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RESONATOR CIRCUITS

Eiichi Goto Meguro-ku, Tokyo, Japan, assignor, by mesne assignments, to Parametron Institute, Tokyo, Japan, a juridical foundation of Japan

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This invention relates to improvements in and relating to non-linear circuits, and more particularly to electric resonators having reactive non-linear circuit elements and the application thereof to the electric computers.

For the "logical elements" (digital computing elements) of electric computers, the general practice has been to use electronic tubes and relays. However, the life of such tubes and relays is comparatively short, and therefore, much difficulty is experienced in the maintenance thereof including the replacement of such tubes and relays. Furthermore, the power consumption for the operation of such tubes and relays is fairly large, and therefore, it is necessary to supply a large amount of power by installing a large capacity plant in cases where large-sized electric computer is used. This is a great disadvantage of the device hitherto employed. Recently, transistors which consume a comparatively small amount of power were invented to replace the electronic tubes. Not only are such transistors expensive, but also the reliability and stability thereof are not yet fully known. The practical value of transistors as "logical elements" depends largely on the future developments thereof.

The object of the present invention is to provide a resonator to be used as a "logical element" and as an electrical element in general. The structure of this resonator is considerably simpler, stronger, and smaller-sized than that of electronic tubes and transistors. Also, this resonator is inexpensive, and can be operated permanently with stability, and the power consumption thereof is very small.

The advantages of the present invention appear in the following description taken together with the accompanying drawings. It must be noted that such description is made for the purpose of exemplification and without limiting the invention or the claims thereto.

In the drawings,

Figs. 1*a*, 1*b* and 1*c* show the connection diagrams of one embodiment of the resonator according to the present invention;

Fig. 2 is the wave form diagram showing the principle of operation of the resonator according to the present invention;

Figs. 3*a*, 3*b* and 3*c* are the block diagrams showing the coupling of resonators according to the present invention;

Figs. 4*a* and 4*b* are the connection diagrams showing embodiments of couplers coupling the resonators of the present invention and other circuit elements;

Fig. 5*a* is the circuit diagram, and Figs. 5*b* and 5*c* are the wave form diagrams, showing the principle of parametric excitation which is applied to the resonator according to the present invention;

Figs. 6*a*, 6*b*, 6*c* and 6*d* are the characteristic curves showing the experimental results of the resonator according to the present invention;

Figs. 7*a*, 7*b*, 7*c*, 7*d*; 8*a*, 8*b*; 9*a*, and 9*b* are the block diagrams, and Fig. 10 is the circuit diagram, showing the examples of circuits of computer elements in which the resonators according to the present invention are used;

Fig. 11 is the table which shows how the arrangement of Fig. 8*a* behaves;

Fig. 12 shows the table of logical function which corresponds to Fig. 8*a*;

Fig. 13 shows the table of logical function which corresponds to Fig. 9*a*; and

Figs. 14–17 show examples of circuits which perform logical operations.

Referring to the drawings, M shows a nonlinear reactor, of which the cores are, for example, laminated cores, ferrite cores, or oxide cores. The coils, L_1, L_1', L_2 and L_2' are wound as shown in the drawing. L_1 and L_1' are in phase and L_2 and L_2' are in counter phase. (L_2 and L_2' may be wound in the opposite direction from cores L_1 and L_1') L_2, L_2' and the capacitor C constitute a resonance circuit having the resonance frequency *f*. Two cores are used, and either the exciting coils L_1 and L_1' or the resonance coils L_2 and L_2' are connected in counter phase, for the purpose of maintaining a balance in order to avoid the direct coupling of the exciting current and the resonance current. To the terminals T_1 and T_1' of the exciting coils L_1 and L_1', are connected in series the exciting current source O_1 having a frequency 2*f*, and the direct current source B which operates the cores of M at the maximum variation point of permeability μ of the magnetisation character of the cores. When switch S_1 is closed and the exciting current 2*f* is supplied to the coils L_1 and L_1', the resonance circuit L_2—L_2'—C oscillates at a frequency *f* (subharmonic of the order of ½ of the exciting frequency). Although the above resonance circuit may oscillate at a subharmonic other than ½ subharmonic, the oscillation most easily occurs at ½ subharmonic, and therefore, the following description takes into account only for the latter case. The manner of oscillation of ½ subharmonic is as shown in Fig. 2. The initial oscillation of low intensity, having frequency *f*, existing in the resonance circuit, is built up, when the resonator is excited by a frequency 2*f*, by closing switch S_1 at the time point Ⓐ in Fig. 2. Then, the amplitude rapidly increases to a certain limited intensity, at the time point Ⓑ, and thereafter the oscillation is sustained with stability. The phase of the above oscillation cannot be other than either one of the phases, counter to each other, shown in solid and dotted lines in Fig. 2. Once such oscillation state is established, the oscillation continues with a high stability as long as the exciting voltage is applied, and it stops when the supply of the exciting voltage is cut off by opening switch S_1. However, when switch S_1 is again closed and the exciting voltage with a frequency 2*f* is impressed, the resonance circuit oscillates again with frequency *f*, as described above. Whether the phase of oscillation in this case is as shown by the solid line or by the broken line in Fig. 2 depends upon the initial conditions of excitation.

The mechanism of the generation of a ½ subharmonic may also be explained as follows: Since the exciting coils L_1 and L_1' and the resonant coils L_2 and L_2' in Fig. 1*a* are wound on ferromagnetic cores in a balanced configuration, no voltage is produced in the resonant circuit L_2—L_2'—C when the exciting current only is applied. However, the exciting current applied to L_1 and L_1' causes saturation in the ferromagnetic cores, and varies the resonance frequency of the resonant circuit. Now, let us assume that a weak resonant current having a frequency *f* is flowing in the resonant circuit. Then, a voltage having a beat frequency between 2*f* for exciting current and *f* for the resonant current is generated in the resonant circuit. The frequency of such voltage is also *f* ($2f-f=f$). When the resonant current has a proper phase, the above beat voltage causes positive feed back which tends to increase the above resonant current, the

resonant current is rapidly increased thereby, and the self-sustained oscillation having a frequency *f* (½ subharmonic of the exciting frequency 2*f*) is produced in the resonant circuit. The above-mentioned positive feed back action takes place for the two oscillation phases shown by solid and broken lines in Fig. 2. Which of the above two oscillation phases is produced depends upon the initial condition of the resonant circuit.

In order to have the above oscillation phase determined, the output of the phase control oscillator O_2 having the frequency *f* is impressed, during the non-excitation period, on the resonance circuit L_2—L_2'—C through a resistance, by making the switch S_2 contact *b*, as shown in Fig. 1. (In the resonator according to the present invention, the electronic tube oscillator or other known oscillator may be used as a phase control oscillator.) Then, the oscillation of the frequency *f* impressed on the resonance circuit by O_2 is amplified during the period Ⓐ–Ⓑ, and the oscillation state is brought about as above-mentioned. Therefore, the oscillation phase in this case is definite, said phase always being determined by the relation between the phase of oscillation applied to the resonance circuit from O_2 and the phase of exciting oscillation from O_1. It is always possible, therefore, to take out the oscillation output of frequency *f*, with a definite phase, from the output terminals T_2 and T_2'.

