

Feb. 25, 1930.

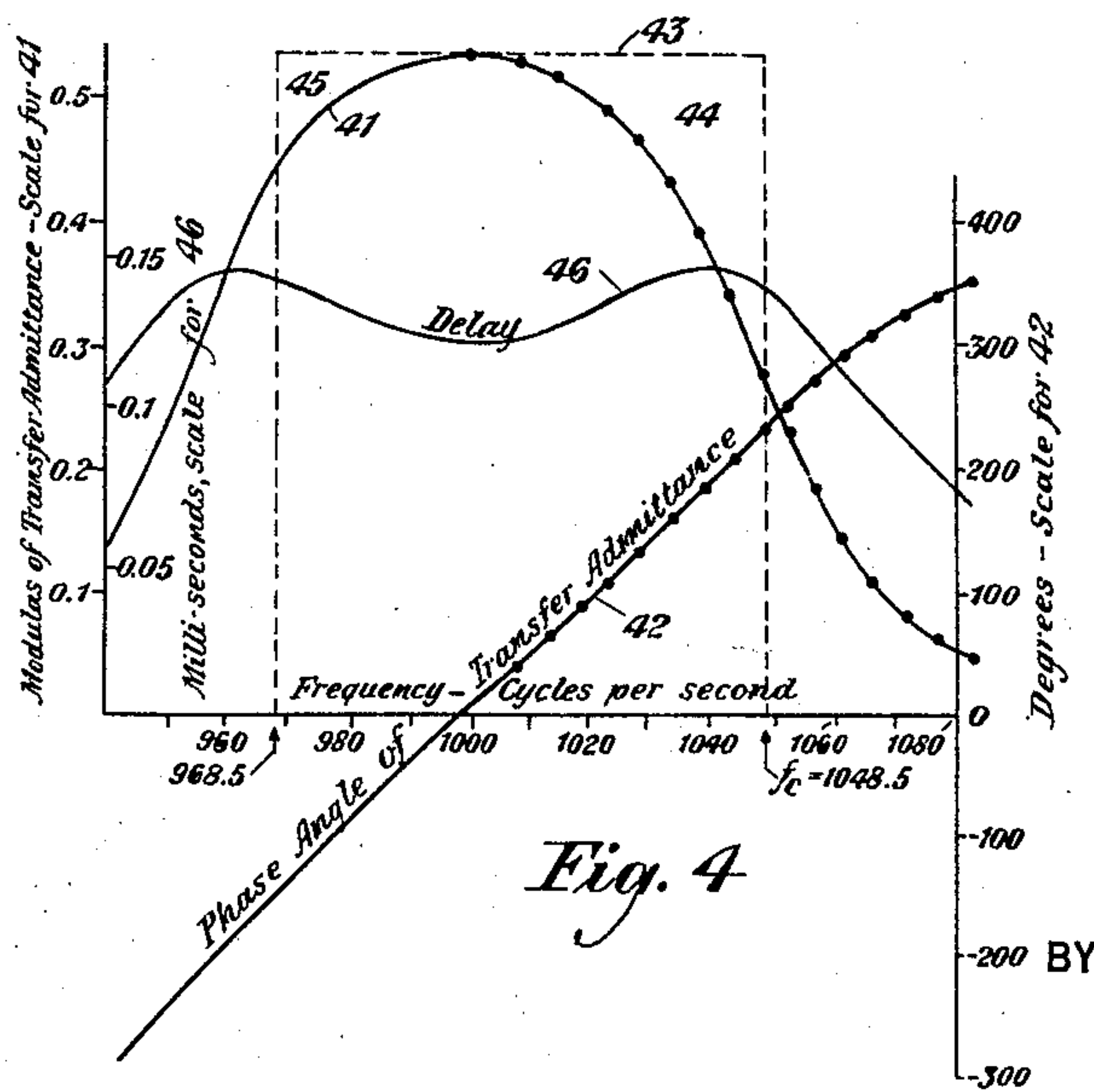
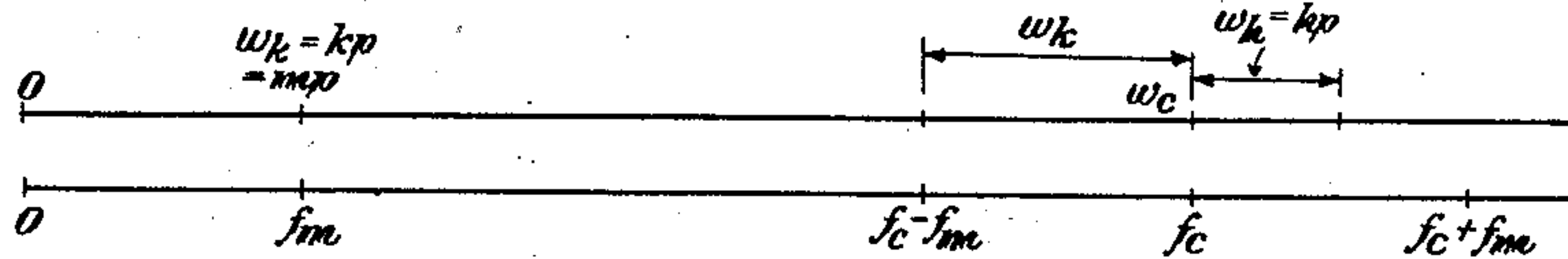
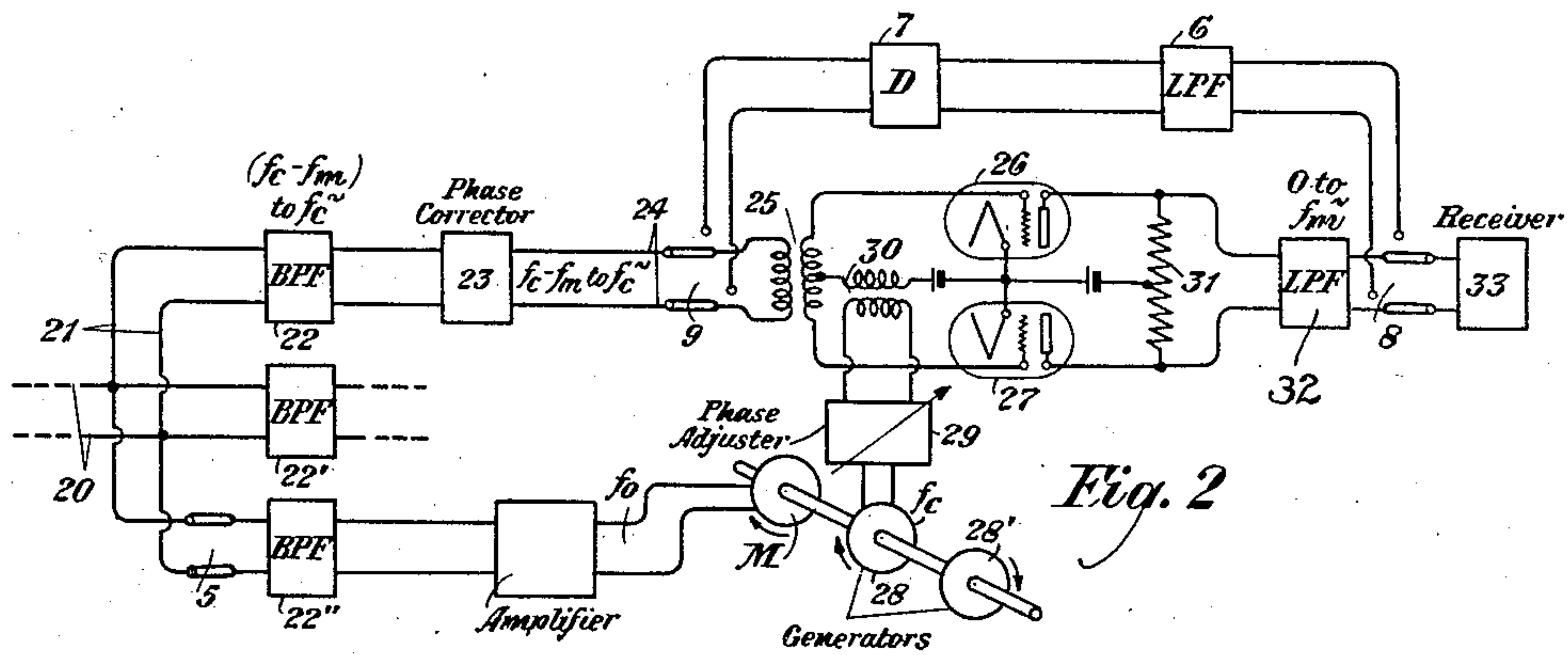
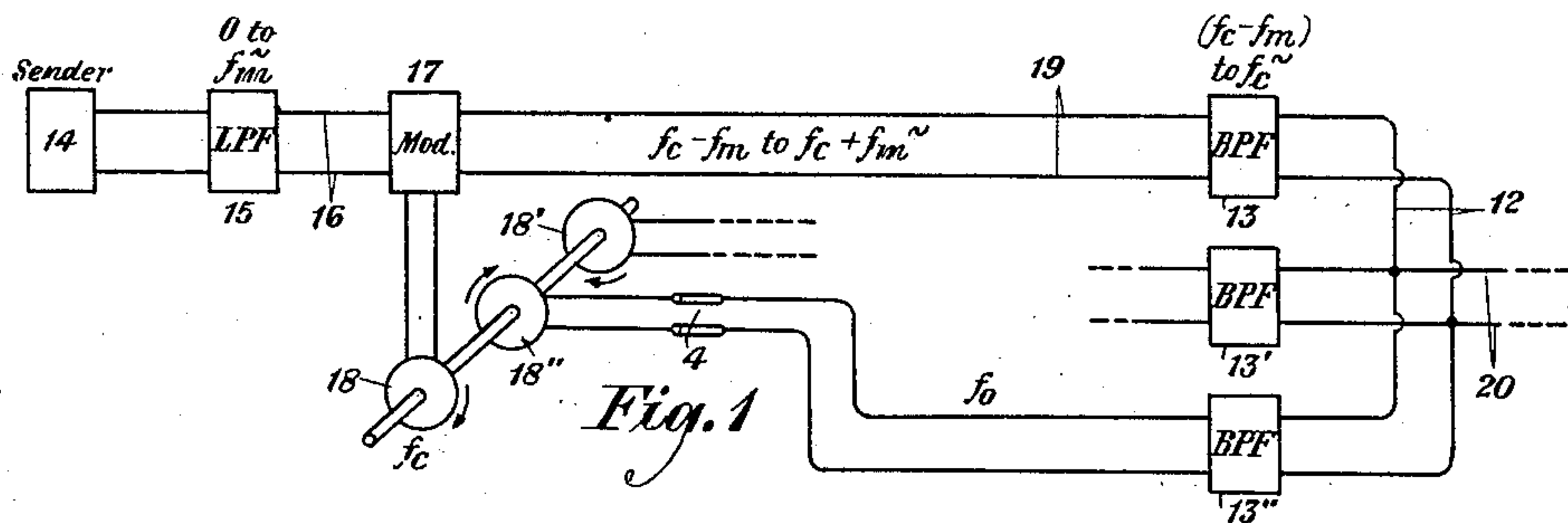
H. NYQUIST

