EXPERIMENTAL TRANSMITTING AND RECEIVING EQUIPMENT FOR HIGH-SPEED FACSIMILE TRANSMISSION

III. DETAILS OF THE RECEIVER

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In the Philips high-speed facsimile transmission system the signal received, the strength of which varies according to the light and shade of the image being scanned, is employed at the receiver to control the current flowing in a gas-discharge lamp. The varying amount of light from this lamp is projected in the form of a spot onto a film by an optical system rotating in synchronism with the rotor of the transmitter. The film is curved to the cylindrical shape of the rotor and passes the latter continuously, so that the light spot traces on it parallel lines exactly corresponding to the scanning lines at the transmitter.

Owing to the very high resolving power of the positive film used, the image can be reproduced in the receiver at 1/6th of the original size, with consequent economy in film. To this end, the diameter of the rotor is only 1/6th the diameter of the rotor at the transmitter, and the recording spot is similarly one-sixth the size of the scanning spot (i.e. 33 \(^\mu\)). In this case, too, the rotor carries three identical optical systems and the film is curved only through 120°. Tolerances governing the relative position, size and intensity of the spot in the three optical systems are essentially very small and extreme precision in manufacture of the rotor and in assembly is necessary. Whereas in the case of the scanning spot at the transmitter a circular form is the most suitable, a substantially rectangular shape is better for the recording spot. This is produced by focusing onto the film the image (reduced 4\(\times\)) of a rectangular diaphragm having all four sides adjustable. The lamp, which is capable of following modulating frequencies up to 100 kc/s and the luminous intensity of which is sufficient to produce a density of 1.5 on the film in 5 \(\mu\) sec, is a gas-discharge lamp filled with mercury vapour and argon at low pressure. The discharge is concentrated within a tube 1 mm in width. A steady current flows through the lamp to assist it in following the necessary high modulation and to give the light-versus-current characteristic the desired form for linear reproduction.

The mechanical features of the Philips high-speed facsimile transmitter have been described in a previous article \(^1\), and here the mechanical and optical details of the receiver will be reviewed.

General arrangement of the receiver

The type of signal supplied by the transmitter is depicted in fig. 5 of the previous article. In the receiver this signal, suitably amplified, is applied to a lamp specially developed for the purpose and with a luminous intensity capable of keeping in step with every variation of the signal strength. The light from this lamp is used in conjunction with an optical system to provide a recording spot which is synchronised with the scanning spot at the transmitter (i.e. at the same speed and in phase) and traces a succession of straight contiguous lines on a strip of light-sensitive material, thus exposing the latter to a degree determined by the instantaneous values of the signal strength.

The transmitter scans 180 lines per second and each line, 22 cm in length, comprises 1100 image-elements of the size of the scanning spot (0.2 mm dia.). The receiver, therefore, must be capable of reproducing 180 \(\times\) 1100 image-elements per second, each with its own individual density, which means that only 1/200,000 sec. is available for the exposure of the sensitized film for each elemental area corresponding to a similar image-element in the original.

Although the luminous intensity of the recording lamp cannot be increased to a very high level, since this would interfere with its ability to be modulated up to 100 kc/s, and although the focal aperture of the optical system in the receiver, like that of the transmitter, is limited by requirements relating to depth of focus and image distance, it has nevertheless been found possible to ensure sufficient density within the very short time available by using ordinary positive film as recording material.

This material is certainly more costly than the recording paper used in the slower types of facsimile equipment. The resolving power of the film (55 lines per mm) is, however, very much higher than is necessary for a scanning and recording spot of 0.2 mm. The receiver is therefore designed to work with a light-spot 1/6th of the size and to give a reproduction 1/6th (linear) of the size of the

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original document. The consumption of film is thus reduced to 1/36th of what it would otherwise be and the cost is therefore of very little importance.

