Dec. 31, 1935. P. T. FARNSWORTH 2,026,379

SYSTEM OF PULSE TRANSMISSION

Filed Dec. 4, 1930 2 Sheets-Sheet 1

Fig. 1.

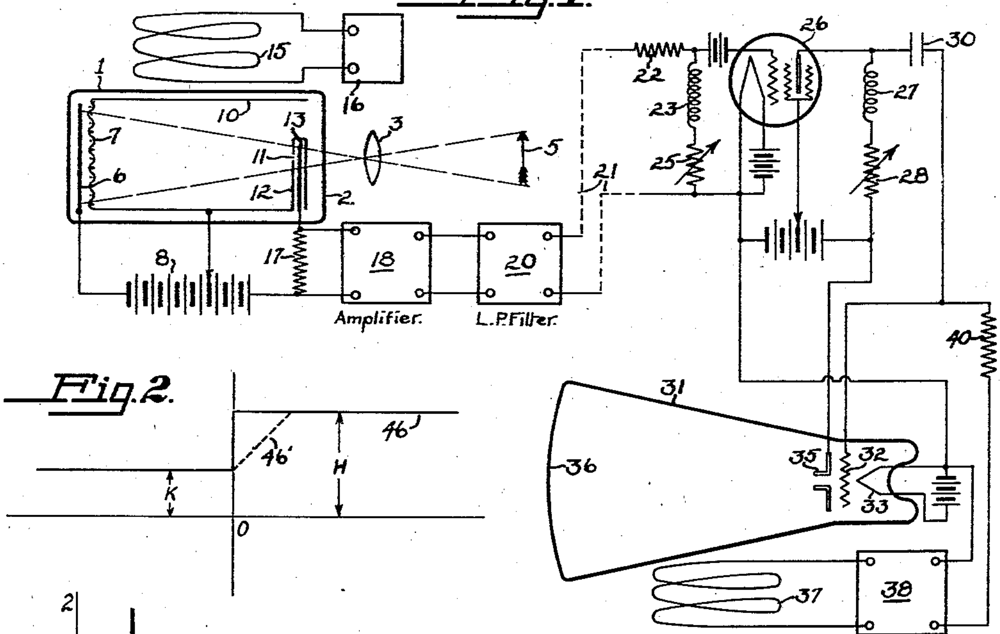

Fig. 2.

Fig. 3.

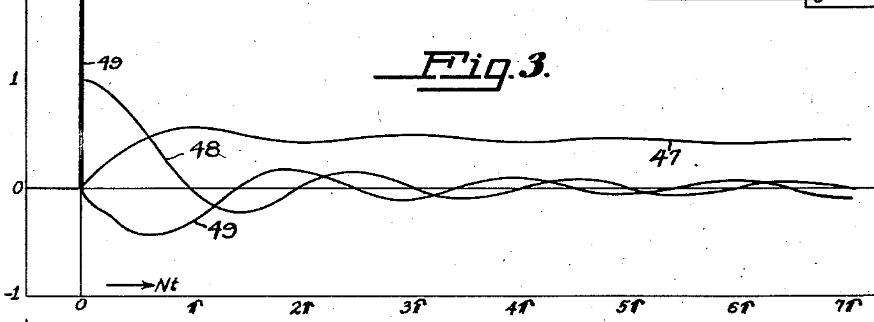

Fig. 5.

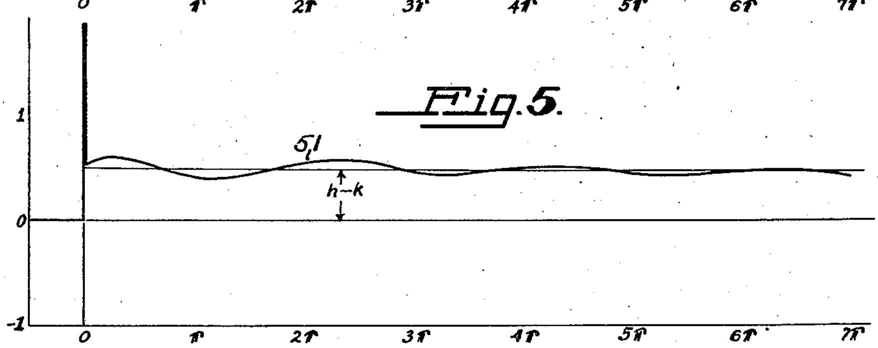

Fig. 4.

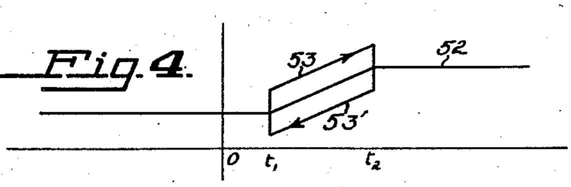

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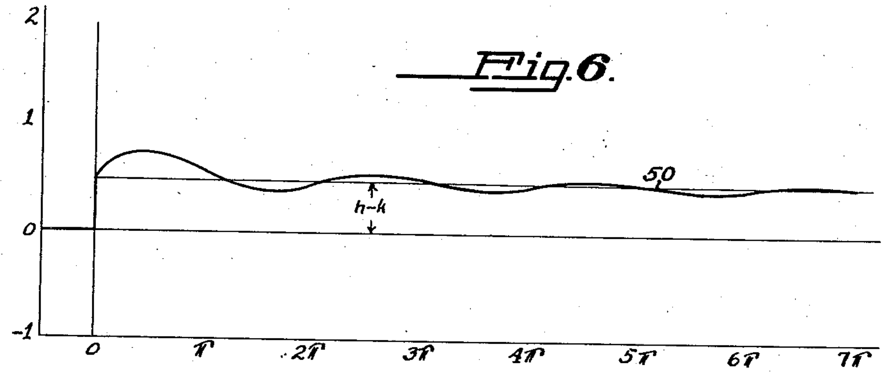
Fig. 6.