1,748,186

SIGNALING SYSTEM

Filed Feb. 11, 1928

3 Sheets-Sheet 1



INVENTOR
H. Nyquist
BY
92402
ATTORNEY

Feb. 25, 1930.

H. NYQUIST

1,748,186

SIGNALING SYSTEM

Filed Feb. 11, 1928

3 Sheets-Sheet 2

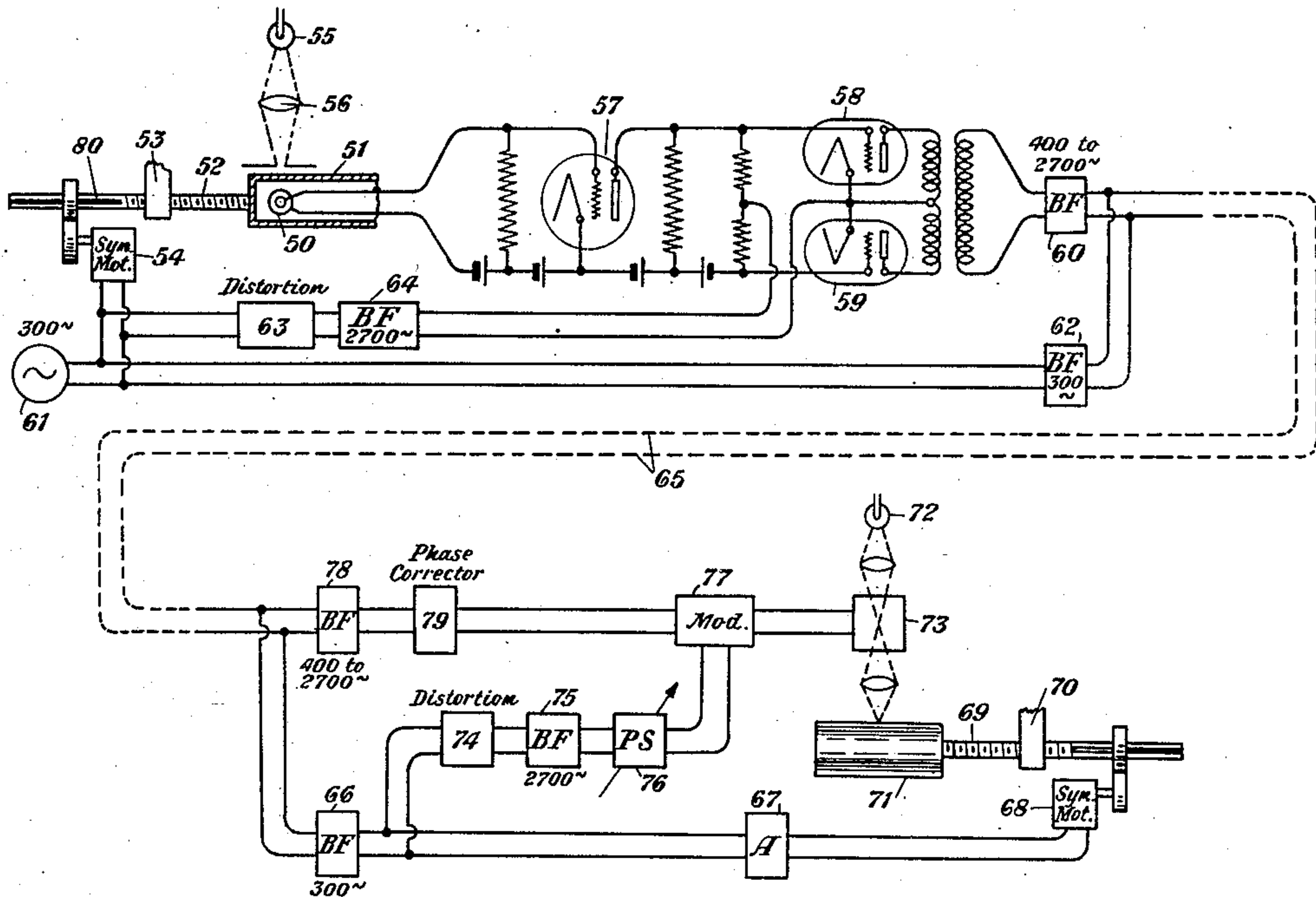


Fig. 5

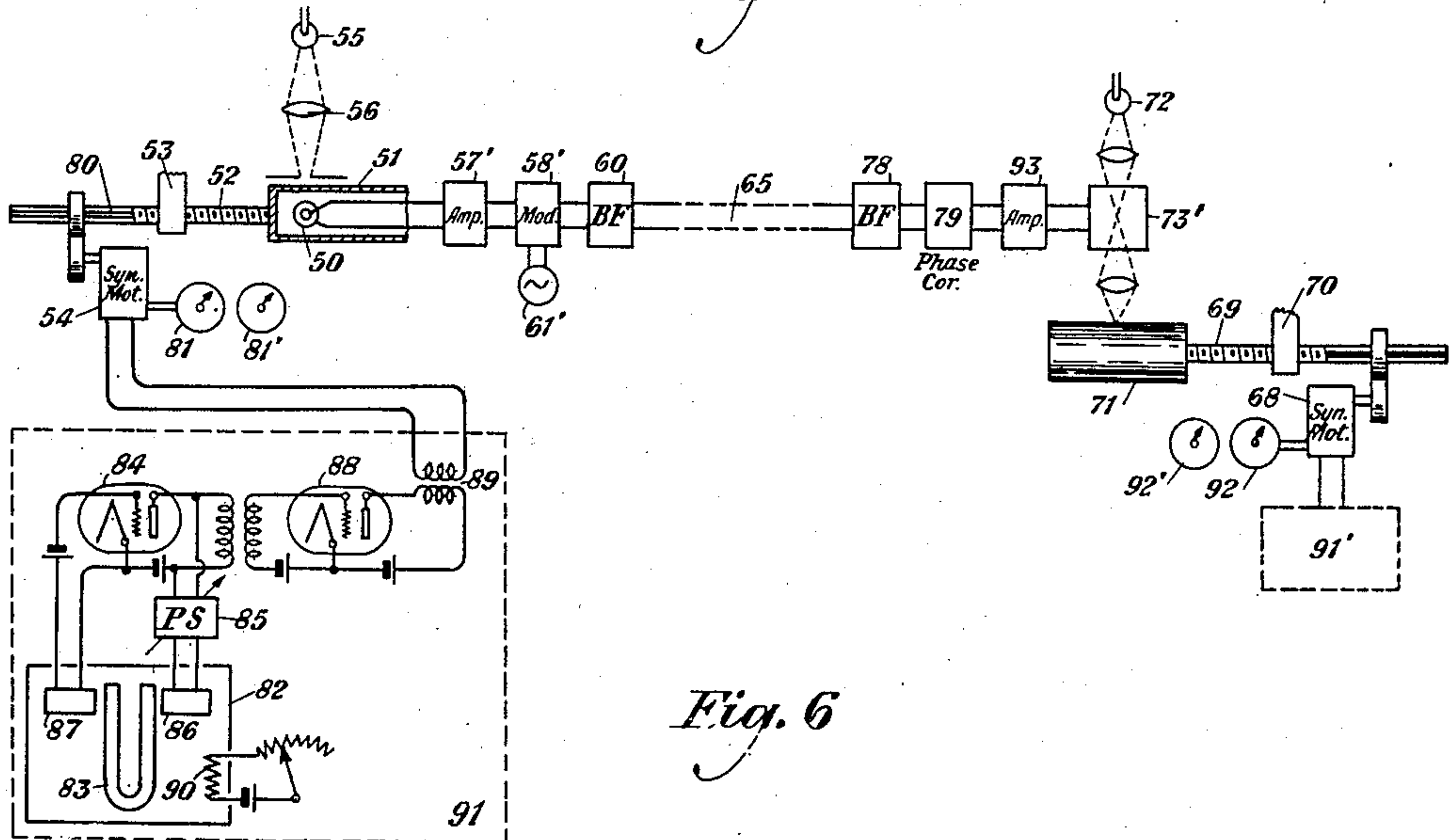


Fig. 6

INVENTOR
H. Nyquist
 BY *g. f. p.*
 ATTORNEY

Feb. 25, 1930.