Similarly, when the switch S_2 is made to contract *a*, the phase angle of the voltage is shifted by π from that of O_2, and is impressed on the resonance circuit L_2—L_2'—C, by means of a transformer or a proper circuit which brings about the counter phase. Then, when switch S_1 is closed, the oscillation having a counter phase to that of the oscillation afore-mentioned is produced, and the oscillation output in counter phase to that afore-mentioned is taken out. Assuming the phase of the afore-mentioned case is shown by the solid line, the phase of the present case is as shown by the broken line in Fig. 2.

Once the oscillation is produced, the initial mode of oscillation (frequency, phase and amplitude) continues with a high stability as long as switch S_1 is closed and the exciting voltage is applied, no matter whether the output of O_2 is cut off from the resonance circuit, whether switch S_2 is switched over to *a* or *b*, or whether an alternating voltage of the frequency different from 2*f* is superimposed on the output of O_1. This control of the phase of the oscillation wave by the phase with a low intensity of the control oscillator O_2 can be compared to the operation of a thyratron where the anode voltage is interrupted and the grid voltage is varied, whereby the operating conditions are varied. (This corresponds, in the present case, to the interruption of the exciting voltage, the variation of the phase of the phase control voltage impressed on the resonance circuit, and the variation of the oscillation state.)

The above description is applicable to a case where the ferromagnetic material is used as the nonlinear element which constitutes the resonance circuit. This is also applicable to the case of Figs. 1*b* and 1*c*, where nonlinear elements D for example barium titanate capacitors C_1 and C_2, are connected in parallel with the condenser C or are connected in series therewith. It is possible to eliminate C. It is also possible to use both of the coils and condensers as nonlinear reactors.

As is clear from the above description, the resonator according to the present invention can perform the amplification of the oscillation voltage and the limiting action of the oscillation amplitude, because the exciting voltage with a frequency 2*f* is impressed on the resonance circuit whereby the initial oscillation of low intensity and with a frequency *f* is rapidly amplified to a certain intensity which is continued with stability. Since the oscillation phase is either δ or $\delta+\pi$ by the "pull in" phenomenon of the phase, and said oscillation phase is maintained during the excitation period, it is possible to have phase

discrimination, and to make the memory of a signal in the form of phase, whereby the resonator according to the present invention is suited for a "logical element." Furthermore, such a resonator is constructed only with the coil L and the condenser C, and a ferromagnetic core is inserted in L for the purpose of giving nonlinear character thereto, or a ferroelectric capacitor is used as C. For this reason, the structure is simple and inexpensive, and can be used permanently because no consumable elements are used as parts, which therefore need not be replaced. The power consumption depends upon the size of the core to be used. About 25 mw. of power was found sufficient for the oxide core with an outer diameter of 4 mm., an inner diameter of 2 mm. and a thickness 1 mm. If the core is smaller, the power consumption can be made smaller. The size of the resonator is smaller than electronic tubes and relays. Even in the construction of a large-sized computer which makes complicated computations, the device can be operated satisfactorily from a small power source.

When a "logical operation" (digital computing operation) is carried out with the known tubes and relays, the value of the "logical variables" (digitally represented numbers) is determined by the presence or absence of voltage or current. Therefore, a misoperation is caused by a noise which is difficult to control. When the resonator according to the invention is used, the value of "logical variables" is determined by the difference of the phase of oscillation voltage (the difference by π), and not by the presence or absence of voltage or current. This, together with the "pull in" action of the phase, improves the *S/N* (signal to noise) ratio (about 70 db), and makes it possible to perform an exact "logical operation" without causing a misoperation due to noise. The resonator according to the invention can also be used as an electrical element in general for other purposes than a "logical computer."

Hereinafter the description is given as to the coupling where a signal is transmitted by coupling resonators with one another, or by coupling resonators with other elements such as electronic tubes, transistor circuits and relay circuits.

Figs. 3*a*, 3*b* and 3*c* concern the signal transmission by coupling two resonators P_1 and P_2. Fig. 3*a* shows the impedance coupling, Fig. 3*b* the admittance coupling, and Fig. 3*c* the mutual inductance coupling. In Figs. 3, the resonators of Fig. 1*a* are shown as P_1 and P_2. The resonator P_1, is presumed to be in the oscillation state by the exciting voltage with a frequency 2*f* being applied to the exciting terminals T_1 and T_1'. The oscillation voltage having a frequency *f* of the resonance circuit P_1 is impressed on the resonance circuit P_2 through the respective coupling element, namely, the coupling impedance Z, coupling admittance Y, or coupling coil L_5. Then, where each coupling element is resistive, the phase of the voltage impressed on the resonance circuit P_2 is in phase with that of the oscillation voltage of P_1 (the frequency of the two is *f*). When the exciting voltage with a frequency 2*f* is impressed on the exciting terminals T_1 and T_1' of P_2, the oscillation voltage impressed on the resonance circuit P_2 rapidly increases, and P_2 oscillates in phase with P_1 at the frequency *f*. Thus, the oscillation state (signal) of P_1 is transmitted to P_2. Then, even when the exciting voltage of P_1 is cut off and the oscillation of P_1 is stopped, P_2 continues its oscillation, as long as the exciting voltage is impressed on P_2, and therefore, the signal of P_1 is completely transferred to P_2. Where each coupling element is reactive, a difference of phase is produced between the oscillation voltage of P_1 and the voltage transferred to P_2. In this case, if the phase of exciting voltage (frequency 2*f*) of P_1 and P_2 is the same, the oscillation phase of P_2 may be indefinite due to noise. It is, therefore, desirable to transfer the phase of the oscillation voltage of P_1 substantially in phase by making the coupling element resistive. The coupling elements must be designed by taking the above into consideration. For example, in case the coupling element is reactive and there is a phase difference in the voltage transferred from P_1 to P_2, it is desirable to shift the phase of the exciting voltage to the extent of the phase difference. In order to reverse the phase of oscillation of P_2, a transformer or other phase-inverter can be used as a coupling element.

There has been described above the case where the signal is transferred from P_1 to P_2. However, by reversing the order of interruption of excitation, the signal can be transferred from P_2 to P_1. Similarly, by successively coupling a number of resonators, the same operation can be repeated, and the signal can be transferred successively.

The resonators can also be used with other circuit elements.