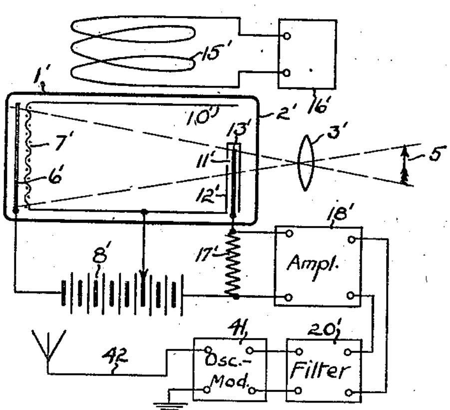


Fig. 7.

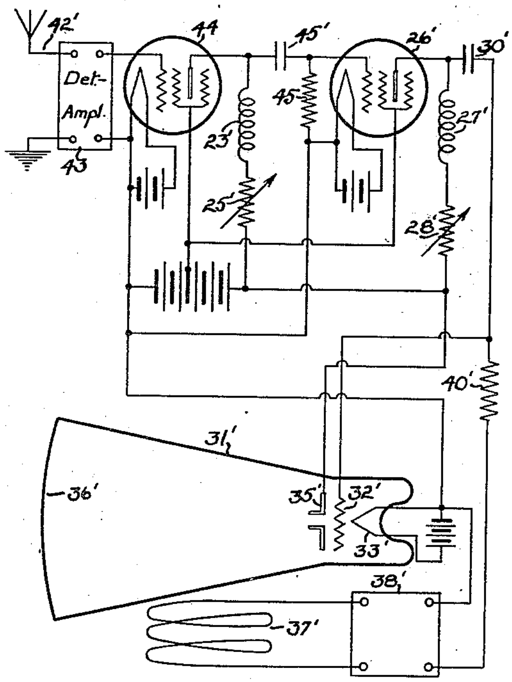


Fig. 8.

Fig. 9.

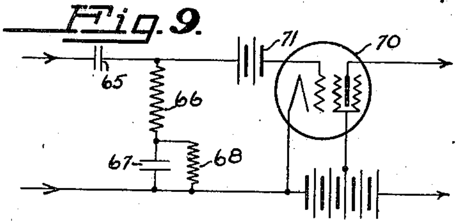
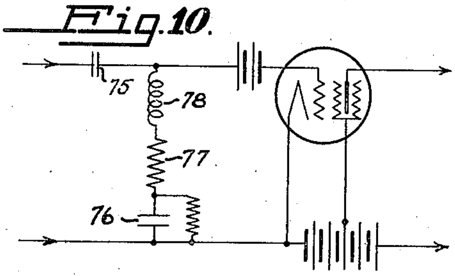


Fig. 10.



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UNITED STATES PATENT OFFICE

2,026,379

SYSTEM OF PULSE TRANSMISSION

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Application December 4, 1930, Serial No. 500,092

11 Claims. (Cl. 178—6)

This invention relates primarily to the electrical transmission and reproduction of pictures, but it is also applicable to other cases where it is desirable to transmit pulses of steep wave front through media which tend to suppress the high frequency components of such pulses, thereby converting the steep wave fronts into waves of gradually sloping front.

Among the objects of my invention are: First, to provide a method of reducing the band of frequencies which it is necessary to transmit in order to produce an electrically transmitted picture having a given amount of detail; second, to provide a method of transmitting television pictures having satisfactory detail over wire lines which are capable of transmitting but a limited band of frequencies; third, to provide a television method which will permit the transmission of television pictures upon radio channels which are comparable in width to those used for sound broadcasting; fourth, to provide a method of picture transmission which will allow facsimile telegrams, tele-photography, photo-radio, and the like, to be transmitted upon frequency bands and at speeds which are of the same order of magnitude as those required for ordinary telegraph code transmission, instead of the wide bands or slow speeds now required; fifth, to provide a method of increasing the speed of transmission of telegraph lines and cables; sixth, pursuant to the above objects, to provide a method of converting an electrical wave or pulse having a sloping wave front into a pulse which rises to its maximum value practically instantaneously; and seventh, to provide electrical circuits of simple and practical form for carrying out the method of my invention.

Other objects of the invention will be apparent or will be specifically pointed out in the description forming a part of this specification, but I do not limit myself to the embodiment of the invention herein described, as various forms may be adopted within the scope of the claims.

Referring to the drawings:

Figure 1 is a schematic diagram of a wire-transmitted television system embodying this invention.

Figure 2 is a curve showing the nature of the pulses generated by a television transmitter.

Figure 3 is a plurality of curves representing a pulse as modified by a filter and derivatives of said pulse.

Figure 4 is a curve illustrating the currents generated by scanning an area of gradually changing illumination.

Figure 5 is a curve representing the sum of proportional parts of each of the curves of Figure 3, and Figure 6 is a similar curve representing the sum of two of the curve of Figure 3.

Figures 7 and 8 are diagrams respectively of the transmitting and receiving apparatus in a radio television system.

Figures 9 and 10 are diagrams of modified forms of differentiating networks.

As is well known, electrical picture transmission, whether it be the transmission of still pictures as in "telephoto", facsimile transmission or of television, the picture is scanned by moving an aperture progressively over the entire area of the picture, in order to generate a current which is at all times proportional to the reflected or transmitted illumination of the area of the picture being scanned. Since the aperture has a finite area no details can be transmitted which are smaller than the aperture itself, and this fact is the fundamental limitation of television and other forms of electrical picture transmission by all methods now known.