H. NYQUIST

1,748,186

SIGNALING SYSTEM

Filed Feb. 11, 1928

3 Sheets-Sheet 3

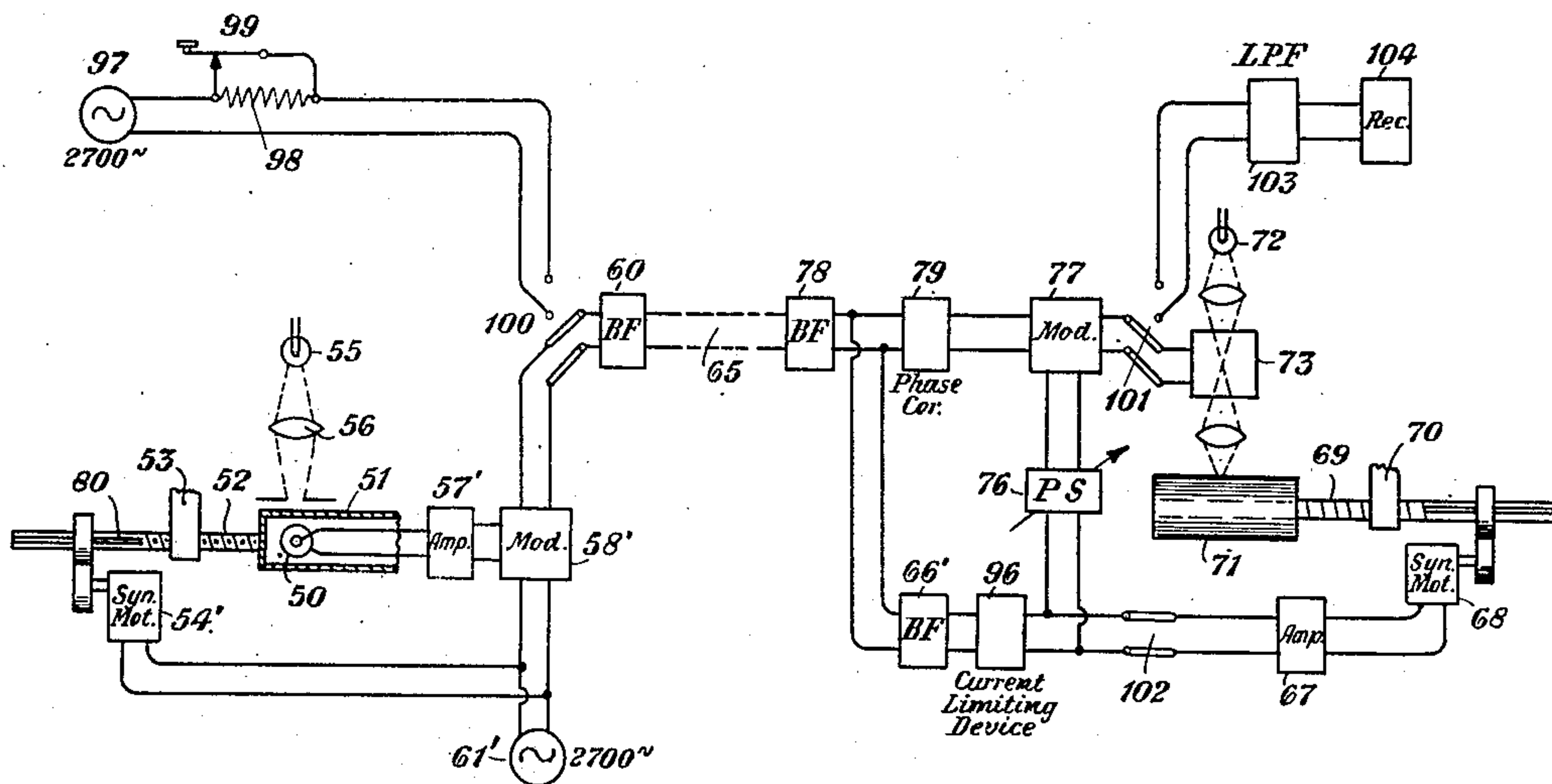


Fig. 7

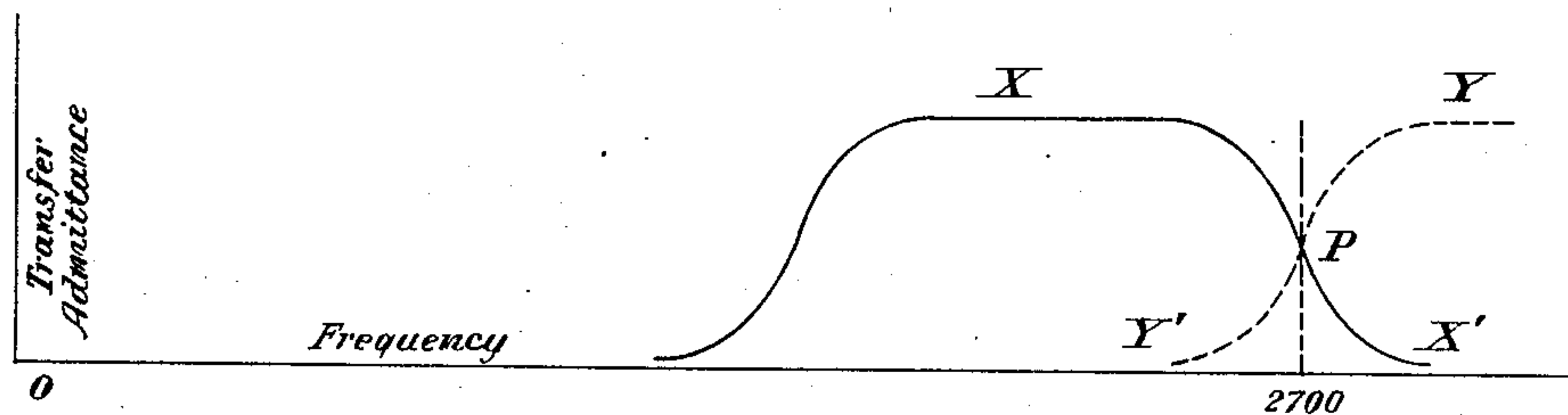


Fig. 8

INVENTOR
H. Nyquist
BY
gertor
ATTORNEY

UNITED STATES PATENT OFFICE

HARRY NYQUIST, OF MILLBURN, NEW JERSEY, ASSIGNOR TO AMERICAN TELEPHONE
AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK

SIGNALING SYSTEM

Application filed February 11, 1928. Serial No. 253,754.

It is an object of my invention to utilize a transmission line and other facilities to the best advantage for signaling. Another object of my invention is to send a sequence of signal currents with a range of frequency as narrow as practicable; or having given a certain available range for such components, to send at as high a speed as practicable within that range. Another object of my invention is to transmit signal currents effectively on a carrier current with only one "side-band" of frequencies, as will be explained hereinafter. Other objects of my invention are to provide a method and the proper apparatus for sending signal currents on one side-band per signal channel and making proper compensation for unequal attenuation and phase delay in the system employed. Still another object of my invention is to provide for overcoming the distortion due to the filter employed when transmitting signal currents on only one side-band of frequencies. All these objects and other objects of my invention will become apparent on consideration of a limited number of examples of practice according to the invention which I have chosen for disclosure in this specification. It will be understood that the following disclosure relates principally to these particular examples of practice of the invention, and that its scope is intended to be indicated by the appended claims.

This application is in part a continuation of my application, Serial Number 198,283, filed June 11, 1927, title Signaling system.

Referring to the drawings, Figure 1 is a diagram of apparatus at the sending end of a telegraph signaling system; Fig. 2 is a diagram of the apparatus at the corresponding receiving end; Fig. 3 is a diagram indicating the relation of various frequencies and frequency ranges that will be mentioned; Fig. 4 is a characteristic diagram for certain band pass filters that will be mentioned; Fig. 5 is a diagram of a telephotograph system em-

bodiment of my invention and employing a balanced demodulator at the receiving end; Fig. 6 is a diagram of such a system without the balanced demodulator at the receiving end; Fig. 7 is a diagram of a system that may be used alternatively for telegraphy or telephotography and employing a balanced demodulator for which carrier current is separated out at the receiving end; and Fig. 8 is a set of curves based on the characteristics of certain filters of Fig. 7.

Referring to Fig. 1, the telegraph sender 14 generates signal waves of direct current corresponding to the signal elements and applies them to the input of the low-pass filter 15 which passes only those frequencies between zero and f_m . The cut-off frequency f_m is chosen at as low a value as practicable to leave the wave coming from the low-pass filter 15 definite enough to identify the intended signal. This signal of frequency components between zero and f_m is applied through the conductors 16 in the modulator 17 to modulate a carrier current f_c from the generator 18. It is assumed that $f_c > f_m$.

Accordingly, as is well known, the conductors 19 from the modulator 17 will carry currents lying in frequency between $f_c - f_m$ and $f_c + f_m$, and these will be applied to the band-pass filter 13, whose pass range is approximately from $f_c - f_m$ to f_c , and accordingly only the components of frequency within this pass range will get from the band-pass filter 13 through the conductors 12 to the line 20.

Similarly, other senders will put their respective side-bands on the line 20 through other band-pass filters, such as 13'.

