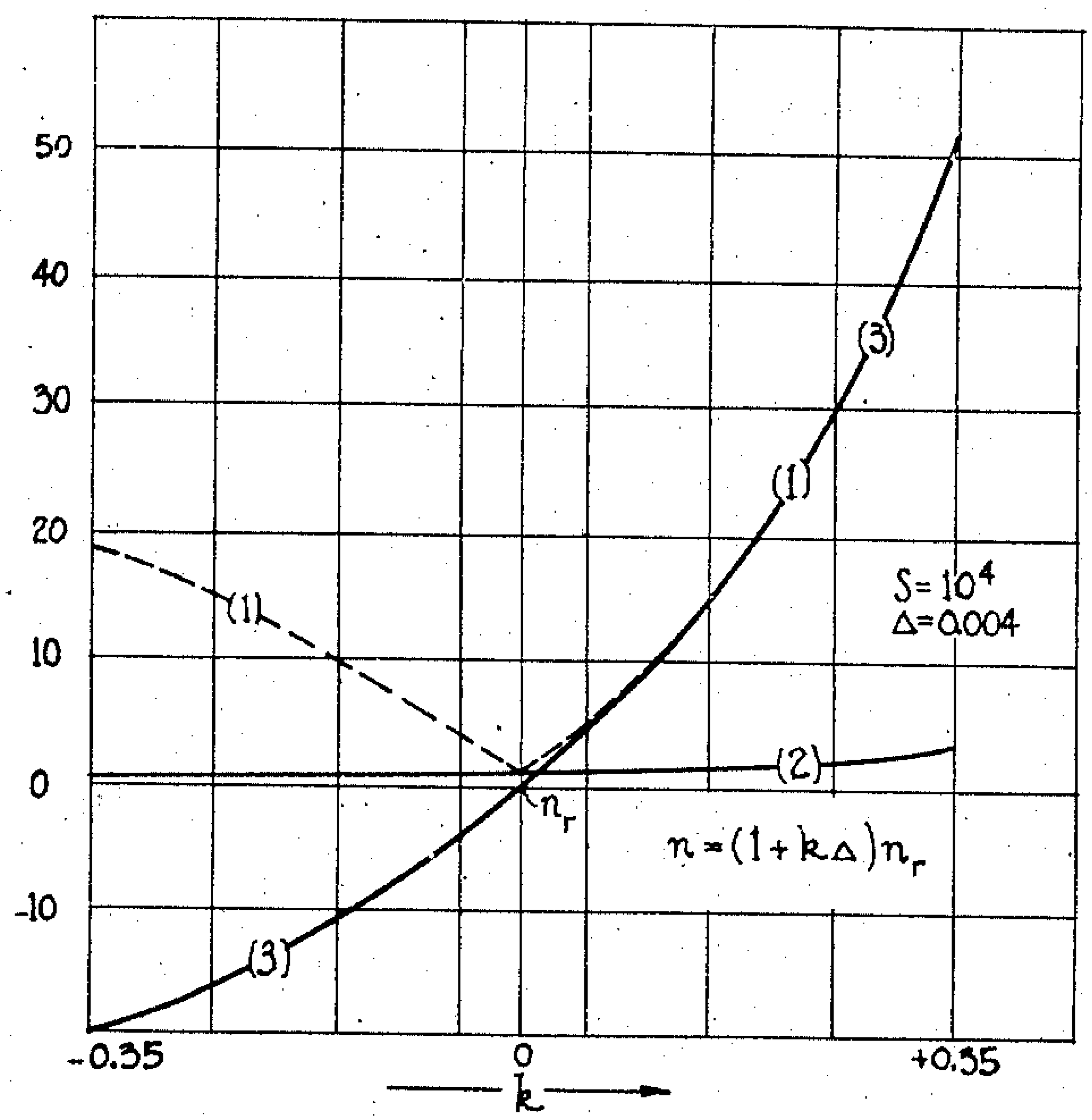

Fig 20

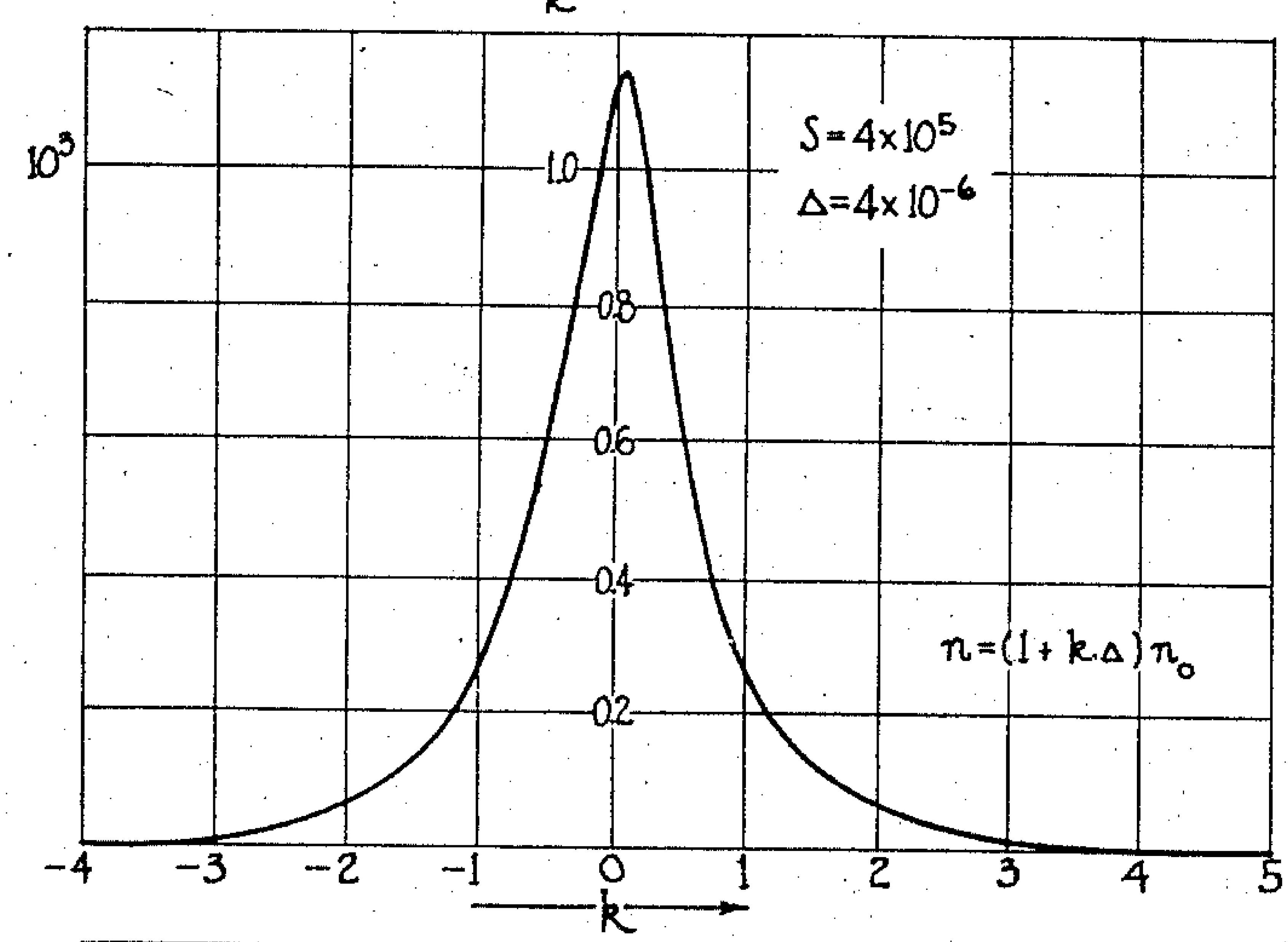

Fig 21

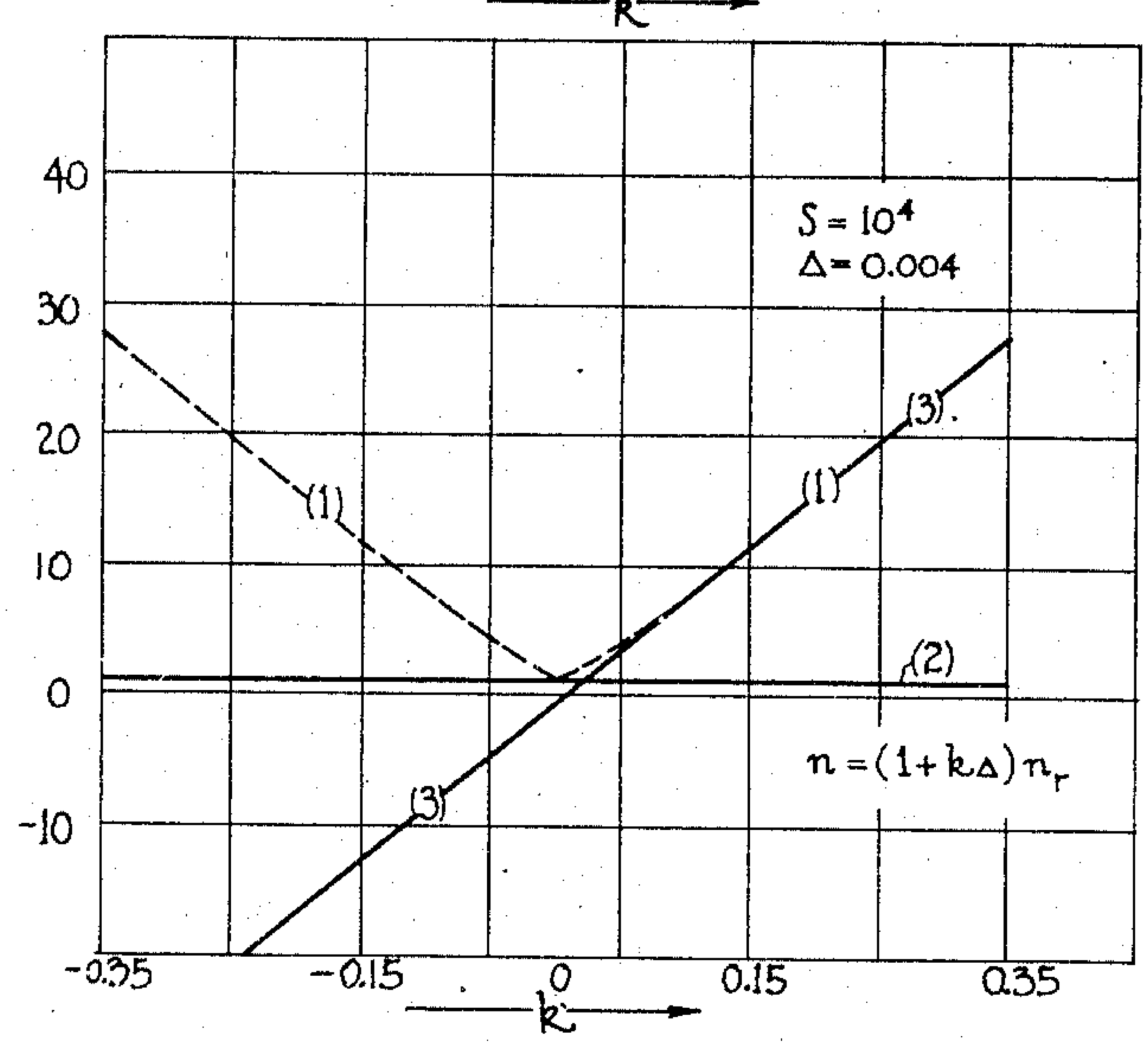

Fig 22

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Patented Nov. 10, 1942

2,301,828

UNITED STATES PATENT OFFICE

2,301,828

FREQUENCY SENSITIVE ELEMENTS

John Stone Stone, San Diego, Calif., assignor to American Telephone and Telegraph Company, a corporation of New York

Application April 12, 1940, Serial No. 329,380

14 Claims. (Cl. 179—171.5)

An object of my invention is to produce improved frequency sensitive elements.

Another object of this invention is to produce an amplifying modulator. Another object of my invention is to produce a constant frequency oscillator.

These and various other objects of my invention will be made apparent in the following specification and claims, taken with the accompanying drawings in which I have illustrated a limited number of specific embodiments of the invention.

The term "frequency sensitive elements" as used in this specification signifies a device which has an impedance-frequency curve whose slope at a point of inflection is very steep. Thus if Z be the impedance of the device at a point of inflection corresponding to the frequency n, and if n_o be the resonance or the antiresonance frequency of the device nearest to n, then

$$\frac{dZ}{d(n/n_o)}$$

has been taken as the measure of the steepness of the impedance curve at said point of inflection.

In United States Patent No. 2,232,891 to J. S. Stone, February 25, 1941, the simple antiresonant circuit of Figure 5 was disclosed as the frequency sensitive element in an amplifying modulator and the mode of operation of the frequency sensitive element in the operation of modulating a high frequency current was there fully disclosed.