The actual construction of the receiver is similar to that of the transmitter; see fig. 1. A 45-mm film continuously passes through the machine and at a given point is curved around a cylinder the radius of which is only 1/6th of that of the scanning cylinder at the transmitter. A rotor mounted coaxially in this cylinder and revolving in synchronism with the transmitter rotor at 3600 r.p.m. carries three identical optical systems, spaced at 120°. Each of the latter contains a diaphragm illuminated by the lamp, which is stationary in the axis of the rotor. An image of this diaphragm, 33 microns in size, is projected onto the film as the recording

Fig. 1. a) The receiver with cover open. b) Schematic cross-section. The rotor $R$ and the stationary recording cylinder $C$ are 1/6th the diameter of the corresponding parts of the transmitter. The 45 mm film $F$ from the spool $T$ is curved over the cylinder $C$ by a specially shaped spring: at this point a light-spot 33 μ in width produced by the optical system in the rotor and originating in a gas-discharge lamp $G$, which is modulated by the incoming signal, traces parallel lines on the film. The rotor driven by motor $F$ by means of a flexible shaft $A$ is synchronised with the rotor of the transmitter. Roller $Z$ pulls the film through the machine and is coupled to the motor by a reduction gear $W$. At $O$ the film passes into a tank where it is automatically developed and fixed.
spot. The movement of the rotor causes each of the light-spots from the three optical systems to trace a line 33 μ in width across the surface of the film. The rotor and the film-feed mechanism are coupled together by suitable gearing to give a rate of feed of film equal to 1/6th of the speed of the conveyor belt in the transmitter, that is 33 μ per line or 6 mm per second. The film spool contains about 120 metres of film, sufficient for recording 2400 documents of quarto size, without interrupting the operation, covering a total working period of 5 1/2 hours.

The exposed film is developed and fixed continuously and automatically in a developing tank mounted on the receiver. Subsequently each document recorded on the film can be immediately enlarged to the original size. As each document can be exposed as a whole, exposure times of a few seconds can be applied. Moreover the lamp employed for the purpose may be of high intensity, so that the film can be enlarged on ordinary photostat paper.

In principle, any one of three different methods could be used for the enlarging process, viz: 1) to run the film through the enlarger continuously together with a strip of printing paper; 2) to project the documents one by one on separate sheets of paper, compensating the continuous movement of the film in the usual manner by means of a moving optical system; 3) as 2), but in this case the compensating optical system can be dispensed with by feeding the film through the enlarger intermittently instead of continuously.

If the latter method is to be fully automatic, some form of mechanism is required to ensure that the film moves forward each time at the commencement of each document, even though the original documents may not be fed into the transmitter at regular intervals; this could be effected by various means suited to the particular purpose for which the high-speed facsimile system is to be used. For the transmission of letter post the following system has been evolved. A row of letters is printed at the top of each document recorded on the film can be immediately enlarged to the original size. As each document can be exposed as a whole, exposure times of a few seconds can be applied. Moreover the lamp employed for the purpose may be of high intensity, so that the film can be enlarged on ordinary photostat paper.

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A brief survey of some of the other features of the equipment may be of interest.

The recording lamp

The problem of modulating a beam of light at high frequency is encountered not only in facsimile transmission but in many other spheres as well, e.g. in television, light-beam telephony, etc. This problem has been solved in different ways to suit the various well-known requirements, either by using a constant light-source in conjunction with an optical device of which the transmission factor is varied mechanically or electrically (as in the Kerr cell), or, again, by direct modulation of the power supply of different types of light-source such as in an incandescent lamp, a gas-discharge lamp or a cathode-ray tube. A modulated incandescent lamp or a gas-discharge lamp provide simple solutions, but owing to the thermal inertia of the filament an incandescent lamp is not suitable for modulation frequencies of 100 kc/s. A specially designed gas-discharge lamp, however, has been found capable of fully meeting these modulation requirements.

Before going into details it will be useful to mention one or two other requirements entailed in the design of this part of the equipment. The brightness of the discharge must be high enough to produce on positive film a density 2) equal to 1.5 or

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2) This is log I₀/I when the portion I of the luminous flux I₀ falling upon an exposed film is transmitted.
rather more if possible in the exposure time of 5 μsec. Further the light beam has to be constant over a sufficiently wide angle in order to fill the rotating optical system with light, without necessitating large distances between lamp and rotor (or a very long rotor; see below). For practical reasons the required currents and voltages must not be too high and, finally, the characteristic (relation between luminous intensity and current or voltage) of the recording lamp must conform to certain other requirements.

