

Sept. 18, 1945.

E. LABIN

2,385,085

METHOD OF PRODUCING FREQUENCY MODULATED WAVES FOR RADIO TRANSMISSION

Filed July 11, 1942

2 Sheets-Sheet 1

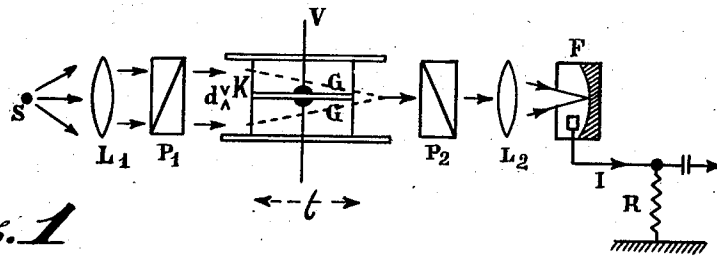


Fig. 1

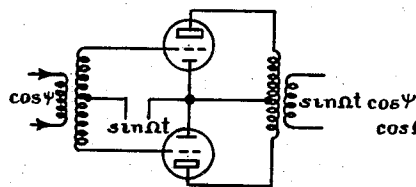


Fig. 2a: Differential intensity modulator

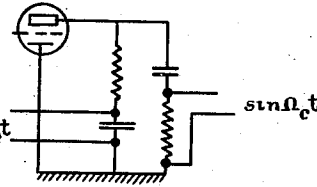


Fig. 2b: Phase shifter

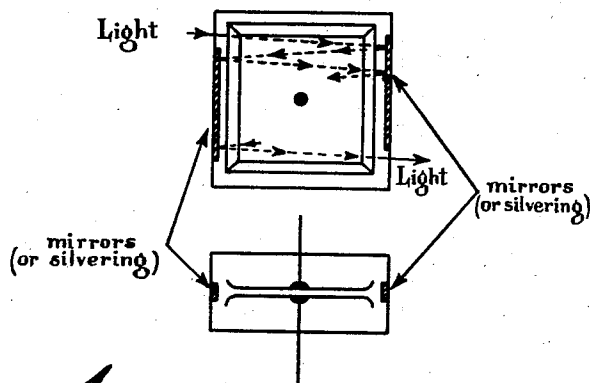


Fig. 3

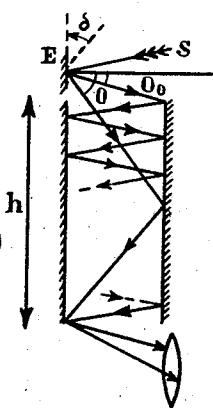


Fig. 4

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2 Sheets-Sheet 2

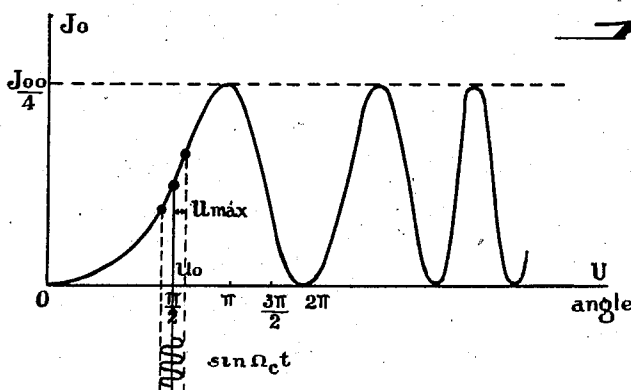


Fig. 6

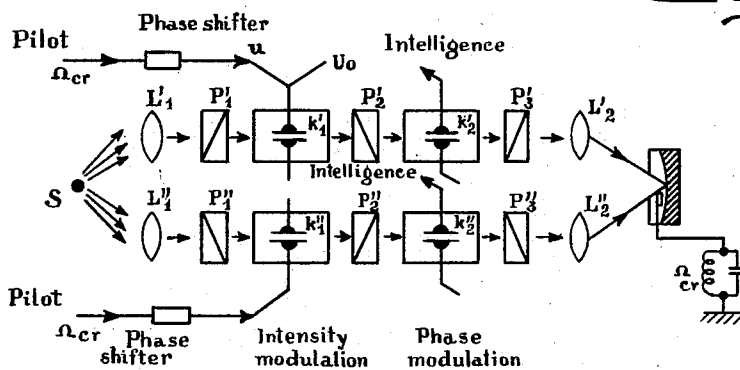


Fig. 7

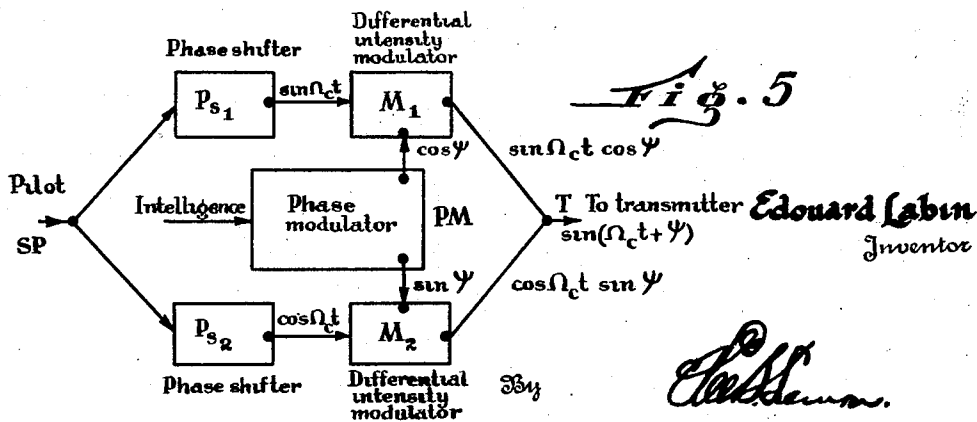


Fig. 5

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UNITED STATES PATENT OFFICE

2,385,085

METHOD OF PRODUCING FREQUENCY MODULATED WAVES FOR RADIO TRANSMISSION

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Application July 11, 1942, Serial No. 450,596

10 Claims. (Cl. 179—171.5)

The present invention relates to radio transmission of the type in which the transmitted wave is frequency modulated. More particularly, the invention is concerned with the production of the frequency modulated wave by a method of direct phase modulation.

It is well known that the chief difficulty encountered in frequency modulated transmission, is that of ensuring the stability of the central or "carrier" frequency (generally referred to by the symbol Ω_c) of the wave. The method of the present invention is based on the idea of generating the wave by taking the carrier term from a quartz pilot oscillator, whereby advantage may be taken of all the stability of standard transmitters.

