The Production and Utilization of Television Signals[1]

By FRANK GRAY, J. W. HORTON and R. C. MATHES

SYNOPSIS: The design of a television system, once the fundamental principles are understood, involves a detailed consideration of the methods by which the several important functions are to be performed.

(1) In the present system the initial signal wave is obtained by sweeping a spot of light over the subject in parallel lines completely scanning it once every 18th of a second. The light reflected is collected by large photoelectric cells which control the transmitted current. At the receiving station the picture current controls the brightness of a neon lamp from which the received image is built up by means of a small aperture moving in synchronism with the spot of light at the transmitting station. For presentation to a large audience television images may be produced by a neon lamp in the form of a grid having a large number of separate electrodes. A high frequency excitation controlled by the picture current is distributed to the successive electrodes in synchronism with the spot of light at the transmitting station.

(2) Space and time variations in the reflecting power of the subject are translated into time variations in signal strength. For design purposes these time variations are represented by component frequencies, a minimum band of which must be properly transmitted to insure an adequate reproduction of the image. Within this band there must be maintained a certain degree of uniformity in the efficiency of transmission of the separate components. Also, their phases must not be permitted to shift unduly in relation to each other.

(3) The design of the terminal amplifiers is based on the quantitatively determined characteristics of the photoelectric cells and of the neon lamps as well as on the limits imposed by the transmission study and by the characteristics of available transmission media, whether telephone line or radio system. The circuits employed at the transmitting station furnish an amplification such that the power delivered to the transmission medium is 10^{15} times the power received from the photoelectric cells.

SECTION I. APPARATUS FOR THE ANALYSIS AND SYNTHESIS OF THE IMAGE

THE introductory paper to this series of articles on television explained principles along which any television system must operate to transmit an image over a single pair of wires or other channel of communication. As the first step in such a transmission, the space variations in brightness from point to point in the view must be translated into time variations in an electrical current that can be sent over the channel of communication. This translation may be accomplished by a scanning process that operates on the view to produce the same effect as if the view were cut up into a single long strip and passed rapidly in front of a light-sensitive cell to generate an electrical current varying with the brightness along the strip. To eliminate flicker in the reconstructed image and also to follow moving

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subjects in a view, the scanning process must be repeated and a new picture transmitted at least every sixteenth of a second.

Many purely theoretical methods could be, and have been, devised to accomplish such a scanning process and to translate a view into electrical currents or signals. Unfortunately, however, a practical system of television must operate with materials and conditions as they exist, and these practical limitations constitute the serious problems of television.

The high speeds and relatively large amplitudes with which any television scanning mechanism must move, and the necessity for synchronizing the transmitting and receiving apparatus lead to the use of synchronously rotating machines as apparently the only practical solution of the scanning and receiving problems. Consequently, the

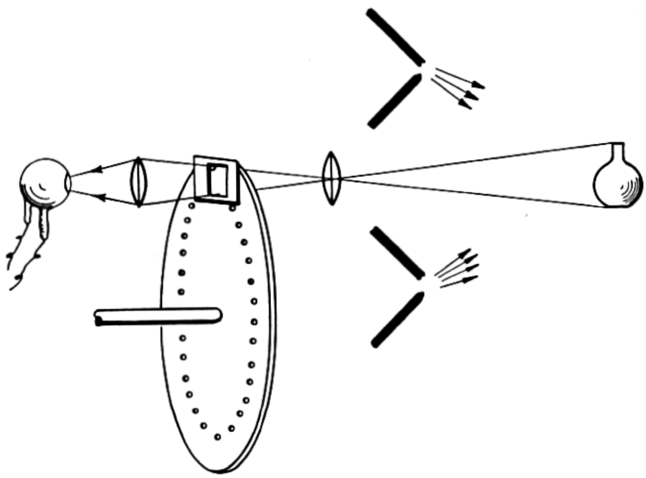


Fig. 1—Several light sources illuminate the subject; a lens forms an image which is scanned by a spiral of apertures, through which the light falls on a single photoelectric cell.

present television system has been designed to operate with continuously rotating mechanical parts.

The efficiency that must be secured in the optical part of any scanning method is fixed by the three following factors—the amount of picture detail that is to be transmitted, the efficiency of the light-sensitive cell, and the practical limit to amplifier systems. The first of these factors decides the area from which light can be collected at any one instant. In the present case this was fixed in an initial survey of the entire television problem when it was decided to confine the first attempt to the transmission of pictures as if they were made up of 2500 small elemental areas; that is, to scan the view in a series of fifty parallel lines. The second factor is determined by the sensitivity of the potassium hydride photoelectric cell. This cell is, at the present time, the most efficient light-sensitive cell that can follow the rapid variations in light intensity without a time lag. The third factor, the limitation of amplifier systems, results from the extraneous currents that are present in metallic conductors and

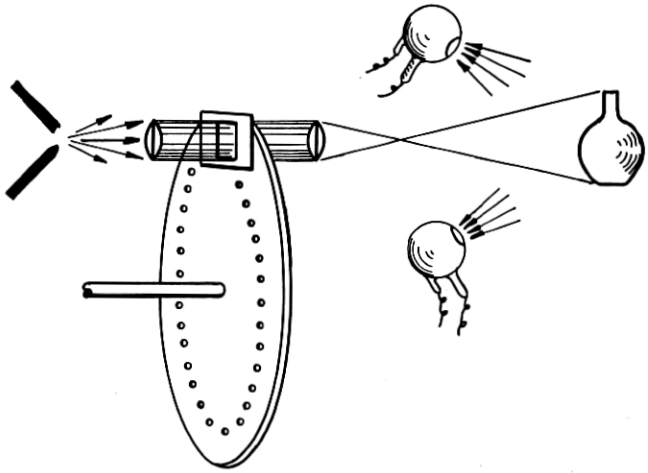


Fig. 2—Light from a single source is projected as a small moving spot on the subject; the reflected light is received by several photoelectric cells

amplifier tubes. The thermal agitation of the electrons in any input resistance generates such currents; and rapid variations in the number of electrons emitted from the hot filament of an amplifier tube also generate disturbing voltages. For successful amplification, the initial photoelectric current must be considerably larger than these extraneous currents. Consequently, the optical arrangement must be such that at any one instant it collects enough light from an elemental area of the view to generate this minimum permissible output current from the photoelectric cell.

The operation and advantages of the scanning method actually used in the present process for transmitting television images may be better understood by first considering a simple and analogous method illustrated by Fig. 1. The subject is illuminated by lights placed in front of it as shown. A lens forms an image of the subject on the rotating disk. This disk is pierced with a series of small holes or apertures arranged in the form of a spiral; and, as the disk rotates, the apertures trace across the image one after the other in a series of parallel lines. The frame limits the size of the image and prevents more than one aperture being in the image at one time. Light, passing through an aperture as it travels across the image, falls in the light-sensitive cell and generates a picture current proportional to the brightness of the image from point to point along strips taken one after the other across the image.

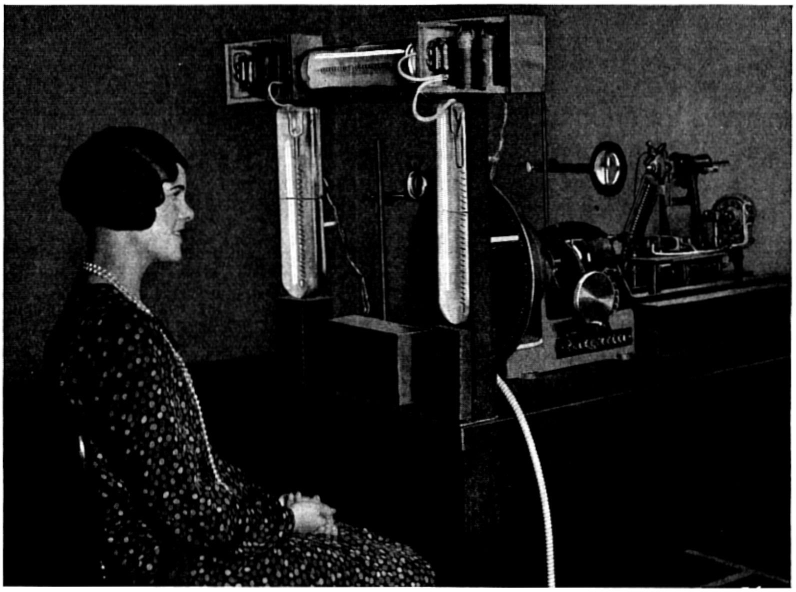


Fig. 3—Illustrative transmitting apparatus. Light from the arc lamp is condensed on the disk, which is driven by a high frequency synchronous motor. The disk carries a spiral of pin hole apertures, each of which in turn projects a moving spot of light on the subject. Reflected light is collected by three large photoelectric cells.

In any system such as that outlined above, which depends upon scanning an image of the view as formed by a lens, the efficiency of the system is ultimately limited, for any given size of image that can be scanned, by the ratio of aperture to focal length of the best lens that can be secured. Experiments show that, with the best lens available to form a one-inch-square image, it would be necessary to illuminate a subject with a 16,000-candle power arc at a distance of about four feet in order to secure an image bright enough for a photoelectric cell to give an output current above the noise level in an amplifier system. In other words, television would apparently be extremely inconvenient to the subject if it were to be carried out from an image formed by a lens.

In the system actually used for television transmission, this apparent limitation has been evaded by reversing the entire optical system of Fig. 1 and arranging it as shown diagrammatically in Fig. 2. Instead of scanning an image of the subject, the actual subject is scanned directly by a rapidly moving spot of light. An illustrative laboratory set-up, Fig. 3, shows the arrangement of parts in such a transmitting station. A fifteen-inch disk rotating approximately eighteen times per second carries a series of fifty small apertures arranged in the form of a spiral. A beam of light is condensed by a lens from a 40-ampere Sperry arc to intensely illuminate a limited area in the path of the moving apertures; and a slender, intense beam of light passes through each aperture as it moves across the illuminated area. A frame in front of the disk permits light to emerge from only one aperture at a time and the lens in front of the disk focuses an image of this moving aperture on the subject. As a result of this arrangement the subject is completely scanned in a series of successive, parallel lines by a rapidly moving spot of light, once for each revolution of the disk; and on account of the transient nature of the illumination the subject is scarcely aware that he is being exposed to it.

As the spot of light traces across the subject, light is diffusely reflected or scattered from the subject in all directions, and some of the light that is reflected forward passes into three large photoelectric cells placed just in front of the person who is being viewed. The current outputs from the three photoelectric cells operate in parallel into a common amplifier system. As the beam of light passes, for instance, across a person's eyebrow less light is reflected to the photoelectric cells, and as the beam passes across his forehead more light is reflected. Since the current output from the photoelectric cells is proportional to the received light, the current follows accurately the brightness of the various elemental areas of the subject's features as he is traced over by the scanning beam. This fluctuating current is unidirectional.

The actual operation of such an optical system, its influence on the lighting effects and quality of the reproduced image, may best be understood by noting that optically the system is identically the same as if all of the rays of light were reversed in direction to give an optical system equivalent to Fig. 1. The television apparatus sees the subject exactly as if rays of light came out of the photoelectric cells to illuminate the subject; the lens formed an image of the subject on the disk; and the apparatus scanned this image and reproduced it at the receiving end. The lights and shadows seen in the image are the same as if the subject were illuminated by three large lights in the positions of the photoelectric cells and looked at from the position of the lens. It also follows from the above considerations that, within its range of resolving power, this scanning method will not only reproduce a plane subject, such as a drawing, but that it will also faithfully reproduce three-dimensional figures with sharp edges and elevations and depressions, just as well as they could be reproduced in a photograph.

In addition, because the light passes in an approximately parallel beam through a disk aperture, the slender beams of light sweeping across the region in front of the transmitter just barely overlap each other even at a considerable distance from the apparatus. Consequently, it is not necessary that the subject be at the exact positions at which the small apertures are sharply focussed; and within wide limits no confusion results as the subject moves toward or away from the apparatus. The brightness as well as the size of the received image decreases as the subject moves away from the photoelectric cells; and for good transmission of the human features, which reflect very little blue light to which the photoelectric cells are sensitive, a person should not be more than a few feet away from the cells.