The present invention will be best understood by having reference to the accompanying drawings. Figures 1, 2, 3, 3*a* and 4 are highly schematic diagrams illustrative of some of the uses to which frequency sensitive elements may be put.

Figure 5 is a circuit diagram of a simple antiresonant circuit. Fig. 5*a* is a circuit diagram used to distinguish between the resonant and antiresonant circuit. Figs. 6*a*, 7*a*, 8*a*, 9*a*, 12*a* and 13*a* illustrate examples of frequency sensitive elements, while Figs. 6*b*, 7*b*, 7*c*, 8*b*, 9*b*, 9*c*, 12*b*, 13*b*, 13*c* illustrate, respectively, these frequency sensitive elements equipped with condenser telephone transmitters adapted to fluctuate the critical frequency of the element. Fig. 10 is a circuit diagram illustrating the circuit equivalent of a piezo electric crystal when vibrating to frequencies in the neighborhood of its resonance frequency n_r and of its antiresonance frequency n_a. Fig. 11 is a circuit diagram used to explain the function and mode of operation of the crystal K' in the organizations of Figs. 12*a*, 12*b*, 13*a* and 13*b*. Fig. 14 is a circuit diagram illustrating how a condenser telephone transmitter may have its apparent capacity magnified. Fig. 15 illustrates how a crystal may have its antiresonance point lowered. Fig. 16 illustrates a feed-back arrangement between the modulator and constant frequency source of energy, and also an arrangement whereby, if desired, the carrier frequency may be suppressed in the output or utilization circuit 3, 3'. Fig. 17 illustrates the orientation of a crystal section in a quartz crystal. The crystal section here shown is known as the Curie cut and is used as the specific crystal of reference in this specification. Fig. 18 is a set of curves illustrating more specifically the mode of operation of the organization of Figs. 6*a* and 6*b*. Fig. 19 is a set of curves illustrating more specifically the mode of operation of the organization of Figs. 8*a* and 8*b*. Fig. 20 is a set of curves illustrating one mode of operation of the devices of Figs. 7*a* and 7*b*, and the characteristic curves of one of our simpler crystals at and in the immediate vicinity of its resonant frequency. Fig. 21 is a curve illustrating the mode of operation of the device of Figs. 9*a* and 9*b*. Fig. 22 is a set of curves illustrating the mode of operation of Figs. 12*a* and 12*b*.

In Figs. 1, 2, 3, 3*a* and 4 the device A is a source of constant and high frequency electromotive force, B is a frequency sensitive element, C (which does not occur in Fig. 3) is a condenser telephone transmitter, and D is any suitable transforming or translating device adapted to pass the energy of the high frequency current on to the utilization circuit 3, 3', either as an amplitude modulated high frequency current or as an audio frequency current depending on the nature of D. 1, 1', 2, 2', 3, 3', 4, 4' are conductors.

In Fig. 1 the frequency elements are combined to form a modulator circuit in which the condenser transmitter C controls the frequency sensitive element B. Fig. 2 is a similar circuit in which the transmitter C controls the source A. In Fig. 3 the source A and frequency sensitive element B are so connected that the frequency of the source A is governed by the natural period of the frequency sensitive element B. In Fig. 3*a* this combination is used to supply the carrier frequency to a second frequency sensitive element B which functions as a modulator, the modulator in turn being controlled by the condenser transmitter C. In Fig. 4 a single frequency sensitive element B serves both as a stabilizer for the frequency of the source A and as a modulating element under the control of the condenser transmitter C.

The frequency sensitive element B may take the form shown in Fig. 5, which illustrates an antiresonant circuit, the behavior of which circuit is typical of the types of frequency sensitive elements disclosed in this specification. In Fig. 5 C is an air-electric condenser, L is an air-cored inductance coil, and G is a source of alternating E. M. F., with respect to which the condenser C and coil L are in parallel with each other. This is the criterion which distinguishes the antiresonant loop circuit of Fig. 5 from the resonant loop of Fig. 5*a*, which latter is the same as the organization of Fig. 5 except that its source of high frequency E. M. F. G, its condenser C and its coil L are all in series with respect to each other.

Fig. 6*a* illustrates how the antiresonant frequency sensitive element of Fig. 5 may be improved so that its rate of change of impedance with respect to frequency at a point of inflection in its impedance-frequency curve may be increased. This improvement is effected by placing the condenser C_1 in series with the antiresonant element of Fig. 5. This condenser must have a predetermined capacity as will be now explained by having reference to Fig. 18.

In Fig. 18, curves 1, 2 and 3 give, respectively, the mode of variation of the impedance, effective resistance, and effective reactance of the antiresonant loops of Fig. 5 and Fig. 6*a* to variations of the relative frequency of the loop circuit and source G when the selectivity S of the loop is 200 and its resistance R=10 ohms. This value of the selectivity of the antiresonant loop is what may be termed the maximum inherent selectivity of a high frequency resonant or antiresonant circuit. It is the selectivity attained by the exercise of the ordinary precautions used in designing the coils and condensers for high frequency resonant or tuning circuits. Lower selectivities may be secured by the purposeful addition of a resistance to the circuit, but higher selectivities up to about 400 can be secured only through the exercise of extraordinary precautions and skill. The ordinates are such that they read in ohms when m ltiplied by 4×10^5 or RS^2, where R is the resistance of the loop.

When the abscissae are multiplied by 4×10^{-3} they give $k\Delta$ in the expression $n=(1+k\Delta)n_a$, where n is the impressed frequency and n_a is the antiresonant frequency. The dotted line curve 4 is the reactance of the condenser C_1, while the dotted line curve 5 illustrates the mode of variation of the impedance of the entire organization of Fig. 6*a* (including elements C, L, and C_1) to variations of the impressed frequency. A comparison of this latter curve with curve 1 shows by simple inspection how much more frequency sensitive between abscissae −1 and 0 the organization of Fig. 6*a* is as compared with that of Fig. 5. The effect of the negative reactance of condenser C_1 is to neutralize the effective positive reactance of the loop at its maximum value 2×10^4 ohms. The value of the reactance of the condenser is therefore, sensibly -2×10^4 ohms at the antiresonant frequency n_a, or

$$C_1=\frac{10}{2\omega_a}=\frac{1}{\pi n_a S^2}$$

where ω_a is the periodicity of antiresonance and S is the selectivity. Thus when $S=200$ and $n_a=10^6$, $C_1=7.958\times10^{-12}$ farads.