It is known that a wave, the instantaneous frequency of which is a function of the time $\Omega(t)$, is written $U \sin \int \Omega(t) dt$, where U is the amplitude of the wave. Now the expression for the wave it is desired to create, as deduced from theory is

$$u = U \sin [\Omega_c t + \Psi] \quad (1)$$

where

$$\Psi = 2\pi k \int s(t) dt = 2\pi k A \int \sigma(t) dt = \beta \int \sigma(t) dt \quad (2)$$

and

$$s(t) = A \sigma(t) \quad (3)$$

is the intelligence of crest A , k being the slope of the characteristic of modulation and

$$\beta = 2\pi k A \quad (4)$$

the excursion of the frequency of the wave.

Integration of the intelligence may readily be obtained by means of an arrangement of parts generally known as an integrating microphone, which is a typical element of frequency modulation and therefore deemed to require no further description.

The integration brings to light an inverse proportionality with respect to the frequency of the intelligence. In fact, if the intelligence is reduced to the only pure sound of frequency:

$$s = A \cos \alpha t, \text{ then } \int s(t) dt = \frac{A}{\alpha} \sin \alpha t$$

and therefore,

$$\Psi = 2\pi \frac{kA}{\alpha} \sin \alpha t = \frac{\beta}{\alpha} \sin \alpha t = \xi \sin \alpha t \quad (4a)$$

The "index of modulation"

$$\xi = \frac{\beta}{\alpha}$$

measures the amplitude of the variable angle, Ψ .

The following table gives values for certain of the principal quantities involved in frequency modulation which values have been calculated in

well-known manner and on reasonable assumptions, as is usual in the art, and are intended to be chiefly illustrative.

Table 1

Quantity	High quality broadcasting	Spoken communications (mobile equipment)
Max. excursion given to instantaneous frequency of transmitted wave in p. p. s. β_{max}	70,000	15,000
Min. frequency of intelligence in p. p. s. α_{min}	35	300
Max. frequency of intelligence in p. p. s. α_{max}	10,000	3,000
Variation of power within the intelligence, in db.....	50	30
Maximum amplitude of phase displacement, Ψ_{max} , in radians.....	2,000	50
Minimum amplitude of phase displacement, Ψ_{min} , in radians.....	0.02	0.15
Dynamic $\Delta = \Psi_{max} + \Psi_{min}$	100,000	350

The value of the dynamic Δ controls the problem of the integrating stage of the intelligence, at least in broadcasting, when it is very high. Indeed, the tension v generated by the integrator must have the same range of variation as Ψ , and this gives rise to a difficulty on the side of the minimum values, since, if the maxima are arranged within the manageable domain of a few volts, the minima will fall within the domain of microvolts, where parasitic tensions reign. The difficulty has been overcome by careful construction of the integrator. In mobile equipment for the transmission of conversations, where the dynamic reduces to 350, the problem no longer arises.

The value of Ψ_{max} controls the problem of the very generation of the frequency modulated wave. Indeed, if Expression 1 for the frequency modulated wave is considered, it might be thought very simple to produce it with an Ω_c as stable as desired, by passing the output of a stabilised pilot (Ω_c) through a phase shifter, the phase displacement of which will be Ψ , and hence controlled by the integrated intelligence. But an ordinary phase shifter never gives phase rotations higher than a few π , in fact much less—about 25° —if fidelity of the control by the intelligence is taken into account. Therefore, in order to secure the 2,000 radians in the case of broadcasting, or even the 50 for mobile equipment, it would be necessary to multiply the argument generated by 500 or 10,000. This method has been, and still is, used, but it suffers from many complications and difficulties in design.

In order to avoid the need for neutralizing the amplifiers of the modulated wave and to bring the pilot frequency generator into the domain in which its circuits and, above all, the quartz shall be more manageable, some frequency multiplications are known to be desirable. According to known practice, the carrier frequency in the generating stage and the total excursion may be made initially small and the requisite higher values obtained subsequently by ordinary frequency multiplication. In some instances, a still lower frequency may be advantageous in the generating stage, in which event the still lower frequency used may be increased to an intermediate frequency without multiplication, by frequency conversion (heterodyning) with a pure sinusoidal wave and the thus obtained intermediate frequency subsequently multiplied in the ordinary way.

Reverting now to the main problem, namely, the production of the frequency modulated wave, it has been shown (above) that that wave may be expressed as $u = U \sin (\Omega_c t + \Psi)$, where Ψ is a term representing the integrated intelligence and is given by $2\pi k f s(t) dt$. It has also been pointed out that the integration of the intelligence is comparatively simple. Now, if it were possible to produce, from the intelligence $s(t)$, an oscillation tension $v = V \cos \Psi$, where the value of the angle Ψ is $k f s(t) dt$, with an amplitude of this angle as large as desired, then evidently the problem would be solved, since it would suffice to mix with an "L. F." tension $v = V \cos \Psi$, a sinusoidal "H. F." oscillation $u = U_0 \sin \Omega_c t$, of the carrier frequency Ω_c , taken from a pilot wave source of perfect stability, to obtain an oscillation u of the type required, which is directly proportional to the sum of the angles representing the carrier frequency and the integrated intelligence, and is written, as above, $u = U \sin (\Omega_c t + \Psi)$, which is the type required.

At this point, it is convenient to study more in detail the process of mixture, on the assumption that a L. F. oscillation varying as the sine or cosine of the integrated intelligence, is available. If the two oscillations $\cos \Psi$ and $\sin \Omega_c t$ are impressed on a modulator, amongst other terms the product $\cos \Psi \sin \Omega_c t$ is obtained, which still differs fundamentally from the desired oscillation $\sin (\Omega_c t + \Psi)$. Since the product contains this oscillation plus an oscillation in $\sin (\Omega_c t - \Psi)$, it might be thought easy to "isolate" one of these expressions by means of a filter; but deeper reflection will show that this would have no meaning. It is necessary to employ the following artifice. Take two radio-frequency oscillations in quadrature and of equal amplitudes:

$$\begin{aligned} u_1 &= U_0 \sin \Omega_c t \\ u_2 &= U_0 \cos \Omega_c t \end{aligned} \quad (5)$$

and two L. F. oscillations, also in quadrature and of equal amplitude:

$$\begin{aligned} v_1 &= V_0 \cos \Psi \\ v_2 &= V_0 \sin \Psi \end{aligned} \quad (6)$$

Thereupon it would be necessary to multiply or modulate u_1 by v_1 , and u_2 by v_2 , in the same degree m , thus:

$$\begin{aligned} mu_1 v_1 &= U \sin \Omega_c t \cos \Psi \\ mu_2 v_2 &= U \cos \Omega_c t \sin \Psi \end{aligned} \quad (7)$$

and then add the two products, giving, by elementary trigonometry:

$$mu_1 v_1 + mu_2 v_2 = U \sin (\Omega_c t + \Psi) \quad (8)$$

On the assumption that an oscillation $\cos \Psi$ can be produced, it is obvious that the complementary

oscillation $\sin \Psi$ can also be produced, so that we have not exceeded our initial hypothesis, and have only added well known and simple operations.