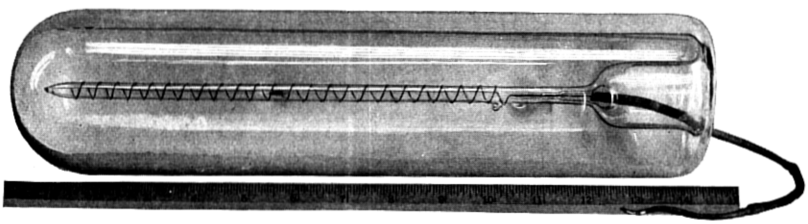


Fig. 4—Large photoelectric cell. The cell presents forty square inches of photosensitive surface to receive light reflected from a subject

This method of scanning permits two very large gains to be made in the amount of light available for producing photoelectric currents. The transient nature of the light permits a very intense illumination to be used without inconvenience to the subject. Furthermore, the optical efficiency of the system is not limited by the apertures of available lenses; but can be increased by using large photoelectric cells and more than one cell connected in parallel.

The photoelectric cells of the potassium hydride, gas-filled type used in the transmitting stations, were specially constructed for the purpose and are probably the largest photoelectric cells that have ever been made, Fig. 4. Three of these cells present an aperture of 120 square inches to collect the reflected light.

With this large collecting area and the strong light intensity that can be used for the transient illumination, the cells give an electrical output that, though still extremely small, is safely above the noise level of an amplifier system.

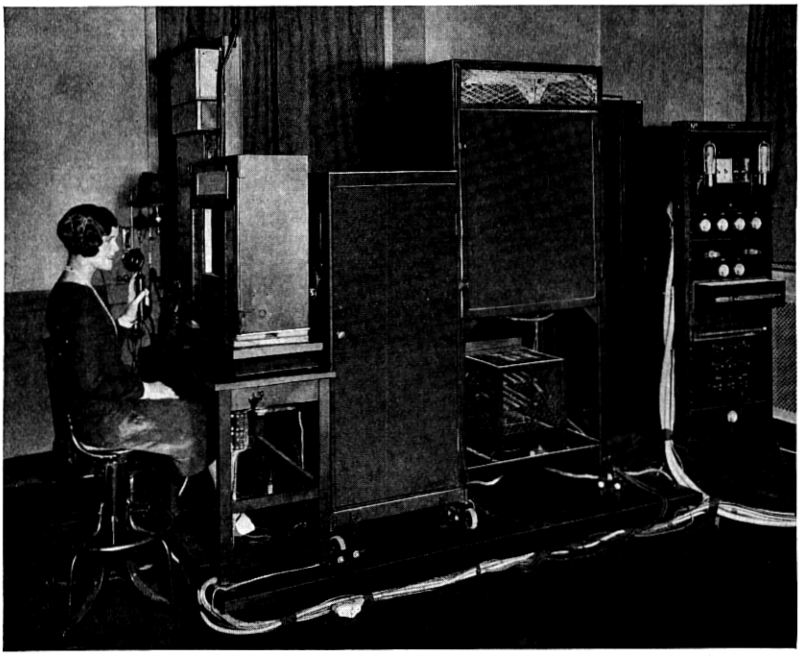


Fig. 5—Television transmitting apparatus. Sweeping beams of light pass out through the tunnel-like opening in the photoelectric cell case; light reflected from the subject is collected by three large photoelectric cells behind the screened openings.

A photograph, Fig. 5, shows the details of a television transmitting station as it is operated in the field. The arc, rotating disk and photoelectric cells are contained in separate cabinets and aligned as shown in the photographs. The three photoelectric cells and first stages of amplification are mounted in a shielded, sound-proof case. The slender, sweeping beam of light coming from the disk cabinet passes through the tunnel-like opening in the photoelectric cell case and scans the subject seated in front of it. The apparatus sees the person from light reflected back into the three large cells located just behind the screened openings in the case.

The variations of the feeble picture currents delivered from these photoelectric cells are highly amplified and transmitted over a wire or radio channel of communication by circuits described elsewhere in this series of articles. At the receiving station this current shape is re-amplified, impressed on a direct current, and finally produces an image in the receiving apparatus.

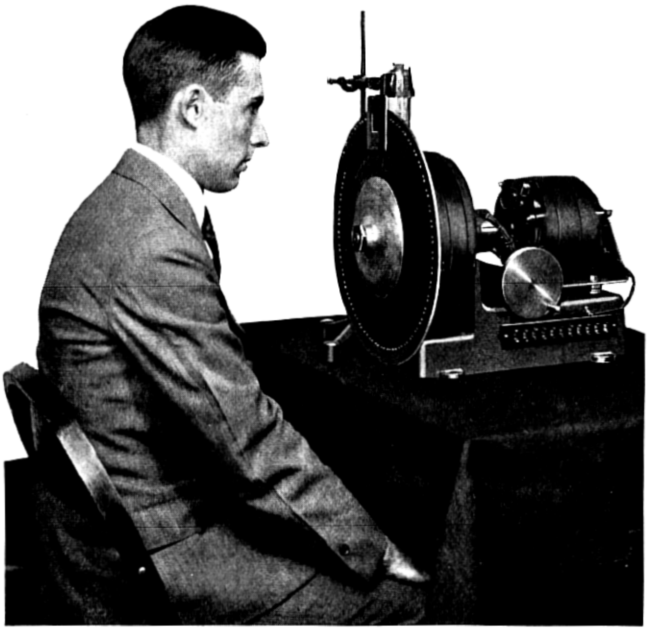


Fig. 6—Illustrative receiving apparatus. A neon lamp operated from the picture current illuminates a series of small apertures as they pass across the field of view; the observer sees an image reproduced in the frame.

A photograph, Fig. 6, shows an illustrative arrangement of the parts in one type of television receiver. An essential part of this type of receiver is a disk similar to the one at the transmitting station and also provided with fifty small apertures arranged in the form of a spiral. The driving motor rotates the disk in exact synchronism with the one at the transmitting station. The observer looks at a small rectangular opening or frame in front of the disk. This frame is of such dimensions that only one aperture can appear in the field of view at a time. As the disk rotates, the apertures pass across the frame one after the other in a series of parallel lines, each displaced a little from the preceding one until in one revolution of the disk the entire field has been covered. Beyond the disk is a special form of neon glow lamp shown in detail by Fig. 7. In this lamp, the cathode is a flat metal plate of a shape and area sufficient to entirely fill the field defined by the frame in front of the disk. The anode of the glow lamp is a similar metal plate separated from the cathode by only a very small space (about one millimeter). At the proper gas pressure this space between the plates is within the "cathode dark space" where no discharge can pass. As a consequence, the glow discharge develops on the outer surface of the cathode, where it shows as a perfectly uniform, thin, brightly glowing layer.

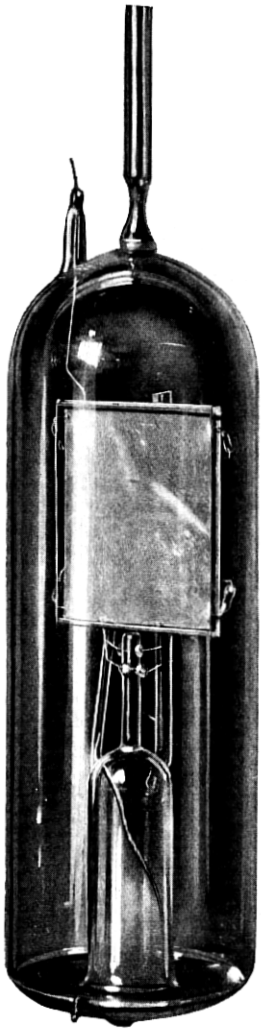


Fig. 7—Neon receiving lamp. The rectangular cathode is covered by a uniform layer of glow slightly larger than the field of view on a television disk

As an aperture in the disk moves across the field, the observer, looking through at the neon lamp behind the disk, sees the aperture as a bright point. When the disk is rotating at high speed, the observer, owing to the persistency of vision, sees a uniformly illuminated area in the frame, provided that a constant current is flowing through the lamp. (The line structure that would otherwise appear in the field is largely eliminated by using apertures that slightly overlap in their paths across the field.)

The brightness of the neon lamp is directly proportional to the current flowing through it; and when a picture is being received, the lamp is operated directly from the received picture current. As a result of the system just described, there is at any instant, in the field of view at the receiving station, a small aperture illuminated proportionally to the brightness of a corresponding spot on the distant subject. Consequently, the observer sees an image of the distant subject reproduced in the frame at the receiving station.

Fig. 8 shows the external appearance of the disk type of receiver in which the images appear. The disk rotates inside of a rectangular cabinet and the observer views the image through the shielding window. The largest disk, three feet in diameter, gives a 2 in. by 2½ in. rectangular image. Each television receiver is also equipped with a telephone receiver and transmitter; and it is possible for the observer to both see and converse with a distant person at the same time.

Considering the limited number of picture elements, a surprising amount of detail can be transmitted with this television system. A distant person can be seen and easily recognized and his motions can be plainly followed as he talks into a transmitter, turns the pages of a magazine and goes through other similar motions. Large-sized pictures in a magazine can be seen as the subject turns the pages and looks at them himself.

Fig. 8—Disk receiving apparatus. The observer looks through the shielding window at a picture on the 36-inch disk

An auxiliary television receiving system also accompanies each transmitting set and enables the operator to see that he is sending a satisfactory picture current out over the channel of communication. This auxiliary or pilot picture is formed on the scanning disk itself. A small fraction of the outgoing picture current is tapped off and amplified to operate a neon lamp, which is placed behind the disk ninety degrees around from the scanning beam. An image of the subject may thus be seen on the scanning disk just as at a receiving station. To correct for the ninety-degree phase shift, the spiral of apertures on the transmitting disk is continued by additional apertures a quarter of a turn beyond the starting point. The first turn alone of the spiral is used for scanning; and the last turn alone, to form the pilot image; consequently, this image appears exactly in frame. A small mirror on the front of the motor cabinet reflects this image to the operator and enables him to see the character of the picture that he is sending out over the channel of communication.

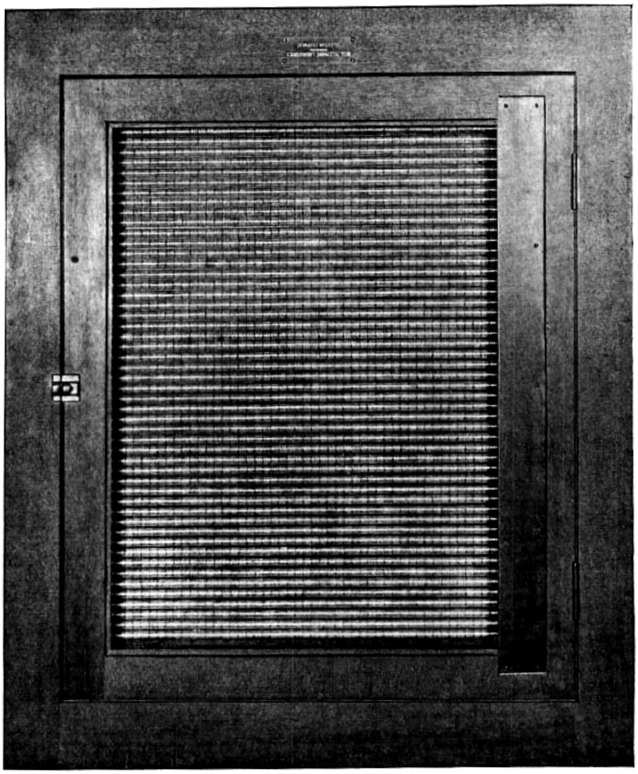


Fig. 9—Large grid. The large grid is a neon lamp with 2500 electrodes on a tube bent back and forth to form a luminous screen that is visible throughout a large auditorium.