In the past, this scanning has usually been accomplished by the Nipkow scanning disk, and mechanical limitations upon the feasible size of the disk and the speed with which it is required to rotate, which must be sixteen times per second or more in order to transmit a substantially flickerless picture, have limited the number of picture elements to approximately 2,500; i. e., the scanning aperture has been about 1/2500 of the area which it has been required to scan.

Electrical methods of scanning, such as are disclosed in my prior Patent No. 1,773,980, remove this limitation on the number of picture elements transmitted, so that the ratio of aperture to picture area may be made as small as is desired, and any required amount of detail may be transmitted insofar as the scanning operation itself is concerned.

An analysis of the problem of picture transmission proves that the most usual condition to be met in scanning a picture is a practically instantaneous change in illumination, i. e., a sudden transition from dark to light or vice versa. Considered electrically, this means that an electrical pulse must be generated which comprises a practically instantaneous rise (or fall) in current from one fixed value of current to another fixed value.

No electrical circuit which it is practical to construct is capable of transmitting a pulse of this character, which may be described as a "square front wave", to any great distance; and to make amplifiers which will truly repeat such pulses is almost impossible. A certain degree of sluggishness of response is inherent in the circuits, which prevents instantaneous current changes and distorts the square fronted waves and causes them to rise slowly, instead of instantaneously, to their new value.

The Fourier method of analysis shows that the square fronted pulse may be considered as made up of an infinite number of sine waves having all frequencies up to infinity, and that the sluggishness of response of a circuit is equivalent to its failure to transmit the higher of these frequencies; the lower the frequency of cut-off, the more sluggish the circuit, and the more gradual the current rise. This results in great loss of detail in the received picture where the high frequencies are not transmitted. Sharp lines are converted into wide, gradually shaded bands, and small details are passed over by the scanning device before the sluggish circuit can respond.

To transmit a picture approaching an optically reproduced motion picture in detail, requires frequencies of the order of 2,000,000 cycles per second, and at the present state of the art, it is an impossibility to provide a land line which would transmit frequencies of this order, together with low frequencies, to any great distance and without frequency distortion.

Moreover, where it is desired to transmit television pictures by radio, the enormous number of frequencies which must be transmitted necessitate very wide side bands, and, even if one of the side bands is suppressed, very wide communication channels. If a television transmitter were assigned to the broadcast band, the entire spectrum now allotted to that service (545 k. c. to 1,500 k. c.) would be inadequate to transmit a picture having the amount of detail above specified, and it has therefore been necessary to use carriers of the order of 60 megacycles in order to obtain channels of the requisite width. Transmission on these ultra high frequency channels is, as yet, unsatisfactory.

Closely analogous in effect to the sluggishness of the circuits is the distortion due to the finite size of the aperture. In its steady passage over the picture field, its response to a change in illumination begins at the instant its front edge reaches the change, but the response is not complete until its rear edge also reaches the change, and the entire aperture covers the region of changed illumination. This makes the wave front more sloping and attenuates the high frequency components. The effect is known as "aperture distortion" or "aperture effect".

The same term is applied to a similar effect occurring at the receiver. The incoming picture is traced by an area of illumination which moves across the picture field in the same manner as the transmitting aperture, and the apparent illumination of any point on the field is the mean illumination of that area as it passes the point. For this reason, if the illumination of the area be suddenly increased, those points near the trailing edge of the area which receives the increased illumination for only an infinitesimal time, appear less bright than those which are near the leading edge when the change occurs, and which receive the increase during the entire time the area is traversing them. Again the effect is to spread sharp lines into shaded bands and spoil detail, and although this has no effect on the transmitted frequencies, its effect upon the eye is the same as would be produced by a further suppression of the high frequencies.

It is to be noted that the frequencies here mentioned are the component frequencies of the pulses, and that the pulses themselves come, in general, at random. The only truly periodic components in the transmission of a picture are the picture frequency itself (say 16 cycles per second) and the scanning frequency, or, as they are sometimes referred to, the lower and upper scanning frequencies. With this in mind, it will be realized that what must be transmitted, in order to produce good pictures, are these two truly periodic frequencies, on which are superposed random pulses or transients, and that the difficulties of transmission relate almost wholly to the latter.

In transmitting or amplifying the transients, as has been pointed out, the steep wave fronts or instantaneous current rises, are converted into sloping wave fronts or gradual current rises. None the less, considered from the receiving end, there is a definite instant of arrival of the wave, which is the instant when the change in current starts to take place. At this instant the rate of change of current, (mathematically its first derivative with respect to time, or di/dt) changes from zero to some finite value. The rate at which the current is changing has a discontinuity or instantaneous change of value at this point.

If there is phase distortion or "envelope delay" in the circuit, even the rate of change may be gradual, and there will in this case be no discontinuity in the first derivative di/dt. There is still an instant of first arrival of the wave, however, and this will be marked by a discontinuity in the second derivative

$$\frac{d^2i}{dt^2},$$

or in some of the higher derivatives. Where a derivative exhibits a discontinuity, all of the higher derivatives have infinite discontinuities, changing from zero to plus or minus infinity at this instant.

If the pulses follow each other so closely that the first change is not complete before the second arrives, the change of slope is no longer from zero to a finite value but from one finite value to another or to zero, but the discontinuity at the instant of arrival remains.