That the process which has just been described on the assumption that the oscillations $\cos \Psi$ or $\sin \Psi$ could be produced would be ideal for obtaining the frequency modulated waves, the central wave of which will have all the stability of the classical pilots, is obvious from the very constitution of such waves, and was recognised from the earliest times by several authors. But what always appeared to be an insuperable difficulty was precisely the generation of tensions of the type $V_0 \cos \Psi$ or $V_0 \sin \Psi$. To say that the variable angle $\Psi = k f s(t) dt$ is the argument of the tension to be generated, is to say that that tension has already been frequency modulated by the intelligence $s(t)$. If this modulation is effected by standard methods, it always appears around a central frequency Ω_c' and, by following the described process, it will readily be seen that a wave would be generated having a central frequency $\Omega_c \pm \Omega_c'$, so that it would be necessary to stabilise Ω_c' . Obviously this is a vicious circle.

Latterly, attempts have been made to escape from the circle, by producing tensions of the type $\cos \Psi$ or $\sin \Psi$, by direct and unusual methods which avoid the passage through a pre-modulation having a central frequency. D. Sabarof has published, in "Communications," September 1941, a diagrammatic description of a method which utilises the trace of a sine wave on black and white paper, a system of illumination, photo-electric cells, rotary mirrors driven by the modulating signal, and systems of slits and optical projections. Such a method is obviously cumbersome and costly, but it represents the only practical suggestion made prior to the present invention.

It has now been found that a very simple and efficient method of obtaining the desired result can be devised by making use of a photoelectric system including in the path of the exciting beam of light a pair of rectilinear polarising means arranged in quadrature and between said polarising means, a medium having voltage responsive double refraction properties, and so adjusting the operating conditions, that the rectilinearly polarised beam entering the medium from the first polarising means has impressed on it during its passage therethrough, a phase displacement which is a function of the intelligence, whereby said beam is enabled to pass through the second rectilinear polarising means and impinge on the photo-electric means, from which a current may then be derived which will contain the desired term.

It is, therefore, a principal object of the present invention to provide a novel and improved method for generating, in connection with frequency modulated radio transmission, an electrical quantity varying as a sinusoidal function of an angle proportional to the integrated intelligence.

Another object of the present invention is to provide a novel and improved method for generating, in connection with frequency modulated transmission, one electrical quantity varying as a sinusoidal function of an angle proportional to the integrated intelligence, and another electrical quantity having a sinusoidal variation proportional to the central frequency, and combining said two quantities to give a phase modulated component of the wave to be transmitted.

A further object of this invention is to provide an improved method of producing a frequency modulated wave for radio transmission by generating a carrier frequency wave in a stabilised pilot, passing said wave simultaneously through two parallel shifting zones one of which is in quadrature with the other, generating an intelligence and applying said intelligence simultaneously to two parallel phase modulation zones one of which is in quadrature with the other, one of the phase modulation zones corresponding to one of the phase shifting zones, and the other phase modulation zone corresponding to the other phase shifting zone, causing a rectilinearly polarised beam of light to pass through each phase modulation zone whereby its polarisation is modified in response to variations in the intelligence, passing said modified beam from each phase modulation zone through a second rectilinear polarisation zone in quadrature with the first rectilinear polarisation zone, whereby to produce a varying issuing beam from each phase modulation zone, the variations of each issuing beam being a sinusoidal function of the integrated intelligence and the variations of one issuing beam being in quadrature with those of the other, converting each of said varying issuing beams into a similarly varying electrical quantity, combining the modulated carrier frequency emerging from one phase shifting zone with the electrical quantity derived from the corresponding phase modulation zone, combining the modulated carrier frequency emerging from the other phase shifting zone with the electrical quantity derived from the other phase modulation zone, and simultaneously applying the two combinations to a common point of a transmitting means.

A still further object of the present invention is to provide an improved method of producing a frequency modulated wave for radio transmission by generating a carrier frequency, passing said frequency simultaneously through two parallel phase shifting zones one of which is in quadrature with the other, generating an intelligence and applying said intelligence simultaneously to two parallel phase modulation zones, one of which is in quadrature with the other, one of the phase modulation zones corresponding to one of the phase shifting zones and the other phase modulation zone corresponding to the other phase shifting zone, generating two beams of rectilinear light, passing said beams through respective preliminary polarisation zones, passing one of said beams through a first intensity modulation zone while applying to said zone the phase shifted carrier frequency issuing from one of said phase shifting zones, simultaneously passing the other of said beams through a second intensity modulation zone in parallel with the first intensity modulation zone, while applying to said second intensity modulation zone the phase shifted carrier frequency issuing from the other phase shifting zone, passing each intensity modulated beam through an intermediate rectilinear polarisation zone in quadrature with the respective first rectilinear polarisation zone, whereby to produce two varying intermediate beams the amplitude variations of which are a sinusoidal function of the carrier frequency, passing the one varying intermediate beam corresponding to the one phase shifting zone through the corresponding phase modulation zone, simultaneously passing the other varying intermediate beam through the other phase modulation zone, passing each phase

modulated beam through a final rectilinear polarisation zone in quadrature with the respective intermediate rectilinear polarisation zone whereby to produce a varying issuing beam from each phase modulation zone, the variations of each issuing beam being a resultant sinusoidal function of the carrier frequency and of the intelligence, simultaneously converting the two issuing beams into a single varying electrical quantity and applying said varying electrical quantity to a transmitting means.

These and other object and advantages of the present invention will become apparent in the course of the following detailed description thereof with reference to the accompanying drawings, in which:

Fig. 1 is a diagram illustrating one method of sinusoidal phase modulation of the present invention.

Fig. 2a is a diagram of the circuit connections of a differential intensity modulator.

Fig. 2b is a diagram of circuit connections for a phase shifter.