At the receiving end the composite signaling currents on the line 20 are separated from the branch conductors 21 by the band-pass filters 22, 22', etc., which correspond respectively to 13, 13', etc. at the sending end. Thus, the band-pass filter 22 passes only the side-band from $f_c - f_m$ to f_c carrying signals

from the sender 14. These currents through the band-pass filter 22 are then put through the phase corrector 23, which equalizes delays on the line and through the filters. Then the currents from the phase corrector 23 go over the conductors 24 to the input transformer 25 for the balanced homodyne detector comprising the two vacuum tubes 26 and 27.

One of the generators 18'' at the sending end sends current of a frequency f_o (f_o is different from frequencies lying in the pass bands of the other filters 13, 13', etc.) through an appropriate band-pass filter 13'', which is separated out by the band-pass filter 22'' at the receiving end, amplified, and applied to control the synchronous motor M which drives the generator 28 of frequency f_c . This locally generated current of frequency f_c is applied from generator 28 through the phase adjuster 29 and transformer 30 as the locally generated homodyne current for the detector 26—27.

Other generators at the sending end, such as 18', for use with other senders, are connected by means of a shaft to have definite frequency and phase relations, and likewise, other generators, such as 28', at the receiving end are similarly connected. It is thus necessary to have only one synchronizing channel such as denoted by the band-pass filters 13'' and 22'' for several sending channels, just as in the case of phase discrimination carrier telegraphy.

As will be explained hereinafter, the band filters 13 and 22 are made with special design and there may be other provisions so that the current from the detector 26—27 through the resistance 31 and low-pass filter 32 to the receiver 33 is substantially an undistorted copy of the current in the conductors 16 from the low-pass filter 15 at the sending end.

As is well known, any signaling current containing frequency components from zero to f_m may be used to modulate a carrier current of frequency f_c where $f_c > f_m$, and in this case the modulated current will occupy a band width from $f_c - f_m$ to $f_c + f_m$, that is, a width of $2f_m$. In carrier telephony it is possible to transmit only half of this band and obtain intelligible speech currents after detection at the receiving end. This is readily done because in the original signal, current components of value close to zero are not essential and hence no harm is done if the apparatus distorts currents of frequency near the carrier, as is likely to be the case in a filter which cuts off half of the band mentioned.

This transmission of only one side-band enables one either to increase the number of available channels when f_m is fixed, or to improve the quality of the telephone transmission by including higher frequency components when the number of channels is fixed.

In carrier telegraphy the transmission of only one side-band would likewise make possible an increase in the number of channels or in the speed of signaling, but this has been somewhat impracticable because of the phase and magnitude distortion introduced by the filter, which cuts off at or near the carrier frequency in order to separate the side-band to be transmitted from the one not transmitted. In carrier telephony such distortion is not serious for the reasons: (1) that the human ear does not notice slight phase distortion, and (2) that very low speech frequencies are not essential to good understanding. However, in the case of telegraph signaling it is important that after detection the original signal components of frequency from zero to f_m shall be reproduced in substantially correct amplitude and phase relationships if the wave shape is to be unaltered. This object is accomplished by the system shown in Figs. 1 and 2, subject to features of design that will be pointed out presently.