While the wave has thus far been considered as a current wave, it will be realized that the above holds equally true for a voltage wave, and this should also be kept in mind in what follows. The transformation theorem which states that in any equation dealing with voltage and current these quantities may be interchanged, and by substituting admittances for impedances the equation still holds, is true here as elsewhere. The term "current" has and will be used in this specification, in order that a clear and connected description may be given without repetitious explanations, but the transformation theorem mentioned, and other similar well known transformations, indicate the breadth of equivalents involved.

Considered from one aspect, the broad invention here presented is a method of communication by electrical pulses which includes the steps of modifying the pulses by removing certain frequency components therefrom, transmitting the modified pulses, and adding, at the receiver, components substantially equivalent to those previously removed to restore their original wave form.

From another point of view, the broad invention is a method of converting waves or pulses having sloping wave fronts into steep fronted waves by adding thereto components proportional to one or more derivatives of the arriving pulse with respect to time, at least one of the added derivative components preferably having a discontinuity at the instant of arrival of the pulse.

The derivative components are supplied by a differentiating network, which, in its preferred form, comprises a relatively large impedance for determining the current flow and establishing the relation of current and voltage waves in the network, and a shunt arm of relatively negligible impedance, wherein the voltage drop leads in phase that in the control impedance, and across which is developed a voltage proportional to the derivative of the arriving pulse. If a vacuum tube be connected with its control circuit across this shunt arm, its output current is proportional to the voltage in this arm, and this current may be circulated through a similar network to generate a higher derivative. By adding proper components of current or voltage proportional to the arriving wave and its derivatives, including a derivative having a discontinuity at the instant of arrival of the wave, square fronted pulses are produced.

As used in television or other electrical picture transmission, these reconstructed pulses are used to control the illumination of the area which scans the field of the received picture, giving detail which is even better than that produced by a receiver connected directly to the transmitter, since the aperture distortion of the transmitter is completely corrected. By adding a still higher derivative component the aperture distortion at the receiver is largely compensated, since the powerful pulse corresponding to the infinite discontinuity at the instant of arrival gives a sharp outline about the pictured masses, producing an illusion of relief.

There will be next described in detail the application of my invention to a television transmitting system, following which a mathematical explanation of its operation will be given, and its application to other uses will be pointed out.

The television system shown in Figure 1 is a simplified diagram of a device utilizing the transmitting and receiving apparatus disclosed in my previous Patent No. 1,773,980, and in my copending applications, Serial Nos. 270,673, 449,984, and 461,111.

The essential feature of this transmitter is a special type of photo cell comprising an envelope 1, preferably cylindrical in form, and having in one end a plane window 2. Through this window a lens system 3 focuses an image of the object 5, whose picture is to be transmitted, upon a photo-sensitive cathode plate 6. Parallel to and closely adjacent to the cathode is a screen anode 7, which is maintained at a potential positive to the cathode by means of a battery or other source 8.

Electrons are liberated from the cathode in proportion to the brightness of the image cast upon it, and these electrons are accelerated by the potential upon the anode, most of them passing through the latter into an equi-potential space formed by the screen or shield 10. The electrons liberated from each point on the cathode are focused at a corresponding point in the plane of an aperture 11 in a small tubuluar shield 12 which projects inward from the side of the envelope adjacent the window. Within the shield is a target or collector 13 which is preferably maintained slightly positive with respect to the shield by means of the source 8, and which collects those electrons which fall upon the aperture. Since electrons are liberated simultaneously from the entire area of the image, there is thus formed a complete electron image of the object to be pictured, and if a fluorescent screen were placed in the tube in the plane of the aperture, the picture would appear upon it.

The electron stream which forms the electron image is deflected magnetically by means of coils disposed about the tube, one of these coils being schematically shown and indicated by the reference character 15. It is supplied by an oscillator 16, and serves to deflect the image across the aperture at the low scanning frequency. A similar oscillator operating at the high scanning frequency supplies a set of coils arranged at 90° to that shown. This is omitted from the diagram for the sake of simplicity. The two deflections of the image cause it to move past the aperture so that the latter traverses the entire area of the picture progressively to accomplish the scanning.

In the preferred method, saw-tooth oscillations are used for the vertical movement of the image, which is moved uniformly downward over the aperture in about $\frac{1}{16}$th second, and then returned to its original position practically instantaneously. At the same time, the other oscillator deflects the image from side to side at substantially constant speed, equivalent to from 2,000 to 4,000 cycles per second, so that electrons enter the aperture consecutively from each unit area of the picture field as projected on the cathode, and fall upon the target.

The electron current collected by the target 13 passes through a resistor 17, causing a potential drop across this resistor which actuates an amplifier 18.

The part of the apparatus thus far described may be identical in construction and operation with that disclosed in my U. S. Patent No. 1,773,980 and applications above mentioned.

The amplifier 18 is shown as feeding into a low pass filter 20 which removes all of the frequencies above a predetermined cut-off value. The filter is shown as feeding into a line 21. The reasons for using the filter will be discussed in detail below.

Connected in series with the line is a resistor 22, and the line is closed through an impedance comprising an inductor 23 and a variable resistor 25 in series. If the ohmic resistance of the line is sufficient so that the current in the line is determined by the line resistance rather than the closing impedance, the resistor 22 may be omitted. The important factor in the network as here disclosed, is that the impedance from which the network comprising the elements 23 and 25 is fed be primarily resistive and of a sufficiently high value so that the effect of the impedance of elements 23 and 25 on the current flow is negligible.

Connected across the closing impedance is a vacuum tube 26, preferably of the screen grid type, so that its output impedance is high. The plate of the tube 26 is connected through another network comprising an inductor 27 and a variable resistor 28.