Fig. 3 is a diagram illustrative of the operation of a Kerr cell.

Fig. 4 is a diagram illustrating another method of operating the Kerr cell.

Fig. 5 is a diagram illustrative of the compounding of the sinusoidal factors corresponding to the carrier frequency and the intelligence.

Fig. 6 is a graph illustrative of the luminous intensity of the Kerr cell, and

Fig. 7 is a diagram illustrating a modified method of compounding the sinusoidal factors corresponding to the carrier frequency and the intelligence.

The essential features of the present invention, namely, the generating of a sinusoidal phase modulation by utilizing a Kerr cell, will best be understood by reference to Fig. 1, in which a source of light S is shown sending a beam through a lens L_1 and then through a Nicol prism P_1 , from which the beam issues as a ray rectilinearly polarised in a certain plane. Said ray then passes through a Kerr cell K, which provides a path l cms. long between two spaced plates G which are d cms. apart, said path being filled with pure nitrobenzene. It is known that if a potential V be applied to the plates G, this liquid has the property of becoming doubly refractive with an index of double refraction proportional to the square of the electric field V/d applied perpendicularly to the passing ray. The index of double refraction is also proportional to the length of path l through the field. When $V=0$ there is no double refraction and the polarisation of the ray remains, at exit from the cell, in the same plane as at entry, so that if on leaving the Kerr cell, the ray is compelled to pass through a second Nicol prism P_2 the plane of polarisation of which is perpendicular to that of said first prism, no light will pass beyond P_2 . But as soon as V has some definite value, the liquid becomes doubly refractive, and causes the ray to leave the cell with a polarisation differing from that impressed thereon by the first Nicol P_1 . Hence, a definite portion of light will pass through and beyond the second Nicol prism P_2 , to be focussed by lens L_2 onto the sensitive surface of a photo-electric cell F. As a net result, an electric current is obtained at the output of the photoelectric cell F, which is controlled by the double refraction of

the liquid and it has been shown that the value of the current is exactly

$$I = \frac{I_0}{4} \left[1 - \cos \frac{2\pi B I V^2}{d^2} \right] \quad (9)$$

where B is the Kerr constant of the liquid and I_0 is the value of the current corresponding to the total intensity of the luminous ray used if it fell directly on the photoelectric cell F.

As is seen, there is, in the variable part of the photoelectric current I, the magnitude in $\cos \Psi$ which is wanted, and the angle Ψ which is desired to create is here given by

$$\Psi = \frac{2\pi B I V^2}{d^2} \quad (10)$$

Before the process of modulator Ψ is explained in detail, it will be as well to consider the problems involved in the calculation of the cell.

The state of affairs from the photoelectric point of view will first be explained. In television, the Kerr cell has had only a limited success, because the attempt was made to use it for the projection of the images, and for this purpose, the luminous efficiency which is normally bad, was of critical importance. But in the present instance, it may readily be shown by calculating limiting values based on considerations of practical dimensions that only the electrical efficiency is of interest, that is to say that the sensitivity of the response to the modulation, and the luminous losses will be of no importance, since they do not call for the use of unreasonably large lamps.

In order to ascertain this last mentioned point, the worst case for the light, that is to say, when the cross-section of the luminous beam has been reduced to the last limit, will now be considered. Such reduction is a natural tendency because, in order to improve the electrical sensitivity, it is always convenient, according to Equation 10, to reduce the thickness d of the Kerr cell, which necessarily forms part of the dimensions of the luminous beam. If the thickness of the Kerr cell be reduced to the lowest desirable workable limit, any trouble with respect to the small value of the thickness may be compensated by a much greater increase in width of the beam. This beam would be defined by the opening in a diaphragm—probably the actual condenser of the Kerr cell would already play this part by reason of the lateral aperture it offers to the light—and such diaphragm would be illuminated by a beam, the cross section of which would be determined by the conveniences of optical construction of the lens L_1 of Fig. 1. The lenses here concerned need not offer refined optical qualities, and there would be no difficulty in finding and using very small lenses with a large relative aperture.

The efficiency of the photoelectric cell F in microamperes of output current per lumen of light input must now be considered. It is already possible to work comfortably with currents the amplitude of which may be indifferently 10, 1, or 0.1 microamperes. Moreover, it is always possible to use photoelectric cells with internal current amplification by secondary emission, and such amplification nowadays reaches, in commercial types, into the millions. This means that if only the output current (not the light for projection purposes) is used, it is possible today to utilize infinitesimally small light fluxes.

Theoretical consideration would seem to show that with a current of 1 μA with which to work, and a sensitivity of the photoelectric cell of 200

μA /lumen, the power required would be 50 watts, and this value can be still further reduced by choosing a slightly smaller value for the current, or a cell with a somewhat greater sensitivity.

The electrical sensitivity may be increased by reducing the wave-length of the light used, as by employing ultra-violet light, as may readily be done with the aid of modern resources, by increasing the length of path through the Kerr cell, and/or by decreasing the separation between the plates. Alteration of the pressure of the liquid used (nitrobenzene) would appear to be a further means of influencing the sensitivity.

The reduction of the separation between the plates and the increase of the length of path through the Kerr cell cannot be carried beyond certain limits in practice, for constructional and manufacturing reasons readily understandable by those skilled in the art. Hence, if further increase of the sensitivity is desired, recourse must be had to supplementary devices. For example, the sensitivity may be increased to almost any desired extent by increasing the effective length l of the path to a value many times more than the length of the plates, by means of a trajectory consisting of a number of to and fro travels impressed on the beam by two lateral mirrors. This type of Kerr cell is known but it was introduced into television for the purpose of increasing the optical efficiency.

Obviously, the increase in electrical sensitivity was also utilized, but the development was towards a multiple cell structure which could accommodate a beam of light the cross-section of which was enormously extended in a direction perpendicular to that of the necessarily reduced separation d of the plates G. This led to quite complicated structures which entailed such an increase in the capacity of the Kerr condenser that, bearing in mind the very high frequencies used in television, the impedance offered to the voltage V dropped until it formed a highly objectionable load for that voltage in so far as the power to be developed was concerned. In the present case, the structure may be very much simpler: two mirrors, or better still, two silver deposits on the glass walls which enclose laterally the Kerr cell, are sufficient, as may be seen from Figure 3. If the light is caused to fall on said mirrors with a small angle of incidence, as many to and fro passes may be made as desired, with a very small width of plate. With a width of 2 cms. for the 5 cms. length which is found admissible, and with a thickness of 0.01 cm., and bearing in mind the dielectric constant of nitrobenzene, the capacity C becomes approximately 1,000 $\mu\mu F$.