In the foregoing discussion the frequency sensitive element is an antiresonant loop. All the remaining improved frequency sensitive elements depend upon the electro-mechanical resonances of piezoelectric crystal sections such as are commonly used in controlling the frequency of radio transmitters. These piezoelectric crystal sections are variously cut from more than one variety of crystal, and this invention is not confined to any particular cut or variety of crystal, but, in order that the disclosure may be as clear as possible, a particular cut, known as the Curie or perpendicular cut of a quartz crystal illustrated in Fig. 17 will be selected for exemplary use in this specification. We shall further assume that the dimensions of the section are given by $l_m=1$, $l_o=0.84$, and $l_e=0.05$, where l_m is the length parallel to the mechanical axis, l_o is the length parallel to the optical axis, and l_e is the length parallel to the electric axis. These lengths are all measured in centimeters. It will be, moreover, assumed that the electrodes are chemically deposited on the crystal surface.

Such a crystal is shown, for example, in Figs. 7*a* and 7*b*. It will have a fundamental resonant frequency of 2.5×10^5 cycles and a fundamental antiresonant frequency of 2.5007704×10^5 cycles. Besides this fundamental pair of frequencies these crystal sections have a large number of higher or harmonic pairs of frequencies which are available for the purposes of this invention, but, in the interest of clarity, only the fundamental pair of frequencies will be used in the illustrations of this specification. Considering how the circuit equivalent of this crystal section, as shown in Fig. 10, the real or electrostatic capacity of the crystal $C_a=6.7588\times10^{-12}$ farads, the resonance capacity $C_r=4.1721\times10^{-14}$ farads, the inductance $L_r=9.7142\times10^{-4}$ henrys. If the crystal surfaces are ground and polished in air at atmospheric pressures, the selectivity S of the branch C_rL_r is about 10^4, while if these surfaces be ground and polished in vacuum, then the selectivity S may be as high as 4×10^5. The effective resistance of the branch C_rL_r may be determined by the expression

$$R=\frac{1}{C_r\omega_r S}$$

Thus in the crystal of selectivity $S=10^4$, $R=1.5259\times10^3$ ohms, while in the case of the crystal of selectivity $S=4\times10^5$, $R=38.1476$ ohms. These constants sufficiently define the two sample crystals used as illustrative examplars in this specification.

In Fig. 19, curves 1, 2, and 3 give the mode of variation, respectively, of the impedance, the effective resistance, and the effective reactance of the sample crystals for variations of the frequency in the neighborhood of the antiresonant frequency which in this diagram occurs at the abscissa designated 0.77. The characteristic curves of the two sample crystals are not identical but cannot be distinguished when drawn to the scale of Fig. 19. When these curves are to be used to interpret the behavior of the crystal whose selectivity is 10^4, the ordinates may be multiplied by 5.7786×10^6 and will then read in ohms. When used to interpret the crystal of selectivity 4×10^5, the ordinates will read ohms when multiplied by 2.3114×10^8.

The abscissae are the same for both crystals. The frequencies are expressed in terms of the resonance frequency n_r by the equation $n=(1+k\Delta n_r$, where $\Delta=0.004$, or $n=n_r+0.004\ kn_r$. Thus the frequency interval between abscissa $k=0.77$ and $k=0.78=0.00004n_r$ cycles. Since the resonance frequency of the crystal is 250,000, each such interval comprises 10 cycles.

Curve 3 discloses for the first time, the useful though theoretically unimportant fact that the maximum value of the effective positive reactance P of the crystal occurs at or approximately at the same frequency as does the point of inflection P_1 of its effective impedance and that the maximum value of the effective reactance is, at least approximately, half the maximum effective impedance of the crystal (at abscissa 0.77) or

$$X'_{max}=\frac{RS^2}{2\rho^2}\text{ (approx.)}$$

An important application of these disclosures will be described later in this specification.

In Fig. 7*a* is shown a frequency sensitive element consisting of a simple crystal adapted to be used at B in Figs. 2, 3 and 3*a*, in each of which an element B without associated condenser transmitter is shown. In Fig. 7*b* is shown how the antiresonant frequency of a simple crystal may be fluctuated at will through the intermediary of a condenser telephone transmitter C′ in series with the element. Its resonant frequency may also be fluctuated at will through the intermediary of the condenser telephone transmitter in series with the crystal as shown in Fig. 7*c*. These alternative combinations of a simple crystal and a condenser telephone transmitter are adapted to be used at B in Figs. 1, 4 and 3*a*, each of which shows an element B having a condenser transmitter associated therewith. When the antiresonant frequency is fluctuated by the transmitter C′, then the frequency of the constant frequency source A is adjusted to approximate one or the other of the frequencies corresponding to the points of inflection P_1 or P_2 on the impedance frequency curve of the crystal at and near its antiresonant frequency. This impedance-frequency curve is curve 1 of Fig. 19.

When, on the other hand, the resonant frequency of the crystal is fluctuated by the series transmitter C″ as shown in Fig. 7*c*, then the constant frequency source A is adjusted to approximate the frequency corresponding to the point of inflection on the impedance-frequency curve of the crystal at or near its resonant frequency n_r. This impedance-frequency curve is the dotted curve 1 of Fig. 20. The frequency of the source in this case may also be adjusted to correspond to such a value as k=.15, .20 or .25, and if the distortion due to the non-linearity of the impedance curve be more than is tolerable, then some of the known methods of diminishing or sensibly eliminating it can be used.

In Fig. 8*a* is illustrated an improved frequency sensitive element in which the effective inductance reactance of the crystal (which as may be seen from curve 3 of Fig. 19 reaches its maximum value at about the point of inflection P_1 of the impedance curve 1) is neutralized by the negative reactance of the condenser C_1. The reactance of condenser C_1 is shown in the dotted curve 4 of Fig. 19. The dotted curve 5 shows the impedance of the combination of crystal K and condenser C_1. This latter curve illustrates that the combination of Fig. 8*a* is markedly more frequency sensitive at or near the point of inflection P of its impedance curve than is the crystal alone at the points P_1 and P_2 of inflection of its impedance curve (curve 1, Fig. 19). Fig. 8*b* shows how the impedance of the combination comprising crystal K and capacity C_1 may be fluctuated by a condenser transmitter C′. As in the case of Fig. 7*b* the modulator frequency should be adjusted to the point of inflection P where the combination is highly frequency sensitive.