In a laboratory circuit as actually constructed for a wave which had passed through a filter designed for substantially complete cut-off above 7 k. c., the resistor 22 had a value of ¼ megohm, and the inductors 23 and 27 a value of about 35 millihenries each. Setting the variable resistors 25 and 28 at about 2,000 ohms gave the best appearance to the picture. The impedance of the line was negligible as compared to that of the control resistor 22.

Coupled to the plate circuit of the tube 26 through a condenser 30 is a cathode-ray receiving tube or oscillight 31, whose grid 32 connects to the condenser 30. The oscillight has a hot filament 33 which releases electrons to be accelerated by the anode 35 and focused in a spot upon a fluorescent screen 36 in the large end of the oscillight. The intensity of this spot is controlled by the grid 32, and it is deflected, preferably magnetically, by the coil 37 supplied by an oscillator 38, in a manner to correspond with the deflection of the electron stream by the transmitting scanning oscillator. This causes the transmitted picture to appear upon the fluorescent screen, traced by the focal spot.

In this case also, but one of the scanning oscillators is shown. The receiving scanning oscillators are held in synchronism by being connected to the oscillight grid 32 through a resistor 40, as is described in my above mentioned application, Serial No. 461,111, the scanning frequency components in the transmitted wave being sufficient to hold the oscillator in step.

If the amplifier 18 be connected directly to the grid 32, and if it be capable of amplifying a broad band of frequencies, say of the order of 300 to 1,000 kilocycles, an excellent reproduction of the object 5 will appear upon the fluorescent screen 36 of the oscillight. The introduction of the filter 20 into the line, without the addition of the other apparatus between the filter and the oscillight, converts the clear-cut picture upon the screen into a blurred image which is almost unrecognizable. The sharply defined edges are spread out into wide, shaded bands, and the picture assumes the general appearance of a shadow cast upon a distant screen by a large light source; i. e., the dark portions of the image are surrounded by a large "penumbra".

The insertion of the network already described between the filter and the oscillight at once restores the detail of the picture, the definition being even better than that obtained by connecting the amplifier directly to the grid of the oscillight.

Practically, enormous advantages are obtained by filtering out the high frequencies before transmission. The filter need not be a separate structure as shown, but may be incorporated in the amplifier, giving a cheaper, smaller, and more efficient structure than that necessary for handling the wide bands heretofore required. Moreover, if the transmitted band be restricted in width, the line may be utilized for carrier telephone (or television) purposes, with consequent savings in investment. In addition to these factors, the effect of phase distortion or envelope delay is minimized, since this effect is a function of the frequencies transmitted. Where these frequencies are but one or two percent of those otherwise required, the undesirable effects produced are reduced in approximately the same proportion, and their correction is rendered correspondingly easier.

The filtering out of the high frequencies is even more necessary where transmission is over a radio channel, as indicated in Figures 7 and 8, since the wide band formerly necessary is difficult to modulate upon any but the highest frequency carriers, difficult to receive without side band cutting, and cause excessive interference with other services.

In the radio transmission system illustrated in Figure 7, the apparatus utilized is identical with that used for line transmission up to, and including the filter 20', and is indicated by similar reference characters, distinguished by accents. Instead of feeding into a line however, the filter feeds into an oscillator-modulator 41 of the same type as is required for sound-radio transmission, and is radiated from an antenna 42.

At the receiver shown in Figure 8, the signals are picked up by the antenna 42', and passed through the amplifier-detector 43, and after detection are impressed upon the grid of the high-impedance tube 44. The plate circuit of this tube comprises an inductor 23' and resistor 25', which have the same function as the similarly designated elements in Figure 1, the resistor 22 being unnecessary in this case since its function is filled by the plate impedance of the tube. From this point forward, the circuit is identical with that shown in Figure 1, with the exception of the grid-biasing resistor 45 and grid condenser 45', which are used in accordance with usual amplifier practice, and which are unnecessary in the line terminal apparatus where the tube 44 is omitted.

The action of the terminal network in restoring the picture can best be understood from a mathematical analysis of the picture pulses and the distortions which they undergo between the transmitter and receiver.

Characteristically, the changes in illumination in a picture are sudden; i. e., the aperture, traversing a portion of the picture having a constant illumination k, suddenly arrives at another portion having a different illumination h. The instant at which this change in illumination occurs may be taken as time $t=0$. The result is a current in the resistor 17 which has, up to time 0, a value proportional to k, and after time 0 a suddenly increased value proportional to h. The form of this current pulse is illustrated in Figure 2.

If the scanning aperture be large, the increase in current from k to h, instead of being instantaneous, occupies a definite time T, the increase in current occurring at a constant rate during this time. This gradual increase is shown by the dotted curve 46' of Figure 2, the condition for an infinitely small aperture being shown by the solid curve 46. With the electrical scanning system however, the aperture may be made as small as desired, approaching very closely the conditions indicated by the curve 46. For the sake of simplicity in the analysis, only the condition introduced by the infinitely small aperture will be considered, since the effect of a larger aperture is substantially the same as that of a low pass filter, as was above stated.