At the highest frequency α_{max} which the applied tension V will contain, that is to say, 100,000 p. p. s., this capacity represents an impedance of 15,000 ohms. It can be shown that, with such an arrangement the impedance constituted by the cell not only represents a completely negligible load for the tension V of the order of magnitude to be used (as hereinbelow defined), but is also advantageous for immediately allowing V to reproduce faithfully the grid voltage of the valve from which it issues, independently of the circuit associated with the plate. In fact, it suffices to employ for that valve a triode with a suitable internal resistance say of the order of 5,000 ohms, in order that the Kerr cell shall always represent an open circuit for the output. This will represent the optimum condi-

tions for the process of integration as known from the theory of this operation.

Calculations following the lines indicated above, lead to a possible maximum value for the

$$\text{Constant } a = \frac{2\pi B1}{d^2} \text{ of } 0.3$$

This shows that the electrical sensitivity also need not be regarded as a troublesome problem, and so much is this so, that in the following, it is possible directly to eliminate all considerations as to the construction of the Kerr cell, since there is the foregone assurance that it can be adapted to all classes of specification with an almost inexhaustible field of play in all the mechanical and optical dimensions.

There are now available three courses for completing the task involved in the present invention, said courses being three manners of modulating the

$$\text{Angle } \Psi = \frac{2\pi B1V^2}{d^2}$$

given by Equation 10, and created by the Kerr cell. The three manners are: (1) Directly, by making V^2 proportional to the integrated intelligence. (2) By using a V comprising a fixed portion and a variable portion proportional to the integrated intelligence, or (3), by making the length of path l in the cell proportional to the integrated intelligence.

In the more obvious first manner or method, the integrated intelligence $v = 2\pi kfs(t)dt$, is passed through a specially designed amplification stage which supplies an output tension V proportional to the square root of the input tension v :

$$V = b\sqrt{v}, V^2 = b^2v = 2\pi kfs(t)dt \quad (11)$$

Such a design is already known by the technique which allows all kinds of response curves to be made with electric waves. See, for example, M. Ziegler; "The Construction of a Hot Wire Anemometer with Linear Scale," *Verhandelingen der Akademie Amsterdam*, Deel xv, No. 1. If the output voltage of the square root stage is applied to the Kerr cell, then $\Psi = kfs(t)dt$ will be obtained directly as desired. The two signals in $\cos \Psi$ and $\sin \Psi$ will be obviously taken from two cells, of which the pairs of Nicol prisms (P_1, P_2) will be disposed perpendicularly to each other.

The electrical design is now very easy. As a matter of fact, the presence of the square root stage makes it possible to work at its input with a large maximum voltage v . Hence, the situation of the intelligence integrating stage which supplies v is considerably relieved with respect to current practice.

If the values of Table 1 are introduced, it follows that the conditions may be fulfilled with the following values:

	Broad-casting	Mobile equipment
$V_{\max}$ in volts	100	50
$a = \frac{2\pi B1}{d^2}$	0.0125	0.0004

This value of a in the case of mobile equipment is such that it can be obtained with perfectly ordinary and small Kerr cells and, if desired, without multiple passages.

In the second manner or method, the special square root amplification can be avoided, by dividing the tension V into a fixed portion V_0 and a portion v which will reproduce the integrated intelligence but which will always remain small compared with V_0 . Then, if a is the proportionality factor

$$\frac{2\pi B1}{d^2}$$

$$aV^2 = a(V_0 + v)^2 = a(V_0^2 + v^2) + 2aV_0v \quad (12)$$

wherefore

$$\cos \Psi = \cos a(V_0^2 + v^2) \cdot \cos 2aV_0v - \sin a(V_0^2 + v^2) \cdot \sin 2aV_0v \quad (13)$$

Let the value V_0 be so chosen that

$$\sin a(V_0^2 + v^2) = 0$$

and therefore $\cos a(V_0^2 + v^2) = 1$. It will be shown below how the upsetting of such a choice by the variations in the term v^2 may be prevented. Then

$$\cos \Psi = \cos 2aV_0v \quad (14)$$

and it is seen that the angle Ψ has now become directly proportional to v , whereby, as indicated, the square root stage is avoided. Moreover the creation of the two complementary signals becomes very easy, since it is possible to use a single pair of Nicol prisms, with two cells of identical geometry located alongside each other. Indeed, it is sufficient to give the second cell a fixed voltage V_0' such that $\cos a(V_0'^2 + v^2)$ will now vanish, while $\sin a(V_0'^2 + v^2)$ takes the value unity. Then, according to (13) the complementary signal is obtained:

$$\sin \Psi = \sin 2aV_0'v \quad (14_2)$$

The values V_0 and V_0' may lie very closely together, since it is sufficient if

$$a(V_0'^2 + v^2) = a(V_0^2 + v^2) + \frac{\pi}{2}$$

and it can be shown that values of V_0, V_0' can be used which are sufficiently big so that the difference of

$$\frac{\pi}{2}$$

shall correspond to differences less than 1% in V_0 . Then the two cells will give exactly the two desired signals.

It is, of course, necessary to limit v so that the angle av^2 shall never exceed a small value. From this it follows that the first condition of the problem will therefore be of the type:

$$av^2_{\max} = 0.25 \quad (15)$$

The second condition will be, as always, that the useful maximum angle $2aV_0v_{\max}$ shall correspond to the desired total excursion. According to Table I, and accepting a normal frequency multiplication, we have a condition of the type:

$$aV_0v_{\max} = \begin{cases} 60 & \text{in broadcasting} \\ 3 & \text{in mobile equipments} \end{cases} \quad (16)$$

Following out the calculations with these conditions, we arrive at values of the following type:

	Broad-casting	Mobile equipment
$\frac{a}{V_0}$	0.05 350	0.02 35

Finally, it should be noted that the present

manner or method of modulation affords a very convenient means of governing the excursion, that is to say, the adjustment of the polarisation V_0 , since the angle ψ created has the value $2\alpha V_0/v$. In ordinary systems, the excursion is adjusted by means of a change in the amplification of the integrating amplifier of the modulation, which change does not always follow immediately, since the operating point of such an amplifier is, as is well known, quite critical.

The third manner in which the process of phase modulation can be practiced, is developed as follows: The use of multiple passes of the ray, which can as easily reach high as well as low values, suggest the utilisation of the same parameter of length l for controlling the angle ψ .