As is clear from the above description, no direct current or voltage is used for the input and output circuits of the resonator according to the invention. It is a circuit element operated solely by the alternating current. On the other hand, for the elements, such as tubes, transistors or relays, which have hitherto been used, direct voltage or current is used in most cases. It is therefore necessary to use a means for converting the alternating current into the direct current, such as rectifiers, and a means for converting the direct current into alternating current, such as modulators, in case resonators and the hitherto used elements are coupled together. Thus in order to take out the A.C. signal produced by a resonator as a D.C. signal, a phase discriminative rectifier, such as a detector for F.M. modulation or a ring modulator for demodulation, may be used. By superimposing the A.C. voltage, the phase of which is being taken as standard, on the output voltage of a resonator, rectifying the same, and changing the polarity of the D.C. output following the phase of oscillation of a resonator, the electronic tube circuit or other circuit can be controlled and can transmit a signal. Where the D.C. signal output from an electronic tube circuit or other circuit is to be given to a resonator, the phase discriminative modulator, such as a ring modulator or frequency doubler type magnetic (dielectric) amplifier (as shown in Fig. 4), may be used. Then, the phase of the A.C. output is varied corresponding to the polarity of the D.C. signal, and said A.C. output may be used as the input signal for the resonator.

Fig. 4*a* shows a well-known frequency doubler type magnetic amplifier. To the primary coils l_1 and l_1' of said amplifier, the A.C. current having frequency $f/2$ is supplied so that the cores d and d' are saturated. In this case, if the D.C. current does not flow in the secondary coils l_2 and l_2', no A.C. component appears on the secondary side. However, if the D.C. current flows from the terminals t_1 and t_1' to l_2 and l_2' the second harmonic of the above A.C. current having a frequency $f/2$, namely the A.C. component having a frequency f, appears on the secondary side. Since the phase of such A.C. component is reversed by the polarity of the D.C. current supplied to l_2 and l_2', the phase of oscillation of the resonator can be controlled by the polarity of the D.C. output, by supplying the D.C. output from the tube circuit of the other circuit to the terminals t_1 and t_1', taking out the A.C. output having a frequency f from the terminals t_2 and t_2', and supplying the same to the input circuit of the resonator. It is necessary to synchronize the A.C. current source having a frequency $f/2$ and the exciting source for the resonator having a frequency $2f$.

Fig. 4*b* also shows a form of magnetic resistance modulator. To the primary coil l_1 of said modulator is supplied an A.C. current having frequency $f/2$ so that the core of such coil is saturated, and the D.C. current flows in the coil l_d. The A.C. output having frequency f is taken out from the secondary coils l_2 and l_2', and in this

case, the phase of the A.C. output having a frequency f is reversed following the sense of the D.C. current in the coil l_d, namely the sense of the magnetomotive force ψ in the core.

As the result of studies made, it has been made clear that the function of the resonator above-mentioned can be explained by the theory of parametric oscillation (J. J. Stoker: "Nonlinear Vibrations," New York (1950), and N. W. McLachlan: "Ordinary Nonlinear Differential Equations," London (1950)). The parametric oscillation is described hereunder with reference to Figs. 5. Fig. 5*a* shows the resonance circuit consisting of the coil L(t) and the capacitor C(t), where L(t) and C(t) show that L and C are the functions of time t. In case L and C are constants, Fig. 5*a* is a known electric resonance circuit. However, a certain oscillation produced in the resonance circuit is built up, as time elapses, by properly varying the value of either one, or both, of L and C as function of time t.

Generally, the oscillation of the resonance circuit having periodic variable constant is represented by the following ordinary differential equation (Hill's equation):

$$\frac{d^2u}{dt^2}+F(t)u=0,\ F(t+T)=F(t) \tag{1}$$

where, F(t) is a certain periodic function having period T. (It is assumed that the resonance circuit is loss-free.)

When F(t) is the sinusoidal function of time t, the Equation 1 is called Mathieu's differential equation:

$$\frac{d^2u}{dt^2}+\omega^2(1+\alpha+\gamma\cos 2\omega t)u=0 \tag{2}$$

where, α is a parameter showing out-of-tuning of the resonance circuit, and γ is a parameter showing the intensity of excitation.

Now, it is known that the differential equation of periodic variable constant having 2ω angular frequency has at least one following solution (periodic function of the second kind):

$$u(t)=t^{\lambda t}\phi(t) \tag{3}$$

where λ is constant (generally complex), and $\phi(t)$ is a periodic function of time t having 2ω angular frequency.

In the Equation 2, when α, γ and λ are all real, it is shown that there exists an oscillatory solution in which the amplitude is built up as time elapses, as shown in Fig. 5*c*. This oscillation is called "parametric oscillation." When λ is imaginary, the oscillatory solution is that in which the amplitude modulation and the frequency modulation are effected simultaneously (Fig. 5*b*).

When α, γ and λ are all real, the oscillation of ½ subharmonic is the most intense.

When excitation is made by 2ω angular frequency, only the oscillation of ω grows up exponentially and the oscillation having other angular frequencies cannot grow up, where parameter γ showing the intensity of excitation is comparatively small and the circuit loss is comparatively large. When γ is considerably large and the circuit loss is very small, the oscillation, other than ½ subharmonic oscillation also can grow up theoretically. However, in practice, it is extremely difficult to realize the above-mentioned requirements.

In the case of oscillation of ½ subharmonic, if the magnitudes of α and γ are small, the approximate solution of the Equation 2 is given as follows:

$$\left.\begin{aligned} u &\doteqdot t^{\lambda t}\sin(t-\delta)\\ \lambda &\doteqdot \frac{\gamma}{2}\sin 2\delta\\ \alpha &\doteqdot 1+\frac{\gamma}{2}\cos 2\delta \end{aligned}\right\} \tag{4}$$

Fig. 5*c* corresponds to the case where $\delta=\pi/4$, and the solid and broken lines show the oscillations in counter

phase. The mode of building up of said oscillations is quite the same. This can be confirmed by the fact that, in the Equation 3, the values of α and λ are not varied but only the sign of u is reversed, when δ is changed to $\delta+\pi$. Also, the oscillation, having a phase different by $\pi/2$ from that above-mentioned, is damped exponentially, as is clear from the Equation 3 in which δ is taken as

$$\frac{3\pi}{4}$$

and therefore, a remarkable "pull in" action of phase occurs. In such oscillation, the phase discrimination is effected.

As mentioned above, the resonator acts due to the excitation action. The exciting circuit and the resonance circuit are separately provided as in Figs. 1; the oscillation and interruption thereof are effected by the control of the exciting circuit (such as make and break of the switch, the variation of bias voltage and the variation of frequency); the control of the oscillation frequency is effected by the frequency of the exciting source; and the determination of the oscillation phase is effected by the control of resonance circuit, namely, the phase of the voltage wave impressed on said resonance circuit during the non-excitation period. In the excitation described above in connection with Hill's Equation 1 and Mathieu's Equation 2, the amplitude grows infinitely as time elapses. However, in an actual circuit, losses exist, and either one or both of the coil L(t) and the capacitor C(t) are made nonlinear, by using a ferrite core as the core of the coil L(t), or by using a ferroelectric capacitor as C(t). Then, taking the parameter of loss as ρ, and by taking the parameter showing the degree of nonlineality of reactor as β, Mathieu's Equation 2 is modified as follows:

$$\frac{d^2u}{dt^2}+\rho\frac{du}{dt}+\omega^2(1+\alpha+\beta u^2+\gamma\cos 2\omega t)u=0 \tag{5}$$

where,

$$\rho\frac{du}{dt}$$

is the term showing the loss, and u^2 is the term showing nonlineality of reactor.