When it is desirable to present television images to a large audience, a special grid type of receiver is used. The grid has the appearance of an illuminated screen and can be seen throughout a large auditorium. The image is not projected on the screen from a lantern like a moving picture; such optical projection would be inefficient and demand

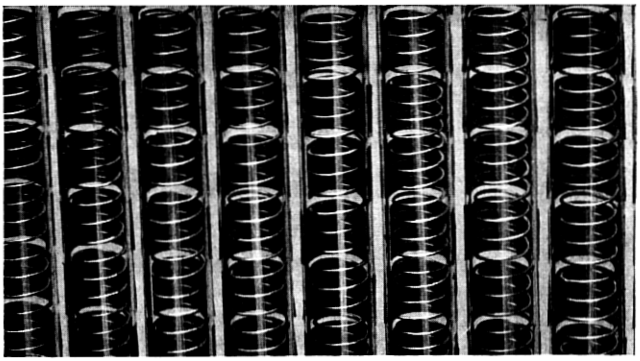


Fig. 10—Detailed structure of the grid. The exterior electrodes are pieces of metal foil cemented to the outside of the tube. The interior electrode is a long spiral of wire.

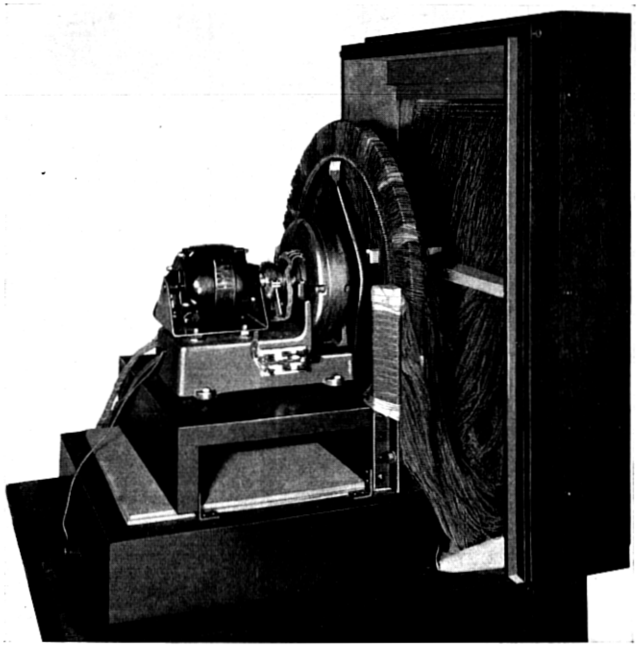


Fig. 11—Distributor and wiring. High frequency current is distributed by 2500 wires to successive electrodes of the grid from 2500 bars on a high speed distributor.

the electrical control of an impractical amount of light. The picture current itself is distributed by a commutator to successive elemental areas of a large neon lamp. This lamp, as shown in Fig. 9, consists of a single, long, neon-filled tube bent back and forth to give a series of fifty parallel sections of tubing. The tube has one interior electrode and 2500 exterior electrodes cemented along the back side of the glass tubing, Fig. 10. A high frequency voltage applied to the

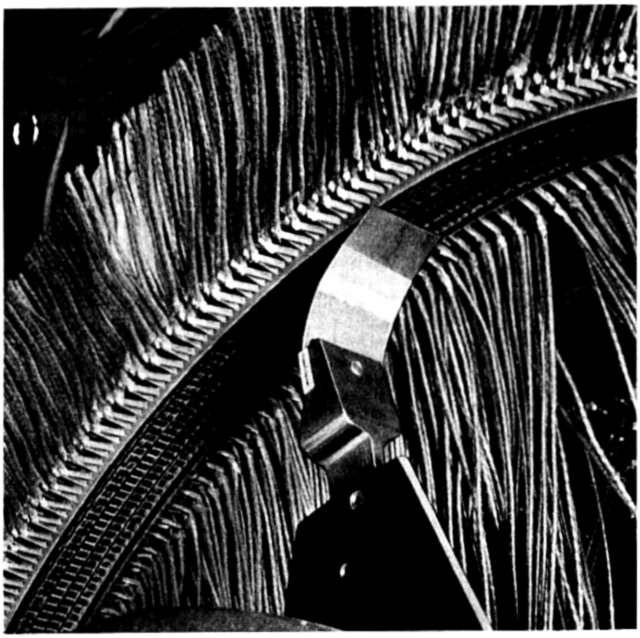


Fig. 12—Details of the distributor. The bars are arranged in four rows each displaced with respect to the other three. The sliding brush is a strip of thin sheet metal.

interior electrode and any one of the exterior electrodes will cause the tube to glow in front of that particular electrode. The glow discharge actually passes to the inside wall of the glass tubing and the high frequency current flows by a capacity effect out through the glass wall to the exterior electrode. The high frequency voltage is commutated to the electrodes in succession from 2500 bars on a distributor, Fig. 11, with a brush, Fig. 12, rotating synchronously with the disk at a transmitting station. Consequently, a spot of light moves rapidly and repeatedly across the grid in a series of parallel lines one after the other and in synchronism with the scanning beam at the transmitting station. With a constant exciting voltage the grid appears as a uniformly illuminated screen; but, when the high frequency voltage is modulated by the received picture current, an image of the distant subject is produced on the screen and his motions can be followed just as in the smaller images formed on a disk.

This method of presenting television images to a large audience permits a very efficient use of the available energy to reproduce a picture. The modulated current produces a glow discharge that exactly covers an elemental area of the picture on the screen and is viewed directly by the audience; consequently, there is absolutely no loss of energy after the picture current has been converted into light. In addition, each illuminated area of the screen responds to the picture current in the same manner; the exterior electrodes are exactly alike, and the use of a single tube assures the same pressure and purity of neon throughout the grid.

Fig. 9 shows such a screen set up for demonstration in an auditorium. A loud speaker is mounted just below the screen and it is thus possible for a large audience to both see and listen to a distant person at the same time.

Section II. The Television Signal Wave

So far it has been assumed that the electrical signal wave is perfectly transmitted between the conversion devices which transform the light variations into electrical variations and back again. Perfect transmission is, however, impossible with practical apparatus. There are certain requirements placed upon the generated signal wave by the characteristics of practical communication channels, and reciprocally certain demands are made upon a transmission system by the inherent nature of an adequate television signal. In addition to exploring these mutual requirements experimentally it is desirable to analyze them in such a way that, as far as possible, quantitative expression may be given to them. This expression in the case of the signal wave is best made by the methods of the Fourier analysis; considering the signal as made up of many sine wave components of various frequencies. The requirement on the signal may then be described in terms of these components and the requirements on the connecting transmission system in terms of attenuation and phase characteristics over a band of frequencies. These requirements will now be discussed as a basis for the subject matter of the succeeding section of this paper and of the following companion papers of this group on "Wire Transmission Systems for Television" and "Radio Transmission Systems for Television."

The problems to be discussed may be conveniently considered under three headings:

(*a*) The Character of the Television Signal.

(*b*) Requirements upon the Signal Wave Set by the Characteristics of Available Transmission Channels.

(*c*) Requirements which the Transmission Channels must meet in order to carry Television Signals.

(*a*) *The Character of the Television Signal.* As we have seen, the voltage produced across a resistance in series with the photoelectric cell is a fluctuating unidirectional potential. The generated signal therefore has frequency components beginning at and including zero frequency. The value of the voltage at any instant is roughly proportional to the average reflected illumination at that instant from an illuminated spot whose size depends upon the apertures in the scanning disk. At any point where there is a sudden change in the tone value of the subject there will also be a sharp change in the generated voltage. It will, therefore, be seen that but for the limits of speed of action of the photoelectric cell and its connected circuits the generated signals would tend to include components over the whole frequency range up to infinity. Since it is possible to effectively transmit but a limited range of these components, the width and location of the frequency band necessary for the acceptable reproduction of a given size and structure of image must be determined. It is convenient to consider first the low frequency end of the band.

In the early experimental work it was soon found that in attempting to amplify the lower frequencies by the use of direct current amplifiers, unstable conditions of operation were reached before sufficient amplification was obtained to operate the receiving apparatus. Experiments were then made with resistance-condenser coupled amplifiers which showed that, if the efficiency of such an amplifier at the frequency equal to the number of pictures sent per second was not more than about two T U below its average efficiency for the transmitted range, acceptable reproduction of the picture was secured together with stable operation of the amplifiers. When the low frequency cut-off of the amplifier was set much above this, spurious shadows were introduced into the picture. That there will be a critical lower frequency for the transmission of an unchanging scene is obvious since the Fourier series into which the signal may be analyzed starts with a constant term and the sine wave terms begin with the picture frequency and include a vast number of its harmonics. If the constant component (d-c.) is removed, the lowest frequency which remains to be transmitted is therefore the picture frequency.

The effect of removing the d-c. component of the signal can be qualitatively traced in a simple manner. Imagine three types of still pictures or scenes to be transmitted by the system. Let the first be quite dark in general effect and require fluctuations in the signal current of a certain average amount for its transmission. Such a picture would have a low direct current component. Let the second picture consist largely of medium grays and require about the same fluctuations in signal intensity for its delineation. Such a picture will have a medium direct current component. Let the third picture be very light in general effect with such difference in light and shadow as would require the same fluctuations in signal intensity as the other two pictures. Such a picture would have a relatively high direct current component. In passing through a resistance-condenser coupled amplifier, the signals for all three types of pictures would be changed from fluctuations superimposed upon direct current to alternating currents, all of about the same average value.

At the receiving end of the circuit the direct current component may be reinserted by superimposing the alternating current fluctuations upon a fixed value of direct current such as the steady state current in the last amplifier tube. This direct current component would give the best average results if it corresponded to that suitable for the gray picture, which would, of course, then be most nearly correctly reproduced. However, most of the detail of the dark and light scenes would also be reproduced though the tone values would be distributed about a medium gray. Fortunately a change in character of this kind has proven for the most part unimportant. Where it is important it can be taken care of very simply by providing, at the receiving end, means, either manual or automatic, for changing, in accordance with the type of scene being transmitted, the magnitude of the unidirectional current upon which the received alternating current is superposed, which amounts simply to the restoration of the direct current.

In the case of scenes which are changing, however, frequencies lower than picture frequency will in general be generated and their suppression may be expected to affect to some degree the perfection of the picture. In effect, these frequencies are analogous to changes in tone values in the case of still pictures and their elimination results in fluctuations in the apparent brightness of the image. This effect is not disturbing with many types of subjects, as for example in the reproduction of the face.

One remarkable result of not transmitting the direct current component of the signal in the case of the reflected beam method of scanning is that the television transmitting apparatus can be located and operated in a well-lighted room, for if this general illumination is constant it simply increases the direct current component of the signal. Similarly if the scene itself contains a source of steady light, this will be visible only in so far as it reflects the scanning beam.

Turning now to the upper part of the frequency range, experimental data on the highest necessary components were obtained by the use of circuits with low pass instead of high pass characteristics. With the television terminal apparatus operating at 17.7 pictures per second, it was found that a filter whose phase distortion had been corrected over practically all of its pass band of 15,000 cycles produced a degradation in image quality which was just detectable when the human countenance was being transmitted. Since the electrical terminal apparatus without the filters would efficiently transmit frequencies higher than this, the experiment showed either that frequencies higher than this were not present in the generated signal, that they were not effectively reproduced, or that they contribute little to the appearance of the image. This upper limit to the useful frequency range for this apparatus is rather lower than was anticipated from the initial survey, but because of psychological factors (decreased discrimination of tone values for fine details, apparent improved resolution when the subject is moving, etc.) it proves satisfactory for television purposes.

It is of importance, however, to know where the limitation in frequency range occurs in the apparatus and how it might be modified. Considerable information on this point is obtained by studying the nature of the distortion introduced by the aperture in the optical system and that introduced by frequency limitation in the electrical part of the system. It is convenient to consider them together as the type of distortion turns out to be similar for the two cases. This distortion may be considered most simply in relation to the type of signal corresponding to a sudden unit change in tone value at some point in the subject. With an ideal television system in which the instantaneous values of signal current are at all times proportional to the tone values of the points being scanned, the resulting signal would be represented by the graph of Fig. 13. Such a consideration involves no real loss in generality as any signal shape may be considered as the result of infinitesimal abrupt changes in intensity.