Effective modulation of the beam can be expected only from a discharge lamp having a comparatively low gas temperature. In the case of an elevated gas temperature such as usually accompanies high gas-pressure and which, it is true, is very advantageous from the point of view of a high luminosity (high-pressure and super-high-pressure mercury vapour lamps), the thermal inertia is usually so great that the emission of light is unable to follow closely any rapid variation in the applied power. One way of obtaining a gas discharge at a low temperature, but nevertheless with a very high brightness is to concentrate the so-called positive luminous column in a very narrow tube (nozzle) and use the light emitted in the longitudinal direction, this being the principle of Ewest’s “Lichtspritze” 3). In this type of lamp the anode, in the form of a ring, is placed in front of the nozzle mentioned above; the use of an incandescent cathode ensures relatively low ignition and working potentials, with long life. Existing types have proved capable of modulation up to 15 kHz and of producing the desired density on film in about 100 μsec.

The lamp developed by Philips is based on similar lines. Modulation is effected by varying the current. A few details of the methods employed to obtain the required higher brightness and better modulation response may be of interest.

Concentration of the luminous column within a nozzle of very small dimensions not only increases the brightness but also the modulation response. This will be appreciated when it is considered that there will be little inertia in the discharge if a surplus of ions can disappear quickly and a shortage of ions can quickly be made good by new ones. For the disappearance of ions a short transit time between the electrodes, that is a short discharge path, is necessary. The recombination of ions, which also assist in eliminating any surplus, can be promoted by reducing the diameter of the nozzle, due to the fact that recombination takes place mainly at the walls, whilst the ratio of wall-area to volume is inversely proportional to the diameter.

For the highest possible modulation response, therefore, a reduction of the cross-sectional area of the nozzle and of the length of the discharge is the solution. At a certain point, however, these conditions will conflict with the requirement that the brightness must also be high. Light being emitted longitudinally, it is evident that any reduction in the length of the discharge must have an adverse effect on the brightness (selective absorption is of minor importance at the low gas-pressure in question). For a given diameter d the nozzle therefore has to be of such a length as to furnish the required width of beam (relation of diameter to length of the nozzle). Similarly, regarding the effect of the diameter the modulation response and brightness are no longer proportional to each other when a certain point is reached, since the current density in the nozzle is limited by the admissible temperature of the wall. For a given wall temperature and angle of emission, a rough calculation will prove the brightness to be $\sim \sqrt{d}$ and the necessary current $\sim \sqrt{d}$. As soon as the permissible wall temperature is reached any increase in brightness therefore actually demands a larger diameter of the nozzle. In that case, however, the required power of the source of current, which following on the above increases directly as the third power of the brightness, must also be taken into consideration.

Another important factor in the design of the recording lamp by means of which the modulation response as well as the brightness can be effected is the choice of gas-filling. Both these properties appeared to be very suitable when the lamp was filled with a mixture of argon and nitrogen at a few millimetres mercury-pressure. Theoretical considerations may well explain that a good modulation response is thus obtained: both argon and nitrogen particles are relatively light and thus involve only short transit times. Moreover, it appears to be important that by colliding with nitrogen molecules, metastable, excited argon atoms, which owing to their long life would delay and therefore unfavourably influence the modulation response, can lose energy. From the aspect of spectral distribution of the light emission, too, an argon-nitrogen mixture is favourable, as the emission is preponderantly blue and violet, these being the colours to which positive film is most sensitive. However, a well-known disadvantage of this gas mixture of a gas discharge in which the current density is high is that in the course of time the nitrogen disappears.

Excellent results, without disadvantages, are obtained with a mercurynapour discharge at very low pressure, containing argon to keep the ignition voltage down to a low value. Theoretically the modulation response will not be so good as in the case of the gas-filling previously mentioned, since the heavy mercury atoms require much longer transit times. This has been confirmed in practice, but it has nevertheless been found possible to obtain the desired modulation up to 100 kc/s with adequate brightness (argon-nitrogen mixtures actually made it possible to record modulation frequencies up to 300 kc/s). This result is partly due to the dimensioning of the nozzle, which approximates the optimum compromise, viz. 1 mm wide and 5 mm long with anode and cathode as close as possible to the ends of the nozzle. Good modulation response is partly due to the fact that a certain steady current is allowed to flow through the lamp even in the absence of signals, thus ensuring a reserve of ions which enables the formation of the required fresh ions to take place much more rapidly when the signal increases from zero than if the discharge were completely extinguished.