Judging from the above Equation 5, the amplitude is limited, and, as shown in Fig. 2, when the initial oscillation in the state of non-excitation is excited at the time point Ⓐ, only the ½ subharmonic oscillation is built up exponentially (amplifying period) which, after having reached a certain value, maintains its state with stability (steady state). It is extremely difficult to find the exact solution of such a nonlinear differential equation as (5). However, the Equation 5 can be solved approximately. It was confirmed theoretically and experimentally that there exist two cases, depending upon the values of α, β, γ and ρ, namely:

(*a*) Two stable states of oscillation having the same amplitude but of counter phase. (Such a resonator having the two stable states is hereinafter referred to as a "bistable resonator.") (Fig. 2 corresponds to this case (*a*).)

(*b*) Three stable states consisting of the two stable states above mentioned in (*a*) and a third state in which the oscillation is positively damped. (Such a resonator having the three stable states is hereinafter referred to as a "tristable resonator.").

Hereunder, a description is given as to the experiments which I made on the circuit shown in Fig. 1*a*. As cores M (non-linear reactor elements), oxide cores (a kind of ferrite core) having the thickness of 2 mm., an outer diameter of 14 mm., an inner diameter of 5.5 mm., and an initial permeability of about 600 were used. On these cores, coils L_1 and L_1' were respectively wound with 20 turns, and coils L_2 and L_2' were respectively wound with 15 turns. The capacity of the capacitor C was 5000 pf. Resonance frequency f was about 250 kc.

To the terminals T_1 and T_1', a bias D.C. current of about 50 ma. (for operating at the most curved point of the magnetisation curve of oxide cores M), and an exciting A.C. current of about 50 ma. having a frequency $2f$ supplied from the exciting source O_1 were applied in supeirmposition. By varying the frequency $2f$ from about 300 kc. to 700 kc., the oscillation voltage (the frequency being ½ of that of the excitation) was measured at the terminals T_2 and T_2', and the load characteristics were obtained as shown in Figs. 6*a*–6*d*. In the above experiment, the output of the phase control oscillator O_2 was not supplied, because such output has no relation to the load characteristics. In Fig. 6*a*, no load was connected; in Fig. 6*b*, 1 KΩ resistance was connected to T_2 to T_2' in parallel with the resonance circuit; and in Figs. 6*c*, and 6*d*, 500Ω and 300Ω resistances were respectively connected. With 250Ω, no oscillation was noted. It is seen that the value of oscillation voltage varies as the value of out-of-tuning varies, that there are three critical frequencies, F_1, F_2 and F_3, at which the value of oscillation voltage varies suddenly, that the oscillation is stable in the region of F_1–F_2, the above-mentioned "bistable resonator" region, and that the hysteresis jump, unique in the "tristable resonator," occurs in the region of F_2–F_3. It was confirmed by the above experiment that the frequency range of oscillation becomes smaller as the load resistance decreases, and that a remarkable constant voltage characteristic exists for the resistive load. The above experiment was made with a comparatively low frequency in order to observe easily the oscillation state with a cathode ray tube. It was also found that the oscillation could be established with an oscillation frequency of up to 4 mc. (exciting frequency up to 8 mc.), by using the same magnetic cores and about the same exciting current value, and by gradually decreasing the capacity of resonance capacitor. Also, in the above experiment, it was found that the mode of oscillation (oscillation frequency, amplitude and phase) was extremely stable, even when the excitation was continued for weeks with a fixed exciting frequency.

From the above description, it will be made clear that the resonator according to the invention has the amplification action, the amplitude limitation action, phase discrimination action and memory action. Such actions, together with its simple structure, high stability, inexpensive cost, permanent life, and small consumption of power, make it possible to use the "parametron" not only as an excellent "logical element," but also as electrical elements in general.

Now, I shall describe the application of the resonator in electric computers.

It is known that the electric computers, without exception, can be constructed with the following four circuit elements:

(*a*) "Delay" circuit,
(*b*) "And" or "Or" circuit,
(*c*) "Not" circuit, and
(*d*) "Branch" circuit.

Fig. 7*a* shows an example of the "delay" circuit, in which the resonator circuit of Figs. 1*a* and 1*b* is represented as P_A, P_B, P_C . . ., and such resonators are coupled together successively as shown, by coupling impedances Z. Resonators in every third place, namely P_A, P_D, . . ., P_B, P_E, . . ., and P_C, P_F, . . ., are taken as groups, and each group is made to oscillate or made to cease to oscillate simultaneously. Let it be assumed that only the resonators P_A, P_D, . . . (group I), shown hatched, are excited, that these are respectively in the state "0" or state "1," and that also these memorize "logical variables," x, y, . . ., which take the value "0" or "1" in the form of a particular oscillation phase. In order to use easily logical algebra, the phase of oscillation of a certain resonator is taken as standard, and the resonators oscillating in phase with the standard resonator are assumed to "be in the state of '1'" or to "be memorizing '1'." The resonators oscillating in counter phase are assumed to "be in the state of '0'" or to "be memorizing '0'." It is to be noted that, differently from relays and tubes, the state "1" or "0" of resonator is distinguished by the phase of oscillation, and irrespective of the state "1" or "0," the amplitude of oscillation is unchanged. In this case, a part of the oscillation voltage of group I is transferred in the two senses to each resonator in the groups II and III (P_B, P_E, . . ., and P_C, P_F, . . .) adjoining the group I, through the coupling impedances Z, as shown in Fig. 3*a*, and each resonator in the groups II and III oscillate with a small amplitude. This state is shown in Fig. 7*b*, in which the coupling elements are not shown.

Then, when the resonators in the group II are excited, the small amplitude oscillation of the group II is amplified through an efficient coupling, and the state of such amplified oscillation is sustained with stability in phase with the resonators of the group I. This is shown in Fig. 7*c*. Then, when the excitation of the resonators of the group I is interrupted, the state becomes as shown in Fig. 7*d*. It is seen that Fig. 7*d* corresponds to Figs. 7*a* and 7*b*, but in which the state of the resonators is moved to the right by one. By repeating similar operations, the "logical variables," x, y, . . ., can be shifted successively to the right, and a kind of shift registers can be obtained thereby. The above shifting of the state by alternately interrupting the excitation of the resonators of the three groups may be compared to the stepping of "dekatron." By applying a "logical variable" x ("1" or "0") to a point of such a circuit, and by repeating the above operations, x shifts successively to the right, and the delayed x can be taken out from a desired point, and therefore, such a circuit can be used as a "delay" circuit.