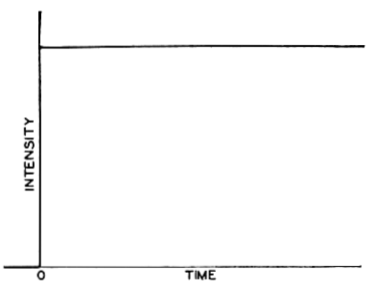


Fig. 13—Elementary signal change

It is readily seen that if a square aperture passes with uniform velocity over a part of the picture having an abrupt change from dark to light the result is that we get a signal from the photoelectric cell which, instead of building up instantaneously, builds up linearly during a time, T, Fig. 14, which is the time required for the aperture to pass a given point.[1] The net effect is an apparent sluggishness in the response of the system. The dotted curve of Fig. 14 shows the integrated illumination passing through a circular aperture of a diameter corresponding to the same time, T, for the condition of Fig. 13. Due to the simpler analysis the discussion will be carried out in terms of the square aperture though the sluggishness due to the round one is seen to be slightly less.

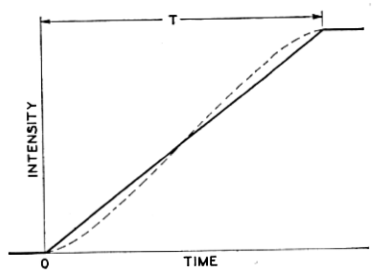


Fig. 14—Elementary signal change as distorted by a square aperture

Now this kind of sluggishness in response is quite similar to that introduced in the electrical part of the system when the upper frequencies are cut out or not transmitted as efficiently as the lower ones. The effect of frequency limitation can be investigated theoretically in a fairly simple fashion if we make the ideal assumption that all frequencies are transmitted without distortion up to a cut-off frequency, f_c, and extinguished beyond it. In Appendix I, it is shown how the signal of Fig. 14 is affected by a frequency limitation of this type. We can then plot a set of curves as shown on Fig. 15

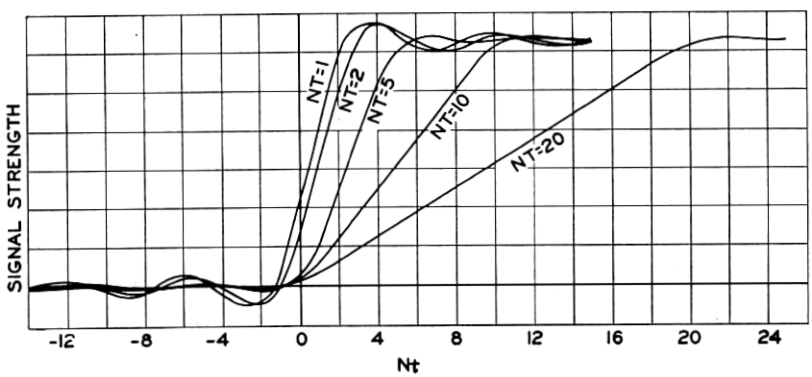


Fig. 15—Elementary signal change as distorted by a square aperture and by ideal frequency restriction

[1] This effect of aperture distortion was pointed out in the paper "Transmission of Pictures over Telephone Lines" by Ives, Horton, Parker and Clark, *B. S. T. J.*, April, 1925.

from which we can measure the total time of rise due to both the aperture and frequency limitation. The abscissa is the product of $N = 2\pi f_c$ and the time, t. Any one curve serves for a wide range of values of N and T as long as their product is the same. Call the new time of rise τ. Then we can plot a relation as on Fig. 16 between

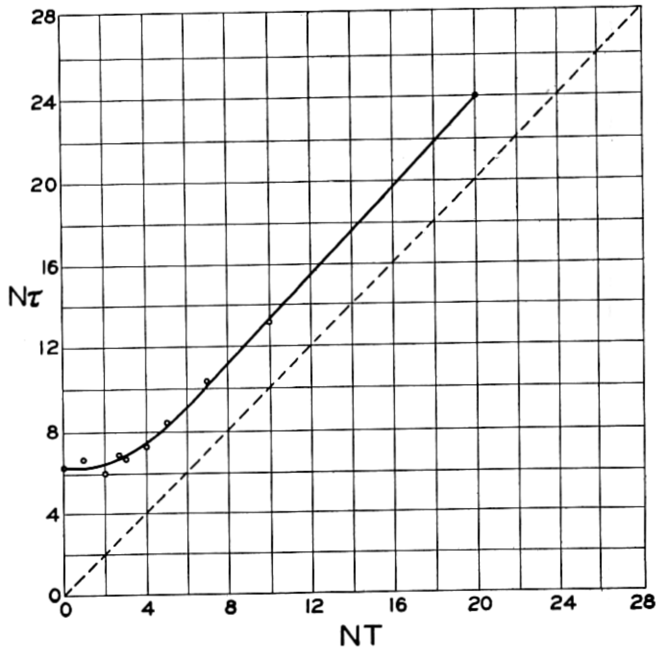


Fig. 16—Sluggishness due to distortion as a function of the aperture width and frequency restriction

$N\tau$ and NT from which we can draw conclusions as to the relative effects of aperture and frequency distortion.

Below the knee of this curve we have approximately

$$N\tau = 2\pi$$

$$\tau = \frac{1}{f_c}$$

and the frequency cut-off determines the whole distortion. Similarly above the knee

$$N\tau = NT + \pi$$

$$\tau = T + \frac{1}{2f_c}$$

and the controlling influence is that of the aperture.

Unless one effect is much more easily remedied than the other, the knee of the curve appears a reasonable point to select for operation. At the knee $NT_k = 2\pi f_c T_k = \pi$ and $T_k = 1/2f_c$. At this point the total lag is not much greater than that due to the frequency restriction alone and is $1/f_c$ or twice T_k. That is, at this point, the additional lag in the time of rise of signal due to the restricted frequency range is equal to that due originally to the aperture, though the additional lag due to the aperture is not much greater than that due to the frequency restriction alone. For a square aperture in a square picture of 2500 elements sent 16 times a second $T = 1/40{,}000$ of a second, and $f_c = 20{,}000$ cycles at the knee of the curve. The point on the curve where the effect of frequency restriction introduces a sluggishness in following light changes comparable to that introduced by a square aperture is the same frequency as that arrived at as the upper limit to useful frequencies by considerations from still picture transmission, in the introductory paper by Mr. Ives. Its value is equal to one half the number of picture elements.

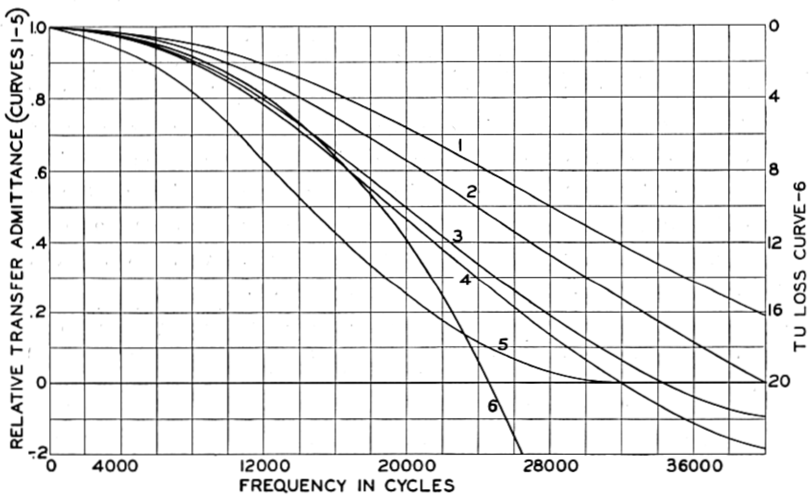


Fig. 17—Equivalent transfer admittance of various apertures

It has furthermore been found possible to determine ideal electrical transmission characteristics or equivalent transfer admittances of circuits which produce exactly the same distortions as various types of apertures. While it appears impossible at present to construct a physical circuit which will produce such characteristics over the whole frequency range, the problem is not difficult if we limit ourselves to the most important frequency band. This is of interest as it points out the possibility of compensating for the effect of the aperture by putting in an electrical network with frequency transmission characteristics the inverse of those so determined. Within the range of important frequencies it turns out that the effect of the aperture is the same as that of a network which changes merely the relative amplitudes of the frequencies into which the picture signal may be analyzed. Neglecting constant multiplying factors, the relative variation over the frequency range for a square aperture is given by the factor $\frac{\sin T\omega/2}{\omega}$ and for a round aperture by $\frac{J_1(T\omega/2)}{\omega}$, where, as before, T is the maximum time for the aperture to pass a given point and J_1 is the Bessel's function of the first order. The derivation of these factors is given in Appendix II. On Fig. 17, Curve 1 gives the relative values of the equivalent transfer admittance for the square aperture and Curve 2 for an inscribed circular aperture, both in case of a 50-line scanned picture which is square and sent 16 times per second. T then is equal to 1/40,000 sec.

In the system as set up for demonstration the image is rectangular with the vertical and horizontal dimensions in about the ratio 5 to 4. The circular aperture is about 1¼ times 1/50 of the vertical height and the scanning is done 17.7 times a second. T is then 3.53×10^{-5} seconds and Curve 3 gives the corresponding frequency characteristics. Curve 4 shows that a square aperture of the same area as the circular aperture for Curve 3 gives a fairly good approximation to Curve 3. Curve 5 gives the combined effect of the two circular apertures, sending and receiving, corresponding to Curve 3. Curve 6 is Curve 5 plotted in terms of T U on the right hand scale.

An inspection of this last curve indicates that this frequency attenuation characteristic of the aperture introduces a considerable loss at 15,000 cycles and leaves little of the signal components above 20,000 cycles. To see if an electrical circuit of characteristics inverse to those of the aperture would materially improve the resolution of the image, the circuit,[1] which, together with its frequency characteristics, is shown in Fig. 18, was inserted between the sending and receiving amplifiers. It was designed to compensate for most of the aperture distortion and its phase distortion was made small below 20,000 cycles. On the fan-shaped test pattern of Fig. 19 a noticeable improvement was observed, the black and white angles being resolved closer to the tip of the pattern. In the case of faces the improvement appeared to be very little but could be detected

[1] This is a constant resistance type of corrective network or equalizer. See Chap. XVIII, "Transmission Circuits for Telephonic Communication," K. S. Johnson.

in the slightly better definition of sharp narrow lines such as the frames of horn-rimmed spectacles. When a system of considerable attenuation is employed between the sending and receiving terminals, it would in general be preferable to split the equalizing between the sending and receiving ends to make the best use of the sending end power in riding over interference.