If we consider the current k as a direct current, on which are superposed the pulses comprising the picture current, we may neglect k and represent the pulse by a Fourier integral

$$I=f(t)=\frac{1}{\pi}\int_0^\infty d\omega\int_{-\infty}^{+\infty} f(\lambda)\cos\omega(\lambda-t)d\lambda,$$

where λ is an auxiliary variable of integration. The value of this integral from $t=-\infty$ to $t=0$ is 0, and from $t=0$ to $t=\infty$ it is $(h-k)$. For positive values of t it may be expressed in the simplified form:

$$I=f(t)=\frac{2}{\pi}\int_0^\infty d\omega \sin \omega t\int_0^\infty (h-k) \sin \omega\lambda d\lambda.$$

The integration with respect to ω indicates the summation of all the component frequencies of the pulse, while the integral with respect to λ gives the amplitude of these frequencies. Performing the first integration and simplifying,

$$I=f(t)=2\frac{(h-k)}{\pi}\int_0^\infty \frac{\sin \omega t}{\omega}d\omega.$$

This represents the original pulse. If we remove from it all frequencies above

$$f_c=\frac{N}{2\pi},$$

the modified pulse can be expressed by the same integral by changing the upper limit from ∞ to N, giving

$$I=f(t)=2\frac{(h-k)}{\pi}\int_0^N \frac{\sin \omega t}{\omega}d\omega.$$

This function is plotted against Nt as curve 47, Figure 3. It will be noted that the current I is zero up to time $t=0$, when it suddenly starts to rise, having its steepest slope at this point. It continues to rise with gradually decreasing slope, to a value greater than its final value $h-k$, and then falls to its final value through a series of damped oscillations about this value. This is the form of the incoming wave at the receiver.

In interpreting this curve, it should be realized that N is merely the value of ω at the cut-off frequency and that the curve holds true whatever the value of cut-off. Dividing all of the abscissas by N would convert the X axis into a true time axis for the one particular value of cut-off chosen.

In the complete analysis, the function, being odd, passes thru values prior to $t=0$ which are equal and opposite to the values assumed for corresponding positive times, i. e., $f(t)=-f(-t)$. This condition cannot obtain in any physical network, however, since it would necessitate that the filter anticipate each pulse, going into oscillation in response to the pulse an infinite time before its arrival, or else that the pulse be infinitely delayed in passing thru the network. What actually occurs, in a system without appreciable phase distortion, is shown by curve 47, which corresponds with oscillograph traces obtained under the conditions given. A definite discontinuity in slope, at the instart of arrival of the pulse, is characteristic of any physical network which can be constructed.

This abrupt change of slope represents a sudden rise or discontinuity in the derivative I′ of the curve, which is plotted as curve 48 of Figure 3. As will be seen, this function is also zero up to time $t=0$, when it rises abruptly to a maximum value, and then falls gradually to a value $I'=0$ through a series of oscillations approximately 90° behind the oscillations of I.

The second derivative I″ of curve 47 is plotted as curve 49 of the same figure. It rises to a value $I''=\infty$ at time 0, falls instantly to zero value, and dies out through a series of damped oscillations lagging about 180° behind those of I.

If a curve be plotted representing the sum of curve 47 and a proportional amount of curve 48 such that the initial value of I′ at $t=0$ is equal to the final value of I, the new curve will be an abruptly rising pulse, substantially equal to the original pulse plus a small damped oscillation, as indicated by curve 50, Figure 6. Adding to this curve a smaller proportion of curve 49 slightly decreases the amplitude of the superposed oscillation, and adds an instantaneous high peak to the steep front of the wave, as indicated by curve 51 of Figure 5.

The effect of the terminal network described above is to add components proportional to the first and second derivatives to the incoming current wave, so that curve 51 represents the resulting wave as applied to the grid 32 of the cathode-ray receiver.

The current I, flowing through the resistor 25, causes a voltage drop IR, where R is the resistance of the element 25. The same current through the inductor 23, produces a voltage drop equal to

$$L\frac{dI}{dt},$$

where L is the inductance of the element 23. The sum of these two voltages is impressed upon the grid of the tube 26.

The quantity

$$\frac{dI}{dt},$$

however, is the same as that which we have already plotted as I′, and the control voltage on the grid of the tube is therefore proportional to curve 50. An excellent picture is obtained by applying this voltage directly to the grid of the oscillight, omitting the tube 26 altogether.

It is preferred, however, to use this tube as shown. A screen grid tube is used, because its high impedance causes its output current to vary in direct proportion to its control voltage, regardless of the impedance in its output circuit. This output current in the resistor 28 produces a voltage drop proportional to I plus a component I′. The same current in the inductor 27 produces a voltage proportional to I′ plus a component I″. The I′ components are additive, and hence the voltage applied to the grid of the oscillight corresponds to the curve 51 already described.

The two resistors 25 and 28 being variable, the relative values of the various components may be easily adjusted until the picture assumes its best appearance.

Up to this point, we have considered only abrupt changes in illumination and current. Such changes comprise a very large majority of the impulses occurring in picture transmission, but in a few cases there is a gradual change of illumination of light to dark or the reverse. These changes also usually involve an abrupt change of slope at their beginning or end, which cause steep fronted derivative waves which are, however, of less magnitude than those produced by a pulse of the fundamental type. Without considering the mathematics of such a condition in detail, the general effect is shown in Figure 4. In this figure, curve 52 indicates a current which is steady up to time t_1, rises gradually between t_1 and t_2, and then resumes a steady state at a new value. The form in which this current would be restored by the network here shown, is indicated roughly by curve 53. The change in slope causes a steep fronted pulse, which raises the level of the entire current at t_1. The fundamental component between t_1 and t_2 causes the gradual increase in current during this interval, while the opposite change of slope at t_2 causes the current again to drop to approximately its steady value at t_2. If the picture is being scanned "back and forth", the return scanning sweep causes the picture current level to follow the level of the curve **53'**. In this curve, the level is as much below the true level as it was above in the opposite sweep, and the average effect is substantially undistorted. The effect is much exaggerated in the figure.

The compensating network differs from the ordinary amplifier, in that the impedance whose voltage drop in applied to the input circuit of the tube does not control its own current flow, which is determined by the much greater external resistance **22**. The circuit being primarily resistive, the current and voltage waves have the same form, and the voltage across the relatively negligible inductance **23** is therefore proportional to the derivative of both current and voltage waves.