Although the above description is made for the situation in which x shifts to the right (I–II–III–I), such shifting can be effected to the left (III–II–I), by reversing the order of excitation and interruption. Resonators coupled with the oscillating resonators are brought to the oscillation state in phase with the oscillating resonators irrespective of their coupling sense. In the above "delay" circuit, every third resonator was taken as a group for simultaneous excitation and the groups I, II and III were excited successively, for the purpose of limiting the shifting sense of the "logical variables" to one side only.

Fig. 8*a* showws an example of the "And" circuit, in which resonators are used. P_x and P_y memorize respectively the "logical variable," x and y, which take the value of "1" or "0" in the form of a particular oscillation phase, P_0 is a constant resonator which always memorizes "0," and three such resonators are coupled with the resonator P_d respectively through the coupling element Z, with equal coupling intensity. P_0 may be replaced by a source of voltage having a definite amplitude and the phase 0. Since each oscillation voltage of P_x, P_y and P_0 is equal, and only the phase angle thereof is either 0 or π, the oscillation voltage with the phase angle π can be represented as e, by taking the oscillation voltage with the phase angle 0, counter phase of π, as $-e$. P_0 always memorizes "0." Let it be assumed that the oscillation voltage of P_0 is $-e$, and the oscillation voltage of P_x and P_y is either e or $-e$, depending upon whether the variables, x and y, are "1" or "0." Supposing that the above oscillation voltages are applied to P_d through the coupling element Z, the coupling coefficient being k, and that P_d is not excited, the oscillation voltage applied to P_d from P_x, P_y and P_0 is ke, $-ke$ or $-3ke$, depending upon whether the phase of oscillation of P_x, P_y and P_0 is π or 0. In case ke and $-ke$ exist in the three voltages applied to P_d, the positive and the negative voltage cancel each other, and the remaining voltage is ke or $-ke$, the phase of the impressed voltage being determined thereby. Also, in case the three voltages are all $-ke$, the impressed voltage is $-3ke$. When P_d is brought to the oscillation state by excitation and amplification to a certain amplitude e, the oscillation voltage is either e or $-e$, depending upon whether the small oscillating voltage impressed on P_d is ke, $-ke$ or $-3ke$. This is represented in Fig. 11, and the logical function table of variables, x and y, is shown in Fig. 12. By coupling the resonator P_d with three resonators P_x, P_y and P_0 as shown in Fig. 8*a*, and by always making P_0 memorize "0," the oscillation phase of P_d is determined by the majority of the phase of impressed voltages. Therefore, an "And" circuit for the two variables, x and y, can be constructed by giving the variables, x and y, to the two resonators, P_x and P_y.

Similarly, an "And" circuit for three variables, x, y and z, can easily be constructed by adding two resonators P_0 which memorize "0," besides the resonators P_x, P_y and P_z. Or, in case only one P_0 is used, as shown in Fig. 8*b*, the two coupling elements Z may be added to P_0. The intensity of the impressed voltage applied to P_d from P_0 through respective Z is made equal to that of the impressed voltage from P_x, P_y and P_z.

An "Or" circuit can also be constructed in the same way, namely, by replacing P_0 by a resonator P_1 which memorize "1," and adding the same to resonators P_x and P_y or P_x, P_y and P_z. Fig. 9*a* shows the "Or" circuit for the two variables, x and y, Fig. 13 shows the logical function table corresponding to Fig. 9*a*, and Fig. 9*b* shows the "Or" circuit for the three variables, x, y and z.

A "Not" circuit also can easily be constructed with the resonator circuits. One has only to reverse the phase in order to replace the "1" of the variables, x, y . . ., to "0" or vice versa, namely, by coupling the transformer T of the ratio 1:1 to the output terminals of the resonator P, and taking out from terminal t_1 the output in counter phase, or by taking out the same from the counter phase terminal t_2 of the resonator P. This is shown in Fig. 10.

Since the variable x and the inverse variable $\bar{x}$ are exactly symmetric (with the same amplitude but in counter phase) in the resonator circuit, it is not necessary to provide an elaborate element for reversing the variable, such as complementing tubes, said element being necessary for the "logical operation" circuit using electronic tubes.

Since the resonator has a large amplification action (more than 50 db amplification can easily be obtained), it is possible to control the oscillation state of a number of resonators by constructing a "branch" circuit and supplying each one of such resonators with the output of one resonator as the phase control voltage.

Thus any complicated "logical operation" circuits, such as arithmetic circuits (adder, subtractor, multiplier, divider, etc.) of binary, decimal or any other radix, counter circuits, arithmetic control circuits, and memory device, can be constructed with resonators according to the invention.

However, the basic "logical operation" of the resonators consists in determining the state of a resonator in accordance with the majority of the states of the oscillation phase of input resonators. Therefore, it occurs sometimes that a desired "logical operation" can be made with a simple circuit, by utilizing the above feature, without combining the aforesaid four circuit elements, when a "logical operation" circuit is to be constructed with resonators.

Now, I shall describe hereunder examples of other important "logical operation" circuits. Fig. 14 shows an example of the "logical operation" circuit in which resonators, x and y, representing two variables and three other resonators are connected in two stages. Fig. 15 shows the case in which resonators, x, y and z, representing three variables and another resonator are connected in one stage. Fig. 16 shows the case in which resonators, representing three variables, and three other resonators are connected in two stages. And, Fig. 17 shows the case in which resonators representing three variable and four other resonators are connected in two stages. In the column B of the above figures, — and + signs indicate the constant input from P_0 or P_1 in Figs. 8 and 9,

$$\begin{matrix}-\\-\end{matrix}\quad\text{and}\quad\begin{matrix}+\\+\end{matrix}$$

signs indicate the constant input twice as intense, and the marks | in the connecting lines of resonators indicate the reversal ("Not") of phase. For the sake of any easy understanding, "And" or "Or" in the column C shows "And" or "Or" circuit instead of constant input. The column A shows the combination of the value of "logical variables," x, y, . . . when the phase of oscillation output w of the last resonator is of the value "1." The order of oscillation in each stage is supposed to progress from left to right. The "logical operation" circuit shown in the upper part of Fig. 15, the oscillation phase of which is determined by the majority of three inputs, can be used as a "Carry" element for the "logical operation" circuit using resonators. Such a circuit is generally used as a "Carry" element for the binary adder circuit. In Figs. 8*a* and 9*a*, a resonator is connected in one stage, to which two variables and one constant are applied. Figs. 8*b* and 9*b* correspond to Fig. 15, and a resonator is connected in one stage, to which three variables and one constant (having twice the intensity as in the above case, Figs. 8*a* and 9*a*) are applied.