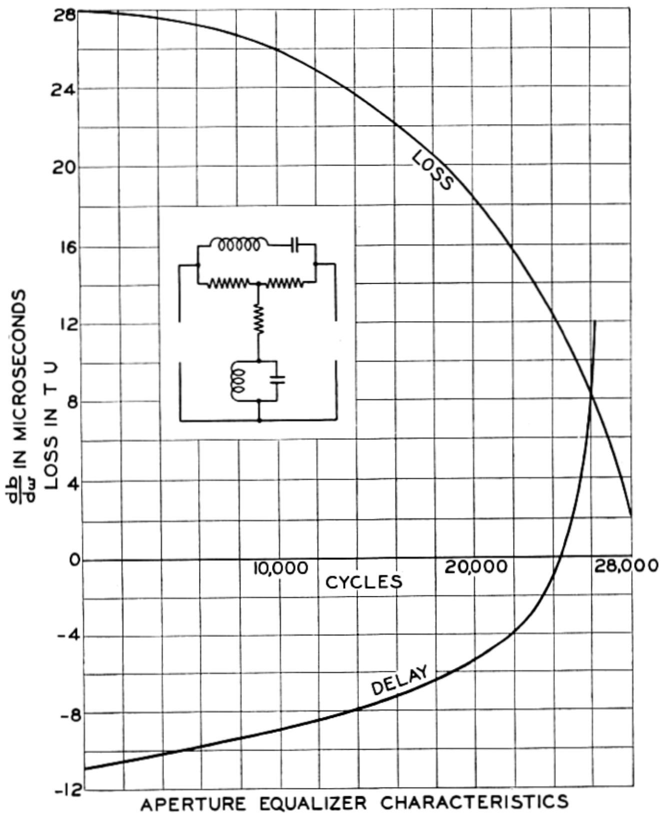


Fig. 18—Circuit for equalizing the aperture effect and its amplitude and phase characteristics

In arriving at the amount of electrical equalization which shall be adopted in any particular case it must of course be borne in mind that as the aperture is made narrower the amount of distortion introduced by it becomes less. As we narrow the aperture, however, the available illumination becomes less and the signal generated by the photoelectric cell becomes smaller. A limit is therefore soon reached at which the difficulties of amplification become greater than the difficulties of equalization and a minimum practical aperture width is thereby determined. If the distortion is corrected by narrowing the aperture, it is apparent that the apparatus will generate, at but little lower than the correct relative efficiency, frequencies much higher than those thought necessary from the more general considerations in Mr. Ives' introductory paper. Decision as to the desirable frequency transmission band for the connecting communication channel would be no different for either method of reducing the distortion due to the aperture.

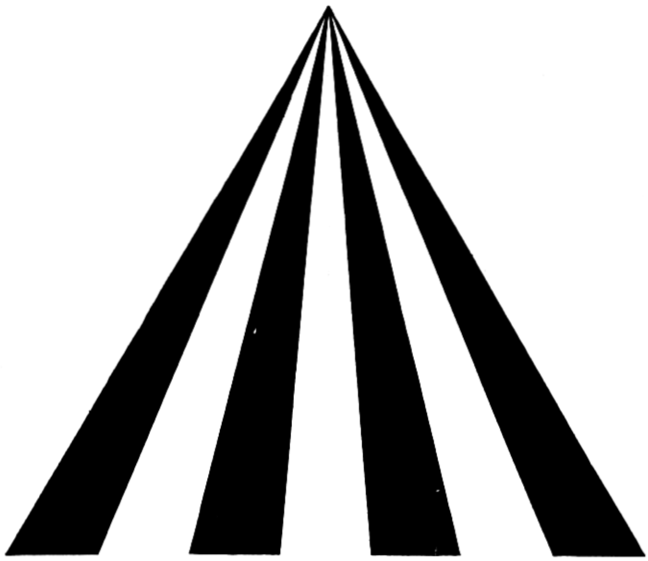


Fig. 19

In summary, then, we may say that experiment and theory show that the lowest frequency essential to satisfactory results is the picture frequency, and the highest frequency required is approximately one half the number of picture elements scanned per second.

(*b*) *Requirements upon the Signal Wave Set by the Characteristics of Available Transmission Channels.* The limitations upon the signal wave set by present available communication channels are:

1. The magnitude of the signal necessary to override the interference to which such channels are subject.

2. The frequency range which such channels can transmit.

The first of these is self-explanatory. It determines the required amplification and load capacity of the transmitting apparatus. In the companion paper on *Wire Transmission Systems for Television* are the data on interference and on permissible signal to noise ratio which were used in the design of the terminal transmitting amplifiers to be described in the latter part of this paper.

In considering the frequency range of lines, it was apparent in the beginning that the wire channel might include sections of cable. With existing loading systems for such cables a frequency range of not over 40,000 cycles appeared available. The terminal apparatus was therefore designed to deliver a generated signal whose essential components lay well within this limit, and the laboratory tests mentioned in the preceding section showed that this requirement was met.

A lower frequency limit was imposed by the necessity of a transformer for joining the transmission line to the terminal equipment. Fortunately it proved possible to design transformers as described in the final part of this paper in which this limit was at or below the essential low frequency limit found in the preceding discussion of the signal wave.

(*c*) *Requirements Which Transmission Channels Must Meet in Order to Carry Television Signals.* We have shown that a certain band width of frequency components is essential to the adequate reproduction of the image. This sets the frequency limits of the transmission channel which must be provided. It is essential, however, that within these transmission limits the channel should present a reasonably uniform attenuation, and that the phase relations should be fairly accurately maintained. The problem as presented to the transmission engineers of wire, radio and terminal equipment for the recent demonstration was to meet the following requirements:

First, transmission must be provided for frequencies between about 10 cycles and 20,000 cycles.

Second, the amplitude frequency characteristics within this range should be uniform to about $\pm$ 2 T U.

Third, the phase shift through the range should be maintained so that the slope of its characteristic as a function of frequency is constant to $\pm$ 10 or 20 micro-seconds over all but the lowest part of the frequency range. There, about 50 times this limit was considered the maximum permissible.

These requirements were arrived at by considerations based on theory and experiments on television and analogy to similar requirements in telephotography. The first requirement follows directly from the discussion of the essential frequencies in the signal. The following paragraphs are intended to illustrate the significance of the remaining requirements.

As we have as yet no quantitative measure of the goodness of reproduction of the image, the matter of the second and third transmission requirements on received amplitude and phase characteristics over the frequency scale is one which had to be decided largely on the basis of the experimental results and judgment based on general considerations. We have already seen that the removal of the very lowest frequencies simply changes the tone value of the whole picture. It may be similarly reasoned that departures from the average efficiency of transmission in the lower part of the frequency range would result in the appearance of diffuse shadows or high lights. Likewise, it may be concluded that broad deviations from the average efficiency of transmission in the uppermost part of the signal frequency range would result in the accentuation or the fading out of the finer detail of the scene. Steep slopes in the amplitude-frequency curve would result in the superposition of oscillations upon signals representing sudden changes in intensity. To reduce these effects every reasonable effort was made to keep the variations in the amplitude characteristic with frequency as slight as possible, aiming to hold these characteristics for the separate parts of the demonstration system to within $\pm$ 2 T U or better.

In addition to transmitting the component frequencies with the same relative efficiency as regards amplitude, it is also particularly essential in television to send them through the system with small relative phase shifts; that is, with constant velocity or what is equivalent, a phase shift proportional to frequency. It has long been known in optical theory that the envelope of a group of waves of nearly the same wave-length and nearly the same frequency may travel along with a "group velocity" somewhat different from the phase velocities of the component elements. If the system has but small departures from a flat amplitude-frequency characteristic and from a linear phase shift frequency characteristic, it can be shown that the time of group transmission or "envelope delay" is given by $db/d\omega^2$, the slope of the curve obtained by plotting the phase shift, b, for the system, against the angular velocity, $\omega = 2\pi f$. The time of transmission of a crest for any sine wave component of frequency $\omega/2\pi$ is, of course, given by b/ω. If $b = c\omega$, $b/\omega = c$ and $db/d\omega = c$. Then the phase and envelope times of transmission are equal and all frequencies as well as their group envelopes get over in the same time. If b is given in radians, $db/d\omega$ is given in seconds. In general a knowledge of b as a function of ω is necessary and sufficient to determine the phase distortion. A knowledge of $db/d\omega$ as a function of ω is not sufficient to determine all factors in signal distortion. It is, however, often easier to measure with the needed accuracy and in transmission systems such as have been used for still pictures and television has proven a useful index of phase characteristics.

After a preliminary estimate from experience with still pictures that the limit on $db/d\omega$ should be $\pm$ 10 microseconds, an electrical network consisting of five sections of a simple lattice structure was used for testing the effect of phase distortion with television apparatus. This network introduced negligible amplitude distortion and a drift in the value of $db/d\omega$ of 50 microseconds over the frequency range of 0 to 20,000 cycles. Its effect was perceptible in blurring the image of a face and it decidedly affected a sharp pattern of two parallel lines of such width and spacing as to be just within the resolving power of the apparatus. This variation of $db/d\omega$ was about $2\frac{1}{2}$ times greater than that postulated. Hence $\pm$ 10 microseconds was agreed on as a desirable limit for $db/d\omega$, though it was felt that this limit might be exceeded by a factor of two in restricted parts of the frequency band.

When this network was combined with a filter the slope of whose envelope delay curve was in the opposite direction so that over the greater part of the frequency range the combined delay of the two

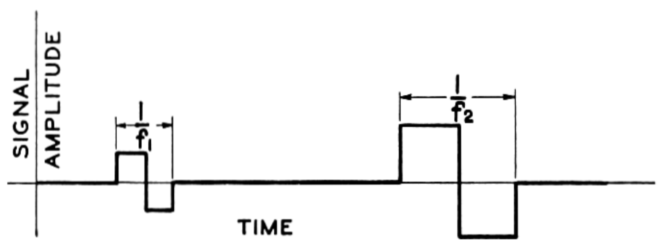


Fig. 20—Signal details of concentrated frequency spectrum for illustrating the effect of envelope delay

circuits was constant and equal to 140 microseconds, this time delay effect was very graphically brought out. Every time the combined circuit was cut in, the undistorted received image jumped to a new position a little over 10 per cent of the width of the picture to one side in the direction of scanning.

To see why $db/d\omega$ should be maintained at a constant value, consider two sharply defined details near together in the picture which would produce a variation in signal intensity with time as indicated in Fig. 20. Imagine each to be cyclically continued so that the small detail defines a frequency f_1 and the other defines a frequency f_2. It is then known from Fourier analysis that the frequency spectra of the two details are chiefly concentrated around the frequencies f_1 and f_2. If $db/d\omega$ is appreciably different at the frequencies f_1 and f_2 for any part of the system, the two details will be displaced relatively to each other along the line of scanning and, in most cases, if this shift is appreciable, some change in the shape of the signal wave defining each detail results with further increase in the distortion. The same relative shift would occur if the narrow detail were located upon the broader one, in which case such a shift would be more apparent. It would seem reasonable to expect then that differences in the envelope time of transmission comparable to a whole picture element (about 28 microseconds in the demonstration apparatus) would be noticeable.

In most images very few details will have signal shapes, as in this special case, in which the frequency components are concentrated in narrow frequency bands. An abrupt change in signal strength, for instance, is represented by components distributed over the whole frequency range. We can imagine these frequencies divided into any arbitrary number of groups, each of which determines a wave form. When these wave forms are added together, they will reproduce the original abrupt change in signal strength. If, however, they are sent through a system in which the envelope delays for the different groups are unequal, the individual wave forms will be relatively displaced and will no longer combine correctly. As a result the image is blurred. For some types of phase distortion the effect appears as an oscillatory transient following sudden changes in intensity.

It was furthermore found by experiment that the limit of ± 10 microseconds was not necessary for the lower frequencies. Reference to the delay characteristics of the transformers described in the latter part of this paper shows that in the lower part of the frequency scale deviations from the nearly uniform value of delay at the upper frequencies appear of magnitude greater than 100 microseconds. When the signal was sent through these transformers, however, there was no observable distortion of the image. The requirements are therefore much more lenient at the low frequencies.

In the terminal apparatus the problem of meeting the above outlined phase transmission requirements was not a very serious one. The circuits involved are such that when a flat amplitude-frequency characteristic had been secured the phase distortion was also negligible.

Section III. Terminal Circuits for Sending and Receiving Television Signals

The preceding sections have discussed the methods by which an object, the image of which is to be transmitted, is made to control the time variations in a light, thus giving a luminous signal wave, and the means by which the image may be reconstructed with the aid of an electric signal wave corresponding to this initial luminous wave in its relative instantaneous amplitudes. Certain important relations between the characteristics of the signal wave and the resulting image have been pointed out. There remains the question of obtaining an electric signal wave suitable for long distance transmission and of providing for the control of the illumination at the receiving terminal by the electric signal wave as delivered by the transmission medium.