Fig. 9*a* illustrates an improved frequency-sensitive combination in which an antiresonant element is secured by placing two predeterminedly detuned crystals in parallel. In this combination the resonance frequency n_{r1} of K_1 is so relatively detuned with respect to the resonance frequency n_{r2} of K_2 that at an intermediate frequency n_a the effective reactance of the two crystals shall be equal but opposite in sign. Under these circumstances n_a becomes a pronounced antiresonant frequency. For example, referring to Fig. 19, the point of positive maximum reactance of crystal K_1, if constructed to resonate at the proper frequency, might occur at a frequency corresponding approximately to the ordinate 0.758 (point P on curve 3) and the maximum negative reactance might occur at approximately the ordinate 0.784. Then if the crystal K_2 is constructed to have maximum negative reactance at 0.758, the reactances of the two crystals will oppose each other at this point.

In Fig. 21 is shown the impedance frequency characteristic of such an organization when the selectivities of the crystals are $S=4\times10^5$, their resistances are 38.1476 and the interval of detuning is $10^{-5}\,n_o$ cycles. The delicate adjustment of the detuning of the two crystals of the organization of Fig. 9*a* may best be effected by means of an adjustable condenser connected in series with one of the crystals. Such a condenser is shown at C‴ in Fig. 9*b*. Fig. 9*b* illustrates how the impedance of such an organization as that of Fig. 9*a* may be caused to fluctuate in accordance with the same waves of speech or music through the association of a condenser telephone transmitter connected in parallel with crystal K as shown at C′ in Fig. 9*b*, or as shown in Fig. 9*c* the condenser microphone might be in series.

The theory of the improvements in frequency sensitive elements composed of combinations of crystals will be greatly facilitated by a consideration of the circuit equivalent of a crystal, shown in Fig. 10, for frequencies in the neighborhood of its primary resonant and antiresonant frequencies and the mathematical expressions therefrom deduced for the behavior of the crystal throughout this range of frequencies.

From the circuit equivalent of the crystal as illustrated in Fig. 10, we deduce that the effective or virtual resistance of the crystal is

$$R'=\frac{RS^2}{\rho^2}\frac{n_r^2}{n^2}\frac{1}{1+S^2\left(\alpha-\frac{1}{\rho}\frac{n_r}{n}\right)} \qquad (1)$$

that the virtual reactance of the crystal is

$$X'=-\frac{RS}{\rho}\frac{n_r}{n}\frac{1+S^2\alpha\left(\alpha-\frac{1}{\rho}\frac{n_r}{n}\right)}{1+S^2\left(\alpha-\frac{1}{\rho}\frac{n_r}{n}\right)} \qquad (2)$$

and that therefore its virtual or effective impedance is,

$$Z'=\sqrt{(R')^2+(X')^2} \qquad (3)$$

In these expressions, R is the effective resistance of the branch C_rL_o of Fig. 10, S is the selectivity of the crystal or circuit equivalent, n is the impressed frequency, n_r is the resonance frequency of the crystal which is sensibly the same as that of the branch C_rL_o of Fig. 10. Because of the high selectivity of the crystal we have

$$n_r^2=\frac{1}{4\pi^2 C_r L_o} \quad (4)$$

ρ is a constant to be determined and α is the frequency function of the branch C_rL_o. It is defined by the expression

$$\alpha=\frac{n^2-n_r^2}{nn_r}=\frac{n}{n_r}-\frac{n_r}{n} \quad (5)$$

C_a is the real capacity between the electrodes and is therefore given by the expression

$$C_a=\frac{l_o l_m}{l_e}\frac{K}{4\pi}\frac{10^{-11}}{9}\text{ farads} \quad (6)$$

where K is the inductive capacity of quartz or 4.55, $l_o l_m$ is the area of the faces of the crystal section and also the area of its electrodes. $l_o l_m=0.84$. l_e is the thickness of the crystal section. $l_e=0.05$. This gives $C_a=6.759\times10^{-12}$ farads.

The antiresonant point is sensibly reached when

$$\alpha_a=\frac{1}{\rho}\frac{n_r}{n_a}$$

or by using the relationship of Equation 5

$$\frac{n_a}{n_r}-\frac{n_r}{n_a}=\frac{1}{\rho}\frac{n_r}{n_a}$$

or

$$\frac{1}{\rho}=\frac{n_a^2}{n_r^2}-1$$

Since these frequencies are readily determined we have an expression for ρ which in the case of the samplar crystal of this specification gives $\rho=162$.

For the antiresonance frequency, we have sensibly the expression

$$n_a^2=\frac{1}{4\pi^2}\frac{C_a+C_r}{LC_rC_a} \quad (7)$$

Therefore substituting the value given by Equation 4

$$\frac{n_a^2}{n_r^2}=1+\frac{C_r}{C_a}=1+\frac{1}{\rho}$$

or

$$C_r=\frac{1}{\rho}C_a \quad (8)$$

In the case of our samplar crystal this gives $C_r=4.172\times10^{-14}$ farads. We have

$$L=\frac{1}{4\pi^2 n_r^2 C_r}$$

which gives $L=9.714$ henrys for our samplar crystal for which resonance frequency $n_r=2.5000\times10^5$ and the antiresonant frequency $n_a=2.5077\times10^5$.

By definition

$$S=\frac{1}{2\pi n_r C_r R}$$

therefore

$$R=\frac{1}{2\pi n_r C_r S}$$

From this formula we deduce that in the samplar whose selectivity is 10^4, the resistance $R=1.526$ ohms, while in the vacuum ground and polished crystal section whose selectivity is 4×10^5, the resistance $R=38.148$ ohms. It but remains to point out that the maximum value reached by the effective resistance R' of the crystal at antiresonance is 5.7786×10^6 when $S=10^4$ and 2.3114×10^8 when $S=4\times10^5$.

These formulae and data, together with the characteristic curves of the samplar crystals in Figs. 19 and 20 make the mode of functioning of these crystals as frequency sensitive elements very clear and explicit. They enable one not only to apprehend their mode of functioning but also to have a quantitative understanding thereof. Thus we see that the crystal is the equivalent of an extremely selective resonant branch C_rL shunted by a negative reactance, which, in the case of our samplar, is about −94,000 ohms in the vicinity of the resonant and antiresonant points of the crystal.

To, in effect, remove this capacity shunt from the crystal would imply an inductance shunt about the crystal of approximately 0.06 henry, as illustrated in Fig. 11 at L_a'. An inductance of such a magnitude can, of course, not be supplied by a coil in the case of the high frequency currents contemplated in this specification, but in practice the attempt has been made to meet this difficulty by shunting the crystal by a capacity C far greater than C_a and then effectively neutralizing this far greater capacity shunt of $C+C_a$ by a correspondingly smaller inductance. Such an organization is illustrated in Fig. 11*a*.