Thus the basic "logical operation" circuits described above above can be combined together, or combined with other circuits composed of tubes, relays and the like, whereby more complicated "logical operation" circuits may be constructed.

I claim:

1. An electric circuit for binary digital operations comprising a plurality of resonant circuits each having a resonant frequency of near f and each including an input, an output and a variable reactance the value of which is a parameter determining the resonant frequency of said resonant circuit, said resonant circuits being coupled to each other with the output of a preceding resonant circuit being coupled to the input of a succeeding resonant circuit, means for varying said parameters comprising at least two alternating power supply circuits each having a frequency $2f$ and a source of D.C. bias, and means applying said $2f$ frequency from one of said power supply circuits to said variable reactances at least in alternate resonant circuits and applying said frequency $2f$ from the other of said power supply circuits to the variable reactances in the remaining resonant circuits to vary the values of said reactances and thereby generate in said resonant circuits parametric oscillations having a frequency f, said power supply circuits being coupled to said resonant circuits in balanced bucking relationship so that said frequency $2f$ of the power supply circuits is not transmitted to said resonant circuits and the frequency f of said resonant circuits is not transmitted back to said power supply circuits, and means for controlling each of said power supply circuits for interrupting the oscillations of frequnecy f in said preceding circuit at a time just after the parametric oscillations are generated in the succeeding resonant circuits, whereby the binary digits are represented by the phase of the parametric oscillations and the phase of the frequency f generated in a preceding resonant circuit controls the phase of the frequency f generated in a subsequent resonant circuit and the oscillation generated in the subsequent resonant circuits is maintained even after the oscillations in the preceding resonant circuit are interrupted.

2. An electric circuit as claimed in claim 1 in which said means for controlling each of said power supply circuits comprises means in said power supply circuits for modulating the amplitude of the frequency $2f$.

3. An electric circuit as claimed in claim 2 in which said means for controlling each of said power supply circuits comprises means for interrupting the flow of current in said power supply circuits.

4. An electric circuit as claimed in claim 1 in which said means for controlling each of said power supply circuits comprises means in said power supply circuits for varying the value of the D.C. bias.

5. An electric circuit for binary digital operations, comprising a resonant circuit having a resonant frequency of near f and including a variable reactance the value of which is a parameter determining the resonant frequency of said resonant circuit, means for varying said parameter comprising an alternating power supply circuit having a frequency $2f$ and a source of D.C. bias and means applying said $2f$ frequency to said variable reactance to vary the value of said reactance and thereby generate in said resonant circuit parametric oscillations having a frequency f, said power supply circuit and resonant circuit being decoupled from each other so that said frequency $2f$ of the power supply circuit is not transmitted to said resonant circuit and the frequency f of said resonant circuit is not transmitted back to said power supply circuit, and means for controlling the power supply circuit for interrupting the oscillation of frequency f in said resonator circuit, whereby the binary digits are represented by the phase of the parametric oscillations and the parametric oscillations built up in said resonant circuit have only one of two possible phases which differ by 180° which is determined by the phase of a signal impressed on said resonator circuit at the start of the build up of parametric oscillations therein and said oscillations continue until the means for controlling the power supply circuit is actuated even though the impressed signal is cut off.

6. An electric circuit as claimed in claim 5 in which said means for controlling the power supply circuit for interrupting the oscillation of frequency f in said resonator circuit comprises means for varying the value of the D.C. bias.

7. An electric circuit as claimed in claim 5 in which said variable reactance is a pair of non-linear magnetic flux circuits and said power supply is coupled thereto in balanced bucking relationship.

8. An electric circuit as claimed in claim 5 in which said variable reactance is a pair of non-linear capacitances and said power supply circuit is coupled thereto in balanced bucking relationship.

9. An electric circuit for binary digital operations comprising a plurality of groups of resonant circuits, each resonant circuit having a resonant frequency of near f and each including an input, an output and a variable reactance the value of which is a parameter determining the resonant frequency of said resonant circuit, said resonant circuits being coupled to each other with the outputs of the resonant circuits in a preceding group being coupled to the inputs of resonant circuits in a succeeding group, means for varying said parameters comprising a plurality of alternating power supply circuits one for each group and each having a frequency $2f$ and a source of D.C. bias and means applying said $2f$ frequency from each power supply circuit to said variable reactance in the resonant circuits in the respective groups of resonant circuits to vary the values of said reactances and thereby generate in said resonant circuits parametric oscillations having a frequency f, said power supply circuits being coupled to said reactances in said resonant circuits in balanced bucking relationship so that said frequency $2f$ of the power supply circuits is not transmitted to said resonant circuits and the frequency f of said resonant circuits is not transmitted back to said power supply circuits, and means for controlling each of said power supply circuits for interrupting the oscillations of frequency f in the resonator circuits of a preceding group at a time just after the parametric oscillations are generated in the resonant circuits in a succeeding group, whereby the binary digits

are represented by the phases of the parametric oscillations in the resonant circuits and the phase of the frequency f generated in a preceding resonant circuit controls the phase of the frequency f generated in a subsequent circuit, and the oscillation generated in the subsequent resonant circuit is maintained even after the oscillations in the preceding resonant circuit are interrupted.

10. An electric circuit as claimed in claim 9 in which the number of groups of resonant circuits and power supply circuits is three.

11. An electric circuit as claimed in claim 9 in which the outputs of an odd number of resonant circuits in a preceding group are coupled to the input of a single resonant circuit in a succeeding group, whereby the phase of oscillation of the single resonant circuit is controlled by the phase of the majority of input signals.

12. An electric circuit as claimed in claim 9 in which the output of a single resonant circuit in a preceding group is coupled to the inputs of a plurality of resonant circuits in a succeeding group, whereby the phase of oscillation of the plurality of resonant circuits in the succeeding group is controlled by the phase of the single resonant circuit in the preceding group.

13. An electric circuit as claimed in claim 9 in which the output of a resonant circuit in a preceding group is coupled to the input of a resonant circuit in a succeeding group for reversing the phase of the output, whereby the phase of oscillation of the resonant circuit in a succeeding group will be opposite to the phase of the resonant circuit in the preceding group.

14. An electric circuit for binary digital operations, comprising a resonant circuit having a resonant frequency of near f and including a variable reactance the value of which is a parameter determining the resonant frequency of said resonant circuit, means for varying said parameter comprising an alternating power supply circuit having a frequency $2f$, a means for producing a D.C. bias in said variable reactance, and means applying said $2f$ frequency to said variable reactance to vary the value of said reactance and thereby generate in said resonant circuit parametric oscillations having a frequency f, said power supply circuit and resonant circuit being decoupled from each other so that said frequency $2f$ of the power supply circuit is not transmitted to said resonant circuit and the frequency f of said resonant circuit is not transmitted back to said power circuit, and means for controlling the power supply circuit for interrupting the oscillation of frequency f in said resonator circuit, whereby the binary digits are represented by the phase of the parametric oscillations and the parametric oscillations built up in said resonant circuit have only one of two possible phases which differ by 180° which is determined by the phase of a signal impressed on said resonator circuit at the start of the build up of parametric oscillations therein, and said oscillations continue until the means for controlling the power supply circuit is actuated even though the impressed signal is cut off.