In the use of wire lines for television it is fortunately true that a suitably prepared open-wire circuit possesses a frequency range sufficient for the transmission of all the essential components of the signal wave. Details regarding the characteristics of the wire circuits are given in a companion paper by Messrs. Gannett and Green, from whose work are obtained data essential to the design of the terminal equipment. These data fix the power level at which the signal should be delivered to the line and the power level which will be available at the receiving end. When the transmission is by radio it is, of course, necessary to effect a frequency translation in order to secure a wave suitable for radiation and transmission through the ether. In this case, however, the radio system, which is described in a paper by Mr. E. L. Nelson, when considered as a whole may be conveniently taken as a system capable of the transmission of a signal wave occupying the same frequency range as that supplied to the wire circuits. In fact the design of the radio system is such that it may be used interchangeably with the wire line in so far as the remaining electrical terminal equipment is concerned.

The terminal circuits, then, fall into two groups: first, those used at the transmitting terminal for building up the wave controlled by the time variations in light to the power level required by the line; and second, those used at the receiving terminal to bring the wave delivered by the line to the proper form for controlling the luminous sources from which the received picture is built up.

Transmitting Circuits

Starting with the photoelectric cell in which the initial luminous signal wave is converted to an electric signal wave, we are interested in the magnitude of various pertinent constants. The cell may be considered for our purposes as an impedance, the value of which is determined by the quantity of light reaching it. With no illumination at all this impedance is almost entirely a capacitance of the order of 10 m.m.f. When the cell is illuminated this capacitance becomes effectively shunted by a very small conductance which is roughly proportional to the square of the voltage between the electrodes.

For a fixed potential the magnitude of this conductance is nearly a linear function of the illumination. With a suitable potential in series with the cell, then, there is obtained a current the amplitude of which is proportional to the quantity of light reaching the cell.

In order to connect the photoelectric cell to the amplifier, there is introduced in series with the cell and its polarizing battery a pure resistance the voltage drop across which is used to control the grid potential of the first tube. It is desirable, of course, to make this resistance high in order to have available as much voltage as possible. Its value is, however, limited by two considerations. The added series conductance must not be so low that it appreciably disturbs the linear relation between the illumination and the total conductance of the circuit. The voltage drop must also be so small, in comparison with the total potential in the circuit, that the photoelectric cell operates at an approximately constant polarizing potential.

In view of the extremely small voltage of the electric signal wave as delivered by the photoelectric cell circuit, it is essential that great care be taken to prevent such interference as may enter the initial amplifier stages from approaching a comparable magnitude. The most troublesome sources of interference are electrostatic induction, electromagnetic induction, mechanical vibration, and acoustic vibration. By mechanical vibration is meant disturbances transmitted through the supports as the result of building vibrations and similar phenomena. By acoustic vibrations are meant impulses transmitted through the air which strike the several elements of the amplifier and cause motion which results in variations in their electrical constants. Electrical disturbances are reduced to a minimum by placing the amplifier as close as possible to the photoelectric cells, thereby keeping the leads short, which avoids electrostatic pick-up and also prevents the formation of closed loops of any appreciable size, thus avoiding electromagnetic induction. The amplifier is provided with a very complete electrical shield and both the shielded amplifier and the photoelectric cells are placed in a carefully shielded cabinet.

The tubes used, namely, the so-called "peanut" tubes, are, under ordinary conditions, remarkably free from any microphonic action. At the very low signal levels used, however, certain extra precautions have to be taken against this effect. In addition to lining the amplifier box with sound-absorbing material, the tubes themselves have been wrapped in felt and placed within a heavy lead case. This prevents such acoustic disturbances as reach the interior of the amplifier container from having any noticeable effect on the tube. The lead container is supported entirely by an elastic suspension and thus serves a dual function, as the heavy mass, supported in this way, is capable of little response to such mechanical vibrations as may be transmitted through the cabinet and the walls of the amplifier shield. With these precautions it has been found possible to make the effect of all external disturbances of about the magnitude of the thermal disturbances referred to in the first part of the paper.

A schematic diagram of the amplifier tubes directly associated with the photoelectric cell is given in Fig. 21. Attention has already been

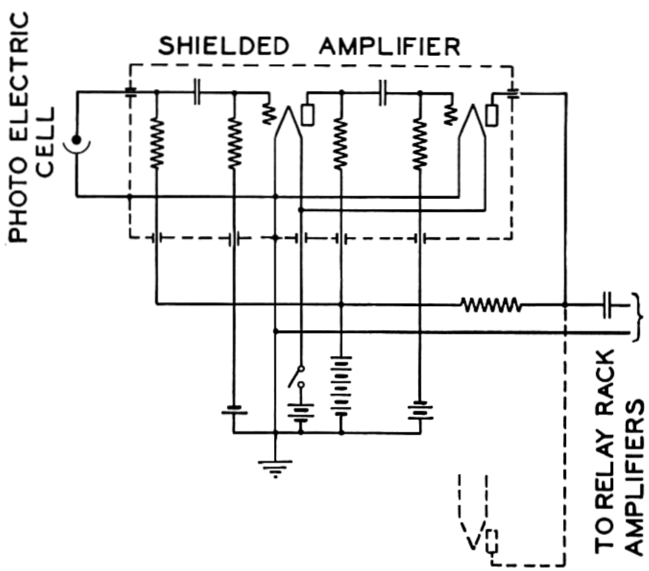


Fig. 21—Schematic of vacuum tube amplifier used with photoelectric cells

called to the fact that the initial signal, that is, the time variation of the light reflected from the scanned object, contains a direct current component. The amplification of this direct current component is, as has been stated, out of the question in any amplifier intended for continued operation over long periods of time. The requirements as to the range of frequencies to be transmitted, as discussed in the preceding section, make it necessary to provide a circuit having practically uniform efficiency from 10 cycles to above 20 kilocycles. The relative phase shift of the several components must also be kept very small. In view of the large amplification and consequent large number of stages necessary, it has been thought impracticable to use transformer coupling between all stages as the aggregate frequency and phase distortion might well be greater than could be tolerated. The so-called resistance capacitance coupling has therefore been used.

The arrangement of the several photoelectric cells in their cabinet, as shown in Fig. 3, is such that one amplifier can be connected directly to two of the cells leaving the third to operate a second amplifier. The outputs of these two amplifiers are then connected in parallel to the common battery supply equipment shown at the bottom of the two vertical cells.

By the use of two stages of amplification in the photoelectric cell amplifier, the signal is brought to such a level that it may be carried by suitably shielded leads to other amplifiers outside the photoelectric cell cabinet. This permits of using the convenient relay rack form of mounting. The signal level is, however, still low and may be adequately handled in amplifier units which differ but little from those used with the photoelectric cell.

The remaining requirements placed on the amplifiers at the transmitting terminal are those set by the telephone line. One of primary importance is that which determines the amount of energy needed. In order that the signal wave shall be of such magnitude that any interference present in the line may be negligible in comparison, it is desired that the alternating current delivered by the final amplifier stage shall be at least 4 milliamperes into an impedance of 600 ohms. The energy to be supplied is, therefore, approximately 0.01 watt, which determines the choice of the last amplifier stage. To build up the signal to a value sufficient to operate this output tube it has been found that eight stages of the small-sized tubes and one stage of greater load-carrying capacity must be used. The total amplification given by these ten stages is approximately 130 T U. It is through this known gain of the amplifiers that we get our only accurate quantitative data as to the magnitude of the initial signal wave. This comes out to be about 10^{-15} watts or, with a 100,000-ohm resistance in series with the photoelectric cell, the potential available at the first tube is roughly 10 microvolts.

The characteristics of the line also determine the means by which it shall be coupled to the final amplifier stage. In order to secure the proper impedance matching and to prevent the line from being unbalanced with respect to ground, it was felt desirable to use transformers if possible rather than to attempt the design of a tube circuit capable of meeting the requirements directly. The problem included both output and input transformers, and specified an amplitude-frequency characteristic constant to within $\pm$ 0.5 T U from 10 cycles to 25,000 cycles. The input coils intended for use at the receiving terminal had the additional requirement that a minimum of interference current should be induced in the secondary due to potentials between the line and ground. The success with which this problem has been solved is shown by the curves of Fig. 22. Curve 1 is the

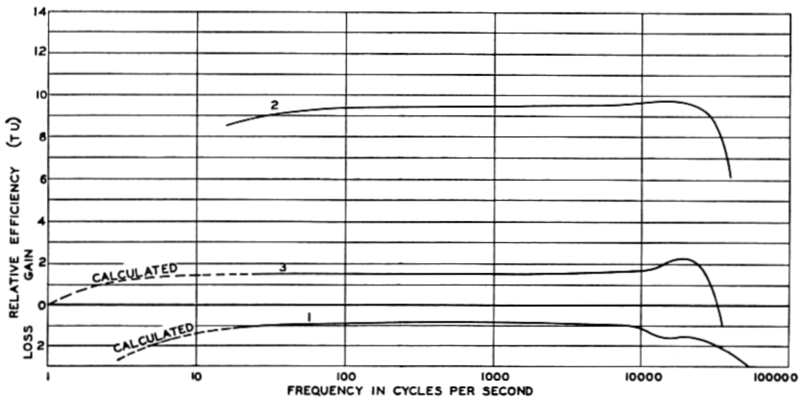


Fig. 22—Transmission characteristics of iron core transformers

1. Output transformer connected between impedances of 2000 ohms and 600 ohms.
2. Input transformer having voltage step-up of 6.5 connected between 600-ohm line and vacuum tube.
3. Input transformer having voltage step-up of 2.5 connected between 600-ohm line and vacuum tube.

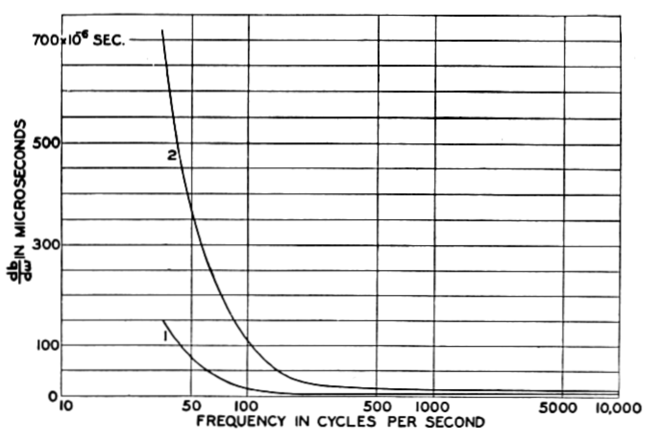


Fig. 23—Envelope delay characteristics of transformers

1. Output transformer
2. High ratio input transformer

transmission characteristic of the output transformer which is designed to work between impedances of 2000 ohms and 600 ohms when connected between generator and load circuits having these values.

Curves 2 and 3 show the effective transmission gain of transformers having voltage step-ups of 6.5 and 2.5 respectively, when used to connect the first stage of the vacuum tube amplifier to a 600-ohm generator impedance. The envelope delay curves for the output transformer and for the high ratio input transformer are given in Fig. 23. Photographs of the coils are given in Fig. 24. A large

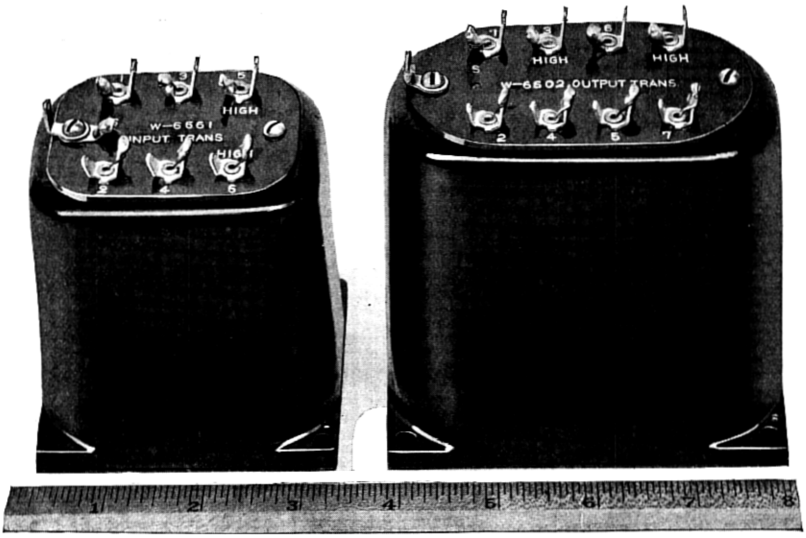


Fig. 24—Transformers used for coupling amplifier circuits to long distance telephone lines

factor in being able to get coils of this type lay in the availability of permalloy for the core material. The output transformer is connected to the amplifier through a blocking condenser in order to avoid possible saturation in the core due to the passage of direct current.