Thus if the added capacity C be $999C_a$, then the required inductance L will be approximately but 0.00006 henry. If the selectivity of the circuit CL comprising the added capacity and inductance be 200, the effective shunt on the crystal at its resonant point will be of the order of 5×10^5 ohms, while if great care be exercised in the construction of the added coil so that a selectivity of 400 is attained for the shunt loop, then the effective shunt on the crystal will be of the order of 2×10^6 ohms. Of course the formula for tuning the inductance and capacity is

$$L=\frac{1}{4\pi^2 n_r^2 (C+C_a)}$$

Since the inherent capacity reactance shunt is of the order of 10^5 it will be seen that no material advantage is secured by the device of Fig. 11*a* unless the coil is so carefully constructed as to secure the maximum available selectivity of 400 for the loop CL.

A better and simpler device for minimizing the effect of the capacity reactance shunt

$$\frac{1}{2\pi n_r C_a}$$

on the resonant branch C_rL of the crystal is illustrated in Fig. 12*a*. By this device the capacity reactance shunt is neutralized by the effective inductance of a second and detuned crystal K'. The crystal K' is made resonant to a frequency n_r' sufficiently below that of the crystal K to make its effective inductance reactance equal

$$\frac{1}{2\pi n_r C_a}$$

so that it forms an antiresonant circuit with the real capacity C_a of crystal K. The reactance, resistance and impedance curves of such a combination are shown in Fig. 22. If the selectivity of the adjunct crystal K' be 10^4, then the effective impedance of the shunt to the branch C_rL of crystal K will be of the order of 10^{11} ohms, while if the selectivity of the adjunct crystal be 4×10^5 then the effective impedance in question will be of the order of 5×10^{12}. If the selectivity of the adjunct crystal K' be equal to or greater than that of the crystal K, it will in general be desirable to reduce it, and to this end a suitable resistance may be inserted at the points *a* or *b*.

The adjustment of the ratio of the frequency of the adjunct crystal K' to that of the crystal K is too delicate to be made structurally, but this adjustment may be made to the desired degree of precision, by an adjustable condenser bridged between the points a and b, or by an adjustable condenser or inductance coil at a or b.

In Fig. 12b is illustrated the preferred manner in which the frequency of the organization of Fig. 12a may be caused to fluctuate in accordance with the vibrations of sound waves impinging on the diaphragm of the condenser telephone transmitter C'.

The frequency sensitive elements of the type of Figs. 12a and 12b are elements which are intended to be used not at, but near the resonance frequency n_r. They are intended for use as relatively low impedance elements. But Fig. 13a illustrates a high impedance or antiresonant frequency sensitive element in which the combined reactance of the real or C_a capacities of the crystals K_1 and K_2 is neutralized by the effective inductance L' of crystal K' at the antiresonant frequency of the element. This organization is therefore an antiresonant frequency sensitive element. A comparison of the frequency sensitive element of Fig. 13a with that of Fig. 9a reveals the fact that these organizations are the same except for the fact that in the case of the organization of Fig. 13a, the capacity shunt formed by the real capacities C_{a1} and C_{a2} of the crystals K_1 and K_2, respectively, is balanced by the effective inductance L' of crystal K' at the antiresonant frequency of the element. In other words, Fig. 13a is in effect Fig. 9a with the crystal K' adjusted to resonate with the real or C_2 capacities of the crystals K_1 and K_2, thus forming an antiresonant combination which eliminates the effect of the C_a capacities.

The effect of so balancing the capacity shunt $C_{a1}+C_{a2}$ by the effective inductance L' at the antiresonant frequency

$$n_r21=\frac{n_{r1}+n_{r2}}{2}$$

of the element is to change the negative reactance shunt of about -5×10^4 ohms to a high resistance shunt of about 10^{11} or 10^{12} ohms at the antiresonant frequency n_{r21} of the element. As in the case of the frequency sensitive elements of Figs. 12a and 12b the adjustments of the relative frequencies of the several crystals is too delicate a matter to be made to depend upon the structure of the crystal sections alone. For this reason the final adjustments are made by the insertion of adjustable condensers in series at a or b and preferably also an adjustable condenser in shunt across between the points a and b. The serially connected adjustable condenser at a or b serves to adjust and fix precisely the frequency interval of detuning between the resonant frequencies n_{r2} and n_{r1} of crystals K_2 and K_1, respectively, while the adjustable condenser in bridge across between the points a and b serves to adjust and fix precisely the capacity reactance to be neutralized by the inductance reactance of the crystal K'.

In Fig. 13b is illustrated a manner in which the frequency of the organization of Fig. 13a may be caused to fluctuate in accordance with the vibrations of sound waves impinging on the diaphragm of the telephone transmitter C'. If desired the transmitter may be connected in parallel as shown in C'' at Fig. 13c.

In Fig. 14 is illustrated a means of imparting an effective capacity C' to a condenser considerably greater than its real capacity C. The condenser telephone transmitter C is shown in series with an inductance coil L. If C and L designate, respectively, the capacity and inductance of these elements, then

$$\omega_0^2=\frac{1}{CL}$$

where ω_0 is the periodicity of resonance of the combination. When this periodicity is greater than the impressed periodicity ω, then the reactance of the branch CL is a capacity or negative reactance given by the expression

$$C'=\frac{\omega_0^2}{\omega_0^2-\omega^2}C$$

This device is a convenient one for amplifying the operative or effective capacity of a condenser, but it must be used with discretion, because the coil L cannot have a Q greater than 400 and its Q is usually in the neighborhood of 200, so when this device is used in conjunction with crystals whose Q's or selectivities are of the order of 10^4 or 4×10^5, an indiscreet use of coil inductance will unduly reduce the selectivity of the frequency sensitive element.

Fig. 15 illustrates a convenient method of adjusting the antiresonant frequency of a crystal. Just as an adjustable condenser immediately in series with a crystal is the most approved device for adjusting the resonance frequency n_r of a crystal, an adjustable condenser immediately in parallel with a crystal is the most approved device for controlling and adjusting the antiresonant frequency n_a of a crystal. This is because of the high Q which condensers may be given as compared with coils and because they are far more easily adjusted as to their capacity than are coils as to their inductance. In connection with the foregoing, it is pertinent to point out that the Q of a circuit, when measured at its resonant or antiresonant point is its selectivity S.