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Fig. 1a

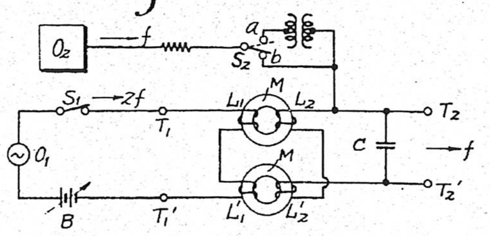


Fig. 1b

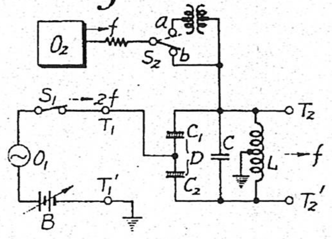


Fig. 1c

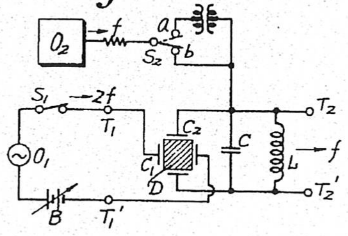
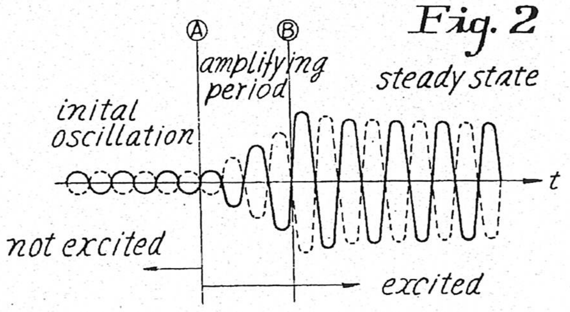


Fig. 2



INVENTOR.
EIICHI GOTO
BY
Wenderoth, Lind & Ponack
Attys.

Fig. 3a

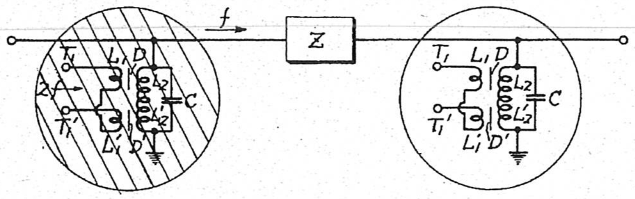


Fig. 3b

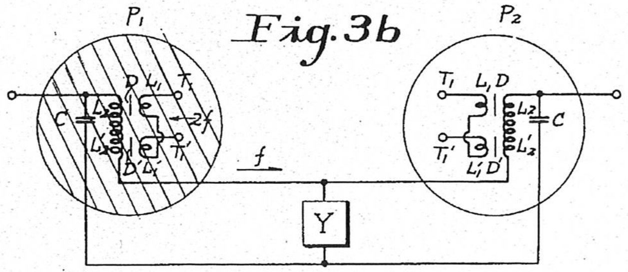
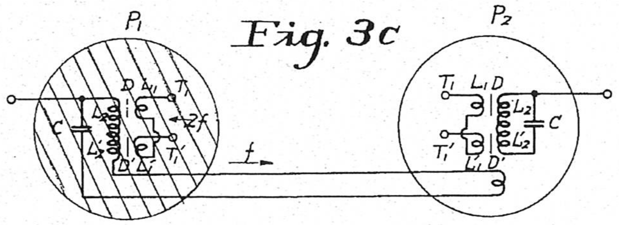


Fig. 3c



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EIICHI GOTO
BY
Wenderoth, Lind & Ponack
Attys.

Fig. 4a

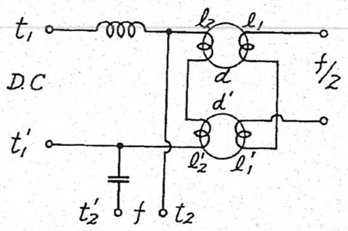


Fig. 4b

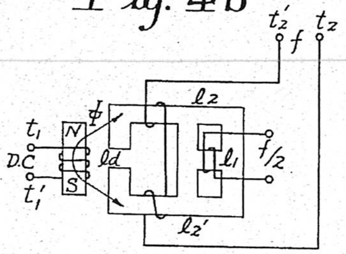


Fig. 5a

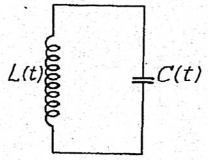


Fig. 5b

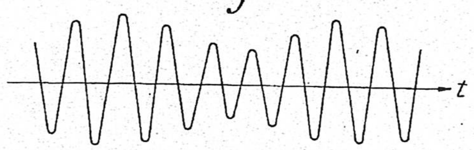
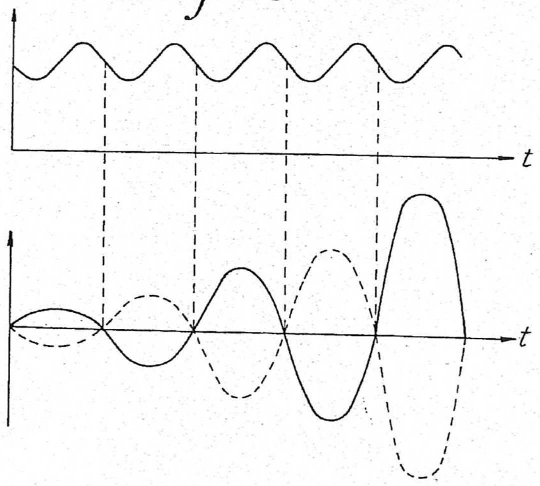


Fig. 5c



INVENTOR.
EIICHI GOTO
BY
Wenderoth, Lind & Ponack
Attys.

Fig. 6a

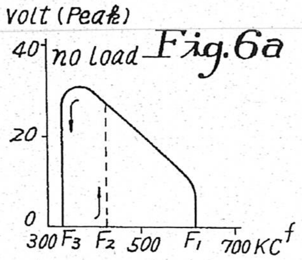


Fig. 6b

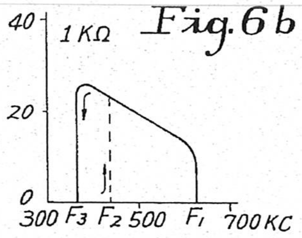


Fig. 6c

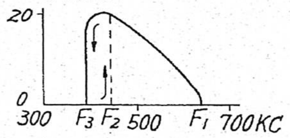


Fig. 6d

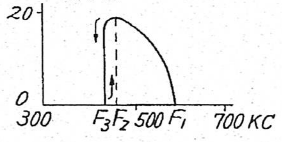


Fig. 8a

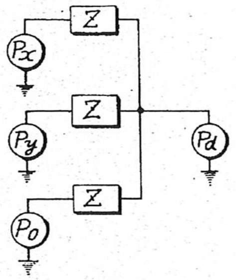
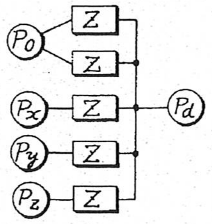


Fig. 8b



INVENTOR.
EIICHI GOTO
BY
Wenderoth, Lind & Ponack
Attys.