Considering Fig. 4 in which the electrical field V is supposed applied perpendicularly to the plane of the paper, it is seen that when the mirror E is turned, on which the ray coming from S is reflected before being admitted into the cell, the length of path may vary enormously, from one to and fro movement to tens of such movements. Obviously the ray will leave the cell from one or other side thereof, and though this cannot be controlled, it is not serious since it is sufficient to locate outside of this cell and to one side thereof, a reflecting system having a field large enough to send everything to one and the same side. A more serious matter would be an irregularity in the length l of the path due to there not always being a whole number of to and fro passes. But on making accurate calculations, it is readily seen that such irregularity does not exist and that the length is always exactly:

$$l = \frac{h}{\sin \theta} \quad (18)$$

if θ is the angle of incidence of the ray at entrance and h the height of the lateral mirrors.

The angle θ is controlled by the rotation δ of the mirror E . If n reflections are used between the rotary mirror properly so called, and the entrance into the cell, then

$$\theta = \theta_0 + 2n\delta \quad (19)$$

where θ_0 is the minimum incidence giving the greatest length of path $l_{\max}$. The rotation δ may be controlled in its turn in several known ways, by the current i , which reproduces the integrated intelligence. For example, the rotary mirror may be suspended from a coil through which said current i passes and which is located in a fixed magnetic field H , as in moving coil ammeters; or else the mirror may be attached to a magnetic needle, the current then circulating in a magnetising coil of field $H = hi$. By adding to the system various fixed magnetic fields, duly arranged, in amplitude and direction, it is readily possible to obtain a law of rotation δ as a function of i :

$$\delta = f(i) \quad (20)$$

such that, when introduced into Equation 18, with the help of (19), a practically linear control of the length l by the current i is obtained, within the limits of variation of i and δ :

$$l = \frac{h}{\sin [\theta_0 + 2nf(i)]} = A + Bi \quad (20 \text{ bis})$$

It should be added that, in order to perfect such an arrangement, another recourse is available which is the shape of the lateral fixed mirrors of the cell, which need not be plane as shown in Fig. 4.

The rotary mirror will naturally be of the ultra-light type as used in mechanical oscillo-

graphs, since it must respond to variations having up to 10,000 periods per second.

In this method or manner, it will be seen that it is possible to use a single Kerr cell for generating the two complementary signals, by separating the paths of the two rays and giving the one, by an arrangement of mirrors, a supplementary travel corresponding to an angle of

$$\frac{\pi}{2}$$

the angle being concisely given by

$$\frac{2\pi B l_0}{\lambda^2}$$

which in practice approximates and is assumed equal to

$$\frac{\pi}{2}$$

In practice the process of mixing the sinusoidal components, which has been disclosed hereinabove, may be performed by using perfectly classical methods, and will offer no difficulties other than those encountered in any radio set.

This classical process is illustrated in Fig. 5. The elements PS_1 and PS_2 , labelled phase shifters, are adapted to give to the oscillation Ω_c originating from the stabilised pilot SP , the two forms in quadrature of Equation 5. The element PM , designated phase modulator, receives the intelligence $s(t)$ —if necessary already integrated—and makes of it the two signals in quadrature of Equation 6. The said phase modulator is precisely the element which comprises essentially the Kerr cell, as hereinabove explained, and in which the phase modulation is impressed on the intelligence according to the method which is the principal object of the present invention. The multiplication of each L. F. oscillation with the corresponding H. F. oscillation is carried out in two classical modulators M_1 , M_2 , which have been designated "intensity modulators" to distinguish them from the phase modulator. To add the two products thus obtained, it is sufficient to apply the outputs of the intensity modulators simultaneously to a common point of a transmitter, as indicated at T in the figure.

An ordinary intensity modulation generates not only the products (7), but at the plate of the modulating tube, there also appear currents which reproduce the two individual oscillations applied. The L. F. oscillation will not give an output voltage, because the plate circuit will be closed through a filter capable of rejecting it completely. But such a filter cannot reject the current in the carrier frequency Ω_c , located right in the middle of the band which it must transmit. However, a differential modulator of the classical type shown in Figure 2a can be used to eliminate the carrier by a process of internal opposition. Furthermore, it should be mentioned that the presence of a certain portion of pure carrier beyond the modulating system, and hence up to within the aerial, does not do much damage to the reception of the useful wave, and so long as such portion does not exceed a value of some tenths (in power) of the useful wave. In fact, it is known that the reception of frequency modulated wave offers a very good protection against interference signals the amplitude of which is a few times lower than that of the desired signal, wherever the frequency of the former is located with respect to that of the latter. The same may be said of any lack of symmetry

between the two paths, which is translated by the persistence of a lateral band at the output, alongside the desired wave. It is thus seen that the arrangement of the system of mixture is not critical. Fig. 2b illustrates one of many possible types of phase shifter.

Direct intensity modulation for application to frequency modulation may be achieved as follows. The multiplication of a L. F. tension $v_1 = V \cos \Psi$ by a H. F. voltage $u_1 = U_0 \sin \Omega_c t$, may be effected without the differential modulators of Fig. 5, whenever the intensity V of the L. F. voltage can be controlled independently. Let it be supposed that the phase modulator which provides $V \cos \Psi$ from $s(t)$ (or from $\Psi = k \int s(t) dt$) operates without perturbations whatever may be the amplitude V , and, more particularly, even if the amplitude V varies in time with a H. F. rhythm. Then it is purposely controlled by the piloted frequency, that is to say, it is made to be of the type $V = V_0 \sin \Omega_c t$, so that from the phase modulator the output is directly the product $V_0 \sin \Omega_c t \cos \Psi$. The complementary phase modulation path, which generates $\sin \Psi$, would be modulated in intensity by the piloted oscillation in quadrature $\cos \Omega_c t$. The combination at a common point of the outputs of the two paths effects the addition required to give the complete wave. In this second method of intensity modulation, two differential modulators as well as two separate outputs for the two phase modulation paths are suppressed, and the necessary devices are added to control the amplitude of the L. F. oscillations in accordance with the rhythm of the H. F. oscillation. The net result of this is always a simplification of the system.

It will now be shown how the amplitude of the magnitude created in the phase modulation Kerr cell may itself be modified.