For a signal wave to be transmitted, the output current in the conductors 16 of Fig. 1 will be a certain function of time t . Assuming that this signal wave is repeated at long intervals it may be accurately represented by a Fourier series; and in practice this representation will be sufficiently accurate for a single signal wave not repeated. Accordingly, we have the equation for such a signal element,

$$f(t) = \frac{A_o}{2} + \sum_{n=1}^m (A_n \cos npt + B_n \sin npt) \\ = \sum_{n=0}^m M_n \sin (npt + \Theta_n) \quad (1)$$

where

$p = 2\pi$ times the assumed frequency of the long interval

$$M_n = \sqrt{A_n^2 + B_n^2}; \text{ except that } M_o = \frac{A_o}{2}$$

and

$$\Theta_n = \tan^{-1} A_n / B_n.$$

The A's and the B's are coefficients which correspond to the form of the wave of signal current, and m is the number of the highest harmonic passed by the low-pass filter 15 in Fig. 1, the fundamental having the frequency corresponding to the long interval, as mentioned heretofore.

Let $\omega_c = 2\pi f_c$, where f_c is the carrier frequency of the generator 18, as already mentioned; also, as already mentioned, we have assumed, to simplify the work, that $f_c > f_m$ which is equivalent to $\omega_c > mp$.

As a function of time t , the current from the generator 18 is given by the expression $\sin \omega_c t$, and this is to be multiplied by $f(t)$ of Equation (1) to get the output from modulator 17; the result is

$$f(t) \sin \omega_c t = \sum_{n=0}^m M_n \sin (npt + \Theta_n) \sin \omega_c t$$

$$= \frac{1}{2} \sum_{n=0}^m M_n [\cos \{(\omega_c - np)t - \Theta_n\} - \cos \{(\omega_c + np)t + \Theta_n\}] \quad (2)$$

As n takes all integer values from zero to m , it will be seen from the foregoing expression that the output current from modulator 17 comprises the range of frequencies from $f_c - f_m$ to $f_c + f_m$. This range is cut down by the band-pass filter 13 to approximately the range from $f_c - f_m$ to f_c and transmitted on the line 20 as described heretofore.

For the present it will be convenient to make two assumptions: (1) that the filters 13 and 22 cut off sharply, and (2) that their cut-off frequencies are

$$(\omega_c - \omega_k)/2\pi \text{ and } (\omega_c + \omega_h)/2\pi,$$

where $\omega_c > \omega_k > \omega_h$, and $\omega_k = kp = mp$, and $\omega_h = hp$. These values are indicated in Fig. 3. These two assumptions will be considered later. Subject to these assumptions, the current (call it $I_s(t)$) in the output from phase corrector 23 may readily be deduced from Equation (2) as having the following value:

$$I_s(t) = \frac{1}{2} \sum_{n=0}^k M_n \cos \{(\omega_c - np)t - \Theta_n\} - \frac{1}{2} \sum_{n=0}^h M_n \{\cos (\omega_c + np)t + \Theta_n\}$$

$$= \frac{1}{2} \sum_{n=0}^k [M_n \cos \omega_c t \cos (npt + \Theta_n) + M_n \sin \omega_c t \sin (npt + \Theta_n)]$$

$$- \frac{1}{2} \sum_{n=0}^h [M_n \cos \omega_c t \cos (npt + \Theta_n) - M_n \sin \omega_c t \sin (npt + \Theta_n)]$$

$$= \frac{1}{2} \sum_{n=0}^k M_n \sin \omega_c t \sin (npt + \Theta_n) + \frac{1}{2} \sum_{n=0}^h M_n \sin \omega_c t \sin (npt + \Theta_n)$$

$$+ \frac{1}{2} \sum_{n=h+1}^k M_n \cos \omega_c t \cos (npt + \Theta_n) \quad (3)$$

For convenience of discussion, let the three summations in the last member of the foregoing equation be represented respectively as σ_1 , σ_2 and σ_3 , so that

$$f^1(t) = \frac{1}{2}\sigma_1 + \frac{1}{2}\sigma_2 + \frac{1}{2}\sigma_3 \quad (3^a)$$

By substitution from Equation (1), $\frac{1}{2}\sigma_1$ becomes $\frac{1}{2}f(t) \sin \omega_c t$, which is in phase with the carrier current, since it contains the factor $\sin \omega_c t$. The envelope of this component

is given by $\frac{1}{2}f(t)$, and hence this component of the received current is seen to build up like the impressed signal wave at the sending end and at the same speed.

The component $\frac{1}{2}\sigma_2$ is likewise seen to be in phase with the carrier but its envelope is $\frac{1}{2}f(t)$ less those frequency components from ω_{h+1} to ω_k . Thus, it builds up more slowly than the signal at the sending end and its presence is objectionable. It will be eliminated by making $\omega_h = 0$, that is, by making the band-pass filters 13 and 22 cut off at f_c at the upper ends of their transmitting ranges respectively, provided as is here assumed, that such cut-off is sharp.

The remaining component $\frac{1}{2}\sigma_3$ contains the factor $\cos \omega_c t$, and is therefore in quadrature with the carrier current. The phase adjuster 29 is adjusted so that the electromotive forces applied through transformer 30 are in phase with the received carrier cur-

rent as represented in the term $\frac{1}{2}\sigma_1$ of Equation (3^a), and therefore in quadrature with the current component represented by the term $\frac{1}{2}\sigma_3$. Since the components in the output from the homodyne detector 26—27 are to be found only among the components of the product of the input currents through transformers 25 and 30, and since currents in quadrature give zero average product, it follows that the output from filter 32 will comprise no components due to the term $\frac{1}{2}\sigma_3$.

Of the two assumptions that were noted above between Equations (2) and (3), we have made the second definite by further assuming $\omega_h = 0$. As to the first of these two assumptions, namely, that the filters cut off sharply, this cannot be realized in practice.

The ideal condition is that the current input to the receiver 33 of Fig. 2 shall be of the same form as the signal current at the sending end in the conductors 16, as given by Equation (1), and subject to an equalized delay T for all components. Such desired current at the input of the receiver 33 is given by substituting $t - T$ for t in Equation (1); thus is obtained the equation,

$$f(t-T) = \sum_{n=0}^m M_n \sin[(npt + \Theta_n) - npT] \\ = \sum_{n=0}^m M_n [\cos npT \sin(npt + \Theta_n) - \sin npT \cos(npt + \Theta_n)] \quad (4)$$

When the products of modulation in device 17, as given by Equation (2), have been actually transmitted to the input of transformer 25 at the receiving end with varying attenuation and varying phase shift for the components of various frequencies, they may be represented by the following expression,

$$f_r(t) = \sum_{n=0}^m M_n [r_n \sin(npt + \Theta_n + \phi_n - \phi_o) + u_n \sin(npt + \Theta_n + \phi_o - \rho_n)] \\ = \sum_{n=0}^m M_n [\{r_n \cos(\phi_n - \phi_o) + u_n \cos(\phi_o - \rho_n)\} \sin(npt + \Theta_n) \\ + \{r_n \sin(\phi_n - \phi_o) + u_n \sin(\phi_o - \rho_n)\} \cos(npt + \Theta_n)] \quad (6)$$

which is obtained by introducing amplitude factors r_n and u_n and phase shift terms ϕ_n and ρ_n in Equation (2):

$$I_r(t) = \sum_{n=0}^m \frac{M_n}{2} [r_n \cos\{(\omega_c - np)t - \Theta_n - \phi_n\} - u_n \cos\{(\omega_c + np)t + \Theta_n - \rho_n\}] \quad (5)$$

Note that when $n=0$ the two angles for the two cosine terms expressed in Equation (5) become of the same angular velocity though different in phase, that is, both involve the same frequency. Therefore, the factors r_o and u_o will be equal in this case, and accordingly, the two angles ϕ_o and ρ_o will be equal.

Let the current applied from source 28 through the phase adjuster 29 in the transformer 30 have the value $4 \sin(\omega_c t - \phi_o)$. Accordingly, the components of the output current from detector 26—27 will be found among the terms in the product of this current from source 28 by the current of Equation (5). Making this multiplication, and

making the transformation indicated by the trigonometric identity.