Were the control impedance inductive, the current wave would differ from the voltage wave, being proportional to its integral. The voltage across the inductance would still be proportional to the derivative of the current wave, but it would be identical in form with the voltage wave. This is the condition in ordinary impedance coupled amplifiers. The restoring circuit as a whole, even including the tube **26**, usually attenuates rather than amplifies the received signal, and an additional tube or tubes must be provided where amplification of the received signals is necessary.

The additional amplifier, where required, may best be inserted ahead of the network, as in the radio adaptation of the invention, and it may be of any approved type which is adequate to amplify the received signal band. Its final tube, however, is preferably, like the tube **44**, of the screen grid type, having a plate resistance which may be considered as infinite, this resistance controlling the current flow and acting as the element **22**.

The value of the second derivative component in the wave lies largely in compensating for aperture effect in the receiver. The sudden large change, coming at the first change of slope of the pulse, forms a sharply defined edge on the image instead of the shaded band the width of the aperture. As has been stated above, this effect may, if desired, be omitted with only slight loss of detail in the picture.

There are certain cases, however, in which, because of phase distortion or through repeated changes of energy form, such as modulation and demodulation by sluggish systems, where the change of slope at the instant of arrival of the transient ceases to be abrupt. Even in these cases there is an abrupt rate of change of slope; i. e., a discontinuity in the second derivative, which enables the original pulse to be substantially reconstructed. In such cases the third derivative may be added to compensate for the aperture effect. Thus far, no cases have been found where the need has arisen to add derivatives higher than the third in picture transmission, but there is no reason why this could not be done if desirable.

In the theoretical consideration of the effect of filtering high frequencies from the picture pulses, it has been assumed that the cut off of the filter is absolutely sharp; i. e., that at the frequency f_c there is no attenuation, while at $f_c+\Delta f$, the attenuation is infinite. In practice this condition never obtains, the cut-off being gradual, and frequencies above f_c being more and more attenuated as we ascend the frequency scale.

The effect of the gradual cut-off is to decrease somewhat the oscillations which are imposed upon the crest of the reconstructed wave. It is therefore advantageous that the filter used should pass uniformly the frequencies up to f_c, attenuate the frequencies from f_c to some other value f' at an increasing rate, all frequencies above f' being substantially eliminated. The conditions of the particular problem will determine the width of the band of increasing attenuation between f_c and f', the compromise being between band width and fringes on the transmitted images due to the oscillations. Even with the sharpest cut-offs obtainable, however, these fringes have not proved in practice to be a serious detriment. It is because of uncertainties as to the sharpness of cut-off in different transmitting systems, or even in the same system at different times, that it is advisable to provide adjustability in the restoring network, so that the proportion of arriving pulse and derivatives may be changed to give the picture its best appearance. It is not necessary that the resistive element in the network be the adjustable one, or even that separate elements be used, since a resistor and a variometer in series, or a variometer wound with resistance wire, would give the effect required.

Other forms of differentiating circuits are also possible. Thus, in Figure 9, there is shown a circuit which will differentiate a voltage wave, although its general applicability is not as great as that of the circuit already described. In this case the high control impedance is provided by a small condenser **65**, the shunt arm being formed by a relatively negligible resistance **66** in series with a large capacity **67**. The latter is bridged by a high resistance leak **68** through which the grid of the tube **70** is biased by a battery **71**.

In this circuit the voltage drop across the resistor provides the derivative component, while that across the condenser represents the original wave.

Figure 10 illustrates a circuit giving components of both first and second derivatives, as well as the fundamental. Here the control impedance is again supplied by a condenser **75**, while the condenser **76** gives a fundamental voltage drop, the resistor **77** a first derivative, and the inductor **78** a second derivative component.

Conditions are rare in which the series resistance in a circuit can economically be made sufficiently small to justify the use of a capacitive impedance as in these two latter circuits, but they are included to illustrate the possible range of equivalents. In general it may be stated that with any control impedance, a voltage drop leading that in the impedance will be proportional to a derivative, the first if the angle of lead be 90°, the second if the angle be 180°.

Actual experiment has shown that the principal effect of eliminating the high frequencies and reestablishing them as here described, is a slight heightening of the contrast in the picture, bringing out the angles and planes in sharper relief, and giving a result which several observers have described as a stereoscopic effect. Obviously, no true stereoscopy is produced, and this stereoscopic effect is an optical illusion resulting from the slight distortion.

It is to be noted that with this system of transmission the actual length of the interval which separates successive pulses is not important, and that it may be much shorter than the period of the highest frequency transmitted. Thus, a pulse of decreasing current may follow one of increasing current long before the final value of the increase has been reached. This results merely in a sudden rate of change of increase, which is transformed by the corrective network into the semblance of the negative pulse. This was well illustrated in one experiment tried, in which the scanning frequency used was 4,000 cycles, the picture current being passed through a filter having a cut-off value of 6,000 cycles. Pictures were transmitted through this system having as many as 20 discrete changes in illumination per cycle. In this case, the cut-off frequency was so close to the scanning frequency that no recognizable picture whatsoever was produced without the restoring network. With the network, the picture was better defined than when transmitted directly over a line of negligible length.

As was indicated above, the condition of sharp cut-off is the least favorable for compensating and reestablishing the sharp fronted pulse. If the attenuation is proportional to frequency above some specified value, the first derivative alone is complete compensation of the original pulse. Second derivatives may be added in this case, as before, to compensate for the distortion of the receiving aperture. It should be mentioned here, that the second derivative also helps to compensate for any distortion caused between the terminal network and the receiving oscillight itself by the capacity of the leads and apparatus. This capacity integrates the pulses fed it, converting a portion of the second derivative back to first derivative, and first derivative to fundamental.