As shown above, a Kerr cell supplies an electric current

$$\frac{I_0}{4} [1 - \cos \Psi] I_0$$

being the intensity corresponding to the total intensity J_0 of the ray of light entering the cell. Now, it is known that the cell has an inertia not greater than 10^{-3} sec., which means that the cell will perform the previously stated work without change in spite of any concomitant variation in I_0 , provided that such variation is no more rapid than 10^3 times a second. It is therefore seen to be possible, with the frequency Ω_{cr} of several megacycles, to utilise the foregoing principle, that is to say, to suppress the separate intensity modulators and directly modulate the luminous intensity J_0 at the rhythm of the piloted oscillation $\sin \Omega_c t$. The subscript r will indicate the magnitudes before frequency modulation.

The modulation of luminous intensity offers no great difficulty; another Kerr cell between crossed Nicol prisms would be used, and such cell will now be briefly described.

Since the luminous response of a cell as a function of the tension U energising the plates, is

$$J_0 = \frac{J_{00}}{4} (1 - \cos aU^2)$$

the first step must be the suppression of the effect of the square of U , by composing this tension, as has already been explained above, of a fixed portion U_0 and of a variable portion u which shall be small compared with U_0 . Moreover, the cosine, in which form u now appears, is here troublesome, since it is desired that the response of the cell vary not as $\cos u$, but as u .

Therefore matters must be so arranged that the angle aU^2 always varies in the neighbourhood of

$$\frac{\pi}{2}$$

that is to say, so that we have:

$$a(U_0 + u)^2 = a(U_0^2 + u^2) + 2aU_0u = \frac{\pi}{2} - \phi \quad (21)$$

where ϕ is small. The arrangement is illustrated in Figure 6 in which the curve represents the normal response $J_0 = f(U)$ of a cell as a function of U (the angle of aU^2 corresponding to U being shown beside U on the horizontal axis), and shows how this is possible by a suitable adjustment of the working point in a manner well known to those skilled in the art.

With this arrangement, a luminous intensity J_0 has been obtained which is not exactly proportional to the piloted voltage u but of the type

$$J_0 = \frac{J_{00}}{4} (1 - Au)$$

provided with a mean portion. Thus the current which will issue from the photoelectric cell will be:

$$I = \frac{I_0}{4} (1 - A \sin \Omega_{cr} t) (1 - \cos \Psi) =$$

$$\frac{I_0}{4} (1 - \cos \Psi) + \frac{I_0}{4} (A \sin \Omega_{cr} t) (1 - \cos \Psi) \quad (22)$$

The second part of this is desired, the first not. But since the useful part is of high frequency, whereas the useless part is of low frequency, it is easy to prevent it from being troublesome by providing at the output, instead of a resistance, a circuit tuned to Ω_{cr} (with a band passing $\pm \beta$). In any event it is always necessary to provide a tuned circuit at a point where it is desired to take off a high frequency voltage.

The diagram of Fig. 7 illustrates the elements included in two modulation paths according to the present method. The light J_{00} generated by the lamp S passes through the lenses L_1', L_1'' , two Nicol prisms P_1', P_1'' , and then through the intensity modulation cells K_1', K_1'' . These have applied to them the same mean voltage U_0 , and the two tensions in quadrature of frequency $\Omega_{cr} \approx 3$ or 6 mc., supplied by phase shifters P_2 connected to the output of the pilot p . The Nicol prisms P_2', P_2'' , through which the two rays pass on issuing from the cells K_1', K_1'' , act simultaneously as prisms of entry to the phase modulation cells K_2', K_2'' , and as complements to the prisms P_1', P_1'' . The last mentioned cells are controlled by the intelligence according to one of the three methods already described above. The device is completed by the two prisms P_3', P_3'' , and the lenses L_2', L_2'' , which direct the two rays together onto a common photoelectric cell F , the output circuit of which is provided with a circuit tuned to Ω_{cr} .

According to the foregoing description and the values which have been found by typical calculations, it will be appreciated that in the practical application of the invention, the whole of the parts which effect the modulation, both as to intensity and as to phase, can always be enclosed in cases the dimensions of which will not go beyond decimeters in the case of mobile equipment, nor be very much bigger in the case of broadcasting. Such cases will have only three external terminals, to one of which the piloted oscillation would be applied, another receiving the (integrated) intelligence, while from the third

the desired wave would be taken off. Said wave need only be amplified in the classical manner through the subsequent stages of the transmitter up to the aerial, with the admissible number of multiplications. All parts within the housing are adjusted at the factory so that the F. M. circuits no longer absorb the largest part of the task of adjusting a transmitter. From this it follows, that the present method offers the possibility, which is interesting from the commercial point of view, of building universal frequency modulation units which will adapt themselves very readily to all the usual types of transmitter.

Although in the course of the foregoing description reference has been made to certain preferred values, modes of operation and forms of embodiment of apparatus, the present invention is not intended to be limited thereby, and it is understood that sundry modifications may be made therein without departing from the spirit and scope thereof as defined in the accompanying claims.

I claim:

1. A method of generating an electrical quantity varying as a sinusoidal function of the sum of two angles, comprising the steps of generating a wave having a stabilized frequency, generating a varying and oscillating electrical quantity, deriving from said wave two oscillations in phase quadrature, rectilinearly polarizing two light beams, the polarization of one beam being in quadrature with that of the other, phase modulating each polarized beam by subjecting the same to voltage excited double refraction, varying the degree of double refraction in response to a control quantity having a relationship with said varying and oscillating electrical quantity, rectilinearly polarizing the doubly refracted beams in quadrature with the respective initial polarization whereby the resultant intensity of each beam is caused to vary as a sinusoidal function of an angle depending on said control quantity, adjusting the relationship between said control quantity and said varying and oscillating electrical quantity so that said angle shall be proportional to said varying and oscillating electrical quantity and each beam has impressed on it a phase shift which is a sinusoidal function of said varying and oscillating electrical quantity and the function in one beam is in quadrature with that in the other beam, converting each beam into a corresponding varying electrical quantity, combining the electrical quantity derived from one of the phase modulated beams with one of the oscillations derived from the stabilized wave, combining the electrical quantity derived from the other of the phase modulated beams with the other of the oscillations derived from the stabilized wave, and electrically combining the so-derived combinations.

2. A method of generating an electrical quantity according to claim 1, in which said control quantity is directly proportional to the square root of the sum of the useful oscillating electrical quantity and a mean quantity equal at least to the maximum of said oscillating electrical quantity.

3. A method of generating an electrical quantity according to claim 1, in which said control quantity is directly proportional to the square root of the sum of a mean portion and the useful and oscillating electrical quantity and said oscillating electrical quantity has such a value with respect to the mean portion that the square root rela-

tionship is substantially equal to a linear relationship.