$2 \sin a \cos b = \sin(a+b) + \sin(a-b)$, and neglecting terms corresponding to $\sin(a+b)$ for the reason that the corresponding currents will be stopped by filter 32, we get, as the output from that filter,

Equations (4) and (6) give the current to the receiver according to two different points of view. In Equation (4) this current is expressed as what is desired for non-distortion of the signal, and in Equation (6) it is expressed as dependent on certain amplitude factors r_n and u_n and phase shifts ϕ and ρ_n determined by the physical condition of the apparatus between the sender and receiver. Before comparing these equations let Equation (4) be modified by substituting β_n for npT and by introducing the factor c_n with the respective terms, giving

$$\sum_{n=0}^m M_n c_n \sin (npt + \Theta_n - \beta_n)$$

$$= \sum_{n=0}^m M_n [c_n \cos \beta_n \sin (npt + \Theta_n) - c_n \sin \beta_n \cos (npt + \Theta_n)] \quad (7)$$

Evidently β_n is a phase shift proportional to frequency; also c_n is a constant amplitude factor. The term β_n is essential to non-distortion, and while the factor c_n affects the intensity, it does not affect the quality, and of course the intensity at the receiving end can be adjusted as desired by amplification.

The conditions that the physically determined received currents of Equation (6) shall be the same as the ideally desirable currents of Equation (7) are given by

$$c_n \sin \beta_n = -[r_n \sin (\phi_n - \phi_o) + u_n \sin (\phi_o - \rho_n)] \quad (8)$$

and

$$c_n \cos \beta_n = r_n \cos (\phi_n - \phi_o) + u_n \cos (\phi_o - \rho_n) \quad (9)$$

These Equations (8) and (9) are obtained by equating coefficients of $\sin (npt + \Theta_n)$ and $\cos (npt + \Theta_n)$ in the right hand numbers of Equations (6) and (7).

The solution of Equations (8) and (9) gives the results

$$c_n = \sqrt{r_n^2 + 2r_n u_n \cos (\phi_n - 2\phi_o + \rho_n) + u_n^2} \quad (10)$$

$$\beta_n = \tan^{-1} \frac{r_n \sin (\phi_o - \phi_n) + u_n \sin (\rho_n - \phi_o)}{r_n \cos (\phi_o - \phi_n) + u_n \cos (\rho_n - \phi_o)} \quad (11)$$

It follows that the transmission through the actual system shown in Figs. 1 and 2 will be with uniform attenuation and undistorted and subject only to a constant delay for all frequencies if such values can be given to r_n , u_n , ϕ_n and ρ_n as to make c_n constant in Equation (10) and to make β_n proportional to frequency in Equation (11). In other words, it should be the object of design to make the transmitting system from the low-pass filter 15 to the receiver 33 such that

$\beta_n = npT$ and c_n is constant, and this would be accomplished by making r_n , u_n , ϕ_n and ρ_n have proper values according to Equations (11) and (10). Thereupon Equation (6) for the current actually received will become the same as Equation (4) for the current that it is desired to receive for undistorted transmission.

Inspection of Equations (10) and (11) shows that there exist an infinite number of combinations of values of r_n , u_n , ϕ_n and ρ_n which will exactly or approximately fulfill the requirements that c_n shall be constant

and that β_n shall be proportional to frequency. Further inspection of Equations (10) and (11) shows that a convenient combination of values will be obtained by making the band pass filters 13 and 22 so that their upper cut-off frequency will be near the carrier frequency, and so that $r_n + u_n = a$ constant, and equalizing the delay so that $\phi_o - \phi_n = \rho_n - \phi_o = npT$. This makes the angle zero for the cosine in Equation (10) and this equation then reduces to $c_n = r_n + u_n$. Also, in Equation (11) these same conditions reduce it to $\beta_n = npT$.

Further to illustrate the foregoing principles, make the reasonable assumption that the band-pass filters 13 and 22 of Figs. 1 and 2 have the actual transfer admittance given by the characteristic curves 41 and 42 in Fig. 4. Also, assume that their delay as a function of frequency is in accordance with the curve 46. These assumed characteristics are in accordance with easily realizable examples of practice. The delay indicated by the curve 46 is so smooth that phase equal-

izers can be omitted when the carrier frequency f_c is located at 1048.5 cycles, and the location at this point gives very nearly constant values for $r_n + u_n$, the u 's being taken at frequencies equally spaced above f_c and the corresponding r 's being taken at equally spaced intervals below, as shown by the dots on curve 41. In similar manner, the dots on curve 42 indicate values of ϕ_n below 1048.5 cycles and ρ_n above 1048.5 cycles.

In short, having the plots 41 and 42 in Fig.

4, we arbitrarily seek to locate f_c at a point that makes $r_n + u_n$ as nearly constant as practicable. This we do after noticing that the phase angle varies linearly at or near the point chosen; if it did not do so we would first make suitable correction for phase by means of device 23 in order that it would do so.

Assuming that $f_m = 80$, that is, that the essential frequency range for components of the initial signal are from zero to 80, this implies transmitting the side-band from 1048.5 down to 968.5. In all this range (and beyond at the right) the phase angle is nearly proportional to frequency, as desired. As explained in the first part of the specification, it would be satisfactory if the modulus of admittance had the ideal form indicated by the dotted line 43. The effect of departure from this form at 44 is overcome by the relationships that have already been discussed in connection with Equations (6) to (11). The departure at 45 is not serious; indeed, it is negligible. For proper interpretation of the signal it has been assumed that signal component frequencies above 80 may be entirely neglected, which means that in Fig. 4 frequencies below 968.5 may be entirely neglected. Going back to the original signal wave, if frequencies above 80 can be entirely neglected, then it is apparent that frequencies only a little below 80 may be somewhat distorted without harm, and therefore frequencies a little above 968.5 may be slightly distorted without harm, which means that the distortion represented by 45 is negligible. The distortion represented by 45 may be minimized by suitable design of the filters 13 and 22.

By throwing the switches 9, 8, 5 and 4 in Figs. 1 and 2, transmission of signals may be effected without sending the special current of frequency f_c through the filters 13'' and 22''. With the switches shifted according to this suggestion, it becomes necessary to send a considerable component of carrier frequency as part of the side band transmitted through the band pass filters 13 and 22. In other words, it becomes necessary that there shall always be a considerable component of current at the frequency corresponding to $f_c = 1048.5$ in Fig. 4. In this case the received current will be "detected" in the ordinary way by the detector 7 of Fig. 2, whose output will go through the low pass filter 6 to telegraph receiver 33. Referring to the foregoing discussion following Equation (3^a), it will be seen that the objectionable term $\frac{1}{2}\sigma_3$ of Equation (3^a) will be present when the receiving path through detector 7 is employed; but under certain practicable conditions of operation, it will not be great enough seriously to impair the received signals. That is, the loss of quality or speed

or both due to the presence of this term may not be great enough to offset the gain by the use of simpler receiving apparatus and the elimination of a special channel for carrier current.

In either case, that is with switches 9, 8, 5 and 4 as shown or all shifted, the special design of filters 13 and 22 will be advantageous according to the foregoing discussion in connection with Fig. 4.

Referring to the diagram in Fig. 5, this shows a single side-band picture transmitting system arranged for the practice of my invention. The glass drum 51 is mounted coaxially with the shaft 52, which has screw-threaded engagement with the support 53 so that as the drum 51 rotates, it is traversed slowly along its length. The synchronous motor 54 drives the drum through gears and a sliding spline connection. Light from the lamp 55 is focussed by the lens 56 on the photoelectric cell 50 within the glass drum 51. The picture to be transmitted, in the form of a semi-transparent film, is wrapped about the glass drum 51 and the narrow area of the film through which the light shines describes a helical course with close turns relatively to the film as a whole.