In Fig. 16, A is a source of constant high frequency E. M. F., being preferably a triode amplifier, B_1 and B_2 are matched or balanced frequency sensitive elements controlled, respectively, as to their antiresonant frequency by the condenser telephone transmitters C_1 and C_2. The branches ab_1c_1d and ab_2c_2d are balanced, the equal loops C_3L_3 and C_4L_4 are tuned to the frequency of the source A, the equal loops C_5L_5 and C_6L_6 are tuned to the frequency of the source. The secondary coil L_7 is so symmetrically related to the two equal primary coils L_3 and L_4 that it receives only the energy of the carrier frequency of the current in the two branches ab_1c_1d and ab_2c_2d of the bridge or balance which the organization of this diagram depicts. The secondary coil L_8 is so symmetrically related to the two equal primary coils L_5 and L_6 that it receives only the modulated component of the current in the two branches ab_1c_1d and ab_2c_2d of the balance. The circuit 4, 4' is used to feed the necessary amount of the energy of the carrier current back to the oscillator A to maintain it in constant and continuous oscillation at that frequency.

The bridge is so balanced that when C_1 and C_2 are not acted upon by sound waves the branches 3, 3' and 1, 1' are conjugate. When C_1 and C_2 are equally but oppositely acted upon by sound waves, the impedances of branches ab_1c_1d and ab_2c_2d are equally but oppositely influenced. The equality of this influence may be secured, to a degree adequate for most practical purposes, through the use of matched condenser telephone transmitters C_1 and C_2 as well as matched frequency sensitive elements B_1 and B_2. A final and more refined adjustment of the bridge may be made through the use of auxiliary reactances in one or both branches in accordance with well-known principles.

When the sound waves act equally and in phase upon C_1 and C_2, then the frequency elements B_1 and B_2 should be of the type illustrated in Figs. 5, 7*a*, 9*a* or 13*a*, in which the impedance characteristic is substantially symmetrical about the vertical axis through the antiresonant frequency. Then B_1 and B_2 are respectively detuned so that B_1 is antiresonant at frequency $n(1+k_1\Delta)$ and B_2 at frequency $n(1-k_1\Delta)$ where n is the impressed frequency. The frequency interval $k_1\Delta n$ is so chosen as to bring the impedance frequency curves of B_1 and B_2 to equal but oppositely sloping inflection points at the impressed frequency n.

While this invention has been disclosed in certain particular arrangements merely for the purpose of illustration, it is to be distinctly understood that the general principles of this invention may be applied in other and widely varied organizations without departing from the spirit of the invention or scope of its appended claims.

What is claimed is:

1. A transmission circuit, a frequency sensitive element in said circuit, said element being antiresonant at a definite frequency and having a maximum effective reactance of one sign at a second frequency near but at one side of the frequency to which said element is antiresonant, a second element in said circuit having a reactance substantially equal and opposite in sign to the reactance of said antiresonant element at said second mentioned frequency, said second element being so connected in the transmission circuit that a condition of substantially zero reactance exists in said circuit at said second frequency, a high frequency wave transmitted by said frequency sensitive element, and means whereby the frequency of said high frequency wave and the second frequency of said frequency sensitive element are shifted with respect to each other in accordance with modulating waves.

2. A transmission circuit, a frequency sensitive element in said circuit, said element being antiresonant at a definite frequency and having a maximum effective reactance of one sign at a second frequency near but at one side of the frequency to which said element is antiresonant, a second element in said circuit having a reactance substantially equal and opposite in sign to the reactance of said antiresonant element at said second mentioned frequency, said second element being so connected in the transmission circuit that a condition of substantially zero reactance exists in said circuit at said second frequency, and means for fluctuating the antiresonant frequency of said frequency sensitive element in accordance with sound waves.

3. A transmission circuit, a frequency sensitive element in said circuit including a crystal section antiresonant at a definite frequency and having a maximum effective reactance of one sign at a second frequency near but at one side of the frequency to which the crystal is antiresonant, said second frequency corresponding to the point of inflection of the effective impedance of the crystal, a second element in said circuit having a negative reactance equal but opposite in sign to the reactance of said crystal at said second mentioned frequency, said second element being so connected in the transmission circuit that a condition of substantially zero reactance exists in said circuit at said second frequency, a high frequency wave transmitted by said frequency sensitive element, and means whereby the frequency of said high frequency wave and the second frequency of said frequency sensitive element are shifted with respect to each other in accordance with modulating waves.

4. A transmission circuit, a frequency sensitive element in said circuit including a crystal section antiresonant at a definite frequency and having a maximum effective reactance of one sign at a second frequency near but at one side of the frequency to which the crystal is antiresonant, said second frequency corresponding to the point of inflection of the effective impedance of the crystal, a second element in said circuit having a negative reactance equal but opposite in sign to the reactance of said crystal at said second mentioned frequency, said second element being so connected in the transmission circuit that a condition of substantially zero reactance exists in said circuit at said second frequency, and means for fluctuating the antiresonant frequency of said crystal in accordance with sound waves.

5. A transmission circuit, a frequency sensitive element in said circuit including a crystal section antiresonant at a definite frequency and having a maximum effective reactance of one sign at a second frequency near but at one side of the frequency to which the crystal is antiresonant, said second frequency corresponding to the point of inflection of the effective impedance of the crystal, a second crystal section connected in parallel with said first section, said second crystal section being so cut that its natural frequency will be detuned with respect to said first section by an amount which will cause its maximum effective reactance of sign opposite to that of said first crystal section to occur at the same frequency as the maximum effective reactance of said first section, whereby a condition of substantially zero reactance will exist in said transmission circuit at said second frequency, a high frequency wave transmitted by said frequency sensitive element, and means whereby the frequency of said high frequency wave and the second frequency of said frequency sensitive element are shifted with respect to each other in accordance with modulating waves.

6. A transmission circuit, a frequency sensitive element in said circuit including a crystal section antiresonant at a definite frequency and having a maximum effective reactance of one sign at a second frequency near but at one side of the frequency to which the crystal is antiresonant, said second frequency corresponding to the point of inflection of the effective impedance of the crystal, a second crystal section connected in parallel with said first section, said second crystal section being so cut that its natural frequency will be detuned with respect to said first section by an amount which will cause its maximum effective reactance of sign opposite to that of said first crystal section to occur at the same frequency as the maximum effective reactance of said first section, whereby a condition of substantially zero reactance will exist in said transmission circuit at said second frequency, and means for fluctuating the antiresonant frequency of said first mentioned crystal section in accordance with sound waves.