4. In the art of radio transmission, the method of generating an electrical quantity having a variation which is a sinusoidal function of an angle proportional to an oscillating electrical quantity, comprising the steps of rectilinearly polarizing a beam of light, subjecting the polarized beam to voltage excited double refraction within a portion of the trajectory thereof, varying the length of path of the beam through said portion of its trajectory in response to a control quantity having a relationship with said oscillating electrical quantity, rectilinearly polarizing the doubly refracted beam in quadrature with the initial polarization whereby the resultant intensity of the beam is caused to vary as a sinusoidal function of a useful angle depending on said control quantity, adjusting the relationship between the control quantity and the useful oscillating electrical quantity so that said useful angle shall be directly proportional to the useful oscillating electrical quantity, and converting the beam into a similarly varying electrical quantity.

5. A method of generating an electrical quantity varying as a sinusoidal function of the sum of two angles, comprising the steps of generating a wave having a stabilized frequency, generating a varying and oscillating electrical quantity, deriving from said wave two oscillations in phase quadrature, rectilinearly polarizing two light beams the polarization of one beam being in quadrature with that of the other, phase modulating each polarized beam by subjecting the same to voltage excited double refraction over a portion of the respective trajectories of the beams, varying the length of path of each beam in said portion of the trajectories in response to a control quantity having a relationship with said varying and oscillating electrical quantity, rectilinearly polarizing each of the doubly refracted beams in quadrature with the initial polarization thereof whereby the resultant intensity of each beam is caused to vary as a sinusoidal function of an angle depending on said control quantity, adjusting the relationship between said control quantity and the varying and oscillating electrical quantity so that said angle shall be proportional to said varying and oscillating electrical quantity and each beam shall have impressed on it a phase shift which is a sinusoidal function of said varying and oscillating electrical quantity and the function in the one beam is in quadrature with that in the other, converting each beam into a correspondingly varying electrical quantity, combining the electrical quantity derived from one of the phase modulated beams with one of the oscillations derived from the stabilized wave, combining the electrical quantity derived from the other of the phase modulated beams with the other of the oscillations derived from the stabilized wave, and electrically combining the so-derived combinations.

6. In the art of radio transmission, the method of generating an electrical quantity according to claim 4, in which the length of path of the beam in the portion of its trajectory subjected to voltage excited double refraction is varied by impressing on the beam an angular change in direction prior to the entry thereof into said trajectory portion, subjecting the beam to a plurality of alternating opposed transverse reflections while traveling through said portion of its trajectory, the number of said reflections being dependent on the degree of said angular change of direction,

and controlling the degree of said angular change of direction by said control quantity.

7. A method of generating an electrical quantity according to claim 5, in which the length of path of each beam in the portion of its trajectory subjected to voltage excited double refraction is varied by impressing on the beam an angular change of direction prior to its entering said portion of its trajectory, subjecting the beam to a plurality of alternating opposed transverse reflections while traveling over said portion of its trajectory, the number of said reflections being dependent in the degree of angular change of direction, and controlling the degree of angular change of direction by said control quantity.

8. A method of generating an electrical quantity varying as a sinusoidal function of the sum of two angles, comprising the steps of generating a wave having a stabilized central frequency, generating a varying and oscillating electrical quantity, deriving from said wave two oscillations in phase quadrature, rectilinearly polarizing two beams of light the polarization of one beam being in quadrature with that of the other, subjecting each beam to voltage excited double refraction while controlling the degree of refraction of one beam by one of the oscillations derived from said wave and the degree of refraction of the other beam by the other of the oscillations derived from said wave to impress on each beam an intensity modulation corresponding to the respective oscillations, rectilinearly polarizing each intensity modulated beam in quadrature with the respective initial polarization whereby the intensities of the twice polarized beams corresponds directly to a sinusoidal function of one of said angles one function being in quadrature with the other, subjecting each polarized intensity modulated beam to voltage excited double refraction, controlling the degree of double refraction in response to a control quantity having a relationship with said varying and oscillating electrical quantity, subsequently rectilinearly polarizing each of said beams in quadrature with the respective second polarization thereof whereby the resultant intensity of each emerging beam varies as a combination of the respective sinusoidal functions of said one of the angles and

of another angle depending on said control quantity, adjusting the relationship between the control quantity and the varying and oscillating electrical quantity so that said other angle shall be proportional to said varying and oscillating electrical quantity and each intensity modulated beam shall have impressed on it a phase shift which is a sinusoidal function of said variable and oscillating electrical quantity the function in one beam being in quadrature with that in the other, converting each beam into a similarly varying electrical quantity and electrically combining the so-derived combinations.

9. A method of generating an electrical quantity according to claim 1, comprising the step of controlling the variation of the electrical quantity by adjusting the mean portion of the varying and oscillating quantity.

10. A method of generating an electrical quantity varying as a sinusoidal function of the sum of two angles comprising rectilinearly polarizing a light beam, subjecting the polarized light beam to voltage excited double refraction proportional to variations of a control quantity, rectilinearly polarizing the doubly refracted beam in quadrature with the initial rectilinear polarization, subjecting the polarized doubly refracted beam to voltage excited double refraction proportional to variations of a second control quantity, rectilinearly polarizing the said beam in phase with the initial rectilinear polarization, rectilinearly polarizing a second light beam, subjecting said second light beam to voltage excited double refraction proportional to variations of a control quantity in quadrature with the first of the control quantities applied to the first light beam, rectilinearly polarizing the doubly refracted second beam in quadrature with the initial polarization thereof, subjecting the so polarized doubly refracted beam to voltage excited double refraction proportional to variations of a second control quantity in quadrature with the other of the control quantities applied to the first light beam, rectilinearly polarizing the second light beam in phase with the initial rectilinear polarization thereof, converting the so treated beams into corresponding electrical quantities, and combining the so derived electrical quantities.

EDOUARD LABIN.

Certificate of Correction

Patent No. 2,385,085.

September 18, 1945.

EDOUARD LABIN.

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows: Page 2, first column, line 51, for the word "though" read *thought*; page 3, second column, line 30, for "sinusoldal" read *sinusoidal*; page 4, first column, lines 4 and 15, page 5, first column, lines 6, 22 and 69, same page, second column, line 8, and page 6, second column, line 13, for that portion of the equations reading "B1" read *Bl*; page 4, first column, line 12, after "which" second occurrence, insert the word *it*; page 5, first column, line 43, for "waves" read *valves*; and second column, line 20, for "choise" read *choice*; and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 25th day of December, A. D. 1945.

[SEAL]

LESLIE FRAZER,
First Assistant Commissioner of Patents.