The photoelectric cell 50 is in a direct current circuit, and the current in this circuit varies with the light getting through the film to the cell. This current determines a correspondingly varying input voltage for the amplifier 57 whose output goes to the input of the balanced modulator 58—59 and is applied thereto to modulate a carrier current of 2700 cycles per second, as will be explained presently. The modulator output current goes through the band filter 60 which cuts off the lower side band according to the principles heretofore disclosed in connection with the band filter 13 of Fig. 1. This lower side band of modulated carrier current is then put on the line 65 for transmission to the receiving station.

The alternating current generator 61 delivers current of 300 cycles per second to drive the synchronous motor 54 mentioned heretofore. Also, this 300-cycle current is passed through the band filter 62 and superposed on the line 65 along with the modulated carrier current that comes through the band filter 60. Still another portion of this 300-cycle current goes through the distorter 63 whose output is accordingly a current rich in harmonics. The band pass filter 64 passes the harmonic of frequency 2700 cycles per second, which is applied as the carrier current to be modulated by the varying picture current in the balanced modulator 58—59.

At the receiving end, the band pass filter 66 draws off the current of 300-cycle frequency and sends it through the amplifier 67 to drive the synchronous motor 68, thereby

rotating and traversing the drum 71 on the screw-threaded shaft 69 in the support 70 in synchronism with the glass drum 51 at the sending end. Light from the lamp 72 is directed by lenses through a variable orifice in the light valve 73 and on a spot of the drum 71, and this spot describes a helical course with close turns relatively to the drum 71.

Some of the 300-cycle current from the band pass filter 66 goes to the distorter 74 whose output is connected with the band pass filter 75 which passes only the harmonic of frequency 2700 cycles per second. This current of carrier frequency 2700 cycles per second goes through the adjustable phase shifter 76 to a pair of input terminals of the modulator 77.

The lower side band of current from 2700 cycles down comes from the line 65 through the band pass filter 78 and thence through the phase corrector 79. The filter 78 corresponds with the filter 22 in Fig. 1, and the phase corrector 79 corresponds with the phase corrector 23 in Fig. 1. This lower side band of current, properly corrected in phase, is then combined in the modulator 77 with the current of 2700 cycle frequency so as to effect demodulation, and the demodulated current goes to the light valve 73 and controls its opening in accordance with the amount of current.

Thus, the opening of the light valve 73 corresponds with the intensity of the light in the photoelectric cell 50, and a sensitive film wrapped on the drum 71 is exposed in proportion to the quantity of light at the corresponding point of the film on the drum 51. It will be seen that if the film on the drum 51 is a negative, the film on the drum 71 will be a positive, and vice versa.

Comparing the system of Fig. 5 with that of Figs. 1 and 2 (with the switches 9, 8, 5 and 4 as shown), it will be seen that in both cases the signaling current is applied to modulate a carrier current, and that only the lower side band of modulated carrier current is transmitted. A balanced demodulator is employed at the receiving end in both cases to eliminate the effect of currents corresponding to the term $\frac{1}{2}\sigma_3$ of Equation (3^a); also in both cases the filters that cut off the lower side band are of special design, as pointed out in connection with Fig. 4, namely, the filters 13 and 22 in Fig. 1, and the filters 60 and 78 in Fig. 5. Also, in both cases, a phase corrector (23 in Fig. 1, and 79 in Fig. 5) is employed, if needed, to get the phase angle characteristic of approximately uniform slope, as shown in Fig. 4.

In Figs. 1 and 2, and likewise in Fig. 5, a special current of frequency f_0 is transmitted over the line for synchronizing and for deriving the carrier current at the receiving end, but in the system shown in Fig. 6 there is no such transmission. Here, the

synchronous motor 54 at the sending end rotates the glass drum 51 as in Fig. 5, and, in a similar manner to Fig. 5, the current from the photoelectric cell 50 is amplified at 57' and applied in the modulator 58' to modulate carrier current of any suitable frequency from the generator 61'. Only the lower side band of the output from the modulator 58' goes through the specially constructed filters 60 and 78 and over the line 65 between them.

At the receiving end, the received current goes through the phase corrector 79 and amplifier 93 to the light valve 73'. This light valve 73' is of different construction from the light valve 73 in Fig. 5. The valve 73 is operated by the demodulated current corresponding to the current through the photoelectric cell 50; but the light valve 73' is operated by the modulated carrier current so that it opens and closes at the frequency of the received current and the extent of the opening corresponds to the amplitude, that is, corresponds to the magnitude of the modulating current at the sending end, which is the current in the circuit of the light valve 50.

The drum 71 at the receiving end is rotated by the synchronous motor 68 in a manner similar to that described for Fig. 5. It remains to describe how the motor 68 at the receiving end is kept substantially in synchronism with the motor 54 at the sending end.

The apparatus at the receiving end in the box 91' is the same as in the symbolic box 91 at the sending end. In each case, this apparatus serves to deliver alternating current of definite frequency to drive the respective synchronous motors at the sending and receiving ends, the motors 54 and 68. Referring to the sending end, the box 82 contains a tuning fork 83 whose vibrations are sustained by an appropriate current in the coil 86. This current comes through the phase adjuster 85 from the three-electrode vacuum tube oscillator 84 whose frequency is determined by the currents in the coil 87 in the input circuit. Accordingly, the currents delivered from the oscillator 84 to the amplifier 88 will be of the natural frequency of the tuning fork 83. The currents from the amplifier 88 go through the repeating coil 89 to drive the synchronous motor 54.

The synchronous motor 54 drives the glass drum 51, as already pointed out, and, in addition, it drives a cumulative indicator 81, in the nature of a revolution counter. By comparing the indicator 81 with an independent standard clock 81', it can be noticed whether the motor 54 is running fast or slow. A small heating coil is provided at 90 within the box 82, and by adjustment of the associated rheostat, the temperature within the box 82 can be changed a little so as slightly to vary the rate of the fork 83 and correct

any tendency of the indicator 81 to get out of step with clock 81'.

At the receiving end, there is an independent standard clock 92', and the synchronous motor 68 drives a cumulative indicator or revolution counter 92 which can be compared with the clock 92' in the same way that comparison is made at the sending end between 81 and 81'. Means of adjustment are comprised within the apparatus 91' the same as within the apparatus 91 at the sending end. Accordingly, synchronism is effected between the sending and receiving ends by keeping the apparatus at those two ends in synchronism with standard clocks, which, of course, are regulated in the usual way either directly or indirectly by the earth's rotation as determined by the meridian passage of an observed star.

In Fig. 7, a system is shown adapted alternatively for transmitting telegraph signals or pictures. In this system, only the lower side band is transmitted, but this comprises, at its upper end, an appreciable component of carrier frequency, and this component is utilized at the receiving end for synchronization and as a source of carrier frequency for demodulation. When sending pictures, the switches 100 at the sending end, and 101 at the receiving end, will be thrown down, as in the drawing, and the switch 102, at the receiving end, will be closed. In this case, the sending end will be very similar to that shown in Fig. 5, except that the carrier current of 2700 cycles per second is generated directly in the generator 61' and is applied not only to the modulator 58' but also to the synchronous motor 54'.

At the receiving end, the current all goes through the special band pass filter 78 that passes substantially only the lower side band. On the output side of this filter, there are multiple branches going to the phase corrector 79 and to another band pass filter 66'. The transfer admittance characteristic for the band pass filters 60 and 78 is shown at X in Fig. 8. It will be seen that the right-hand part of this characteristic has the same relation to the carrier frequency of 2700 cycles per second that the right-hand part of the characteristic 41 for transfer admittance in Fig. 4 has to the carrier frequency in that case, which is 1048.5 cycles per second.

The band pass filter 66' is designed so that its transfer admittance characteristic Y in Fig. 8 is symmetrical to the characteristic X with respect to the ordinate for 2700 cycles; that is, XPX' is the mirror image of YPY'. Accordingly, the attenuation characteristic for the current through the band filters 60, 78 and 66', that is, the current in the output of 66' is symmetrically attenuated on both sides of the ordinate for 2700 cycles in Fig. 8. This current in the output of band filter 66'

will therefore have the basic frequency of 2700 cycles per second, but will vary somewhat in amplitude. It goes to the input of the current limiting device 96, which may be a thermionic vacuum tube operated on the saturation part of its current-voltage characteristic. This gives an output current of the basic carrier frequency and of substantially uniform amplitude. This current goes through the phase shifter 76 to the receiving modulator 77 and also through the amplifier 67 to drive the synchronous motor 68.