Measurements made on the several elements of the amplifier system have shown that its overall frequency characteristic is constant to within $\pm$ 2 T U from 10 to 20,000 cycles.

In an amplifier having as much gain as that just described it is apparent that a slight change in the potential of the power supply will cause a considerable change in the overall efficiency. Moreover, variations in the intensity of the light source used with the scanning system will cause corresponding changes in the intensity of the initial luminous signal wave. To insure that the energy level supplied to the line is at all times of the proper magnitude a level indicator has been provided to permit continuous observations of the output of the amplifier. This consists of an amplifier-rectifier circuit so arranged that the space current of the last tube is a function of the alternating current voltage impressed on the first, being roughly proportional to the square of its amplitude. By means of a direct current milliammeter, therefore, it is possible to keep a very accurate check on the amplitude of the signal delivered to the line.

Receiving Circuit

Coming now to the receiving terminal equipment we find that the signal wave which was delivered to the line at a power level of 10 milliwatts may, under some conditions, be reduced to a level 50 T U below this, or to 0.1 microwatt. It is, therefore, necessary first of all to provide amplification to bring the signal to a level where it may operate the circuits controlling the illumination from which the image is to be reconstructed. In view of the fact that several types of receiving equipment are to be operated and also since the signal may be derived from any of several sources, either wire line, radio or local transmitting station, it is desirable to fix some one energy level as a reference point and to bring all signals to this value so that they may be supplied interchangeably to the several receiving systems. A convenient reference level is that already set as the proper input to a telephone line, namely, 10 milliwatts. At the receiving terminal, therefore, amplifiers have been provided which are similar to the final stages used at the transmitting terminal. These include units containing the small-sized tubes and terminate in units identical with that supplying current to the line except that the output transformer is omitted. The first stage is, as mentioned in the preceding section, connected to the line through an input transformer. The amplifiers associated with the several incoming signals are each provided with a level indicator of the type already described. These terminal amplifiers and the several receiving circuits are all terminated in jacks, exactly like telephone circuits, and it is possible, therefore, to connect any receiving machine to any desired transmitting station simply by patching the proper jacks together, exactly as telephone circuits are connected at the central office.

Before describing the final stages of the amplifier circuits it is necessary first to examine the properties of the light source which is to be controlled. In the case of the disk receiving machines described in the first section of this paper it is recalled that a single neon lamp is used having a rectangular electrode the entire area of which glows at each instant with an intensity proportional to the intensity of the initial luminous signal. The current voltage characteristic of a typical neon lamp is given in Fig. 25. It will be seen that no current flows until the voltage across the lamp reaches the breakdown potential which, in the example shown, is about 210 volts. From this point on the current increases linearly with respect to voltages in excess of a value somewhat below the breakdown point. It will also be seen

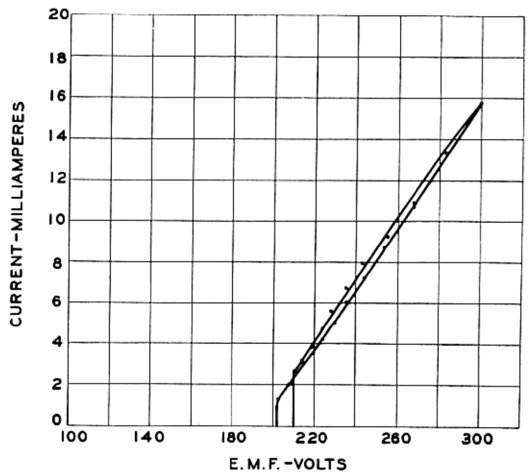
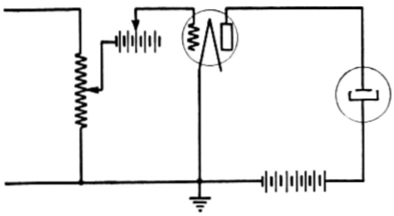
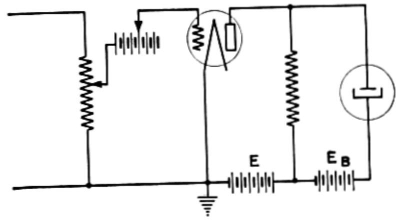


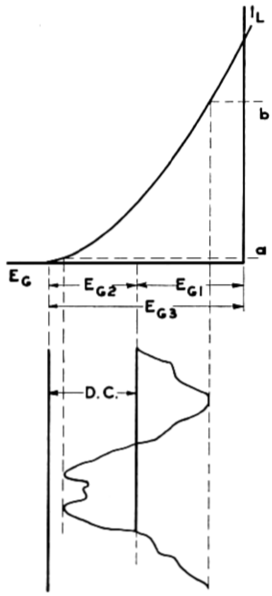
Fig. 25—Current voltage characteristic of typical neon lamp

from the curve that the value of current depends somewhat upon the direction in which the voltage is changing. In most cases, however, the function comes sufficiently close to being single valued for our present purposes. In view of the well-established linear correspondence between the intensity of the illumination resulting from the glow discharge and the current, it is required to so arrange the circuits that the current through the lamp is at all times proportional to the illumination at the transmitting terminal.

It will be recalled that the electric signal wave as transmitted through the various amplifier circuits differs fundamentally from the initial luminous wave in that the direct current component has been eliminated. It is necessary, therefore, to restore this component before the changes in light intensity at the receiving terminal will follow those at the transmitting terminal. The several factors entering at this point may perhaps best be examined in terms of an elementary circuit such as given in Fig. 26. In this case the neon lamp is connected in series with the plate circuit of a vacuum tube and its polarizing battery. The circuit may be considered for the present as equivalent to one in which the neon tube is replaced by an ohmic resistance and in which the potential of the polarizing battery is







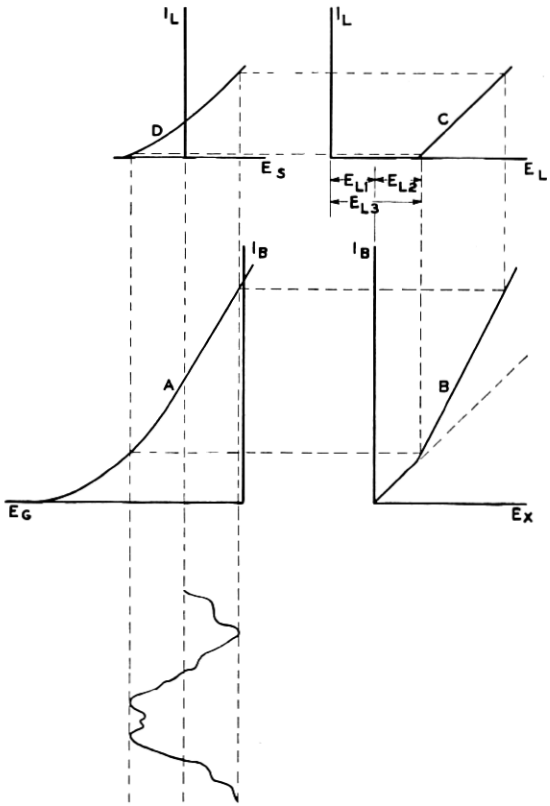


Fig. 26—Circuit schematic and operating characteristic of neon lamp amplifier

Fig. 27—Circuit schematic and operating characteristics of circuit arranged for linear operation of neon lamp

reduced by an amount corresponding to the back e.m.f. of the lamp. Under these conditions the relation between current—and therefore illumination—and the voltage on the grid of the vacuum tube is as shown by the curve given with the figure. This curve takes into account the change in potential between the plate and filament of the vacuum tube due to the voltage drop in the lamp resistance. If the reactances in the circuit are negligible, this curve may be taken as the dynamic characteristic of this portion of the system.

Let us assume that to properly build up the desired image at the receiving terminal the light is to be varied between the limits set by the two horizontal lines *a* and *b*. It is apparent that two adjustments are necessary in the grid circuit. The amplitude of the impressed alternating current must be such that the difference between its positive and negative maxima is equal to the difference between the grid voltages corresponding to these currents. This is taken care of by suitable adjustments of the amplification. It is further necessary that the bias introduced by the grid polarizing battery be such that the positive and negative peaks coincide with these same values of grid voltage. Under these conditions the grid battery must be looked upon as supplying two absolutely distinct biases, one the bias for the tube and the other the bias for the signal. For example, if the signal wave as delivered to the grid circuit contained the original d-c. component properly amplified, it would be necessary to adjust the system so that zero current would be obtained with no impressed signal. To accomplish this the tube would require the negative grid bias E_{G3}. Variations in signal voltage would then be considered as taking place about this value of grid potential as the origin. Thus E_{G3} is the operating bias of the tube. To properly locate the signal wave, however, it is necessary to add the positive bias E_{G2}. It will be seen from the curve that this bias corresponds exactly to the direct current component which is to be restored to the signal. The sum of these two biases, obviously, gives the actual bias, E_{G1}, with which the tube is operated.

In the circuit as shown the well-known curvature of the vacuum tube prevents us from obtaining a linear relation between the current through the neon lamp and the signal voltage. This condition may be overcome by a number of circuit modifications of which that shown in Fig. 27 is typical. Instead of connecting the neon lamp and the vacuum tube directly in series, a resistance is provided across which is set up a potential, E_X, proportional to the current through it. Across this resistance is shunted the neon lamp and a biasing battery, E_B. The adjustment of this circuit is indicated by the curves shown.

Curve A expresses the relation between the grid potential of the vacuum tube and its plate current. Curve B shows the relation between this same plate current and the voltage across the external resistance. When no current is flowing through the vacuum tube, the potential of the biasing battery is insufficient to break down the neon lamp and no current flows through the circuit containing the neon lamp and the plate circuit resistance. As the current through the vacuum tube is increased from zero, the total current flowing is that through the resistance branch. When, however, the potential drop across this resistance reaches such a magnitude that, together with the potential of the biasing battery, it is sufficient to break down the neon lamp, the latter will begin to draw current which thereafter increases linearly with further increases in the voltage, E_X, across the external resistance. The voltage across the neon lamp itself differs from that across the resistance by the amount of the battery E_B. The relation between the neon lamp current and the voltage across it, as given by Curve C, may therefore be plotted directly above the characteristic just discussed by displacing the vertical axis an amount corresponding to E_B. This amount is shown as E_{L1}. Here again we have two separate biases controlled by a single adjustment. The potential E_{L2} is fixed by the minimum plate current which can be taken from the tube without departing too seriously from the linear portion of the tube characteristic. It is, therefore, an operating bias of the circuit which is unaffected by any characteristic of the neon lamp. The latter, however, must be operated with a bias E_{L3} corresponding to its effective back e.m.f. As in the case of the grid circuit bias just considered, the bias E_{L1} actually introduced into the circuit is the difference between these two independently determined biases.

By projecting values of lamp current horizontally and plotting their intersections with vertical projections through the corresponding grid potentials on the vacuum tube characteristic we obtain Curve D, which expresses the relation between the instantaneous value of the signal and of the current in the neon lamp as derived from the characteristics of the several elements of the circuit. Inasmuch as the intensity of the illumination is proportional to the lamp current, it will be seen that we have approached the desired linear correspondence between the instantaneous values of the signal and of the light.

It will be noted that care has to be exercised to insure that the alternating current as impressed on the last vacuum tube is of the proper polarity. If it is not, the received image will be a negative instead of a positive. This may be controlled either by the connections to any one of the transformers or by the number of vacuum tube stages. With an even number of stages the polarity will be reversed from that given by an odd number. This is because an increase in negative potential on the grid of a vacuum tube causes a decrease in the space current and hence a decrease in the negative potential applied to the grid of the next tube.