While I have described my invention primarily as applied to television signals, for which service I have succeeded in narrowing the required band of frequency by a factor as high as one hundred, it is obvious that it is also applicable to the transmission of still pictures, in which it will give comparable narrowing of the band, and also to telegraph and cable signals.

I am aware that Carson and others have used differentiating circuits to correct wave form in submarine cables and thus increase signaling speeds. In this case, however, the high frequencies, although attenuated, are not removed, and the excessive phase delay so distorts the waves that many successive derivatives are necessary to build up a steep wave front. It has escaped notice in the past that the presence of these high frequencies is unnecessary and undesirable; on the contrary, their presence has been deemed essential to give a true reconstruction of the wave.

Moreover, although the use of differentiating circuits for cable use has been known for over twelve years to experimenters in television and picture transmission in general, it is by no means obvious that they are applicable to these latter uses, and no attempt has heretofore been made to apply them in this manner. This is quite probable because of the misinterpretation of the Fourier integral mentioned above.

It will be seen that this invention, by reducing the requirements which have heretofore been imposed upon land lines and radio links required for television, removes the outstanding difficulties in the way of a commercially practical television system. Actual experiments show that satisfactory pictures may by this system be transmitted over ordinary telephone lines. Parallel to this is the fact that present day broadcasting equipment may be utilized to transmit radio television pictures upon wave bands no wider than those now used for sound radio transmission. Additional detail can be secured by widening the band allotted to the picture, but the detail of a picture transmitted upon any band may be increased in the order of 100 to 1. This makes possible the transmission by television of pictures comparable in detail to those projected upon the moving picture screen, and by removing the limitation heretofore imposed by the transmitting medium, throws the burden of development back once more upon transmitting and receiving equipment.

I claim:

1. The method of picture transmission which comprises the steps of scanning a picture field to produce picture current corresponding to a predetermined degree of detail, filtering said current to remove the high frequency components thereof, transmitting said currents, initiating at the receiving end components substantially equivalent to the components removed in filtering, and combining said components with components equivalent to the received current.

2. The method of picture transmission which comprises the steps of scanning a picture field to produce picture currents corresponding to a predetermined degree of detail, transmitting pulses corresponding to the low frequency components only of said current, receiving said pulses, initiating at the receiving end components substantially equivalent to the high frequency components of the original picture current, and combining the transmitted pulses with the locally initiated components.

3. The method of picture transmission which comprises the steps of scanning a picture field to produce picture current corresponding to a predetermined degree of detail, transmitting pulses corresponding to the low frequency components only of said currents, receiving said pulses, and adding to the received pulses components proportional to a derivative of said pulses with respect to time.

4. The method of picture transmission which comprises the steps of scanning a picture field to produce picture current corresponding to a predetermined degree of detail, transmitting pulses corresponding to the low frequency components only of said currents, receiving said pulses, and adding to the received pulses components proportional to a plurality of derivatives of said pulses with respect to time.

5. The method of picture transmission which comprises the steps of scanning a picture field to produce picture current corresponding to a predetermined degree of detail, transmitting pulses corresponding to the low frequency components only of said currents, and utilizing changes of slope in the wave front of the received pulses to create steep fronted pulses for forming the received picture.

6. In a picture transmission system, means for scanning an object to produce a picture current, means for attenuating the high frequency components of said current, a communication channel for conveying impulses corresponding to the modified current to a receiving station, means actuated by the received impulses for regenerating components substantially equivalent to the attenuated components, and means responsive to said regenerated components for forming the received picture.

7. In a picture transmission system, means for scanning an object to produce a picture current, means for attenuating the high frequency components of said current, a communication channel for conveying impulses corresponding to the modified current to a receiving station, means actuated by the received impulses for generating an impulse substantially proportional to a derivative of the received pulse with respect to time, and means responsive to said derivative impulse for forming the received picture.

8. In a picture transmission system, means for scanning an object to produce a picture current, means for attenuating the high frequency components of said current, a communication channel for conveying impulses corresponding to the modified current to a receiving station, said channel terminating in a circuit of relatively high impedance, an element in said circuit wherein the voltage drop leads the drop in said circuit and having relatively low impedance with respect thereto, and means responsive to the voltage drop in said element for forming the received picture.

9. In a picture transmission system, means for scanning an object to produce a picture current, means for attenuating the high frequency components of said current, a communication channel for conveying impulses corresponding to the modified current to a receiving station, said channel terminating in a circuit of relatively high resistance, an inductor in series with said circuit having a relatively low impedance with respect thereto at the highest transmitted frequency, and means responsive to the voltage drop in said inductor for forming the received picture.

10. In a picture transmission system, means for scanning an object to produce a picture current, means for attenuating the high frequency components of said current, a communication channel for conveying impulses corresponding to the modified current to a receiving station, said channel terminating in a circuit of relatively high impedance, a closing impedance comprising elements wherein the voltage drop has components leading and in phase with the drop in said circuit impedance and of low impedance relative to said circuit at the highest frequency transmitted, and means responsive to the voltage drop in said elements for forming the received picture.

11. In a picture transmission system, means for scanning an object to produce a picture current, means for attenuating the high frequency components of said current, a communication channel for conveying impulses corresponding to the modified current to a receiving station, said channel terminating in a circuit of relatively high resistance, a closing impedance comprising an inductor and a resistor having substantially equal impedances at the highest frequency transmitted, said impedances being low relative to the impedance of the circuit, and means responsive to the voltage drop in said impedance for forming the received picture.

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