When the system is to be used for telegraph signaling instead of picture transmission, the switch 102 is opened, and the switches 100 and 101 are thrown up. The alternating current generator 97 generates a current of carrier frequency, and its amplitude is changed back and forth between two stages, one for marking and the other for spacing by means of the key 99 controlling a short circuit or shunt around the series resistance 98. Accordingly, there goes through the switch 100 a modulated carrier current of basic frequency as determined by the generator 97. In accordance with the principles explained for Figs. 1 and 2, the lower side band is cut off by the filters 60 and 78, and only this side band is transmitted over the intervening line 65.

At the receiving end, the carrier current is separated out the same as in the case of picture transmission, through the band pass filter 66' and the current limiting device 96 and applied to the modulator 77. The output from the modulator 77 then goes through a low pass filter 103 to the telegraph receiver 104 the same as to the receiver 33 in Fig. 2.

I claim:

1. The method of signaling on an approximate single side-band which consists in cutting that side-band off somewhat gradually near the carrier frequency, with phase shift increments proportional to frequency increments near the carrier frequency and with amplitude factors equally above and below the carrier frequency that add in pairs to a constant value, whereby the distortion that might be caused by departure from a sharp cut-off is obviated.

2. The method of signaling which consists in generating a signal wave of current, applying it to modulate a carrier current, transmitting approximately only one side-band of such modulated current, making the cut-off gradual on both sides of the carrier frequency, varying the phase shift uniformly near the carrier frequency and varying the amplitude oppositely and symmetrically about the carrier frequency as a mean value, and at the receiving end detecting this current with balanced detector elements and a locally applied current in phase with desired

components, whereby undesirable components in quadrature are eliminated.

3. The method of cutting off a part of a frequency range of modulated carrier currents which consists in making the cut-off gradual on both sides of the carrier frequency, and varying the phase shift uniformly near the carrier frequency and varying the amplitude oppositely and symmetrically about the carrier frequency as a mean value.

4. The method of signaling on an approximate single side-band which consists in cutting the side-band off as nearly as practicable at the carrier frequency, and compensating for the approximate character of the cut-off by varying the phase shift increments proportionally with frequency increments near the carrier frequency, and by varying the amplitude factors in the same range so that any pair of such factors equally spaced above and below the carrier frequency shall add to a constant value.

5. The method of signaling on an approximate single side-band which consists in cutting the side-band off somewhat gradually on both sides of the carrier frequency, and receiving with balanced detection to eliminate undesired components in quadrature with those desired, and varying the phase shift and amplitude factor at and near the carrier frequency to compensate for the gradual cut-off as compared with an abrupt cut-off.

6. The method of signaling on an approximate single side-band of carrier current in cases where current components of frequency close to the carrier frequency are essential, which consists in compensating components near the carrier frequency above and below it to obviate distortion due to the necessarily gradual cut-off for the side-band transmitted.

7. The method of compensating for gradualness of cut-off by a filter, which consists in varying the component currents above and below a suitable mean cut-off value of frequency, so that components above and below will combine to effect the desired compensation.

8. In the method of transmitting signals on a single side-band of carrier current, the procedure which consists in making the cut-off gradual on both sides of the carrier frequency and varying the phase shift uniformly near the carrier frequency and varying the amplitude oppositely and symmetrically about the carrier frequency as a mean value, and in homodyne receiving on a balanced detector whereby received components of current in quadrature to those desired are eliminated.

9. In combination, means to generate a signaling current and to modulate a carrier current thereby, a line, a filter that will pass to the line approximately only one side-band of

the modulated current, said filter being adjusted so that it cuts off somewhat gradually at and near the carrier frequency, and with phase shift increments proportional to frequency increments in this range, and with amplitude factors that add to a constant value equally spaced above and below the carrier frequency, and a balanced homodyne detector for receiving the transmitted side-band.

10. In combination, means to generate a signal current and to modulate a carrier current thereby, a line, a filter to pass approximately only one side-band of the modulated current and put it on the line, and a balanced homodyne detector to receive the current from the line, the said filter being designed to cut off at or near the carrier frequency, with phase shift increments proportional to frequency increments in the neighboring frequency range and with amplitude factors that add to a constant value at equal frequency intervals in pairs above and below the carrier frequency.

11. The method of utilizing a frequency range effectively for multiplex signaling which consists in applying the currents of the respective signal channels to modulate carrier currents, cutting off and transmitting only one side-band for each signal channel, and compensating the currents near the cut-off frequency for each channel to obviate distortion that might be caused by the necessary gradualness of the cut-off.

12. The method of signaling with a band of frequencies requiring the presence of low frequency components, which consists in applying said band to modulate a carrier current of higher frequency, thus producing upper and lower side bands with essential frequencies close to the carrier frequency, and cutting off and transmitting one such side band with gradual cut-off near the carrier frequency, with phase shift increments proportional to frequency increments near the carrier frequency and with amplitude factors equally above and below the carrier frequency that add in pairs to a constant value, whereby the distortion that might be caused by departure from a sharp cut-off is obviated.

13. The method of cutting off one of two side bands adjacent to a carrier frequency, which consists in varying the modulus of transfer admittance symmetrically as a function of frequency above and below the carrier frequency and varying the angle of phase shift uniformly as a function of frequency above and below the carrier frequency.

14. The method of cutting off one of two side bands adjacent to a carrier frequency, which consists in varying the transfer admittance gradually as a function of frequency near the carrier frequency to compensate

values thereof above and below the carrier frequency.

15. The method of cutting off one of two side bands adjacent to a carrier frequency, which consists in varying the transfer admittance as a function of frequency so as to compensate the values thereof near the carrier frequency.

16. The method of signaling on an approximate single side band of current which consists in cutting off that side band as nearly as practicable at the carrier frequency but with some necessary lack of sharpness in the cut-off, and varying the transfer admittance as a function of frequency over the neighboring frequency range on both sides of the carrier frequency so as to compensate for the said necessary lack of sharpness.

17. In combination, means to generate and modulate a carrier current, and a filter to cut-off a side band of the modulated current, the cut-off being necessarily somewhat gradual, and the carrier frequency being adjusted at an intermediate value in the range of gradual cut-off to effect compensation therefor.

18. In combination, means to generate a signal current with essential components of low frequency, means to generate a carrier current of a certain frequency, means to modulate the carrier current by the signal current thus producing two side bands with essential frequencies close to the carrier frequency, and means to cut off one side band with necessary gradualness, the frequency of the said carrier current being adjusted to an intermediate frequency value in the range of gradual cut-off to compensate for the departure from abruptness of cut-off.

19. The method of signaling with a band of frequencies requiring the presence of low frequency components, which consists in applying said band to modulate a carrier current of higher frequency, thus producing upper and lower side bands with essential frequencies close to the carrier frequency, and cutting off and transmitting one such side band with gradual cut-off near the carrier frequency, with phase shifts and amplitude factors at various frequencies near the carrier frequency so related as to make the phase shifts proportional to frequency and to make the amplitude factors constant for the low frequency range.

20. The method of signaling with a band of frequencies requiring the presence of low frequency components, which consists in applying said band to modulate a carrier current of higher frequency, thus producing upper and lower side bands with essential frequencies close to the carrier frequency, and cutting off and transmitting one such side band with gradual cut-off near the carrier frequency, demodulating after the transmission, and making the phase shifts and

amplitude factors in the region of said gradual cut-off so that c_n shall be constant in Equation (10) and β_n shall be proportional to frequency in Equation (11).

In testimony whereof, I have signed my name to this specification this 10th day of February, 1928.

HARRY NYQUIST.

75

80

85

90

95

100

105

110

115

120

125

130