The relation between the luminous intensity and the lamp current is by no means linear, as might be considered desirable at first sight. In practice, however, this is not a disadvantage, but even an advantage, since it partly assists in compensating for the very pronounced non-linearity in the density curve of the positive film in question. In connection with this, the actual value of the steady current of the lamp is of special importance. The density of the enlarged print made from the film negative can in this way be made to approximate very closely the density of the original document, which is the essential requirement for a true reproduction of half-tones. If the facsimile apparatus were to be used only for the transmission of black-and-white images the characteristics of the lamp used would not be very important; the only requirement would be a sufficiently high intensity to expose the film to the necessary degree for the black part of the image.

A further advantage of the mercury-vapour filling is that the maximum luminous flux required is attained for a current of only 70 mA (at a working voltage of 30 V), so that it is possible to feed the lamp from a single output valve of the EL 6 type (argon-nitrogen necessitates three of these valves in parallel).

The design of the lamp used is shown in fig. 3a, whilst a photograph of the lamp is given in fig.3b.

Fig. 3. a) Schematic cross-section, b) photograph of the lamp. A concentrated discharge of relatively high brightness occurs in the narrow tube nozzle between the cathode and the annular anode $A$. Due to the carefully proportioned system of electrodes, the luminous flux is capable of responding accurately to current modulations up to 100 kc/s. The tube is mounted on a molybdenum disc $M$, which also serves for alignment purposes.

To prevent the discharge from taking any path other than through the nozzle the latter is fixed to a molybdenum disc sealed into the glass bulb and dividing the lamp into two separate compartments for the anode and cathode, the connection between these compartments being formed by the nozzle. At the same time this molybdenum disc, which projects outside the wall of the bulb and which can be manufactured with a high degree of precision, facilitates centring of the light-spot exactly in the axis of the rotor in the receiver.

The optical system of the receiver

Fig. 4 is a cross-sectional diagram of the rotor, showing details of the optical system. A set of three mirrors $(S_i)$ arranged around the axis of the rotor transmit radially three beams of light from the stationary lamp at angles of 120°. Each beam is then deflected in a direction parallel to the axis by

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4) The spectral distribution of the light of the mercury discharge is in fact even more favourable than that of argon-nitrogen.
another mirror (\(S_2\)) and is concentrated by a condenser onto a diaphragm. A microscope objective of numerical aperture 0.3 then throws a 4 times reduced image of the diaphragm via a final mirror (\(S_3\)) onto the film.

The numerical aperture of the objective, which together with the brightness of the lamp determines the luminous flux of the light-spot, was not made larger for the reason already given in connection with the transmitter, i.e., the distances must not be too small as otherwise the depth of focus will be insufficient. To manage with the same depth of focus as in the transmitter, the absolute tolerances in eccentricity of the rotor or cylinder, vibration etc. are only 1/6th of those which are admissible in the transmitter, in view of the corresponding reduction in size. In fact these tolerances have to be even closer, since fluctuations in the size of the spot in the receiver are more troublesome than in the transmitter; variations of as little as 20% will give the image a badly striped appearance. The relative dimensions of the three light-spots therefore must not differ more than about 6 microns, and similarly tangential or axial discrepancies in the location of the spot must not exceed 6 \(\mu\). Irregularities in the motion of the film and axial movement of the rotor are subject to the same tolerance. The luminous flux of the three light-spots individually must not differ more than 10%.

To satisfy such requirements it was necessary to maintain a degree of precision in the manufacture of the rotor approaching the limits of practical achievement 9). All the lenses and mirrors as well as the diaphragms are adjustable, so that the proper location, size and brightness of each of the light-spots can be adjusted individually. Axial movement of the light-source as formed in the diaphragm by the condenser, with a diameter of approximately 0.5 mm in order to allow sufficient latitude in the location of the diaphragm. The diameter of the nozzle of the recording lamp is 1 mm, so the image of it produced by the condenser must be reduced 2 times, from which it follows that \(\gamma \approx \frac{1}{2} \beta\), that is \(\gamma > \frac{1}{6} \alpha\). A larger aperture is advantageous, other things being equal.