7. A transmission circuit having two parallel branches, each branch having included therein a crystal section antiresonant at a definite frequency, and each section having points of maximum positive and maximum negative effective reactances at frequencies near to but spaced from the antiresonant frequency of the crystal section on either side of said resonant frequency, the tuning of said branches being such that their frequencies differ from each other by an amount whereby the maximum effective positive reactance of one crystal section and the maximum effective negative reactance of the other section will occur at the same frequency, said crystal sections being so cut that their antiresonant frequencies will differ from each other by an amount substantially equal to the detuning of said branches, a condenser associated with each of said crystal sections for aiding in precisely determining the detuning of the branches with respect to each other, a high frequency wave transmitted by said transmission circuit, and means whereby the frequency of said high frequency wave and the frequency at which substantially zero reactance is produced in said transmission circuit are shifted with respect to each other in accordance with modulating waves.

8. A transmission circuit having two parallel branches, each branch having included therein a crystal section antiresonant at a definite frequency, and each section having points of maximum positive and maximum negative effective reactances at frequencies near to but spaced from the antiresonant frequency of the crystal section on either side of said resonant frequency, the tuning of said branches being such that their frequencies differ from each other by an amount whereby the maximum effective positive reactance of one crystal section and the maximum effective negative reactance of the other section will occur at the same frequency, said crystal sections being so cut that their antiresonant frequencies will differ from each other by an amount substantially equal to the detuning of said branches, a condenser associated with each of said crystal sections for aiding in precisely determining the detuning of the branches with respect to each other, and means for fluctuating the capacity of one of said condensers in accordance with sound waves.

9. A transmission circuit, a frequency sensitive crystal in said circuit antiresonant at a definite frequency, means to practically annul the reactance of said crystal at a second frequency at one side of said antiresonant frequency and corresponding to the frequency at which said crystal element has its greatest effective positive reactance, said crystal having such characteristics that it is equivalent in effect to a series resonant combination in parallel with its electrode capacity, means connected to said crystal to minimize its negative electrode capacity at frequencies in the neighborhood of the frequency at which it is antiresonant by opposing to said capacity a positive reactance, a high frequency wave transmitted by said frequency sensitive crystal, and means whereby the frequency of said high frequency wave and the second frequency of said crystal are shifted with respect to each other in accordance with modulating waves.

10. A transmission circuit, a frequency sensitive crystal in said circuit antiresonant at a definite frequency, means to practically annul the reactance of said crystal at a second frequency at one side of said antiresonant frequency and corresponding to the frequency at which said crystal element has its greatest effective positive reactance, said crystal having such characteristics that it is equivalent in effect to a series resonant combination in parallel with its electrode capacity, a second crystal section in parallel in said first crystal section, said second crystal section being detuned with respect to the first by such an amount that its effective reactance at frequencies in the neighborhood of the antiresonant frequency of said first crystal section will be substantially equal to but opposite in sign to the electrode capacity of said first crystal section at frequencies in the neighborhood of its antiresonant frequency, a high frequency wave transmitted by said first mentioned frequency sensitive crystal, and means whereby the frequency of said high frequency wave and the second frequency of said first mentioned crystal are shifted with respect to each other in accordance with modulating waves.

11. A transmission circuit, two crystal sections connected in parallel with each other in said circuit and having antiresonant frequencies differing from each other by such an amount that the maximum effective positive reactance of one crystal at a third frequency on one side of its antiresonant frequency will be opposed by a substantially equal negative reactance of the other crystal at said third frequency, whereby the reactance of said transmission circuit will be substantially zero at said third frequency, each of said crystal sections being equivalent in effect to a series resonant combination in parallel with the electrode capacity of the crystal, means associated with said parallel crystals having such electrical characteristics as to minimize the effect of the combined negative electrode capacities of the two crystal sections at frequencies in the neighborhood of the antiresonant frequency of one of said crystal sections by opposing thereto a positive reactance, a high frequency wave transmitted by said transmission circuit, and means whereby the frequency of said high frequency wave and the third frequency at which substantially zero reactance is produced in said transmission circuit are shifted with respect to each other in accordance with modulating waves.

12. A transmission circuit, two crystal sections connected in parallel with each other in said circuit and having antiresonant frequencies differing from each other by such an amount that the maximum effective positive reactance of one crystal at a third frequency on one side of its antiresonant frequency will be opposed by a substantially equal negative reactance of the other crystal at said third frequency, whereby the reactance of said transmission circuit will be substantially zero at said third frequency, each of said crystal sections being equivalent in effect to a series resonant combination in parallel with the electrode capacity of the crystal, means associated with said parallel crystals having such electrical characteristics as to minimize the effect of the combined negative electrode capacities of the two crystal sections at frequencies in the neighborhood of the antiresonant frequency of one of said crystal sections by opposing thereto a positive reactance, and means to fluctuate the antiresonant frequency of one of said two crystal sections in accordance with sound waves.

13. A transmission circuit, two crystal sections connected in parallel with each other in said circuit and having antiresonant frequencies differing from each other by such an amount that

the maximum effective positive reactance of one crystal at a third frequency on one side of its antiresonant frequency will be opposed by a substantially equal negative reactance of the other crystal at said third frequency, whereby the reactance of said transmission circuit will be substantially zero at said third frequency, each of said crystal sections being equivalent in effect to a series resonant combination in parallel with the electrode capacity of the crystal, a third crystal section connected in parallel with the first two, said third crystal section being detuned with respect to the first two crystal sections so that its effective positive reactance at frequencies in the neighborhood of the antiresonant frequencies of said two crystal sections will minimize the combined negative electrode capacities of said sections at frequencies in the neighborhood of the antiresonant frequency of one of said sections, a high frequency wave transmitted by said transmission circuit, and means whereby the frequency of said high frequency wave and the third frequency at which substantially zero reactance is produced in said transmission circuit are shifted with respect to each other in accordance with modulating waves.

14. A transmission circuit, two crystal sections connected in parallel with each other in said circuit and having antiresonant frequencies differing from each other by such an amount that the maximum effective positive reactance of one crystal at a third frequency on one side of its antiresonant frequency will be opposed by a substantially equal negative reactance of the other crystal at said third frequency, whereby the reactance of said transmission circuit will be substantially zero at said third frequency, each of said crystal sections being equivalent in effect to a series resonant combination in parallel with the electrode capacity of the crystal, a third crystal section connected in parallel with the first two, said third crystal section being detuned with respect to the first two crystal sections so that its effective positive reactance at frequencies in the neighborhood of the antiresonant frequencies of said two crystal sections will minimize the combined negative electrode capacities of said sections at frequencies in the neighborhood of the antiresonant frequency of one of said sections, and means to fluctuate the antiresonant frequency of one of said first two crystals in accordance with sound waves.

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