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RESONATOR CIRCUITS

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Fig. 7a

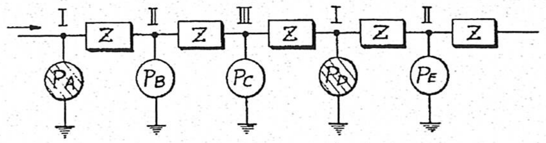


Fig. 7b

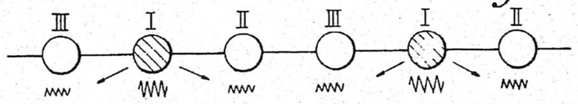


Fig. 7c

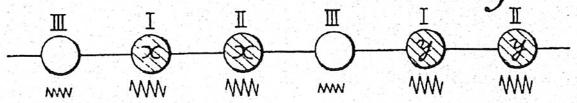


Fig. 7d

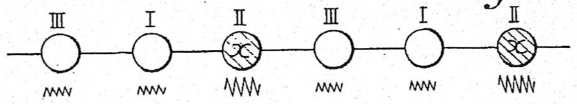


Fig. 9a

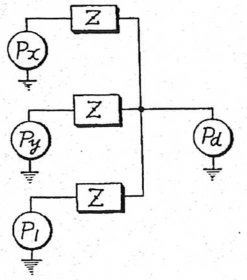
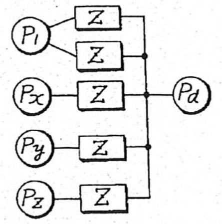


Fig. 9b



INVENTOR.
EIICHI GOTO
BY
Wenderoth, Lind & Ponack
Attys.

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Fig. 10

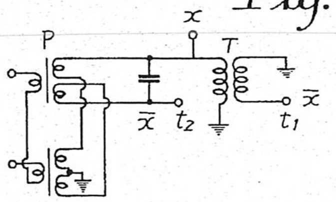

Fig. 11

P_o		P_x		P_y		P_d		
						before excitation	after excitation	
0	voltage	x	voltage	y	voltage	voltage	d	voltage
0	$-e$	1	e	1	e	ke	1	e
0	$-e$	1	e	0	$-e$	$-ke$	0	$-e$
0	$-e$	0	$-e$	1	e	$-ke$	0	$-e$
0	$-e$	0	$-e$	0	$-e$	$-3ke$	0	$-e$

Fig. 12

y x	1	0
1	1	0
0	0	0

$d = x_\wedge y$

Fig. 13

y x	1	0
1	1	1
0	1	0

$d = x^\vee y$

INVENTOR.
EIICHI GOTO
BY
Wenderoth, Lind & Ponack
Attys.

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Fig. 14

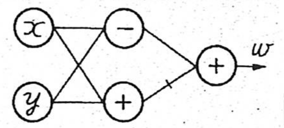
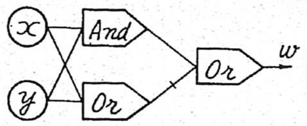
A		B	C
x	y		
1 0	1 0		

Fig. 15

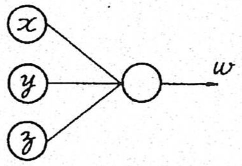
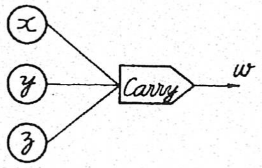
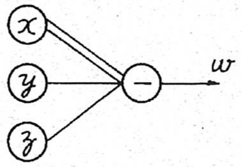
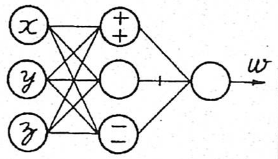
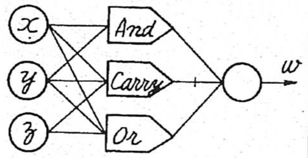
A			B	C
x	y	z		
1 0 1 1	1 1 0 1	1 1 1 0		
1 1 1	1 0 1	1 1 0		

Fig. 17

A			B	C
x	y	z		
1 1 0 0	1 0 1 0	1 0 0 1		

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Aug. 9, 1960 EIICHI GOTO 2,948,818

RESONATOR CIRCUITS

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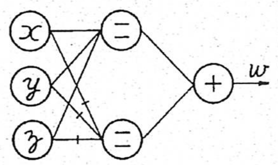
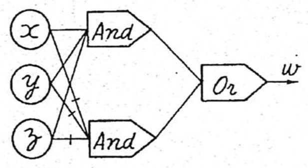
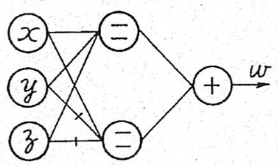
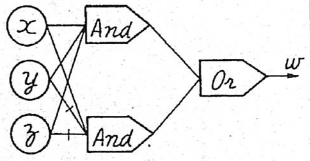
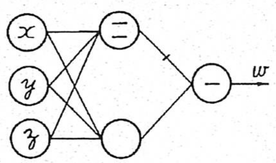
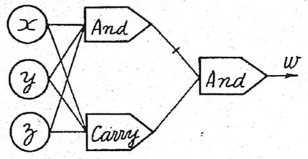
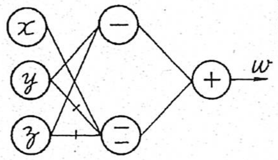
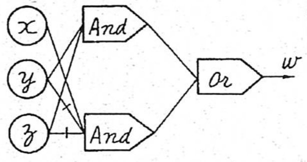
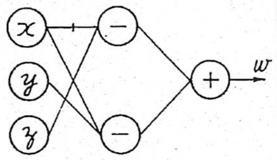
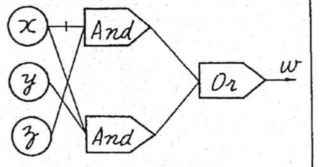
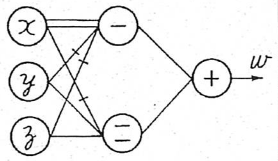
Fig. 16

A			B	C
x	y	z		
1 0	1 0	1 0		
1 1	1 0	1 0		
0 1 1	1 0 1	1 1 0		
0 1 1	1 0 1	1 0 1		
0 0 1 1	0 1 1 1	1 1 0 1		
0 1 1 1	1 0 0 1	1 0 1 0		

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