![Fig. 4. Diagram of one of the three optical systems in the rotor. G stationary recording lamp; \(S_1, S_2\) mirrors; C condenser; \(D\) diaphragm; \(M\) microscope objective; \(S_3\) mirror, recording light-spot on the film F.](image)

![Fig. 5. The light-path in one of the three optical systems, from the light source \(C\) to the recording light-spot \(s\), determining the conditions governing the aperture \(\gamma\) of the light beam. \(C\) condenser; \(D\) diaphragm; \(M\) objective.](image)

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9) Acknowledgements are due to Mr. H. Grandjean Ferrenod-Comtesse of N.V. Philips' Telecommunicatie Industrie, who played a very active part in the mechanical construction of the rotor and other parts of the receiver, notably the above-mentioned punching device.
The shape of the recording spot at the receiver and of the scanning spot at the transmitter

To avoid a striped appearance of the image the lines traced by the three light-spots must not only be actually contiguous but each line, measured across its width, must be of equal density. The light-spot, therefore, must not be round but rectangular. Of course the most obvious shape would then be square, but this does not actually give the best results. Suppose that the transmitter is scanning a grid of black and white lines, which in the idealised case would give a signal consisting of pure square waves, see fig. 6a. The recording spot will vary in brightness in an exactly similar manner, but owing to the finite length of the spot in its travelling direction the transition between black and white will be blurred (fig. 6b). In order to limit this effect the longitudinal dimension in question is made slightly smaller than the width, viz. in the ratio of about 2 : 3. The spot cannot be made much shorter as this would reduce the exposure time at each point on the film below the required level.

If the exposed lines on the film, the centre distances of which are 33 μ, are to be really contiguous, the image of the diaphragm must be slightly less than 33 μ in width; scattering of the light in the film then ensures an effective width of spot of exactly 33 μ.

It must of course be possible to adjust the three diaphragms in the prescribed form and, further, to render each one displaceable as a whole. Each of the diaphragms therefore comprises the aperture between four blades, all lying in the same plane and each one capable of a small amount of adjustment in this plane.

In this connection it should be realised that the requirements imposed by the scanning spot in the transmitter are very different from those to which the recording spot in the receiver must conform. The function of the former is merely to make possible the measurement of the local "blackness" of the document or, in fact, its average value within an area equal to the smallest detail to be transmitted, i.e. a square of 0.2 mm × 0.2 mm. Since we are prepared to accept the fact that no detail will be distinguishable within an area of that size, it is also permissible in principle to assume that the density is uniform within that area. It therefore makes very little difference if the scanning spot covers slightly less than the whole area. In the transmitter it is thus quite permissible to employ a circular spot, which involves much less difficulty in manufacture than the rectangular form. Curiously enough it can be shown that, as far as the scanning spot is concerned, a circular form is actually better for the purpose than a square (or rectangular) form. Let us once more assume the transmission of a black and white grid, in which the width of the lines is equal to the resolving power of the scanning spot (i.e. its "longitudinal" dimension). The resultant signal will not be of rectangular wave-form as argued above, but in the case of a rectangular spot will be triangular or "saw-toothed", see fig. 7a, for when the light-spot

![Fig. 6. a) Idealised signal supplied by the transmitter when scanning a black and white grid. b) Pattern produced on the film by modulation of the luminous intensity of the receiving lamp, in accordance with (a). Owing to the finite width of the recording spot the boundaries between the black and white lines of the grid as reproduced are not sharply defined.](image1)

![Fig. 7. a) Signal produced by the transmitter when scanning a grid as shown, using a rectangular scanning spot (length of spot equal to the width of the grid lines). b) The same as applied to a circular scanning spot (diameter equal to the width of the grid lines).](image2)
moves from a black line to a white one the increase in that part of it which is filled with “white” is linear with time, hence the increase in signal strength is linear from the lowest value ($A$ in the black) to the highest ($B$ in the white). The boundaries between the black and white lines will therefore be reproduced with a lack of definition even if there were no blurring effect caused by the recording spot at the receiver. In the case of a circular spot, however, the luminous flux intercepted in the scanning of the grid follows the sinusoidal (dotted line) curve shown in fig. 7. It is true that the slope at the steepest parts of the gradient, which determines the extent of the blurring, is then exactly the same as in the case of the saw-tooth characteristic, but as the levels of black and white ($A$ and $B$ respectively) must be the same in both cases, after amplification the curve takes the form shown in fig. 7b, from which it will be seen that the slope is now much steeper than that of the saw-tooth curve. The round scanning spot, therefore, ensures better definition.

These considerations apply only where the satisfactory reproduction of half-tones is concerned; for purely black and white images a different method of amplification is employed and the circular scanning spot no longer has any advantage over the rectangular. In this case the signal is actually cut off sharply at top and bottom after suitable amplification and the arbitrary cut-off levels are employed as “black” and “white” respectively. This, however, brings us into the province of the electrical circuits, which are to be reviewed in the following article.