In the case of the grid type of lamp with the individual external electrodes, the impedance to which energy must be supplied differs materially from that presented by the rectangular electrode lamp already described. For low voltages the impedance between any electrode and the central helix is effectively a capacitance of the order of 6 m.m.f. When, however, the voltage gradient in the interior of the tube becomes sufficient to break down the gas and cause a discharge to take place, the capacitance is increased to about 15 m.m.f. In fact, the tube may be looked upon as consisting of two capacitances connected in series. When the applied potential is sufficient to break down the gas and cause a glow discharge, that capacitance corresponding to the portion of the path inside the tube is effectively shunted by an ohmic resistance. The minimum discharge potential has been found to be independent of frequency over a wide range, but the current between electrodes is inversely proportional to the frequency because of the presence of the capacitance between the electrode and the glowing gas. Now, the brightness of the discharge is a function of the current sustaining it so that it becomes desirable to use high frequencies in order to get sufficient light without going to prohibitively high potentials. It is also desirable to operate at such a portion of the frequency scale that the percentage difference between the limits of the range shall be small, thus avoiding signal distortion due to the effect referred to above. There is, however, a definite upper limit to the frequency beyond which it would be impossible to operate because of the stray capacitances in the cable connecting the grid to the distributor. It has been found feasible to operate at a frequency of the order of a half million cycles.

The circuit problem, therefore, involves the production of a high frequency wave which varies in amplitude in accordance with the amplitude of the received picture signal. The solution has been conveniently obtained by using a radio broadcast transmitter the voice frequency circuits of which have been so modified that the extended range of frequencies required might be handled with minimum distortion.

The envelope of the 500-kilocycle wave modulated by the picture signal, as shown in Fig. 28, is proportional to the signal amplitude plus a direct current biasing component of such magnitude that when the envelope reaches 160 volts the tube fails to light. This corresponds to a black area in the picture. When no picture signal is being received, the amplitude of the unmodulated carrier wave causes the tube to light at average brightness, corresponding to the locally introduced d-c. component of the signal. It follows, then, that the amplitude of

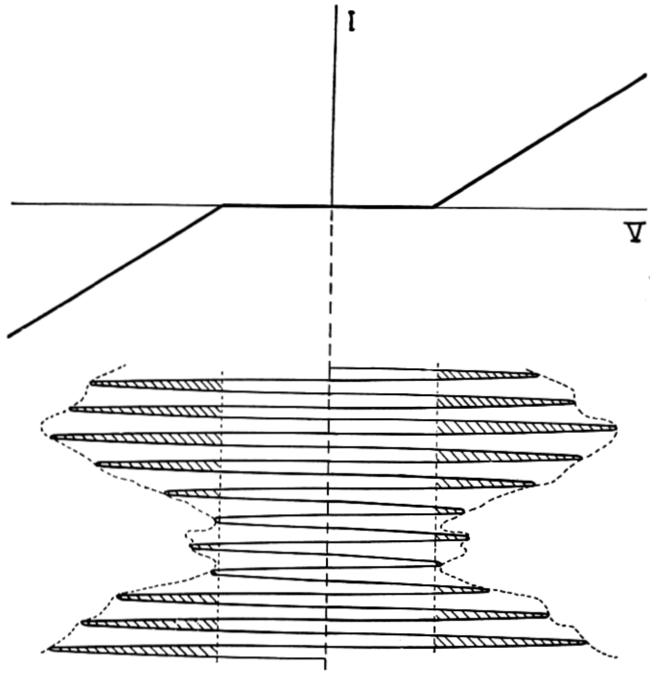


Fig. 28—Diagrammatic representation of relation between modulated high frequency wave impressed on grid type neon lamp and lamp characteristics. Intensity of glow is proportional to shaded area.

the unmodulated carrier is fixed, as in a previous example, by the joint requirements of two biases, that of the lamp and that of the signal bias.

There is a slight distortion inherent in this method due to the fact that the light, which is proportional to the shaded area of the curve of Fig. 28, is not strictly proportional to the amplitude of the envelope with respect to the 160-volt limit. This is, of course, because these peaks are portions of a sine wave and hence the time variation of the glow resulting from any given carrier cycle is a function of its amplitude. The effect is small, however, being most noticeable at low values of illumination.

In the case of the grid-lamp receiver the signal amplitude is adjusted, as for the disk receiver, by a potentiometer in the low frequency portion of the circuit. The carrier amplitude, however, is adjusted by varying the plate potential applied to the oscillating tube. The coupling to the lamp is made by connecting the central helix and the distributor brush across a portion of the condenser of the oscillating circuit.

The frequency-amplitude relation of the envelope has been made practically constant by employing resistance capacitance coupling in the signal input amplifiers, by providing extremely high inductance retard coils for the modulator—which is of the Heising type—and by inserting resistance in the oscillating circuit to provide sufficient damping. The relations between the original picture signal and the envelope of the high frequency wave, with respect to both amplitude and phase shift, were observed over the signal frequency range by means of a Braun tube and found to be satisfactory. The impedance of the connecting leads to the commutator was also measured and found to have a negligible effect on the frequency and damping of the oscillating circuit.

It has been found that there may be a lag between the time when the potential is applied to an electrode and the time when the gas breaks down. This is especially true following an interval during which there has been no discharge within the tube. Because of this those electrodes which are the first to be connected in any one of the parallel portions of the tube may fail to light. To overcome this effect a small pilot electrode is kept glowing at the left-hand end of each tube, thus irradiating the branch in such a way that the illumination of all electrodes follows immediately upon the application of potential. These pilot electrodes, which are obscured from view of the audience by the frame of the grid, are supplied by means of an auxiliary connection to the oscillator with a potential somewhat lower than that ordinarily impressed upon the picture segments.

Appendix I

The signal of Fig. 13 in the body of the paper may be represented as follows:

$$\left.\begin{aligned} f(t) &= 0 \qquad \text{for } t < 0 \\ &= \frac{t}{T} \qquad \text{for } 0 < t < T \\ &= 1 \qquad \text{for } t > T \end{aligned}\right\} \tag{1}$$

or by a Fourier integral in the form

$$f(t) = \frac{1}{\pi}\int_0^\infty d\omega \int_\infty^\infty f(\lambda) \cos \omega(t - \lambda) d\lambda, \tag{2}$$

where λ is an auxiliary variable of integration and ω is 2π times the frequency. To get the effect of sending this signal through a system which transmits all frequencies without phase or amplitude distortion up to a cut-off frequency f_c it is only necessary to replace the upper limit of the first integral sign by N where $N = 2\pi f_c$. Thus:

$$F(t) = \frac{1}{\pi}\int_0^N d\omega \int_{-\infty}^\infty f(\lambda) \cos \omega(t - \lambda) d\lambda.$$

Then from (1):

$$F(t) = \frac{1}{\pi}\int_0^N d\omega \int_0^T \frac{\lambda}{T} \cos \omega(t - \lambda) d\lambda + \frac{1}{\pi}\int_0^N d\omega \int_T^\infty \cos \omega(t - \lambda) d\lambda$$

$$= \frac{1}{\pi NT}\Big\{ \cos Nt - \cos N(t - T)$$

$$+ Nt[Si(Nt) - Si(Nt - NT)]\Big\} + \frac{1}{\pi}\left[\pi + Si(Nt - NT)\right].$$

If we write $Nt = x$, $NT = z$, and $\pi F(t) = y(x)$, then

$$y(x) = \frac{1}{z}\Big\{ \cos x - \cos (x - z) + x[Si(x) - Si(x - z)]\Big\}$$

$$+ \frac{\pi}{2} + Si(x - z),$$

where

$$Si(x) = \int_0^x \frac{\sin x}{x} dx.$$

A series of graphs of $y(x)$ for different values of the product NT is given in Fig. 15 in the body of the paper. These are generalized curves, the time scale depending on the particular value of cut-off frequency used. From these curves we can get the additional lag in the time, τ, in the rise of these curves over the original time T in Fig. 14.

Appendix II

Let $f(t)$ be the instantaneous intensity of the picture, and let it be represented by a Fourier integral:

$$f(t) = \int_0^\infty A(\omega) \cos [t\omega + \Phi(\omega)] d\omega. \tag{1}$$

Let T = time required for the aperture to pass a given point, Fig. 29.

Let $\varphi(t_1)$ be height of aperture at distance t_1 from its center.

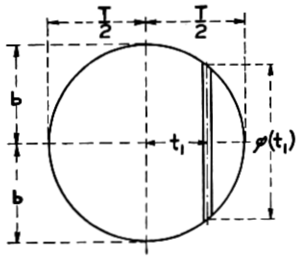


Fig. 29

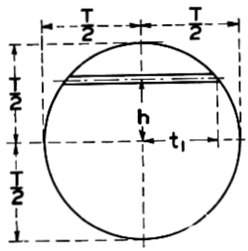


Fig. 30

Analysis of the aperture

The instantaneous amount of light passing through the aperture is

$$
\begin{aligned}
F(t) &= \int_{t-T/2}^{t+T/2} \varphi(t_1) f(t_1) dt_1 \\
&= \int_{t-T/2}^{t+T/2} \varphi(t_1) dt_1 \int_0^\infty A(\omega) \cos [t_1\omega + \Phi(\omega)] d\omega \qquad (2) \\
&= \int_0^\infty A(\omega) d\omega \int_{t-T/2}^{t+T/2} \varphi(t_1) \cos [t_1\omega + \Phi(\omega)] dt_1.
\end{aligned}
$$

In the case of the rectangular aperture

$$\varphi(t_1) = \text{a constant} \qquad (3)$$

and, except for a negligible constant factor,

$$
\begin{aligned}
F(t) &= \int_0^\infty A(\omega) d\omega \int_{t-T/2}^{t+T/2} \cos [t_1\omega + \Phi(\omega)] dt_1 \\
&= \int_0^\infty A(\omega) \left\{ \frac{\sin [(t + T/2)\omega + \Phi(\omega)]}{\omega} - \frac{\sin [(t - T/2)\omega + \Phi(\omega)]}{\omega} \right\} d\omega \qquad (4) \\
&= 2 \int_0^\infty A(\omega) \frac{\sin T\omega/2}{\omega} \cos [t\omega + \Phi(\omega)] d\omega.
\end{aligned}
$$

The transformation from $f(t)$ to $F(t)$ amounts merely to changing the relative amplitude of the Fourier components of $f(t)$ by a factor proportional to $\frac{\sin T\omega/2}{\omega}$.

In the case of the circular aperture we can divide the aperture up into narrow elements parallel to the direction of motion, as shown in Fig. 30. Elements at a distance h from the middle line of the strip have lengths

$$2t_1 = 2\sqrt{T^2/4 - h^2}. \tag{5}$$

Each element considered as an independent *rectangular* aperture has the frequency characteristic

$$\frac{\sin t_1\omega}{\omega} = \frac{\sin \omega\sqrt{T^2/4 - h^2}}{\omega}.$$

The mean of all of these elementary frequency characteristics is

$$\begin{aligned}\frac{1}{T}\int_{-T/2}^{T/2}\frac{1}{\omega}\sin\left[\omega\sqrt{T^2/4 - h^2}\right]dh &= \frac{2}{T\omega}\int_0^{T/2}\sin\left[\omega\sqrt{T^2/4 - n^2}\right]dh \\ &= \frac{1}{\omega}\int_0^{T/2}\sin\left[\omega T/2\sqrt{1 - \frac{4h^2}{T^2}}\right]\frac{2dh}{T} \\ &= \frac{1}{\omega}\int_0^1 \sin\left[T\omega/2\sqrt{1 - x^2}\right]dx \\ &= \frac{\pi}{2\omega}J_1(T\omega/2),\end{aligned} \tag{6}$$

where J_1 indicates a Bessel function of the first order. In place of the amplitude variation function $\frac{\sin (T\omega/2)}{\omega}$ for the square aperture, we have $\frac{J_1(T\omega/2)}{\omega}$ as such a factor. From the very nature of the physical processes under consideration it follows that this average value of the elementary frequency characteristics is effectively the frequency characteristic of the aperture as a whole.